Automatic Control of Manufacturing Variation Propagation

PhD in Manufacturing Engineering

James Tudor, BEng

A thesis submitted for the degree of
Doctor of Philosophy



Department of Mechanical, Materials and Manufacturing Engineering

University of Nottingham

Abstract

Manufacturing variation and its propagation is an ever-present challenge for assembly. Nowhere is this a more difficult problem than in the aerospace industry. An industry where components are large and complex and tolerances are tight. This difficulty has halted the aerospace industry's progress towards greater automation, cheaper production and faster production rates. There is a lack of research considering automatic manufacturing variation control methods that are active during the production process: both for part-to-part assemblies and fixtured assemblies.

This research addresses this gap by developing a novel and generalised data model, complete with two adaptive methodologies; one for each of the two types of assembly. The data model, drawing upon object-oriented programming techniques, improves upon the traditional static design approach to manufacturing and replaces it with a dynamic, adaptive and machine-readable model-driven approach. When supplied with metrology data, the data model monitors and automatically corrects the state of the key characteristics of assemblies effected by manufacturing variation. The first methodology leverages the data model to enable adaptive part-to-part assembly in low-tolerance applications. Applications such as those found in the aerospace industry, where part-to-part assembly can vastly reduce tooling and gauge costs and decrease assembly lead times. The second methodology enables the automatic control of multiple key characteristics for metrology-guided robotic assembly in low-tolerance applications. In addition to this, the methodology does not rely on any prior known mathematical or mechanical relationships. This ensures the methodology is robust to: variation in the components, location errors of the fixture and assembly robot, and errors in the pickup location between the robot and the component being assembled. This robustness to location errors is used to enable high-precision mobile assembly systems and reconfigurable/flexible factories. Ultimately, this work is a paradigm shift for the assembly of aerospace components. It provides generalised approaches to either flexibly and robustly automate the existing techniques of aerospace assembly using only off-the-shelf automation, or it circumvents the traditional challenges by enabling adaptive part-to-part assembly.

The thesis achieves this by following a structured research methodology. The research methodology focuses on three research objectives which have been developed from knowledge gaps identified from a review of the current literature. The thesis details each of the contributions in their respective chapters and each objective has been verified and evaluated against aerospace requirements by implementing technical demonstrators. An example of adaptive part-to-part assembly is presented for aerospace applications. It also presents two instances of metrology-guided robotic assembly systems; also for aerospace application. The first is a

static robot cell where the fixture is mobile and the second is a mobile assembly robot with a static fixture. All demonstrators focus on rib-to-wing box assembly, since it is the most prevalent of primary structure assembly operations on each aircraft.

This thesis provides an automated and flexible approach to controlling manufacturing variation and its propagation during production. This is shown via capability studies applied to each of the technical demonstrators presented in this thesis. These studies validate that both of the methodologies presented are repeatable and capable of aerospace requirements. They also validate the practicality of the overall adaptive approach enabled by the data model developed in this thesis.

Acknowledgements

Firstly, I would like to thank my supervisors Prof. Svetan Ratchev and Prof. Atanas Popov for their support and guidance throughout the PhD process. Their knowledge, expertise and experience kept me from straying too far from the central theme of this thesis and ensured that timely progress was made.

I would like to thank Dr. Joseph Griffin for the expertise, advice and support he has generously given both on the page and in the workshop. His example and guidance were valuable for both my PhD and the industrial research projects I work on. I would also like to specifically thank him for masterminding and coordinating the VADIS project demonstrators some of which are showcased in Chapter 5.

Many thanks to Dr. Alison Turner for keeping a firm hand on the tiller, her patience, and for guiding me through the administrative labyrinth of the university. I would also like to thank her for her advice and support both technical and otherwise.

I would also like to extend a thank you to my colleagues at the Centre for Aerospace Manufacturing (CAM) and the Precision Manufacturing Centre (PMC) for sharing a friendly and helpful working environment.

I would like to thank Aled Hooson and Kevin Forster at Airbus Broughton for their support and advice on all things metrology, tooling and aerospace manufacturing. I would also like to thank them for being a continuous and selfless voice of reason. I would also like to specifically thank Aled for his direct support on the AutoRamp project and for providing additional validation for the methodology developed in Chapter 6 with a laser tracker setup. Although not discussed in this thesis, the results provided additional clout and confidence as well as being a very jovial experience.

Finally, a special thanks to Darren Culshaw without whom none of this would have been possible. His support, flexibility, patience, technical knowledge, advice, and most importantly his no-nonsense approach have been immensely valuable and a great source of guidance. Thank you.

Contents

Abstract i

Acknowledgements iii

List of Figures x

List of Tables xi

List of Abbreviations xii

Nomenclature xiii

1 Introduction 1
- 1.1 Background and Motivation . . . 1
- 1.2 Research Aim . . . 2
- 1.3 Research Objectives . . . 3
- 1.4 Applications of Research . . . 3
  - 1.4.1 Scope of Application . . . 4
- 1.5 Thesis Structure Overview . . . 6

2 Literature Review 8
- 2.1 Introduction . . . 8
- 2.2 Manufacturing Variation and its Propagation . . . 8
- 2.3 Mechanical Assemblies . . . 9
  - 2.3.1 The Key Characteristic . . . 10
  - 2.3.2 Type 1 and Type 2 Assemblies . . . 10
  - 2.3.3 Traditional Approach to Aero-Structure Manufacture . . . 11
- 2.4 Controlling Variation Propagation in Mechanical Assemblies . . . 12
- 2.5 Flexible and Active Manufacturing Technologies . . . 17
- 2.6 Metrology-Assisted Processes . . . 19
- 2.7 Enabling Part-to-Part Assembly . . . 23
- 2.8 Assembly Modelling for Manufacturing and Industry . . . 24
- 2.9 Discussion . . . 27
- 2.10 Chapter Summary . . . 28

3 Research Methodology 29
- 3.1 Introduction . . . 29
- 3.2 Research Approach and Contributions . . . 30
- 3.3 Evaluation and Verification . . . 35

3.4 Scope of Research . . . 37
3.5 Selected Use Cases . . . 38
3.6 Chapter Summary . . . 40

4 Data Model for Automatic Variation Propagation Control 41
4.1 Introduction . . . 41
4.2 Automatic Adaptive Assembly . . . 42
4.3 Data Model Overview . . . 45
4.3.1 Introduction to the Object-Orientated Paradigm . . . 47
4.4 Spatial Elements . . . 48
4.5 Data/Context Elements . . . 50
4.5.1 Common Behaviours . . . 50
4.5.2 Structure Elements . . . 50
4.5.3 Connection Elements . . . 52
4.6 Solution/IO Elements . . . 54
4.6.1 KCsolver . . . 55
4.6.2 Metrology Integration Forms . . . 55
4.6.3 Automatic Generation of a Data Model . . . 57
4.6.4 CAD File Output . . . 58
4.6.5 Direct Machine Control . . . 59
4.7 An Illustrative Example . . . 60
4.8 Chapter Summary . . . 63

5 Automatic Variation Propagation Control in Part-to-Part Assemblies and Technical Demonstrator 65
5.1 Introduction . . . 65
5.2 Adaptive Part-to-Part Assembly . . . 66
5.3 Methodology Overview . . . 67
5.4 An Illustrative Example . . . 69
5.4.1 Adaptation Phase . . . 70
5.4.2 Output . . . 73
5.5 Technical Demonstrator . . . 74
5.5.1 Key Characteristic Solution Routine . . . 76
5.5.2 Interfacing Surfaces . . . 78
5.5.3 Prototype Software . . . 79
5.5.4 Methodology Trial . . . 81
5.5.5 Results . . . 82
5.5.6 Full-Scale Demonstrator . . . 84
5.6 Chapter Summary . . . 84

6 A Control Methodology for Setting Multiple Key Characteristics For Robotic Assembly 86
6.1 Introduction . . . 86
6.2 Multiple Key Characteristic Control for Robotic Assembly . . . 87
6.3 Methodology Overview . . . 88
6.3.1 Multi-Key Characteristic Control Method . . . 89
6.3.2 Job File Parsing . . . 92
6.3.3 Component Referencing Routine . . . 93
6.3.4 Assembly Paths . . . 94

6.4 An Illustrative Example: Robotic Aerospace Rib Positioning 98
6.5 Chapter Summary 110

7 Technical Demonstrators for Robotic Assembly 111
7.1 Introduction 111
7.2 Presentation of Demonstrators 113
7.2.1 Test Cell 1 113
7.2.2 Test Cell 2 117
7.3 Methodology Validation & Evaluation 120
7.3.1 Experimental Procedure 120
7.3.2 Results of Demonstrators 121
7.3.3 Robot Pose Repeatability 126
7.3.4 Process Capability Analysis 128
7.4 Chapter Summary 132

8 Conclusions and Future Work 133
8.1 Introduction 133
8.2 Review of Aims and Objectives 133
8.3 Contributions 135
8.4 Future Work 138
8.5 Concluding Remarks 139

A Detail Definitions of Data Model Classes 150
A.1 Introduction 150
A.2 Core Elements of the Data Model 150
A.2.1 Data Types 151
A.2.2 Frame Class 152
A.2.3 J_Object Class 154
A.2.4 Connection Class 155
A.3 Modelling Products 155
A.3.1 Part Class 156
A.3.2 Assembly Class 161
A.3.3 Modelling Assembly Connections 163
A.3.4 Data Model Summary 177

B Quantitative Analysis and Simulation of Adaptive Part-to-Part Assembly 182
B.1 Introduction 182
B.2 Analysis in a Single Degree of Freedom 184
B.3 Analysis of Representative Assembly Joints 187
B.4 Analysis of Larger Assemblies 188

C Data Model Extension: Metrology Objects 194
C.1 Introduction 194
C.1.1 Data Model Extension: Metrology Objects 194

D Job File for Test Cell 1 198

E Job File for Test Cell 2 202

List of Figures

2.1 Overview of information model structure for Dantan et al. 15
2.2 Example of numerically controlled programmable fixturing element 18
2.3 Example of force controlled robotic assembly of a demonstrator rib to a simulated wing box 18
2.4 Swarm fixture example 19
2.5 Single key characteristic control of hinge line alignment using metrology guide positioning 21
2.6 Metrology-guided robot example 22
2.7 Object-Orientated Approach to Assembly Modelling 25
2.8 Feature-based assembly model for an example product depicting greater information concerning the relationships between object in the model 26

3.1 Overview of Research Methodology. 32
3.2 Overview of aircraft wing box assembly 40

4.1 Comparison of (a) the current approach to manufacturing aerospace structures. And, (b) the adaptive approach enabled by the data model. Here, dedicated and independent metrology feedback loops are enabled for each instance of manufactured product. The number of iterations, state of the data model, and the derived manufacturing data will be different for each product. This is in stark contrast to (a) where all products are manufactured to the same immutable manufacturing data, regardless of the deviations of the manufactured components. 44
4.2 Overview of the major elements required to construct the data model. 46
4.3 Cross-section of the generic structure of the data model. Each structure element can be linked to be any number of *connection* elements. They only exception is the *parent* connection of which an element can only have one. 47
4.4 A visual representation of the transform ${}^{A}T_{B}$ which describes the pose of frame B from frame A. 49
4.5 A visualisation of a kinematic network created from linked *frames*. . 49
4.6 A general definition of a standard hole. 51
4.7 A general definition of a standard pad. The pad has been defined in the same system as a simple hole. 51
4.8 Diagram of a single *part* object consisting of several *feature* and *geometry* objects. All the arrows are *parent* connections. 52

4.9 Diagram of a single *assembly* object assembling two *part* objects. The black arrows are *parent* connections, the green arrows are *key characteristic* connections, and the red arrows are *join* connections. 53
4.10 A visualisation of the join connection. Two holes on two separate parts are bolted together. The mechanical connection provided by the bolted joint is modelled via a join connection. 54
4.11 Diagram detailing the encoding of measurement data and metadata. It also expresses the relationship between the format of the encoding and the data model structure itself. 56
4.12 (a) Simplified example of rear spar to trailing edge rib assembly. (b) Overview of the key geometry for the trailing edge rib. (c) Overview of the key geometry for the rear spar section. 60
4.13 Overview of key characteristics and tolerances for the rear spar-to-rib assembly. (a) Key characteristics in the X-Y plane. (b) Key characteristic in the X axis. 61
4.14 Diagram of the data model for the product shown in Figure 4.12(a). 62

5.1 Overview of the adaptive variation propagation control methodology. 68
5.2 Simple assembly example. It is an assembly of two plates. They are joined together by two pairs of dowelled holes. 70
5.3 Overview of the methodology operating in the assembly upon Figure 5.2. The green lines indicate the measured values of Part *A* and the dotted lines indicate the nominal values of Part *A*. (a) State of the data model after the metrology data is imported. (b) State after key characteristics have been adapted to nominal. (c) State at the conclusion of the methodology. 71
5.4 Visualisation of the *join* object being used to determine the corrective transform for a hole on part *B*. 73
5.5 Representative case study of a rib to wing cover assembly. 74
5.6 Diagram detailing the assembly requirements (key characteristics) for the rib to wing cover assembly. This type of diagram is sometimes referred to as a build philosophy. 75
5.7 Diagram of the optimisation problem for minimising the sacrificial material between the wing cover and the rib body. 77
5.8 Image of the GUI for the prototype software. The prototype software automatically generates a data model and implements the variation control methodology by adapting the data model. It outputs adapted CAD models to achieve variation propagation control. . . . 80
5.9 Folder structure which takes the places of a traditional database. . . 80
5.10 Manually fabricated, drilled and reamed rib cover. 81
5.11 Final assembly of the rib cover to the rib body. 82
5.12 Diagram detailing the measured gap and the location of the measurement on the final assembly. Where "NG" refers to no gap or the gap was too small to be measured. All measurements are in millimetres. Each gap is the value presented in the diagram or within +0.05 mm larger than it. Since 0.05 mm was the smallest resolution of measurement available on the feeler gauges. 83

5.13 Full-scale demonstrator for the metrology-enable adaptive assembly methodology. 84

6.1 Overview of the methodology. 89
6.2 Overview of the adaptive variation propagation control method at the focus of this methodology. The "Key Characteristic Routine" here refers to the sequential use of *KCsolver* algorithms to digitally find the solution to the set of key characteristics. This is discussed in detail in Section 6.4. 91
6.3 Visualisation of the general definition of an adaptive assembly path. 95
6.4 Overview of the methodology if an assembly path has been provided in the job file. 97
6.5 Overview of an general example of a rib-to-wing box assembly. (a) Overview of typical component geometry. (b) Key features on the wing box sub-assembly. (c) Key features on a typical aerospace rib. (d) Key characteristics between the key features. 99
6.6 Flowchart of the key characteristic solution routine (*Key Characteristic Routine* in Figure 6.2) for the automatic rib positioning application. 100
6.7 Flowchart of the general *KCsolver* method used for setting a single key characteristic. 101
6.8 Visualisation of the plane to plane align problem within the data model's spatial network. 101
6.9 Temporary frame generated upon the key characteristic geometry. . 102
6.10 Visualisation of the modification to the data model's frame network to correct a key characteristic, using the temporary frame generated from the key feature geometry. 103

7.1 Test Cell 1 setup. 113
7.2 Layout of Test Cell 1. 114
7.3 The aerospace rib used to demonstrate the assembly operation. The rib has been fitted with metrology facilities and photogrammetry targets for automatic measurement and live tracking. Note: the tooling nests have been fitted for the laser tracker cross-reference experiment and are not necessary for the methodology to function. . 115
7.4 The aerospace rib and demonstrator wing box whilst mounted upon the robotic manipulators. 115
7.5 Overview of the key characteristics for the assembly operation in Test Cell 1. 116
7.6 Image of a metrology tooling pin used to measure the intersection of the hole vector and the contact surface. 117
7.7 Test Cell 2. 118
7.8 The aerospace rib used to demonstrate the assembly operation. The rib has been fitted with metrology facilities and photogrammetry targets for automatic measurement and live tracking. 118
7.9 Overview of the key characteristics for the assembly operation in Test Cell 2. 119

7.10 The final measurement results of the four key characteristics for Test Cell 1. The green and blue lines are the aerospace tolerance and control tolerance, respectively. (a) The results of the primary key characteristic. The coloured crosses are each associated with the average measurement of one of the points on the datum plane of the rib. (b) The results of the secondary B1 key characteristic. The bold blue cross is the average measurement of the key characteristic, the coloured crosses are the associated measurements. (c) The results of the secondary B2 key characteristic. (d) The results of the tertiary key characteristic. 123
7.11 Image of the the rib with all key characteristics set in Test Cell 1. . 124
7.12 The final measurement results of the four key characteristics for Test Cell 2. The green and blue lines are the aerospace tolerance and control tolerance, respectively. (a) The results of the primary key characteristic. The coloured crosses are each associated with the average measurement of one of the points on the datum plane of the rib. (b) The results of the secondary B1 key characteristic. The bold blue cross is the average measurement of the key characteristic, the coloured crosses are the associated measurements. (c) The results of the secondary B2 key characteristic. (d) The results of the tertiary key characteristic. 125
7.13 Image of the the rib with all key characteristics set in Test Cell 2. . 126
7.14 Standard deviations for the robot wrist frame in Test Cell 1, as measured from its internal joint encoders. The base frame of the robot is the reference system. (a) Translational standard deviation. (b) Rotational standard deviation. 127
7.15 Comparison of the process repeatability as measured by the robot against the applied tolerance for Test Cell 1. 128
7.16 Standard deviations for the robot wrist frame in Test Cell 2, as measured from its internal joint encoders. The base frame of the robot is the reference system. (a) Translational standard deviation. (b) Rotational standard deviation. 129
7.17 Comparison of the process repeatability as measured by the robot against the applied tolerance for Test Cell 2. 129

List of Tables

7.1 Summary of the key characteristics for the assembly in Test Cell 1. 117
7.2 Summary of the key characteristics for the assembly in Test Cell 2. 120
7.3 Measurement error analysis for Test Cell 1. All values are in millimetres 130
7.4 Measurement error analysis for Test Cell 2. All values are in millimetres 130
7.5 Process capability analysis for Test Cell 1. 131
7.6 Process capability analysis for Test Cell 2. 131

List of Abbreviations

2D	Two Dimensional
3D	Three Dimensional
AGV	Autonomous Guided Vehicle
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CMM	Co-ordinate Measurement Machine
CNC	Computer Numerical Control
DIY	Do It Yourself
DOF	Degrees of Freedom
DRW	Drawing
DTI	Dial Test Indicator
ENG	Engineering
FINS	Factory Interface Network Service
GUI	Graphical User Interface
IO	Input and Output
KC	Key Characteristic
KCs	Key Characteristics
MAA	Metrology-Assisted Assembly
NC	Numerical Control
PDU	Power and Data Unit
PLC	Programmable Logic Controller
SQL	Structured Query Language
UML	Unified Modelling Language
XML	Extensible Markup Language

Nomenclature

$^{\mathbf{A}}\mathbf{T}_{\mathbf{B}}$	Transformation from reference frame **A** to reference frame **B**
$^{\mathbf{A}}\mathbf{T}_{\mathbf{A}'}$	Transformation from reference frame **A** to the next iteration of **A**
$^{\mathbf{A}}\mathbf{T}_{\mathbf{A}^*}$	Transformation from reference frame **A** to the ideal location for frame **A**
$\mathbf{p_i}$	The i^{th} point vector
$\mathbf{p}'_\mathbf{i}$	Next iteration of the i^{th} point vector
$\mathbf{v_i}$	The i^{th} direction vector
$\mathbf{c_i}$	The i^{th} centre point vector
$\mathbf{q}$	Point vector
α, β, γ, k	Scalar multipliers
θ	Angle (rad)
$\mathbf{n_i}$	Normal vector to the i^{th} plane
$\hat{\mathbf{n}}_\mathbf{i}$	The unit vector coincident with the normal vector $\mathbf{n_i}$
$\mathbf{Rot}(\theta)_\mathbf{i}$	Rotation matrix about the i^{th} axis by an angle of θ
$\mathbf{A}^*$ or $\mathbf{A}_*$	The ideal solution for the location of frame **A**
$distance_{perp}$	The perpendicular distance between a point and plane (scalar)
$\mathbf{v_{perp}}$	The vector form of the perpendicular distance between a point and plane
$\mathbf{v_{offplane}}$	The component of $\mathbf{v_{perp}}$ which is not on the interface plane
$\mathbf{v_{inplane}}$	The component of $\mathbf{v_{perp}}$ which is on the interface plane
$\mathbf{pln_i}$	The i^{th} plane
σ	Standard deviation (typically in mm)
σ_m	Standard deviation of measurement (typically in mm)
σ_p	Standard deviation of total process (typically in mm)
C_p	Process capability index
C_{pk}	Process capability index
C_{pku}	Process capability index (upper band)
C_{pkl}	Process capability index (lower band)
$\bar{x}$	Mean of measurement dataset for measurand x

Chapter 1

Introduction

Assembly is the keystone of manufacturing. It is the process that either validates all preceding design, engineering and manufacturing operations, or it is the point that creates heart-wrenching disappointment when two parts simply can not fit together. Poorly engineered assembly operations have expensive repercussions, invariably resulting in: component rework, modification of components and tooling, and re-engineering of manufacturing operations [1]. Unlike its counterpart machining, assembly has received far less research attention which is unusual as single-part products are rare; crowbars and cutlery are notable exceptions.

1.1 Background and Motivation

The aero-structures industry is characterised by large and complex assemblies with tight tolerances applying over great distances. Traditional manufacturing methods have overcome these challenges with monolithic major assembly jigs, rigidly designed fixtures and tooling methods whom themselves are accurately set or machined, implying that the produced assemblies are too. Adjustable assembly processes, such as fettling, shimming and rigging in combination with gauges to accommodate tolerances beyond the capability of their methods [2]. However, these approaches are costly, inflexible and difficult to automate; resulting in expensive redesign and modification of jigs and tooling when: the product design is modified, faults in the assembly process are identified or variation propagation becomes too great [3]. It is these costs, in combination with a desire to decrease production lead times, that have pushed the aero-structures industry to seek new technologies and approaches to control the variation of propagation without relying on traditional methods [4].

Muelaner et al. [5] summarise the practical challenges the industry must overcome to achieve low-cost and high-quality aero-structures assembly. These are:

part-to-part assembly, low-cost flexible tooling and automation, traceable quality assurance and control, elimination of excess weight, and more accurate aerodynamic profiles. It is part-to-part assembly and low-cost flexible tooling and automation which are most pertinent to this thesis. However, the remaining three challenges are natural outcomes and further developments from it. A significant amount of research has already bore excellent results towards low-cost flexible tooling and automation [6, 7, 8, 9, 10], providing both flexibility and incentive to develop new approaches for automation in aero-structures assembly. Moreover, it highlights the growing use and reliance of the industry on metrology equipment; not only as quality assurance and certification but as a key driver during the manufacturing process [11]. This is a trend that is still currently in-progress [12]. Despite the newly available technology, new methodologies taking advantage of them have largely not been researched. Moreover, part-to-part assembly and flexible autonomous assembly have remained inaccessible for the aero-structures industry.

Alternate approaches aim to study variation propagation in aero-structures before metal (or composite) is cut. Resulting in more intelligently designed products that are robust against variation, with sensibly allocated tolerances using the most appropriate manufacturing resources [13, 14, 15, 16]. Although, these methods are useful at the product design phase, they have few applications once the initial product design is complete. Furthermore, they fail to capitalise on the achievements towards low-cost flexible tooling and automation.

It is the combination of these two major streams of effort that is the subject of this thesis. The first, focuses on developing new technology to decrease the reliance on traditional tooling and fixturing approaches. And the other, modelling and analysing to identify, diagnose and study manufacturing variation propagation. It is at the cross-over of these approaches that novelty and immediately beneficial progress can be made for the aero-structures industry. This thesis will investigate novel approaches to automatically control manufacturing variation propagation in mechanical assemblies during their production.

1.2 Research Aim

Manufacturing variation and its propagation in mechanical assemblies, especially in aero-structures assembly, is a major challenge. It creates a number of difficulties for the aerospace industry and its current methodologies for achieving successful product assembly are:

- expensive and heavily reliant on fixtures, tooling and gauges;

- labour-intensive and difficult to automate;
- inflexible and rigid;
- and, preclude part-to-part assembly techniques.

The aim of this thesis is to develop novel approaches to automatically control and manage manufacturing variation propagation in mechanical assemblies during their production. The work will develop this approach with the aerospace industry in-mind and ensure all methods are evaluated against the typical tolerances applied in this industry. It shall demonstrate this automated variation control for both types of assembly: fixtured assembly which is the typical form of assembly in the aerospace industry; and, part-to-part assembly which at present is not utilised for major aero-structures assembly, since it is not capable of achieving the required tolerances. Mechanical assemblies, the two types of mechanical assembly and other key terminology are defined at the beginning of Chapter 2. Achieving this aim of automatically controlling manufacturing variation propagation during production will remove the limitations mentioned above from aero-structures manufacturing.

1.3 Research Objectives

The knowledge gaps, identified and discussed in Chapter 2, have been rewritten as research objectives to focus the efforts of this thesis and develop an actionable research approach towards completing the aim of the thesis. That is, the development of novel approaches to automatically control and manage manufacturing variation propagation in mechanical assemblies during their production. The research objectives are listed below:

1. Develop a generalised data model for the automatic control of manufacturing variation propagation in mechanical assemblies.
2. Develop and validate an automated methodology for controlling manufacturing variation propagation in part-to-part assemblies.
3. Develop and validate an automated methodology for simultaneous control of multiple key characteristics of fixtured assemblies.

1.4 Applications of Research

This section discusses the future application of this research. The data model and the associated manufacturing approach that comes with it, form the basis of an

automated manufacturing variation management system. The methodologies on the other hand can be thought of as additional tools for a manufacturing engineer. A manufacturing systems engineer can utilise it when designing the manufacturing operations for a product. Moreover, this approach and methods can be applied retrospectively to existing products that are in need of greater variation control or automation.

The research in this thesis present immediate benefits for manufacturing engineers and manufacturing system designers. The methodology in Chapter 5 should be utilised to convert as many fixtured assemblies as possible into part-to-part assemblies. This will reduce production lead times and remove the requirement for expensive and high-tolerance fixtures, tooling and gauges. Where this cannot be done, the methodology in Chapter 6 is to be employed to at least automate the process and the variation propagation control. This methodology also removes any requirement for expensive and high-tolerance end effector tooling and fixtures. If neither methodology is appropriate for a particular operation, utilising the data model (Chapter 4) as the backbone of the manufacturing system still provides a structured approach to automatically collecting metrology data from the results of manufacturing resources. This data could be used further down the line by one of the methodologies mentioned above, or it could just be used for typical manufacturing system improvement.

This research also presents a number of advantages for the product designer as well. This work enables the dimensions of a product to adapt to measured variations. This enables the typical tolerance requirements for aerospace parts and assemblies to be loosened. They can be loosened since the applied tolerances of the parts and assemblies that form the chain of features for any particular key characteristic have been partially decoupled. Since, the achievable tolerance for a key characteristic is no longer the sum of the tolerances on the parts that construct it. The decoupling, enabled by this research, can be used to reduce the cost of aerospace components and the resulting sub-assemblies. The relaxed approach to tolerancing also extends to the pickup features used by automation for positioning. The methodology in Chapter 6 determines these relationships during production.

To summarise, the work presented here is another step towards a fully automated production line for aero-structures manufacturing. Which in itself is a step towards cheaper and better quality aircraft at increased production rates.

1.4.1 Scope of Application

Given the discussion above, it is also worth discussing the scope of this work with respect to applying it and scaling it up for industrial demands. The data model is

applicable to any mechanical assembly but it is only worth utilising if the product being manufactured suffers from difficult to achieve key characteristics and accumulations of manufacturing variation. This will likely limit it to larger assemblies such as those in the space, aerospace, ship and transport industries. And, of those industries it will again be useful to those where tolerances are tight enough to warrant novel approaches to variation control, making the aerospace and space industry its main audience. However, this may change if western manufactures decide to revitalise their train, car and ship building capabilities; perhaps targeting the luxury variant markets as a start.

Using the data model and the two methodologies developed in this thesis demand significant data input and using the data requires significant computation. This thesis has validated the methodologies on a single assembly operation from number of demonstrator products. So how this approach would affect a product's manufacturing system and organisation if it was to be used at multiple stages has not been investigated and is an interesting avenue for future research. That said, the aerospace industry manufactures at a rate far slower than those of most other industries and as such the work in this thesis has always represented a significant increase in production rate. However, it is possible that the automation enabled by this thesis increases production rates to a point where the computation and data gathering required for the data model driven approach becomes the limit for production rates. At this point the manufacturer will need to balance the number of assembly operations which utilise the adaptive capabilities of the data model driven approach and those which do not. It is envisioned that the methodologies presented in this thesis are to be used strategically at key points in a product's manufacture where high tolerance key characteristics are required and traditional methods of variation control are unavailable, uneconomical or impractical. Moreover, it can also be used to loosen the engineering requirements of difficult and expensive sections of a product's manufacture by introducing this adaptive approach after it. Correcting and controlling the increased variation introduced by cheaper and less controlled parts and sub-assemblies.

Lastly, a final discussion revolves around product design and how it plays a significant role in extracting the full benefits of this adaptive approach. The methodologies developed in this thesis utilise aerospace designs that had the adaptive approach in mind. This achieves more efficient assembly operations and maximises the benefits of an adaptive manufacturing approach. The adaptive part-to-part methodology developed in Chapter 5 operated on a wing box product with ribs designed to have sacrificial material on each of the rib feet surfaces. This enabled the methodology (in addition to setting all the key characteristics and matching the full-size assembly holes) to minimise the gap conditions between the rib feet and

wing cover eliminating the requirement for shimming. Shimming is a time consuming manual operation required to remove any voids between mating parts. The methodology itself is not limited by the design decision to include the sacrificial material or not. But, it does make the overall process less viable if the rib is adaptively machined to achieve a set of key characteristics and part-to-part assembly but the time-consuming manual process of shimming is still required afterwards. Likewise, the automatic component positioning methodology in Chapter 6 also benefits from a rib design which only has rib feet on one side. This is because the interface on the wing box is designed to be a lap joint. This reduces the use of shim to only the bottom cover and the gap can be minimised by biasing the rib position towards the exposed spar heels. The variation of the clearance to the upper cover is washed-out into the lap joint. In both these examples the design of the product has a large role to play in maximising the benefits of this data-model driven approach and without significant benefits it is not likely to disrupt the status-quo. This thesis presents the means to automatically control manufacturing variation by adaptively changing the designs of components and assembly operations during production. Future research will need to consider how best to use this new paradigm to design new products and assembly sequences that leverage these advances and maximise its benefits. Moreover, other avenues of research should consider how best to integrate this approach retrospectively on existing products in need of greater automation, increased production rates, and decreased production costs.

1.5 Thesis Structure Overview

The following paragraphs provide a brief overview of the chapters in this thesis:

Chapter 1 discusses the motivation for the research. It also presents the aim of the thesis.

Chapter 2 provides a discussion of prerequisite material and current literature is presented. With the aim of this thesis in mind, the chapter reviews the current advances manufacturing variation control methods. This review leads to further investigations into the current research of manufacturing technologies and manufacturing methodologies for the aerospace industry. The review reveals a lack of automated methodologies that control variation propagation during production. The chapter concludes with a summary of the knowledge gaps this thesis will answer.

Chapter 3 outlines the research objectives designed to answer the knowledge gaps identified in the literature review. It also presents the research methodology followed throughout this thesis to achieve each of the research objectives. The assumptions and scope of the thesis are given and a discussion of the verification of the work discussed.

Chapter 4 presents the data model intended to implement a paradigm change for aero-structures manufacturing. The data model is a single machine-readable and editable entity that is part data structure and part mathematical model, and encompasses all the information required to manufacture a product. It is a radical change from the current approach of human-readable manufacturing data which is spread across several formats. The data model enables an automated feedback loop between production output and the data driving the production. This novel format and feedback loop is the foundation upon which automated manufacturing variation propagation control methodologies can be developed.

Chapter 5 develops an automated manufacturing variation control methodology for part-to-part assemblies. The methodology is defined and an illustrative example given, building upon the data model presented in Chapter 4. The methodology is then verified by implemented a prototype software and by using it produce a technical demonstrator. The technical demonstrator implements a rib-to-wing box assembly operation using adaptive part-to-part techniques made possible by the methodology developed.

Chapter 6 develops an automated, multiple key characteristic control methodology for fixtured assemblies. The chapter develops the core methods which when aggregated, form the whole automated methodology. It builds again upon the data model approach presented in Chapter 4. The chapter concludes with a discussion of a rib-to-wing box assembly example. This example is related to the technical demonstrators shown in Chapter 7 which validate this methodology.

Chapter 7 details two technical demonstrators designed to verify and evaluate the methodology developed in Chapter 6. The technical demonstrators both implement an automated rib-to-wing box assembly operation utilising a robotic manipulator and a metrology device. An experimental procedure evaluates the capability of the methodology against aerospace assembly tolerances.

Chapter 8 gives a summary of the knowledge contributions of the thesis and reviews the research objectives and research aim against the presented content, together with directions for future work.

Chapter 2

Literature Review

2.1 Introduction

This chapter will discuss the background material and review the current literature concerned with controlling variation propagation. The purpose being to identify several knowledge gaps in the current body of work that can be answered by this thesis. Beginning first with a discussion of manufacturing variation itself in Section 2.2. This is followed with a discussion, presented in Section 2.3, of the major concepts concerning mechanical assemblies and the current approach to manufacturing aero-structures. Following this, Section 2.4 discusses the approaches in current literature directly seeking to control the variation in mechanical assemblies; of which aero-structures assembly is a subset. Reviewing this literature leads into investigating flexible assembly technologies (Section 2.5), metrology-assisted processes (Section 2.6), methods of enabling part-to-part assembly (Section 2.7) and assembly modelling approaches (Section 2.8). Section 2.9 presents a discussion of the limitations of the current literature and provides a summary of the knowledge gaps this thesis answers.

2.2 Manufacturing Variation and its Propagation

Manufactured components invariably deviate from their nominal design. This deviation is called manufacturing variation and it typically occurs unpredictably. It originates from random variations in the parameters underlying the manufacturing processes. Parameters such as temperature, tool wear, machine repeatability and random defects in the material, to name only a few, all contribute to the variation experienced in the component's final dimensions and geometry. This manufacturing variation accumulates as components are assembled together, causing large

variations in the dimensions critical to the final product (also known as key characteristics). This is central to the challenge in the aerospace industry, since tolerances are tight and the components large and complex. The tolerances applied to the key characteristics of its assemblies are quickly exceeded if manufacturing variations are left to accumulate.

There are several approaches to mitigating the issue of manufacturing variation and its propagation throughout assemblies, these include but are not limited to:

- Develop more accurate manufacturing methods to reduce the magnitude of variation.
- Develop flexible and adjustable assembly methods to reduce the propagation at the point of assembly.
- Design products with greater robustness to variation to allow for greater accumulation within the product without invalidating its purpose (or reducing its market value).
- Design methods of intelligently allocating tolerances to avoid applying unnecessary controls and limits.

All of these approaches are present in the aerospace industry. But, their current implementations are slow, laborious and expensive. Specialist manufacturing centres use bespoke machines and production processes to produce aero-structures components to within sub-millimetre accuracy. Bespoke jigs and tooling, complete with vast arrays of gauges, enable manually adjustable assembly techniques to correct excessive deviations between mating parts. Despite this, the complex nature of the product still requires additional manual adjustments such as shimming (filling voids between components) and fettling (removing excessive material) after assembly has concluded. And, to enable all this, massive major assembly jigs ensure the shortest possible tolerance stacks available to the product's design. These approaches are slow, expensive, inflexible and require a great deal of manual labour; both on the shop floor and by the engineering teams supporting them. It is these costs and limitations that have led both the academic and industrial research communities to seek of alternate approaches and technology towards controlling the variation in aero-structures assembly or automate existing approaches.

2.3 Mechanical Assemblies

Mechanical assembly occurs when two components, that is a stand-alone part or sub-assembly, are joined together. This join, or joint, could be a weld, fastener

(bolt or rivet) or simply a glued bond. The main point is that after the assembly operation the two components are rigidly constrained to each other; where the degrees of freedom constrained depends on the definition of the joint. The objective of good mechanical assembly is to do this in such a way that the intended assembly after the operation meets the requirements specified by the designers and engineers. This process repeats, in an almost recursive manner, such that parts and sub-assemblies are aggregated and themselves assembled together until a final product emerges from the assembly line.

2.3.1 The Key Characteristic

The quintessential definition of a key characteristic comes from Thornton [17]: "Key characteristics are the product, sub-assembly, part, and process features whose variation from nominal significantly impacts the final cost, performance (including the customer's perception of quality), or safety of a product. Special control should be applied to those key characteristics if the cost of variation justifies the cost of control."

This definition is widely accepted and practised in the aerospace industry where the success of a manufacturing or assembly operation is decided with measurements of, or between, a key subset of all the available features on the part or assembly. If the key characteristic is out of tolerance the item must be reworked or scrapped at great cost to the company.

It is often the case, however, that an assembly will have multiple key characteristics that must all be met simultaneously. However, prioritising one key characteristic comes at the cost of another; this is known as a "key characteristic conflict". This situation is highly likely as the final assembly's key characteristics are an aggregate of multiple sub-assemblies and ultimately parts, each with their own sets of key characteristics whose relationships to each other are unlikely to be advantageous.

2.3.2 Type 1 and Type 2 Assemblies

Mantripragada and Whitney [18, 1] describe two categories of mechanical assembly which is helpful to understanding how variation accumulates and propagates.

An assembly where all the interfaces and joints between the components are created during their respective machining, forming or fabrication processes is known as a Type 1 assembly. These will be referred to a part-to-part assemblies in this thesis. Since, the variation in the final assembly is completely defined by the variation of the mating features of the parts.

In the aerospace and automotive industry it is commonplace to fixture or offer-up components relative to each other with tooling, jigs or gauges, setting the desired characteristics before creating the joints between them to lock-in this relationship. Mantripragada and Whitney refer to this type of assembly as Type 2 assembly. However, this thesis will refer to it as fixtured assembly but the Reader should think of this type of assembly as anything that is not part-to-part assembly.

2.3.3 Traditional Approach to Aero-Structure Manufacture

A product typically has two major phases in its life-cycle: its design phase and its production phase [19]. The design phase is where the engineering design loop process takes place and iteratively the decisions are made regarding how a product will be made up from sub-assemblies, what key characteristics each assembly will achieve, what form and function its subsequent parts will have, and what tolerance the dimensions and geometry of the features on the parts will be assigned. The output of this phase is a CAD model of the total assembly and its parts, and build philosophy. These manufacturing data are then used to generate supporting data such as 2D engineering drawings, instructions and NC code to help communicate the design intent. These sources of information are collectively referred to as *manufacturing data* in this thesis. The production phase uses these manufacturing data to direct *manufacturing resources* to produce the parts and iteratively assemble them into the final product. Where *manufacturing resources* refers to the equipment used to complete the manufacturing operation, be that tooling, CNC machines, robots, or even human resources like machinists and fitters.

This is true for aero-structures industry too. The design phase produces a CAD model and build philosophy document. These two items of information describe all the information required to produce the final product. The CAD model describes the product and its parts in their nominal condition. Detailing every feature and dimension. The build philosophy document identifies the order of assembly, the key characteristics and the tolerances on those key characteristics. All other supporting information is merely a translation of these original information for the purpose of being read more easily by a machine or human. Alternatively, it can be used to group together usually disparate pieces of information onto a single document.

2.4 Controlling Variation Propagation in Mechanical Assemblies

The aim of this thesis is to develop novel approaches for controlling component variation propagation in key characteristics. To that end it is useful to begin reviewing literature that claims to provide a solution or method towards this aim; regardless of their approach. The literature appears in two categories: Those who focus on modelling variation and its effects on the key characteristics of a product, and those which attempt to develop methods to deal with the variation as it appears. The former, the largest category, aim to minimise the effect of variation on product performance or provide tools and framework for evaluating product, process designs and tolerance application. And, the latter aim to remedy or accommodate the variation as it appears.

Beginning with the largest category, methods for controlling variation before the manufacturing process is in operation. Traditionally the control of variation propagation was achieved by designing a product, assigning the initial manufacturing tolerances and performing a tolerance stack-up analysis for the key characteristics of the product. If the tolerances assigned at the part level allowed tolerances at the assembly level to be exceeded they would be tightened until a feasible design is achieved. If a lower tolerance is not feasible, then a redesign is required. Ensuring that parts are reliably manufactured within their allocated tolerance ranges is achieved using statistical process control [20]. This tolerance stack-up analysis has traditionally had two forms; worst-case and statistical analysis [13, 1]. Worst-case analysis assumes that every part is manufactured at one of the extremes of its allowable tolerance. However, this often invalidates larger volume assemblies since many components are involved. Statistical tolerance analysis was introduced to take a more practical approach to assessing a product's design. It acknowledges the fact that each feature manufactured on a part has a probability distribution associated with it and that the probability of all the parts being at the extreme of their tolerance range is low. Therefore, by analysing the tolerance range and the probability distribution within that range, it is possible to allocate tolerances that will achieve an acceptable assembly at a designated confidence level, usually 99% or 95% depending on the complexity and size of the product.

This traditional approach has been developed upon to perform increasingly more advanced and complete tolerance analysis in both 2D and 3D models. Some developments focus on providing methodologies and frameworks for constructing statistical variation models that can analyse the cascading effects of tolerance allocation. These aim to describe, simulate and visualise the variation of manufacturing processes and product designs. Identifying parts and manufacturing

processes that need to be changed, improved or statistical process controls tightened. Zhou et al. [21] lays out a methodology for constructing state-space models for describing the variation in multi-stage machining processes. Incorporating sources of variation such as re-datuming of the work piece into different jigs and fixtures and variation in the fixture setup as well. The model is validated by experiment. Comparing the predicted variation against the actual variation exhibited by an engine block manufacturing process. Bakker [22], alternatively, suggests a framework of developing a stream of variation model for aerospace structures assembly. The work then goes on to simulate the build-up of variation in a concept wing box assembly. Both approaches produce methods for visualising the build-up variation with the aim of root cause identification or process design validation. Thornton and Lee develop a modelling method to analyse the sensitivity of key characteristics to manufacturing variation. Initially the method is used to find critical key characteristics in a products design [23]. This is later developed upon to identify critical product design parameters [24, 17]. The idea being that design parameters can be optimized to reduce the sensitivity of a product against it. The result is a method for improving product design. The method is validated against a car door sub-assembly case study, described in Leland's thesis [25]. Thimm et al. [26] provides a method for optimizing datum hierarchies to minimize the build-up of variation to much of the same effect.

Other researchers have made developments towards increasingly integrating tolerance analysis methods and tools into manufacturing systems and enterprises. An early example of this is presented in Terry's thesis where a mathematical model is developed that considers the true manufacturing process capabilities against the required tolerances [27]. It presents a case-study where a 70% reduction in non-conforming parts is achieved with their approach. Jeffreys develops a methodology, and ultimately a software architecture, for utilising tolerance analysis methods at the early stages of product design development before significant effort has been committed towards detailed component design. The methodology identifies critical areas of a product's concept design that are likely to be a major contributor to exceeded tolerances. These parts can then be focused on for greater tolerance analysis and design attention [28]. Another example is presented by Goetz et al, where they suggest a methodology that incorporates early manufacturing trial data to improve tolerance models and hasten the product design phase [29]. Diet utilises a Chernov bound approach to modelling and analysing tolerance allocations in a product. They then develop a methodology to use this model to allocate tolerances in the design phase and enable these tolerances and the model itself to be re-adjusted using in-service data. The methodology also uses measurement data to identify risk areas in the production process that are likely to exceed allowable

dimensional ranges [30, 31].

Some research attention has been focused on developing variation models to compare and contrast different potential manufacturing approaches with respect to cost and feasibility. This is the case for Bacharoudis et al. [15]. A variation model is developed based on the connective assembly modelling techniques described by Whitney [32, 1], in order to select an appropriate design for an aerospace wing box joint. McKenna et al. [14] directly links cost into their variation modelling approach such that variation build-up and associated cost of different manufacturing scenarios can be simulated and compared. Both of these examples aim to provide tools for product designers and manufacturing engineers for improving product design and process down-selection. Interestingly, both papers use the aerospace industry as a case-study to demonstrate their approach.

Other variation modelling approaches focus on studying tolerance allocation and optimising it throughout a key characteristic chain. Yang et al. [33, 34] gives an example of a connective assembly approach for axis-symmetric straight-build assemblies; such as an aerospace engine assembly. The method simulates the potential geometric variation the stack of components could experience with the aim of producing probability density functions to describe the build-up of variation. Ultimately, to provide a tool for better tolerance allocation for product designers. Etienne et al. [16] develops an extensive methodology and toolkit for simulating different tolerance allocations, manufacturing processes and their associated costs against the necessary tolerances required for key characteristics. The idea being to find the perfect ratio between tolerance allocation and manufacturing cost.

A different approach is taken by Dantan et al. [35] where they combine typical variation models with an “information model” (a database); taking in data such as the product and part key characteristics, manufacturing resource plans and mappings of causality between key characteristics. The information model assists with product design and process planning (manufacturing resource selection) activities by associating the effects of selecting a particular manufacturing resource for a part key characteristic with the high-level assembly key characteristics. An overview of the modelling approach is visualised in Figure 2.1.

Moving onto more active methods of controlling variation in mechanical assemblies, Hussain [36] builds upon Yang’s work to analyse the propagation of variation through axis-symmetric straight-build assemblies and control the propagation by rotating each component in the assembly about its symmetric axis to cancel the current variation build-up. The paper provides a simulation of the methodology to detail its advantages. However, the approach is heavily dependant on the straight-build and axis-symmetric properties of the target application which limits its wider usability.

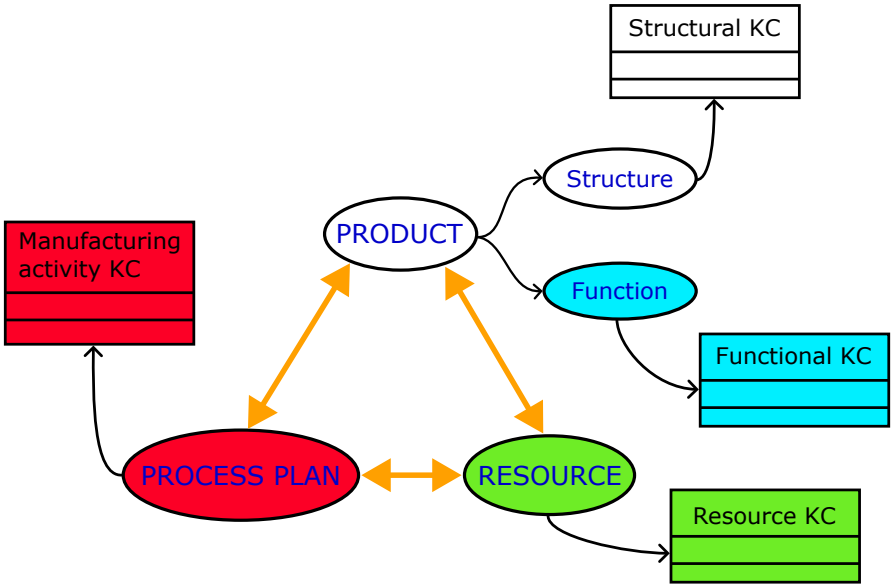


Figure 2.1: Overview of information model structure for Dantan et al. Figure redrawn from [35].

Mantripragada and Whitney [18] derive two state transition models, one describing a datum flow chain in a Type 1 assembly (part-to-part) and the other a Type 2 assembly (fixtured assembly). The model simulates variation by adding an additional randomly generated vector at each transition. Moreover, the adaptability of a Type 2 assembly is simulated by the addition of a corrective vector which may only be applied at a subset of the available states. The work then draws parallels from control theory to define an algorithm to generate the appropriate control vector or adjustment that is required at that assembly stage. The control function is applicable to only Type 2 assemblies and the model only considers a single datum flow chain suggesting that only one key characteristic can be corrected at a time and only if the assembly is straight-build (i.e. no closed-loops in the connective assembly model).

An alternate active variation control approach is selective assembly. This is the process of assembling components which have manufacturing variation which positively compliment each other. That is, if one part is larger than nominal, it is paired with a part that is smaller than nominal to reduce the resultant variation. Wang et al. employs a genetic algorithm method to find optimal pairs of simulated components [37]. Another example is provided by Xing et al. [38]. In this case automotive body part assemblies are used as a case study.

It is clear from the above literature that a great deal of the research effort towards controlling manufacturing variation has been focused on providing methodologies and tools for optimizing product design, process selection and tolerance allocation rather than more active approaches. Traditional methods such as toler-

ance stack-up and cascade analysis, in combination with statistical process control, largely only apply to the machining level of product manufacture and can only improve assembly control by tightening the control at the part level. For the aerospace industry, these controls are already at their practical limit. Although these traditional methods and those developed from it are useful at the product design phase, they have few applications once the initial product design is complete. The aerospace industry still relies on the large scale assembly jigs and laborious adjustable processes to accommodate for the fact that they cannot control their part dimensions enough to achieve a unmodified assembly. Moreover, in the Author's experience, the allocated tolerances at the product design phase are often overruled by what the manufacturing processes are capable of achieving.

It is also apparent that despite these novel tools, the issue of component variation propagation still exists; at least in the aerospace industry. The scope of the manufacturing issues that these design and analysis tools can resolve must be fairly limited. Therefore, it becomes clear that more research attention is required on active variation control methods to find other novel solutions. Methods that are active during the production phase of a product's lifecycle.

Of the active methods reviewed here, selective assembly is the easiest to dispel. Selective assembly often requires large batches of ready-made components from which to select from. This is not the case in the aerospace industry. Lead times are large and components made to order. Moreover, components are assigned to a manufacturing serial number which is itself assigned to specific customer orders. This assignment is made before they are manufactured which makes reassignment of one component to a different product administratively difficult at best, and at worst actual manual rework is required to modify serial numbers on parts to match their associated paperwork.

The remaining active methods, of which there are not many, utilise connective assembly models which have the limitation of requiring open key characteristic chains which is seldom the case and severely limits their applications. The lack of examples is likely due to technological limitations and the limitations of the connective assembly model. The technology to enable flexible manufacturing approaches is under-development itself (as will be discussed in the next section) and it is a hotbed of activity in the research and industrial communities. Moreover, the technology required to measure variation and use the data as input to these active variation models is expensive and utilising this data effectively requires significant effort in and of itself [2].

It is clear that a completely novel approach is required towards controlling variation within mechanical assemblies. This thesis must develop a data model which integrates both product design information with an extended connective

assembly model. This model must enable closed-loop connective assembly models to enable its generalised use. This model must also enable active variation control methodologies by inherently implementing a feedback loop with the output of production equipment.

2.5 Flexible and Active Manufacturing Technologies

A significant amount of research has already delivered excellent results towards low cost flexible tooling and automation providing both the flexibility and incentive to develop new approaches for automation in aero-structures assembly. Moreover, it highlights the growing use and reliance on metrology, not only as quality assurance and certification, but as an key driver during the manufacturing process [11].

Kihlman's thesis [39], and related works, provides a lot of research literature detailing the motivations of the aircraft industry to push towards greater automation and flexibility. He is also an early proponent of a lot of research areas which are hotly researched today. The body of work contains early examples of a manually and automatically reconfigurable fixtures [40, 41, 42, 43]. Most of these examples either demonstrate or cite aircraft assembly as its intended application. The work also contains examples of metrology guided robotics utilising a laser tracker combined with industrial robots [44, 6]. However, these examples only demonstrate the feasibility of the approach without context.

Jonsson's thesis and related works [10, 45] builds upon Kihlman's work, again providing a number of contributions in a wide area of research. The majority of the work builds upon the flexible and reconfigurable tooling and fixtures, see Figure 2.2. Developing and providing demonstrators of numerical controlled fixtures for quick reconfiguration. She also develops a number of examples of force controlled robotics for both machining and assembly. Interestingly a rib to wing box rib assembly example is used as an example of force controlled assembly, see Figure 2.3. Later developments consider the integration of force sensors to provide intelligent tooling [46, 47, 48, 49]. This is often referred to as active tooling and active fixtures.

In the area of programmable and reconfigurable fixtures, Ryll's work [7, 8] develops a framework upon which these devices could themselves become reconfigurable and subsystems interchangeable. It also details the growing requirement for flexible, adaptable and interchangeable equipment as products themselves become increasingly customisable. The work concludes with a technical demonstrator to validate the reconfiguration methodology. In the same vain, Molfino et al. [9] de-

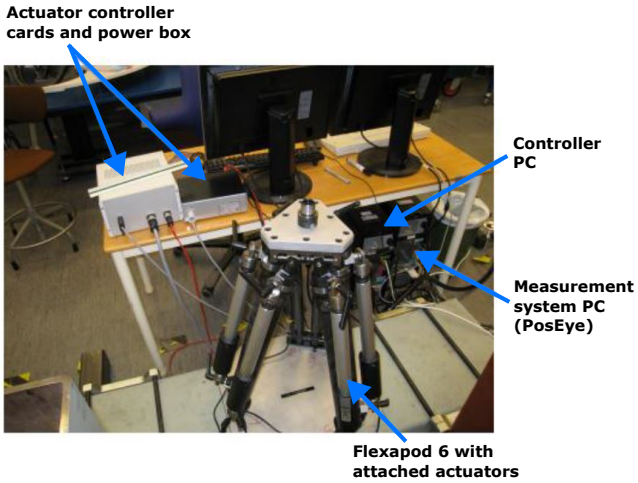


Figure 2.2: Example of numerically controlled programmable fixturing element [10].

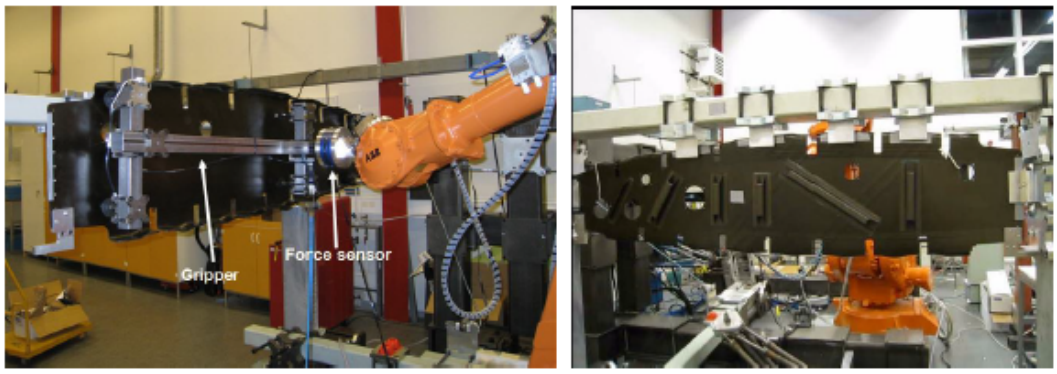


Figure 2.3: Example of force controlled robotic assembly of a demonstrator rib to a simulated wing box [10].

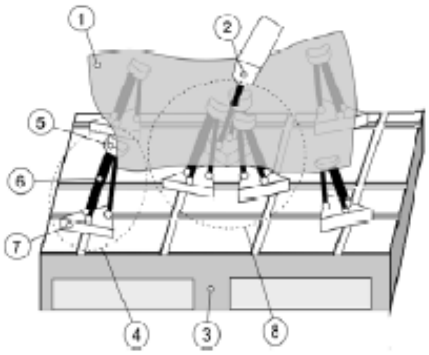


Figure 2.4: Swarm fixture example [9].

velops a reconfigurable fixturing system utilising a agent-based distributed control system, see Figure 2.4.

The above literature confirms the motivation of the aerospace industry for greater flexibility and adaptable manufacturing approaches. It also highlights the requirement for flexible and interchangeable manufacturing equipment. However, a key note to be taken is the acceptance of this adaptability within the production environment. Employing greater automation and metrology devices not only for inspection but as key parts of the manufacturing process. This is confirmed by Muelaner in his review of the requirements of the aerospace industry [5]. Towards this end, an investigation of metrology adaptive processes in the aerospace industry is required.

2.6 Metrology-Assisted Processes

Muelaner et al. [50] performed a review of measurement-assisted assembly (MAA) and its potential to modernise the often conservative aerospace industry. The work begins by discussing the difficulties found in traditional aerospace manufacturing environments, such as; tight tolerances over large distances, inflexible manufacturing systems and tooling, complex assembly sequences and component geometry. Following this, Muelaner describes concepts such as part-to-part assembly, one-way assembly, predictive shimming, measurement-assisted-assembly, and determinant assembly with reference to their increasing relevance to the aerospace industry. Finally, it concludes with a discussion of the relationship of these concepts to each other and how they all implicitly deal with interface management between components. This specific work does not layout any specific solutions but it does provide motivation and cause for this thesis. Muelaner [51] then goes on to describe how measurement data could be used in a “digital Factory” environment to optimize tolerances in tooling and product design. However, he goes on to suggest that during production this approach could allow early detection of

quality faults and facilitate predictive shimming. The work is very high-level and does not provide much detail beyond describing that it would be beneficial.

Maropoulos et al. [52] also reviewed the current challenges in aero-structure manufacturing and discussed potential applications of measurement-assisted assembly. A case study presenting a predictive rib foot fettling case study was included. The case study used metrology data from a wing box cover to alter the preprogrammed path of a metrology-assisted robot equipped with a milling end-effector; yielding satisfactory results. The work also called for further research into reducing the cost of data acquisition in manufacturing, dimensional variation management methodologies, software solutions to assist MAA and thermal compensation for optical metrology devices to name but a few.

Jamshidi et al. [53] reviewed the potential of metrology in aero-structures manufacturing. The paper concludes with a metrology enabled predictive shimming case study. Scanned data from a composite wing cover is used to modify a robotic machining path used to tailor the sacrificial material on the rib feet; minimising or eliminating shimming activities. However, the trail was unsuccessful as the required accuracy was not met.

Martin's [2] thesis provides a comprehensive review of the metrology and assembly activities typical of the aero-structures industry and its future requirements. Among other subjects, the thesis describes a MAA process where a robotic Hexapod (parallel kinematic machine) is actively controlled with live metrology data from a laser tracker; manipulating a trailing edge rib such that its hinge bore is coincident with the assembly's hinge line vector, see Figure 2.5. His approach however, actively controlled a single key characteristic in 3 degrees of freedom and the manipulation was achieved by distorting the wing cover the hinge rib was attached to; suggesting application is more of an active-fixture example than an example of assembly.

Similarly, a trailing edge hinge line setting application conducted by Vaughan [54] combined an active fixture with a laser tracker to adjust a trailing edge rib to meet its hinge line key characteristics. However, a selective assembly process determines, from CMM measurements of the ribs and laser tracker measurements of the spar, opportunities for variation to cancel each other out. despite this the results were not satisfactory since the desired accuracy was not met. Moreover, the process suggested was too verbose and abstract to be applicable to industry.

Kingston [55] developed a real-time closed feedback loop between a KUKA KR240 equipped with a Leica T-MAC, and a Leica AT901, see Figure 2.6. The system would correct deviations from a preprogrammed path using the live metrology data. Reducing the required teaching time typically found in industry after off-line programming. Path accuracies of 0.2mm at speeds of 50mm/s were achieved.

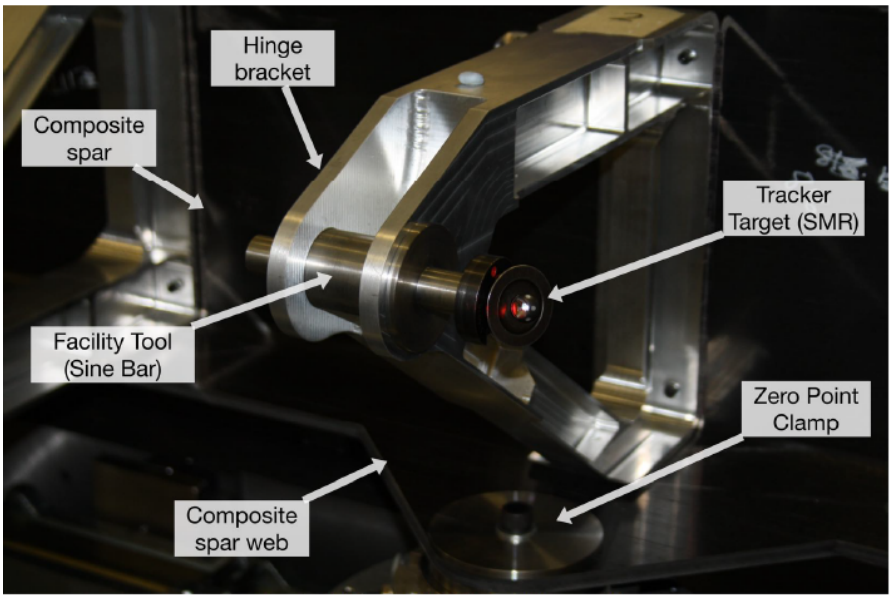


Figure 2.5: Single key characteristic control of hinge line alignment using metrology guide positioning [2].

Brown [56] builds upon Kingston's work, applying it to robotic machining activities. However, the accuracy could only be maintained on softer materials such as aluminium and with simple geometric cuts. Turning this closed-loop corrective positioning approach to assembly, Drouot et al. [57] integrated a K-CMM with a KUKA industrial robot for the purpose of refining a component a nominal location in the work cell.

The above research can be split into three categories: metrology-guided machining, metrology-guided positioning and metrology predictive processes. Metrology predictive processes encompass predictive shimming and fettling. These are typically used as early fault or quality detection systems. Metrology guided machining is not of particular interest to this thesis since the aim is to control variation during the assembly process. These processes typically focus on controlling a single point, or frame, to a precise pose or along a predefined continuous path. These are not typically the same challenges faced by assembly activities. Metrology guided positioning however is key to achieving robotic fixtured (Type 2) assembly methods.

Of the examples of metrology-guided positioning reviewed in this section, a number of limitations are noted. The first, and most important, is that all examples only control a single key characteristic in isolation which is seldom the case in actual assemblies. Another limitation is that each example is an example of a rigid setup, both physically and mathematically. The physical equipment setup and integration between the metrology devices and the assembly equipment is closely coupled. This precludes the reconfigurability, flexibility and interchangeability

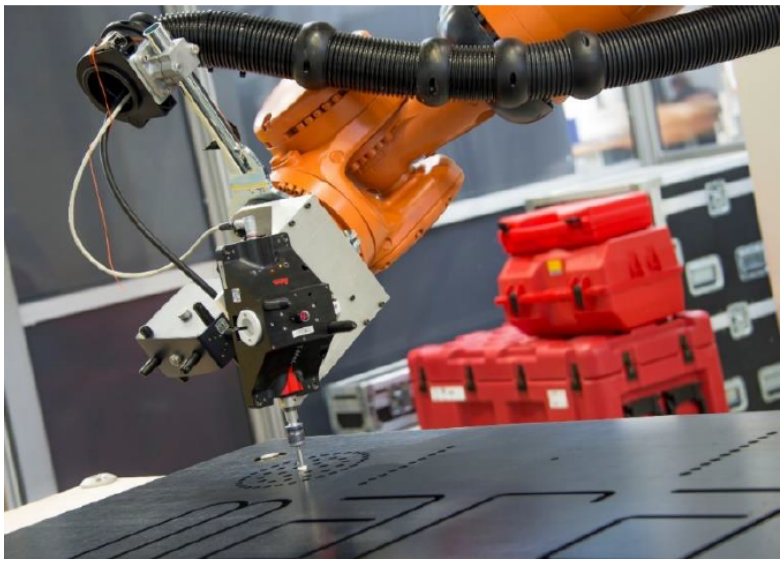


Figure 2.6: Metrology-guided robot example [55].

highlighted in the previous section. In terms of mathematical rigidity, a number of prior relationships are manually determined in advance of the metrology guided process. The robot's base frame location relative to the metrology co-ordinate system is taught in advance. The robot's wrist frame is taught relative to the metrology device mounted to the robot's flange (typically a Leica T-MAC [6, 44]) and the actual point of interest of the robot's end effector (component location point for example). This ensures that the process itself is inflexible, fragile and difficult to turn to other assembly activities quickly. Moreover, it requires static robot and fixture placement and high-tolerance tooling to ensure components are accurately located repeatedly. Moreover, all this research literature investigates the metrology-guided processes in isolation of a greater methodology for applying these processes in a manufacturing system.

It is clear that what is required is a methodology for control of multiple key characteristics for robotic assembly. The methodology should be adaptable and robust to variation in the components themselves, the robot and fixture location and the pickup location between the robot and the component being positioned. The methodology should also be general applicable to and should be easily turned to position different components with minimal down-time. Moreover, the methodology should link into the data model discussed previously to achieve a unified adaptable assembly system. It would also be a boon if the assembly technology developed to demonstrate this approach was itself flexible and interchangeable to capitalise on this growing trend.

2.7 Enabling Part-to-Part Assembly

Part-to-part assembly is rare in aero-structures assembly since the large and complex geometries of aerospace components quickly exceed the tight assembly tolerances when manufacturing variations are allowed to propagate. Therefore, traditional part-to-part designs are just not feasible. However, there has been some research attention dedicated to seeking methods for enabling part-to-part assembly for the aerospace industry. These typically take the form of determinant assembly approaches. This is where assembly interfaces are specified from the condition of the corresponding mating part.

Williams et al. [58] discussed the origins of determinant assembly at the Boeing Company and how the methodology allows for greater flexibility for the manufacturing engineer, shorter tolerance chains and reduces costs since there are further requirements from the tooling and fixtures combined with a reduction in rework. He then suggests how this design methodology could be combined with measurement data and automation; among other thoughts to the future of determinant assembly design methodology. Muelaner also stresses the benefits of applying determinant assembly to aero-structures assembly [5].

With specific regards to part-to-part assembly, Irving et al. [59] enabled part-to-part assembly by optimising the design of the interface between the two components. However, this approach does not combat propagation of variation. Muelaner and Maropoulos [60] give an example of measurement-assisted part-to-part assembly for assembling brackets to a spar but they focus on the design requirements of components necessary to enable its application as opposed to providing a methodology for its industrial implementation.

There is a lack of research in general on methods for enabling part-to-part assembly techniques in the aero-structures industry. This comes from two main sources. Since part-to-part assemblies are not currently feasible and therefore do not appear in any aircraft designs there is no demand for research into methodologies to enable them. The other issue is that determinant assembly and metrology assisted determinant assembly is essentially a huge design alteration loop that must occur for every part-to-part joint in an aircraft, for every aircraft manufactured. This design alteration loop requires metrology data to be captured, processed and formatted into the product's design. With this data the assembly design must be adapted, keeping in mind the key characteristics of the assembly, and the part-to-part joints between the components maintained. Following this virtual design change the data must be communicated to the manufacturing resources to bring into reality the adaptation process. It will become immediately clear that this is a laborious alteration process involving many function areas of a manufacturing

enterprise whom will become immediately overwhelmed in work and unable to conduct their usual activities the moment this process is introduced.

It is clear that this process needs to be formalised into a methodology and automated. This methodology should also include an adaptive process not only enabling part-to-part assembly but control of variation in part-to-part assemblies. Something not currently shown in the above literature. This methodology should, ideally, be unified with the methodology discussed in the previous section. To create a unified metrology adaptive approach to controlling variation in all types of assembly; part-to-part (Type 1) or fixtured (Type 2).

2.8 Assembly Modelling for Manufacturing and Industry

It is clear from the above literature that a novel data model is required to capture product requirement information and manage live variation information as it is captured from physical instances of the product. Towards this end a review of research concerning product and assembly requirement modelling is given below.

Early influential works track back to Wesley [61] who uses object-orientated programming to model simple geometry parts and their assemblies in a hierarchical tree, see Figure 2.7. In this work Wesley creates an early example of modern computer aided design (CAD) tools.

Wu and Kim [62] build upon simple assembly models to incorporate contact constraints in part-mating operations. The aim being to develop assembly strategies that could be executed by automation fitted with a compliance device.

Shah and Rogers [63] review the current approaches to modelling assembly. They then go on to develop a feature-based assembly modelling approach to extend traditional assembly representation models to included a greater amount of information, see Figure 2.8. Information that could be used to perform validation methods on an assembly model rather than just for visualisation.

Callahan [64] builds on Wesley's approach to enable re-use of sub-systems of the design. Allowing for designers to add multiple instances of the same part or sub-assembly into a single product. It also begins the discussion of applying automation programmes to assembly models. However, the intention is to track design changes to avoid errors.

As the problem of capturing assembly and product requirement information has been incrementally solved (commercial CAD software packages are now available), attention has moved towards providing methods of analysis of assemblies via their models. Whitney's textbook [1] provides a number of examples of analysing

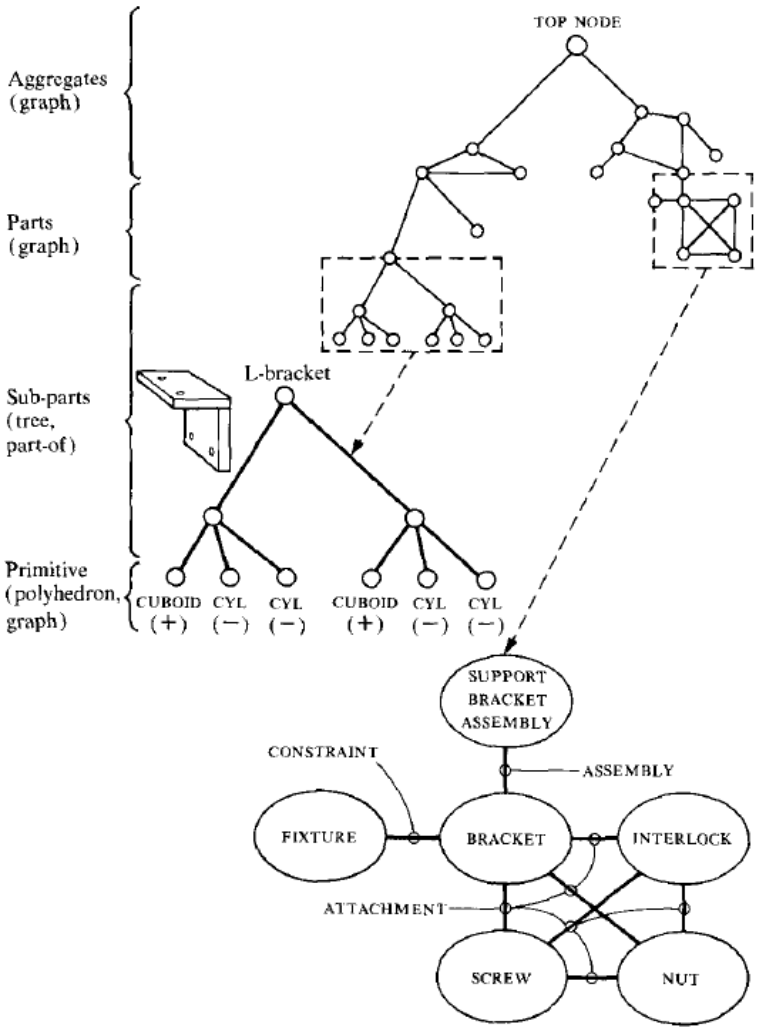


Figure 2.7: Object-Orientated Approach to Assembly Modelling [61].

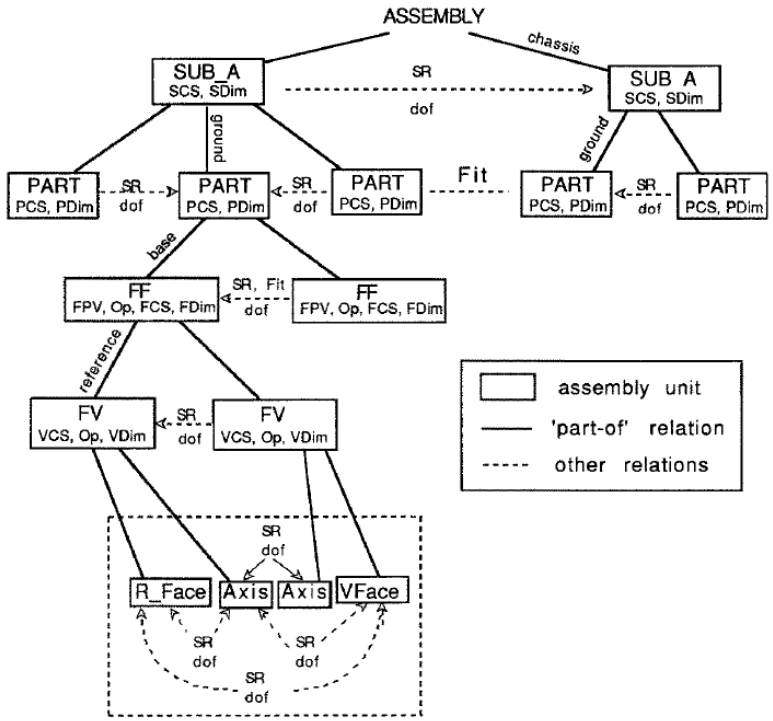


Figure 2.8: Feature-based assembly model for an example product depicting greater information concerning the relationships between object in the model [63].

assembly models to understand information concerning variation of key characteristics, find under or over constrained parts, calculate assembly scenarios and model mating constraints, to name a few. More recent papers have attempted to link manufacturing processes to features within the model [65].

From the above literature it is clear that the assembly models, that is models used for the capturing and communication of assembly requirement information is largely considered solved. However, to enable the adaptive approach to controlling variation discussed earlier, it is believed a more complete assembly model is required. Taking inspiration from Shah and Rogers [63] feature-based approach in combination with Wesley's object-orientated design [61] and the connective assembly theory from Whitney [1], a data model can be developed that more-completely captures the entirety of the manufacturing data for a product. The data model is to designed for automation and will primary be a machine-readable data structure and mathematical model. This is in complete contrast to the current approach which stores the manufacturing data for a product in separate human-readable formats. For example; the CAD model captures the nominal dimensions of a product's parts and assemblies but the order of and key characteristics for each assembly are described in a build philosophy document.

2.9 Discussion

From reviewing the above literature, it is clear that there is a lack of automated manufacturing variation control methodologies that are active during manufacture. This is due to the following knowledge gaps:

The first knowledge gap is concerned with the lack of a data model that enables automatic variation propagation control during production. A novel data model is needed to create a single machine-readable entity that contains all the information required to manufacture a product. And, it must inherently create a feedback loop between the data driving production and the output thereof. This is to supersede the current approach of driving production with several immutable human-readable data sources. This data model will provide the platform for which adaptive methodologies can be developed.

The second knowledge gap is concerned with enabling variation propagation control in part-to-part assemblies. Currently there are few examples of part-to-part assembly being applied to the aero-structures industry. This is likely due to two issues: The tolerances in aero-structures assembly are quickly exceeded in traditional part-to-part assembly. And, its difficult, multi-disciplined and laborious process-loop makes the process too expensive and time consuming. What is needed is a automatable methodology. A methodology that includes an adaptive stage to correct key characteristics due to measured variation and lock-in this adaptation by modifying the part-to-part interfaces. This methodology should be general applicable and able to be easily turned to other products and assemblies

The third, and final, knowledge gap stems from automated control of variation propagation in fixtured assemblies. Fixtured (Type 2) assemblies already control excessive variation using adjustable processes, typically using gauges and tooling to achieve assembly key characteristics. However, of the examples reviewed, there are no methodologies which automatically control multiple key characteristics simultaneously. This is strange as assemblies that only have a single key characteristic are rare and if a Type 2 assembly is to be generally automated then a methodology is required which can control several at once. In addition to this it would be ideal if the methodology was free from prior known mathematical relationships. Relationships such as those described in Kihlman, Kingston and Brown's work [6, 55, 56]. The methodology should allow variation, not only in the components themselves but also in the location of the robot, fixture, product or the tooling/component attached to the robot. It would also be ideal if this flexibility methodology itself. It should be general applicable and able to be easily turned to other products and assemblies. Moreover, it would be convenient is the device architecture itself is interchangeable.

The aim of this thesis is to develop novel approaches to automatically control and manage manufacturing variation propagation in mechanical assemblies during their production. The literature review above has identified a number of knowledge gaps that must be answered to achieve this aim. To summarize the gaps currently in the research and industrial literature:

- There is a lack of a generic data model to enable automatic variation propagation control.
- There is a lack of research concerning variation propagation control methodologies in generalised part-to-part assemblies.
- There is are no generalised methodologies that provide multi-key characteristic control for metrology-guided robotic assembly.

2.10 Chapter Summary

This chapter has reviewed in detail the current literature concerning methods towards controlling variation in mechanical assemblies and methods of automating them. Discussing the state-of-the-art in metrology assisted processes, flexible assembly technologies, methods of enabling part-to-part assembly, assembly modelling techniques and plethora of approaches toward modelling and controlling variation. From this review, a number of knowledge gaps have been identified, these are; a lack of suitable data model for automatic control for adaptive assembly modelling, a lack of methodologies for adaptive part-to-part assembly, a lack of methodologies for multiple key characteristic control for robotic assembly.

Chapter 3

Research Methodology

3.1 Introduction

A review of the current literature has identified several knowledge gaps regarding the control of variation propagation in aero-structures assembly. Since the aim of this thesis is to automatically control manufacturing variation and its propagation in assemblies, this thesis will develop methods for both types of assembly, as defined by Whitney [1]. Type 1 assemblies, which in this thesis will refer to as part-to-part assemblies, are assemblies where each assembled part is fully constrained by the other parts in the existing assembly. Type 2 assemblies are everything else, or as they will be referred to in this thesis, fixtured assemblies. This is because some of the degrees of freedom of a component added to an assembly are supplied from external tooling, gauges or fixtures. Automatic methodologies for controlling variation propagation for part-to-part and fixtured assemblies is covered in Chapters 5 and 6, respectively. When combined, both methodologies provide a variation control methodology for all types of mechanical assembly. However, for these methodologies to be an intrinsic and automatic part of the manufacturing process, a new approach to the utilisation of manufacturing data must be developed. This alternate approach to manufacturing is enabled by the development of a data model which is covered in Chapter 4.

This chapter details the plan for the thesis. Beginning first with how the major chapters answer the aim of this thesis, as just discussed. Section 3.2 presents the overall research methodology and the contributions this thesis intends to deliver. Section 3.3 discusses the evaluation and verification approach for each of the research objectives, presented in Section 1.3. The assumptions and scope of the thesis are discussed in Section 3.4. The chapter concludes with Section 3.5 which discusses the selected use cases targeted for technical demonstrators throughout this thesis.

3.2 Research Approach and Contributions

The thesis follows a structured approach towards achieving the aforementioned objectives. An overview of this approach is given in Figure 3.1. The figure details which chapters are associated with which objectives. The plan begins with the literature review, its associated discussion and resulting knowledge gaps. The knowledge gaps revealed a lack of research considering active methods of controlling variation propagation during production. This is likely due to the traditional lack of metrology, sensing and flexible manufacturing technology in the aerospace industry. However, as discussed in the literature review, this has already changed. In combination with increased computational power and lower computational costs, it is possible to seamlessly integrate advanced adaptive systems into manufacturing enterprises. This adaptive approach presented in this thesis compliments the traditional approaches of tolerance analysis, variation resistant designs and tightening production controls, and provides an additional tool in the arsenal of methods for combatting manufacturing variation propagation. A tool that is sorely needed since the traditional methods can only reduce the effect of manufacturing variation and cannot eliminate it entirely. They also suffer from diminishing returns since the cost tightening manufacturing control raises exponentially and design iteration loops stall product development and are costly to keep running. Moreover, in the aerospace industry these traditional methods are at their practical limit. Large and expensive machining centres and composite layup tooling manufacture aero-structures to sub-millimetre accuracy but when it comes to assembly even these deviations propagate to amounts that exceed the tolerances required at the assembly level. It is for these reasons that new ideas are needed.

The knowledge gaps are used to create research objectives for the thesis and a research methodology. The research objectives are designed to deliver verifiable examples of this adaptive approach and its capability for both types of mechanical assembly. Developing this approach and using it in representative aerospace examples provides concrete evidence that the methods solve the problem and the approach is valid and useful. The first objective begins with the initial development of the data model that forms the platform upon which the subsequent methodologies will be developed. The plan then identifies two paths towards implementing automatable methodologies for part-to-part and fixtured assembly. The methodology for part-to-part assembly is developed first. This is covered in Chapter 5. In this chapter the methodology is discussed in detail building up its constituent elements, mathematical methods and algorithms. The chapter also implements a prototype software to provide an example of how the data model

and methodology can be practically employed into a production environment. The chapter concludes with an analytical and simulated evaluation of the methodology and an experimental verification by way of technical demonstrator. The final methodology handles fixtured assembly operations and is covered in Chapter 6. This chapter also details the core elements of the methodology, supporting mathematical methods and algorithms. The chapter concludes with the development of a prototype software and interchangeable device control platform. Chapter 7 presents two technical demonstrators to validate and evaluate the capability of the methodology detailed in Chapter 6.

The following sections discuss in detail the contributions delivered by this thesis for each research objective presented in Section 1.3.

Research Objective 1: Develop a data model for the automatic control of variation propagation

The data model acts both as a representation model and as a networked series of connective assembly models. It captures the hierarchical structure of the product, organises the relationships between parts and assemblies, and stores any metadata for interrogation and identification. The connective assembly network creates a kinematic-like backbone which can be used for both analysis of the current state of the model or for adaptive algorithms to make automated changes to the dimension and geometry of the product. The model is constructed using object-orientated programming techniques, where classes are created to model key concepts of an assembly. And, each class structures the data and implements the methods (functions) for generation, interrogation and modification of the instantiated objects.

The model builds upon the feature-based and hierarchical modelling approaches [61, 63] but draws in ideas from the information model approach described by Dantan [35]. The data model developed in this thesis models new relationships between the objects to enable a more complete description of the requirements of an assembly than has been previously covered in the literature. Relationships such as key characteristics, joints, constructions and references are all added, in addition to the typical parent-child relationships, to record more completely the elements of an assembly and enable automated analysis and adaption of the product.

The model also extends the use of connective assembly models [66, 1] and circumvents the limitation of open-chain models. The data model enables the automatic generation of an inter-connected network of connective assembly frames. This network enables automatic interrogation and variation analysis of an assembly between any two objects in the product. The network invariably contains

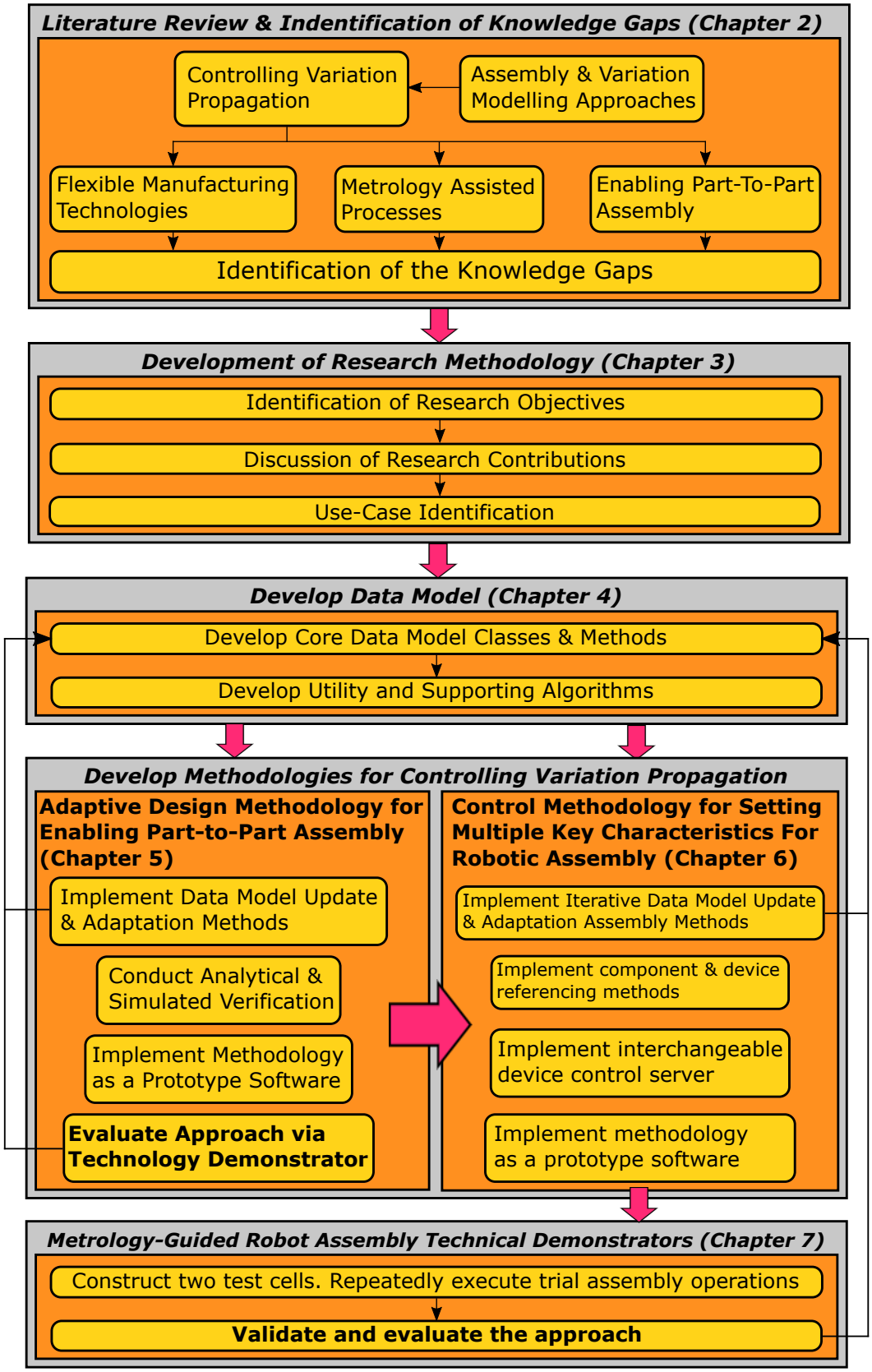


Figure 3.1: Overview of Research Methodology.

closed-loops, leading to over-constrained conditions in the connective assembly models. However, these are managed automatically by the relationships of the information domain. This ensures that the network of the spatial domain remains consistent and no two (or more) paths through the model describe the same location differently. The result is that the model can be analysed and modified without losing any information from the model or invalidating its purpose.

The data model represents a paradigm change and is intended to supersede traditional CAD models and 2D engineering drawings as the main source of manufacturing data. It opens a fast and automatic feedback loop between the manufacturing data driving production resources and the output of those resources. It is a live data structure, of which a copy is created for each physical instance of the product being manufactured. And, into which, metrology and inspection data of the parts and sub-assemblies is fed. This ensures the model changes to accurately represent the associated physical instance of the product as it is being manufactured. But, it also, more importantly, serves as a platform upon which adaptive methodologies can be employed to automatically react, adapt and change manufacturing data to achieve novel results. In this case the goal is to provide novel methods for controlling the propagation of variation in both part-to-part and fixtured assemblies but this is just two use-cases. This approach could be used to achieve adaptive results towards a plethora of manufacturing challenges and any form of mechanically assembled product.

Research Objective 2: Develop and validate a automated methodology for controlling variation propagation in part-to-part assemblies

The first methodology uses the data model to enable variation propagation control in part-to-part assemblies. This is achieved by leveraging the natural feedback loop enabled by the data model and adding an adaptation phase. This adaptation phase review the current state of the product's manufacture and adapts the assemblies and structures of parts to nominalise deviated key characteristics and correct misaligned assembly features. The data model is then used to modify nominal manufacturing data to create adapted manufacturing data to drive manufacturing resources accordingly.

The first contribution of this methodology to mention is that it achieves variation propagation control for one of the two major types of assembly; contributing towards the aim of this thesis.

The second contribution is that the adaption phase of this methodology is what enables the use of part-to-part assembly for aero-structures assembly. Traditional part-to-part assembly would quickly exceed the tolerances applied in the aerospace

industry. The adaption phase is where the current state of variation is measured and used to change the manufacturing specifications of down-stream components to control the propagation of this variation. And, fulling the aim of this thesis for one type of assembly.

The last contribution is the generalisation of the approach. A data model can be automatically generated from the CAD model of any mechanical assembly and metrology or inspection data supplied into it. The adaption phase can be tailored using different methods from the *KCsolver* class to correct the specific set of key characteristics for the new assembly. If the specific set of key characteristics or the methods to resolve them are not currently implemented (see Chapter 4) then the data model or *KCsolver* class can be extended by defining a new subclass or adding the new method; respectively. Therefore, the approach can, in theory, be applied to any product, for any number of assemblies within that product.

Research Objective 3: Develop and validate a automated methodology for simultaneous control of multiple key characteristics for robotic assembly

The second methodology handles the other type of assembly. Fixtured, or Type 2, assembly is itself a method of controlling the propagation of variation. However, of the methods reviewed many of the attempts to automate the approach only consider a single key characteristic for a bespoke situation. Moreover, they rely heavily of prior known relationships, manual teaching and referencing procedure and high-tolerance tooling relationships between metrology devices and true points of interest. This methodology does away with these limitations. The methodology firstly implements a set of methods for generalising robotic assembly operations. It also derives a set of methods for referencing and locating the objects within the assembly. The methodology then implements an iterative data model update and adaptation loop, where each iteration measures the state of the assembly operation, updates the data model accordingly, analyses the deviations in the key characteristics, calculates the corrective transform and controls the robot to correct the key characteristics.

The major contribution centres on the multiple key characteristic driven metrology guided robotic assembly. Since the approach is driven by measurements of the key features involved in the key characteristics, the assembly methodology inherently adapts to component variation in the constituent components. Therefore, the set key characteristics are set to a nominal condition regardless of the manufacturing variation in either the dynamic or static component.

The next contribution, stems from the set of methods for automatically locat-

ing the static and dynamic components within the assembly. It also references the automatic manipulator's control co-ordinate system relative to the dynamic object's geometry and the metrology systems relative to any fixture or product system (if supplied). These methods ensure complete flexibility of location of the components to be assembled, the automatic manipulator (typically a 6-axis robot) used for assembly, the relative location between the dynamic object and manipulator mounting point, and the fixturing system used to mount the static component. Moreover, it makes the methodology robust against unintentional errors in these relationships. In short, this enables: automatic mobile assembly robots, flexible positioning of all objects involved in the assembly operation (and process robustness), No high-tolerance tooling, fixturing or end-effector requirement, and avoidance of manual teaching operations.

The last contribution to discuss is the generalisation of the approach. Again, the data model can be automatically generated from metrology objects or CAD data. This data model, in addition to the job file, fully generalises the assembly operation and its requirements. Therefore, any mechanical assembly can be automatically assembled by this methodology if a data model can be constructed for it and the adaption loop modified as discussed for the part-to-part methodology and the assembly is physically possible. This also extends from the device control platform where assembly algorithms make reference to a device mapping such that the physical implementation of the device can be interchanged without consequence.

3.3 Evaluation and Verification

Evaluation and verification in this thesis tackles two separate aspects of the proposed methodologies and therefore the underlying data model. Verification refers to proving the functionality of the methodology under examination in general. Evaluation, in this thesis, assesses the functionality of the methodology and data model against the requirements for aero-structures assembly. These requirements typically being sub-millimetre tolerances. Since these methodologies are generalised and can be turned to any mechanical assembly, and their practical implementation can change depending on the requirements and available equipment of the manufacturing enterprise, the verification validates the process in isolation of the aerospace industry. The evaluation stage requires the construction and operation of a technical demonstrator to actually implement the methodology to achieve a representative assembly operation.

The verification and evaluation procedures for each research objective is discussed:

Research Objective 1: Develop a data model for the automatic control of variation propagation

The data model itself is verified and evaluated as the subsequent methodologies are evaluated and verified. Each of the subsequent methodologies handles one of the two categories of mechanical assemblies. Such that, when unified by the shared data model, an automatic control of manufacturing variation propagation is available for all types of mechanical assembly. Therefore, by achieving research objective 2 and research objective 3, research objective 1 is also achieved.

That is the data model will demonstrate adaptive live variation control methodologies for both part-to-part and fixtured assemblies. The data model will have been demonstrated on multiple components is a variety of assembly situations, using various assembly equipment. Since the assemblies are not axis-symmetric straight-build assemblies, the limitation of the open-chain connective assembly models will have been resolved.

Research Objective 2: Develop and validate a automated methodology for controlling variation propagation in part-to-part assemblies

This methodology is verified by implementation of a prototype software. This software automates the adaptive design change loop in a way which maintains the typical interfaces with a traditional manufacturing enterprise. It also demonstrates the ease of use and ability to apply the process to other assembly examples. Since this methodology's output is digital (a traditional CAD model to be used to communicate adaptations to a manufacturing resource), the methodology is verified by analytic methods and a simulation. The methodology is then evaluated against aerospace tolerances with a technical demonstrator; presented in Chapter 5. The technical demonstrator enables part-to-part assembly techniques for a rib-to-wing box assembly operation by adapting CAD models to stem variation propagation as it appears during assembly.

Research Objective 3: Develop and validate a automated methodology for simultaneous control of multiple key characteristics for robotic assembly

This methodology is verified by implementation of a prototype software which is used to drive two technical demonstrators. Each showcasing metrology-guided robotic assembly operations focusing on a rib-to-wing box assembly. Each opera-

tion controls the variation of propagation by setting the live condition of the set of key characteristics required for the assembly.

Two technical demonstrators are presented to demonstrate the interchangeability of assembly equipment used to implement the process, the ability of the methodology to be easily turned to different assemblies and key characteristic sets, and demonstrate the methodologies robustness to errors in either fixture (or product) location, location of the assembly device or the pick-up location on the component. Each technical demonstrator exhibits capability of the methodology against aerospace requirements, its ability to cope without manual teaching or prior known mathematical relationships, and robustness to errors in the locations of the assembly equipment and components involved in the assembly.

3.4 Scope of Research

The result of this thesis is a model-driven approach to manufacturing, complete with a pair of methodologies for metrology assisted variation control for both forms of mechanical assembly. The approach and its methodologies are designed to be general and apply to any form of mechanical assemblies. However, a number of assumptions are made to focus the scope of the research.

The research presented in this thesis is validated for products conforming to the below stipulations:

- *This work only applies to mechanical assemblies*
  A mechanical assembly, here, is defined as being the rigid aggregation of two components into a single component. There is the implicit assumption of rigidity, of the parts before assembly and of the aggregate after assembly, which is necessary for the connective assembly model to be applicable [1]. Fortunately, this includes most products and parts. Even those which are relatively compliant, such as those in the aerospace industry, can be made rigid with the use of support tooling and fixtures.

- *The assembly is properly constrained*
  The methodologies implemented in this thesis assume a set of key characteristics is properly constrained and as such a precise solution can always be found. That said, a number of optimisation routines are implemented in a case by case basic to demonstrate how more complex key characteristics can be resolved. However, the methodology does not fully consider an over-constrained set of key characteristic where possible solutions may not exist.

- *key characteristics are locating*
  Key characteristics can technically be any aspect of the assembly, part ot process that is important. For example; surface finish, paint colour, fastener protrusion, etc. However, this thesis only considers locating key characteristics. That is, key characteristics which define the pose of one component relative to another. The gap condition of Chapter 5 is a notable exception.

- *Predefined product design*
  This research does not tackle the challenge of product or assembly design. It is assumed that the target product to apply this approach to has already gone through the iterative product design process and is about to enter its production phase. Therefore, all joints, key characteristics, parts, feature and sub-assemblies are known.

- *Key characteristics are assembly key characteristics*
  This body of work only considers assembly key characteristics. Therefore, when a key characteristic is discussed in the thesis it should be assumed to be an assembly key characteristic, unless otherwise stated. Key characteristics can also be applied to parts and processes to monitor and control important parameters of a product's manufacture.

- *Correct key characteristic definition*
  It is assumed that the set of key characteristics are such that the assembly is properly constrained. That is the key characteristics neither under or over constrain the assembly. This is a fair assumption since this would represent an error for any manufacturing process. That said, an over-constrained set of key characteristics could feasible be solved by this data model approach. This is because every feature can me independently modified (as is demonstrated in Chapter 5). However, this approach has not been implemented for the key characteristic solution phase yet.

3.5 Selected Use Cases

This thesis focuses its approach on aero-structures assembly and specifically rib to wing box assembly. This is due to the unique combination of tight tolerances and large, complex components. This makes the aerospace industry the prime user of this approach and the rib to wing box assembly operation its prime candidate for application. An aircraft wing's primary structure typically consists of 2 spars, 2 wing covers (complete with stringers) and between 27 to 35+ ribs, see Figure 3.2. The ribs are also a highly constrained component, it interfaces with all of the

other primary structural elements and acts as a mounting structure for internal fuel systems and auxiliary structures. This ensures the rib has a difficult set of key characteristics and is an ideal demonstrator for the methodologies presented in this thesis.

Rib to wing box assembly is a ubiquitous manufacturing operation for all aero-structures manufacturer. It can be found on all modern aircraft; from large commercial airliners, to small private jets, and even the rotor blades of helicopters. The rib is a central component for all aerofoil construction. It ties the spars and skin covers together strengthening the wing and enabling it to withstand torsional loading. The ribs also create the lift generating aerofoil shape, a vital requirement for heavier-than-air flight. In addition to these structural requirements, some ribs serve as a means to divide the wing box into separate watertight boundaries, creating multiple fuel tanks along the length of the wing. This avoids vast quantities of fuel sloshing about during flight and destabilising the aircraft. And, when in combination with the fuel pump system, which is also mounted along the ribs, they allow the weight of the fuel to be distributed strategically about the wing structure. This is used to maintain optimal lift generation despite the wing bending during flight.

Traditional rib to wing box assembly is a manual operation. And, based on the experience of the Author, it can take a couple of forms, depending on whether one of the wing covers is installed before the ribs. Since the rib connects the major structures, it is usually the component where a great deal on manual adjustment is required. The process typically takes the form of offering the rib up to the rib posts. These are brackets mounted to the inside surfaces of the spars. The rib is then fixed in-situ using clamps or tooling. At first it is fixed by just enough to hold it in position but loosely enough to be nudged with a nylon or hide mallet. Gauges are then used to measure the step condition between the spar heel and the adjacent rib foot. This step is to be a nominal value and if a deviation is measured the rib is tapped in the corresponding direction to achieve the correct step condition. Depending on whether a wing cover is in place or not, this needs to be done on either 2 or 4 corners of the rib (forward and aft, top and bottom); respectively. Once the gap measurements are satisfied the clamps and/or tooling are fully tightened and the rib is drilled and bolted up, fully fixing the rib in place. However, depending on the size of the rib and wing span, these 2 or 4 points of measurement can be separated two flights of stairs of a major assembly jig and up to a 30 m walk around the tip or root of the wing to access the other side. It is for this reason that the operation usually requires 2 or 3 operators and around an hour of allocated operation time for a 2 m long rib.

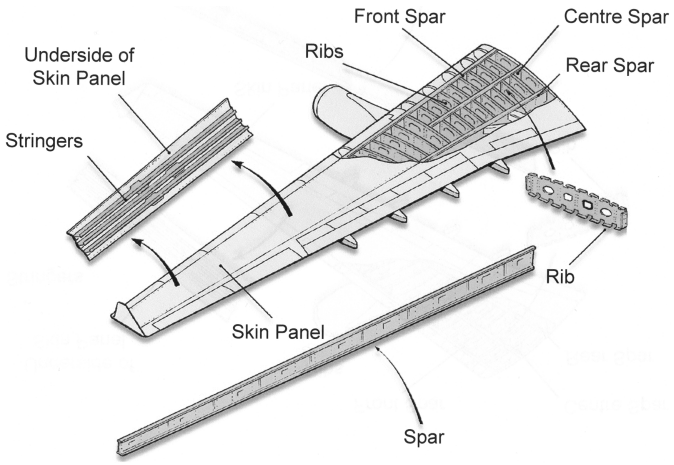


Figure 3.2: Overview of aircraft wing box assembly, for source ref:[67].

3.6 Chapter Summary

This chapter has outlined the strategy towards completing the research objectives of the thesis and verifying the work, ultimately fulling the identified knowledge gaps. The chapter has also outlined the general assumptions and limitations of the research. It has also discussed the motivations behind the chosen use-cases for the technical demonstrators.

Chapter 4

Data Model for Automatic Variation Propagation Control

4.1 Introduction

This chapter develops the data model for automatic variation control of mechanical assemblies during their manufacture. Existing formats of manufacturing data do not allow for integrated adaptive approaches for assembly or manufacturing in general. Moreover, integrated automation as part of the manufacturing system is also difficult to achieve. This is because current formats are designed for human-readability instead of machine-readability and modification. The data model improves on current approaches to manufacturing by conglomerating the major functions of the CAD model and build philosophy into a single, machine-readable data model and augmenting it with additional functions. These functions include: the integration of metrology inspection data, the association of a data model per physical instance of a product, and the instantiation of a feedback loop between manufacturing output and manufacturing data/resources. It also discusses the programming implementation of the data model concept for the work presented in this thesis. The chapter also deals with how data models can be automatically generated from existing product data, ensuring the added functionality does not come at a cost to practicality. Ultimately, this chapter develops the generalised platform upon which the methodologies of the following chapters are built.

The data model incorporates the manufacturing data for a product using the object-orientated programming paradigm. Here, a product is defined as the output of the an assembly operation that is deliverable to a customer. This could be a market saleable item such as an aircraft or engine. Alternatively it could be a major sub-assembly delivered to someone else to complete the final assembly

operations. This thesis proposes that a product can be modelled as a network of connected nodes. Each connection carries context and spatial information. Whilst the nodes each model one of four major elements. These elements are either an assembly, part, feature or geometry.

This chapter develops the data model by first developing the argument for it. Section 4.2 discusses the requirement and context for the data model and what functionality the data model is intended to implement. Then a overview of the data model's structure is given in Section 4.3. In that section the three categories of elements that construct the data model and enable its use are presented. The following sections are dedicated to detailing the purpose and main concepts implemented by each group and its elements. Section 4.4 discusses the mathematical core of the data model, Section 4.5 provides the elements which add data and context to the data model, and Section 4.6 gives the elements that operate on a data model. The chapter concludes by presenting an illustrative example in Section 4.7.

4.2 Automatic Adaptive Assembly

Based on the experience of the Author, the current approach to manufacturing presents a number of issues for implementing active automatic variation control methods. Traditionally, CAD models, and the complimentary data developed from those CAD models (build philosophy, engineering drawings, operating instructions, NC code, etc.), have been used to machine and assemble aerospace structures. These manufacturing resources are static and are designed to be read by a human. At sometime, each aero-structure is manufactured to the same set of manufacturing data. This approach to manufacturing presents a number of issues for an automatic active variation control methodology.

- It stores the sum of manufacturing data into two major human-readable formats: The CAD model which details the nominal (ideal) state of the product and all the detailed dimensions and shapes required to produce all the parts and assemble them. And, the build philosophy document which is often a series of documents, describing the order in which components are assembled, the key characteristics to be observed during manufacture and the tolerances on those key characteristics. All other types of manufacturing data are derived from one or both of these two documents.

- These formats are static and immutable under normal manufacturing conditions. Once the engineering design process has concluded and production has begun, the CAD model, build philosophy and their derivatives do not

change. The exception to this is when there are problems during manufacture, or if a modification is required to reinvigorate customer interest.

- This does not allow for a feedback loop with production or integrated adaptive processes.
- It does not allow for integrated automation since the root manufacturing data is not machine-readable.

The approach developed in this thesis removes these limitations with the introduction of a data model at the focal point of the manufacturing system. This data model stores all the core manufacturing data as a single entity such that the CAD model and build philosophy document can be derivative of it. The data model is machine-readable such that automatic methodologies can be developed for intelligently modifying the data model when given live feedback from production. Figure 4.1(a) presents the traditional approach to manufacturing where the same manufacturing data drives every manufactured instance. Figure 4.1(b) details the adaptive approach of this thesis. It shows the feedback loop with the output of manufacturing data and it also shows that the manufacturing data is derivative from the data model. Each physical instance of the product, and its components, is associated with it own instance of data model, operating it own isolated feedback loop. Since the data structure elements of the data model can be modified using metrology data taken from the output of machining or assembly operations the output data likewise is modified; providing the means by which an active variation propagation control methodology can be achieved. As the figure suggests this can be done at multiple instances throughout the manufacture of a products components, right up till the point where the final product is ready for the market.

To summarise, the data model is a means of changing the existing approach to manufacturing to allow for feedback from the output of manufacturing processes and, as will be discussed in Chapters 5 and 6, enable automatic adaptive manufacturing processes. The major functions implemented by the data model are:

- The data model captures all the manufacturing data for a product in a single machine-readable format.
- The data model can be used to generate manufacturing data as output. This can be but is not limited to: CAD models, 2D engineering drawings, engineering instructions, robotic machine control (direct manufacturing resource control).

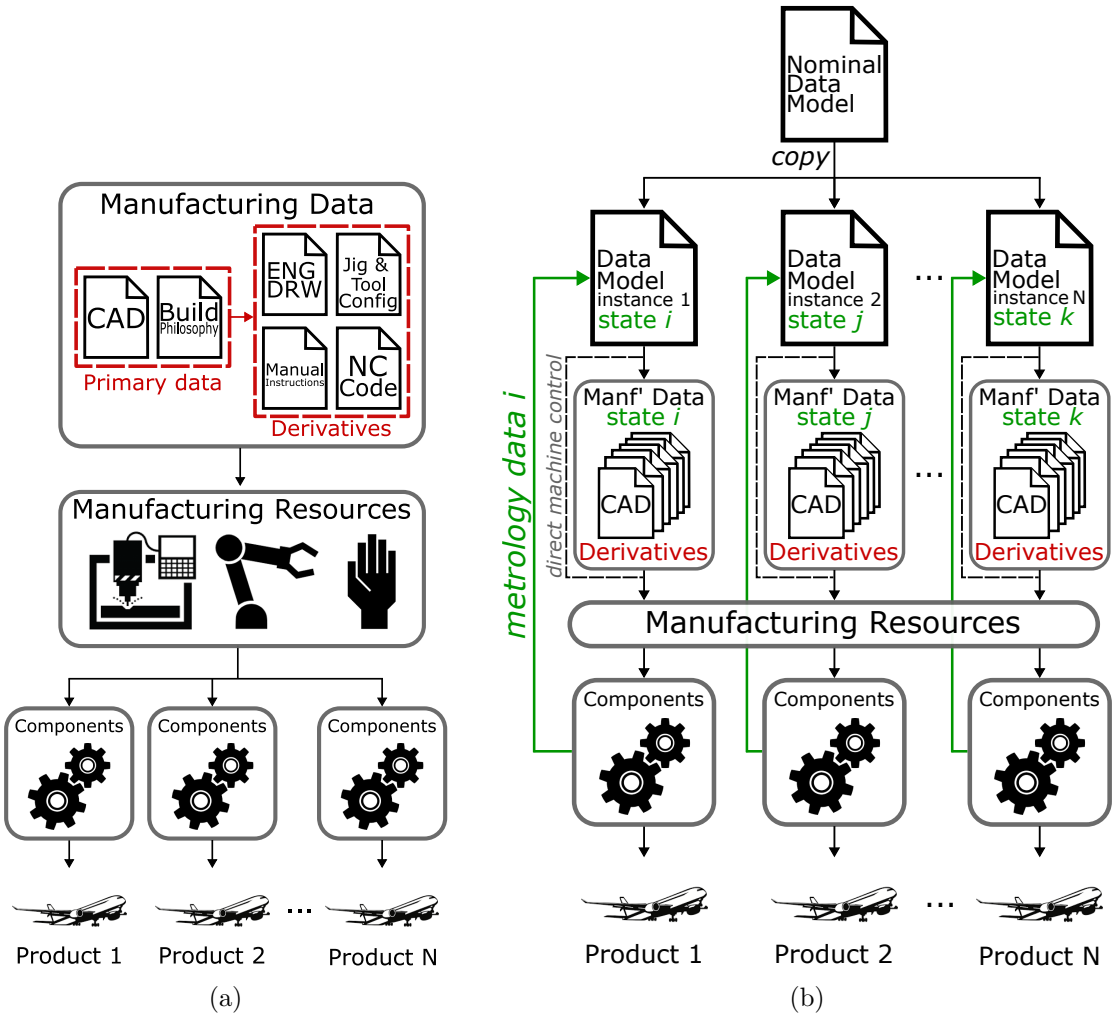


Figure 4.1: Comparison of (a) the current approach to manufacturing aerospace structures. And, (b) the adaptive approach enabled by the data model. Here, dedicated and independent metrology feedback loops are enabled for each instance of manufactured product. The number of iterations, state of the data model, and the derived manufacturing data will be different for each product. This is in stark contrast to (a) where all products are manufactured to the same immutable manufacturing data, regardless of the deviations of the manufactured components.

- The data model can be augmented with metrology data from parts, sub-assemblies and live manufacturing operations; creating a feedback loop between the data model driving the manufacture data and the output of that data. Modifying the data model inherently modifies the output from it.
- Each physical instance of a product is permanently associated with an independent copy of the nominal data model into which its, and only its, metrology data is supplied.
- Ultimately, the data model can also be analysed and modified by automatic methodologies to achieve automatic adaptive manufacturing for variation propagation control.

The data model as it is described, developed and used in this thesis is an example of digital twin driven manufacturing. However, there is some confusion in the current literature on what exactly a digital twin is and the term is applied too liberally. This is why it is avoided in this thesis. In an effort to add some clarity, Kritzinger's paper on digital twins provides a good reference for what constitutes a digital twin [68] and what is better described as a digital model or a digital shadow. With reference to this paper, the work presented in this thesis is a true digital twin since it meets all the specified criteria. The physical object (in this case the product) and the virtual object (data model) are fully integrated together, influencing either automatically influences the other. Moreover, the data model is often the driving influence over the physical object, using the methodologies presented in Chapters 5 and 6 to change the physical object's future state.

4.3 Data Model Overview

The central premise of the data model is that a product's manufacturing data can be modelled as a set of nodes networked together by connections. Each node has a type and, depending on it type, contains a specific set of parameters. Each connection links two nodes and describes the relative pose between those nodes. The connections also have types and the type, again, determines the set of parameters associated with it. The nodes come in four major types: *assembly*, *part*, *feature* and *geometry*. And, the connections come in three major types: *parent-child*, *join* and *key characteristic*. This format is infinitely extensible in size and node-subtypes, allowing for any product to be entirely modelled by this approach. It is also machine-readable, allowing for automatic reading, writing, copying, modifying and analysis.

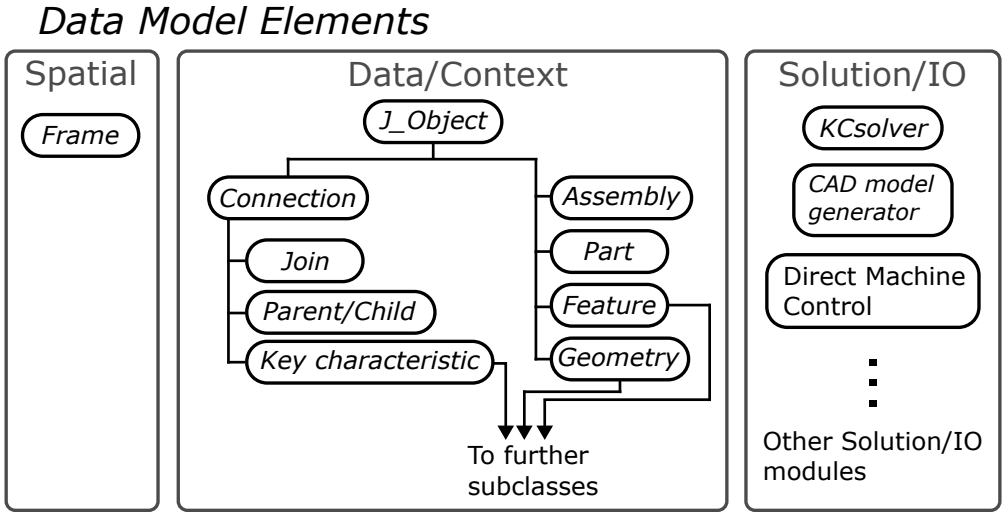


Figure 4.2: Overview of the major elements required to construct the data model.

The data model consists of elements which are categorised into three major groups. There is the *Data/Context* group which provides the hierarchical organisation of the product's elements, context information for the links between elements and implements the parametrisation of the physical dimensions of said model elements. The *Spatial* group generates the mathematical backbone of the data model creating a kinematic-like model positioning each element in space. And, finally there is the *Solution/IO* group which is where elements which read, modify and extract information from a data model are organised. These groups of elements are summarised in Figure 4.2.

For the construction of a data model a standard structure appears. Each *Data/Context* element is permanently linked with a *frame* element from the *Spatial* group, referred to as its datum. A product's manufacturing information is parametrised and modelled as *Structure* elements linked by *Connection* elements maintaining this *Data/Context*-to-*Spatial* association. This generic structure is visualised in Figure 4.3. Bearing in mind that any one *Structure* element may link with any number of other *Structure* elements, creating potentially vast networks of connections until the entire scope of a product's manufacturing information in captured.

The thesis implements the data model and its constituent elements using the object-orientate programming paradigm [69, 70]. The elements of the data model are programmed as classes which can be instantiated as objects to model a product. The following sections provide more detail on the classes comprising the data model and its active approach to variation propagation control. The following section briefly discusses the major concepts involved in object-oriented modelling and object-oriented programming since they are used extensively in the following discussions. A deeper discussion of the implementation of the data model

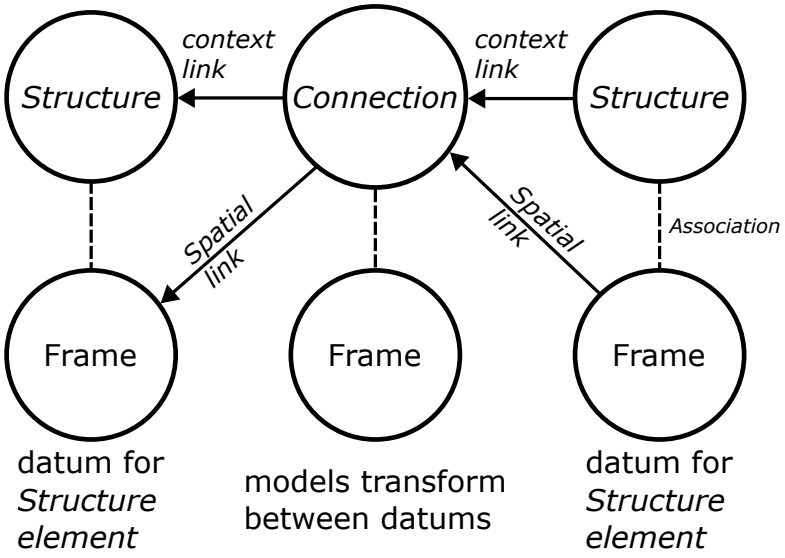


Figure 4.3: Cross-section of the generic structure of the data model. Each structure element can be linked to be any number of *connection* elements. They only exception is the *parent* connection of which an element can only have one.

classes complete with UML (Unified Modelling Language) diagrams is included as Appendix A.

4.3.1 Introduction to the Object-Orientated Paradigm

Before going into the definitions of the data model elements, a brief overview of the object-oriented programming paradigm is presented [69, 70]. The structure of the data model draws heavily on the concepts of the object-orientated approach. And, the prototype software developed in Chapters 5 and 6 uses it for the implementation. The term "element" has been used so far to discuss the concept of something that models the behaviour and properties of something. In the object-oriented programming paradigm this term is replaced by classes and objects.

Systems in object-orientated paradigm are created from the interaction of objects. Objects are a combination of data and functions which operate on data. These are typically called the properties and methods of the object. Objects are designed by creating a class. A class can be thought of as a blueprint for a type of object and from this class infinitely many instances of an object can be created (assuming it is not a singleton)[71]. This concept of the object-orientated paradigm is called encapsulation.

The next major concept is abstraction. This is where the low-level complexity and implementation of an object is hidden from higher-level objects which use that object. For example, the low-level command protocols for communicating and controlling 6-axis industrial robots are implemented into a "robot" object. And, the use of these complex low-level protocols are simplified into a list of methods

with simple arguments which can be called by other objects. This approach ensures that complex and complicated systems can be divided into smaller more manageable problems.

Inheritance is another major concept to discuss and it features extensively in this thesis. The idea here is that classes can inherit the methods and properties from another class. This is in addition to methods and properties defined in the class receiving the inheritance. This enables groups of classes to be created that share known and common behaviours and properties. The class that inherits from another class is referred to as a subclass of it. The class being inherited from is referred to as the superclass. Often classes are created for the sole purpose of being inherited from, these are called abstract classes. This thesis uses this inheritance concept to ensure the methodologies and utility functions are able to deal with generalised products and assembly equipment.

4.4 Spatial Elements

The *frame* class is the only occupant of this group. Its purpose being to provide spatial information to all the *data/context* elements within the data model. And, in doing so, generate a networked kinematic-like model. The model behaves like a kinematic model since modifying the local definition of one frame, modifies the global definition of all the frames directly or indirectly linked from it. However, it does not exactly behave like a kinematic model since closed-loops, that is *frames* with more than one definition, are possible using a special *connection* element. This situation is explained in detail in Appendix A.

Each *frame* object models a single 4-by-4 homogenous transform, of the form in Equation 4.1. It defines the relative pose between two *frames*. Where $\mathbf{T}$ is the transformation between the two *frames*: r_{11} to r_{33} is a rotation matrix and $\mathbf{p_{x,y,z}}$ is a position vector; the bottom row enables matrix multiplication. This is visualised in Figure 4.4. With this simple building block infinitely many *frames* can be linked together to create vast networks of poses, see Figure 4.5.

$$ {}^{\mathbf{A}}\mathbf{T}_{\mathbf{B}} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4.1} $$

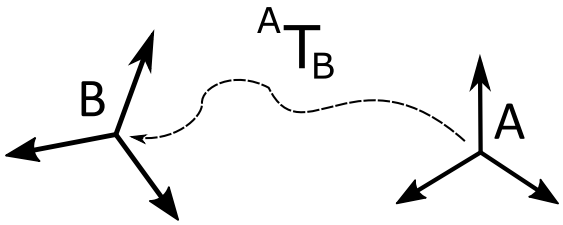


Figure 4.4: A visual representation of the transform ${}^{A}T_{B}$ which describes the pose of frame B from frame A.

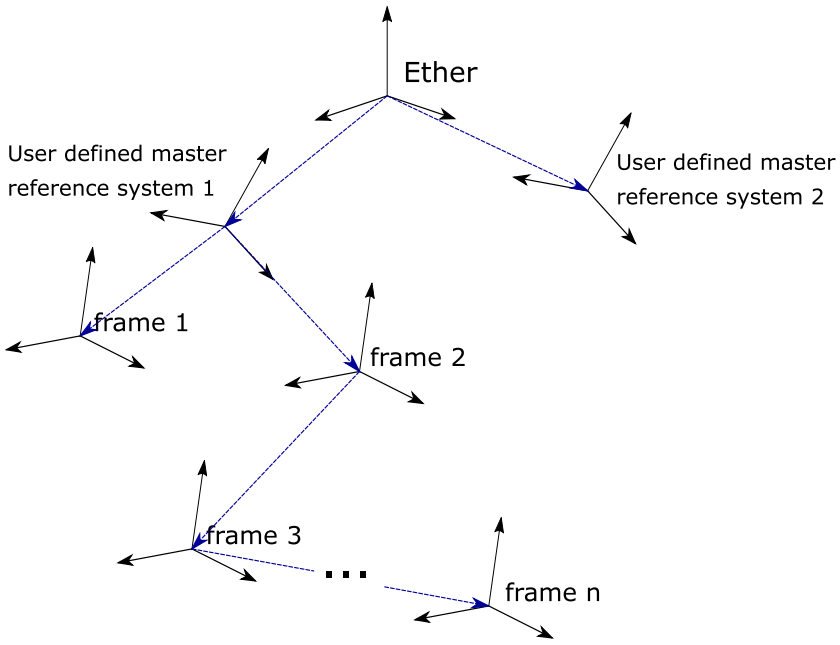


Figure 4.5: A visualisation of a kinematic network created from linked *frames*.

4.5 Data/Context Elements

These elements are what parametrise the manufacturing information in the data model and provide context to the association between them. They can be sub-categories into two main groups: *Structure* and *Connection* elements. *Structure* elements are the element which describe the shape and form of the product and the *Connection* elements are what link them together.

4.5.1 Common Behaviours

The set of *Data/Context* classes all inherit from an abstract class called *J_Object*. In short, this ensures that all instances of the Data/Context objects, and any subclasses of them, have known behaviours and properties. The *J_Object* abstract class adds a set of metadata to each object. The first, and most important, is a unique and permanent identification number for the object. That is, every instance of a data/context element has a unique identification number even if two objects are of the same type and contain identical information. A part number, product number and name is also added to the metadata. These can be used to reduce search times in the data model and provide a identification number linking the digital instance of the data model to a physical instance of the product being manufactured.

4.5.2 Structure Elements

These elements describe the physical and geometric form and shape of the many facets of a product. They also organise and structure these forms and shapes into logical groups and hierarchies. The major elements here are; geometry, feature, part and assembly. Each is briefly discussed, starting from the most simple elements and building up.

Feature

The first fundamental class to discuss is the *feature*. A *feature* models any physical form on a continuous mass of material. For example; a pad, hole, face and pocket are all examples of features. These forms are either positive or negative. That is, they either add or remove material. Each *feature* type can be defined by a standard set of parameters. For example, the standard definition for a hole is shown in Figure 4.6 and the standard definition of a pad is shown in Figure 4.7. Both figures show how the location of the standard form is positioned using its associated *frame* element.

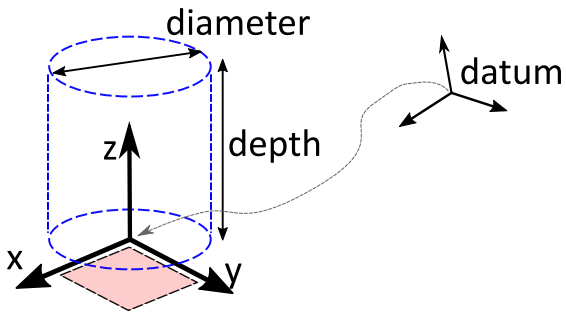


Figure 4.6: A general definition of a standard hole.

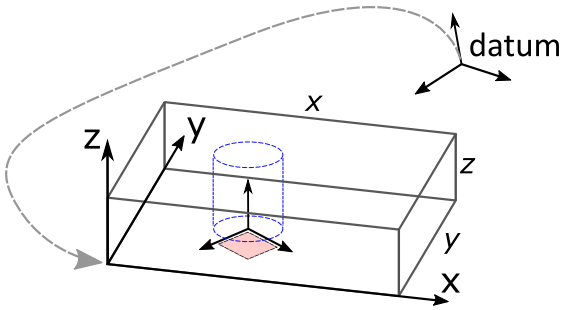


Figure 4.7: A general definition of a standard pad. The pad has been defined in the same system as a simple hole.

Geometry

The second fundamental class is *geometry* which models instances of geometry. Geometry is required to model mathematically perfect imaginary forms and features in a product. Although geometry is not physically present in a manufactured item their use is often important in manufacturing of items. Items such as points, line, vectors and spheres are some examples of *geometry* element types. And each *geometry* type is defined by a standard set of parameters, see Appendix A for some examples. Geometry, and collections thereof, are often the bridge between mathematically ideal and reality. For example, a hole is modelled perfectly as a negative cylindrical *feature* but when drilled it is seldom perfectly cylindrical. Conversely, when measured a collection of points is used to mathematically approximate a ideal cylinder to indirectly measure the parameters of the hole.

Part

A *part* class organises a set of *features* and a set of *geometries* in a single group associated with the same continuous mass of material. In effect, it is the manufacturing data required for the machining operation to create a particular part. Each of the *features* and *geometry* elements use the part datum as the reference system for their own *frame* datum, see Figure 4.8. It should now be clear how any general part can be modelled using the elements discussed so far.

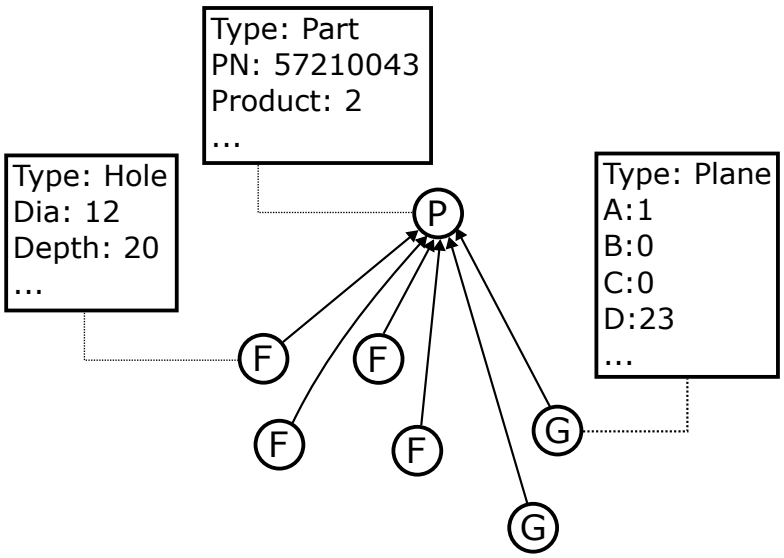


Figure 4.8: Diagram of a single *part* object consisting of several *feature* and *geometry* objects. All the arrows are *parent* connections.

Assembly

The final structural class is the *assembly* element. This groups *part* and other *assembly* objects into a single entity and associates it with a set of *key characteristic* and a set of *join* connection elements. This models a single assembly operation combining both components involved in the assembly with the design requirements for it. The datum of the *assembly* element is the reference *frame* for the *parts* and/or *assemblies* it combines, see Figure 4.9. Once an *assembly* has been defined it can be itself included in another *assembly* to build-up increasingly more complex assemblies. This process can be repeated until a top-level assembly finishes the product's manufacturing definition. This is *assembly* element and is often referred to a the root assembly or final assembly.

4.5.3 Connection Elements

Connection elements are the means by which context and additional information is given to the *frame*. There are a number of types of connection elements but the main three types are: *parent-child*, *join* and *key characteristic*. Each *connection* element encapsulates the spatial link with its own *frame* element and captures the contextual link by referencing the two *structural* elements involved, see Figure 4.3.

Parent-Child

Parent and *child* connections are inverses of each other and together they create the hierarchical structure which has been shown during the discussion of the structural elements. Every structural element has a single *parent* connection, except the

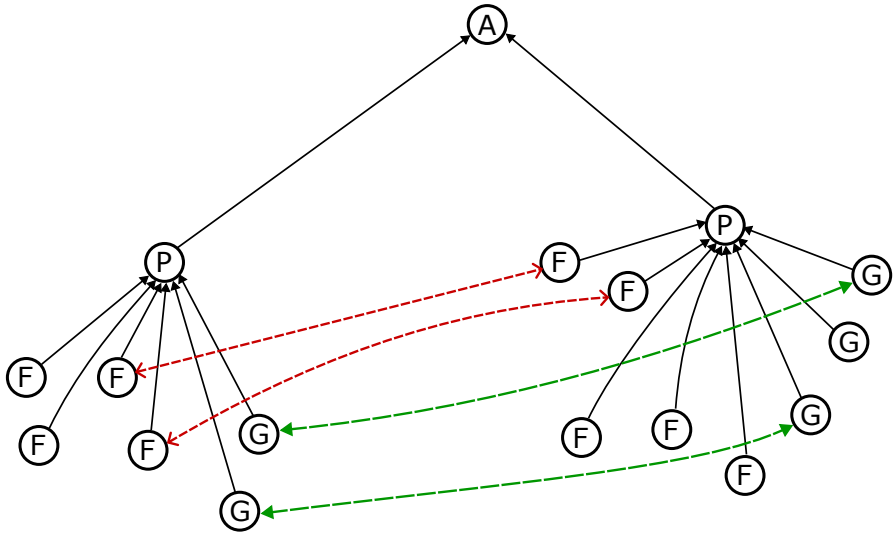


Figure 4.9: Diagram of a single *assembly* object assembling two *part* objects. The black arrows are *parent* connections, the green arrows are *key characteristic* connections, and the red arrows are *join* connections.

final *assembly*. And, every *structural* element can have many *child* connections. For example, every part element typically has many *child* connections, each to a item of *geometry* or a *feature*. Assemblies usually only have two child connections, one of reach of the *parts* or *assemblies* it is combining. The parent connection moves up the hierarchy and the child *connection* moves down.

In context, these connections define the poses of elements relative to important manufacturing reference *frames*. *Features* and *geometries* are located relative to *part* datum systems. *parts* and *assemblies* are located relative to important *assembly* datum systems. These connections are important for generating CAD models and other manufacturing data from the data model.

Join

Join connections model the mechanical joining of two *features*. The connection is associated to an *assembly* element but the contextual references link the two *features* involved and defines the nominal spatial relationship under which the join can be successfully completed, as per the design. A typical *join* models something like two holes connected by bolt or rivet. A whole joint between two parts is modelled as a set of *joins*, one for each hole-to-hole fastening in the joint. Each *join* connection has its inverse with a *join* linking the *features* in the opposite direction. A visualisation of a typical *join* is shown in Figure 4.10.

A number of assumptions are made in this thesis for *join* connections. The first is that the *join* connection fully defines the position of one *feature* relative to another. It is also assumed that if the *features* involved in a *join* are in the relative

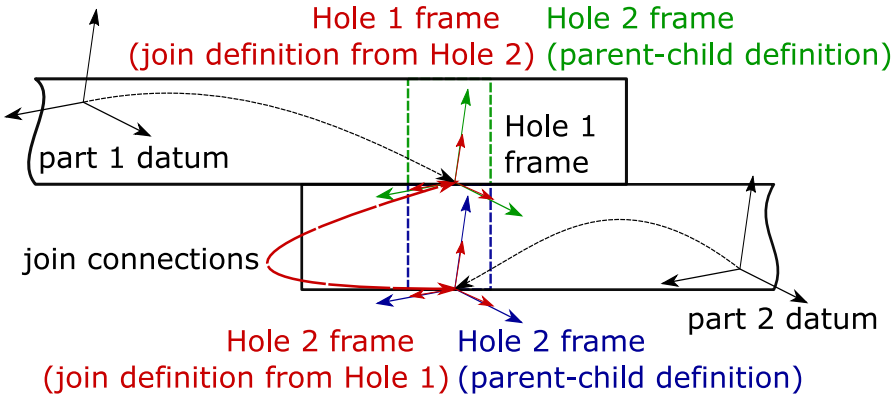


Figure 4.10: A visualisation of the join connection. Two holes on two separate parts are bolted together. The mechanical connection provided by the bolted joint is modelled via a join connection.

nominal condition at the point of manufacture, they will assemble successfully. This can be safely assumed since they will be in their design condition and issues such as limits, fits and tolerances will have been considered during the design phase of the product's inception and already present in the manufacturing data.

Key Characteristic

The *key characteristic* connection models an assembly key characteristic. A key characteristic typically takes the form of a linear measurement between features and/or ideal geometry on the two components involved in the assembly. The trick to a good key characteristic is that is easily confirmed on the physical product. These measurements are usually gaps, steps, alignments and intersects. Moreover, each assembly usually has several key characteristics defining an acceptable assembly.

The *key characteristic*, like the *join*, is associated to an *assembly* element but the contextual references link the two *geometries* involved and defines the nominal spatial relationship between them. However, this spatial relationship is superfluous since a key characteristic only constrains a subset of the degrees of freedom. And, each key characteristic provides information regarding the type of key characteristic it is, the nominal condition of the key characteristic, the tolerance for deviation from this nominal value, any additional conditions associated with it and the priority of the key characteristic.

4.6 Solution/IO Elements

This group contains classes which implement solutions for either reading or extracting information from data model, writing or modifying a data model's current

state or analysing a data model. They implement the general purpose algorithms, or sets of algorithms, used for implementing the methodologies in Chapters 5 and 6 as software applications.

4.6.1 KCsolver

The *KCsolver* class acts like a folder for a set of standard algorithms for solving the geometric relationships between *geometry* objects. This class is instantiated by the methodologies developed in the following chapters to solve misaligned sets of key characteristics. This solution information is then used to correct the data model to restore the condition of the key characteristic connections to a nominal state. For example, this class contains algorithms for finding transforms to align one plane parallel to another and set a specific gap between them, it set a point at an offset to a plane or line, and align a vector to a point. The class is extensible such that new algorithms can be added for new combinations of geometry.

4.6.2 Metrology Integration Forms

The parametrisation of manufacturing data into a interconnected series of machine-operable objects enables the automatic integration of metrology information into a data model. Measurements of a feature, part location or sub-assembly location can be included into the data model by modifying a *structural* object's parameters or a *connection* object's *frame*. However, the gathering of metrology data and conduction of measurements cannot always be automated, therefore a generalised approach, for man or machine, to mapping the information between data model objects and real-world measurements is required.

To this end, a Metrology Integration Form is created for the inspection of a part or assembly. It is simply an XML list of all the features and geometry linked below the component under inspection. That is, all the *features* and *geometry* are listed for a *part* and all the *features* and *geometries* are listed for all the parts that make up an *assembly*. The object that generates these forms automatically includes the necessary metadata. Such that, when the form is filled the measurements are easily linked to the object to which they are intended. Figure 4.11 gives an example of this when applied to a single hole on a aerospace cover.

Alternatively, some metrology software applications can receive CAD data to direct and provide metadata for a set of measurements. In that instance a CAD model can be provided using the CAD model generation element.

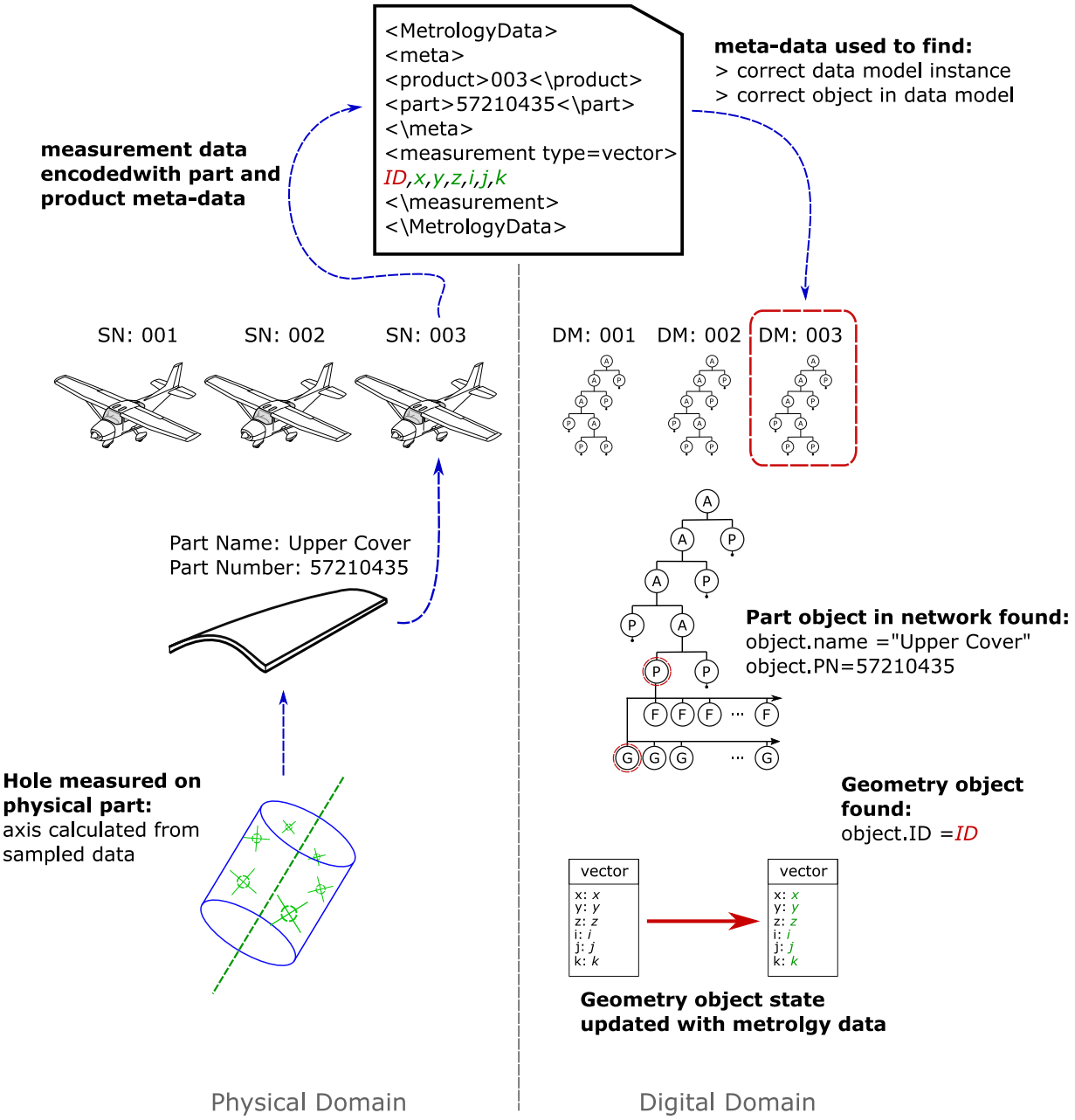


Figure 4.11: Diagram detailing the encoding of measurement data and metadata. It also expresses the relationship between the format of the encoding and the data model structure itself.

4.6.3 Automatic Generation of a Data Model

The presented description may seem overwhelming and the idea of manually creating a data model one object at a time obscures the practicality of this approach. Fortunately, a data model can be generated automatically from the CAD model and manufacturing build philosophy. The *Parent-Child* connections, *assembly*, *part*, *feature* and *geometry* objects are all automatically created from the CAD model files of a product.

The aerospace applications in this thesis all use hole-hole joins (bolted or riveted) and as such all *join* and *joint* connections can be, and are, automatically found and created using a method implemented by the *assembly* object. The current method searches through all the components involved in the *assembly* object for *hole* objects and finds pairs between holes which are not on the same part or sub-assembly. Once a pair has been found, two joins are created between them as specified in the above section. All joins that link the same two components together are grouped together in a *joint* object that links the component at the *part/assembly* level.

The key characteristics are harder to identify as any two or more objects can be involved in a key characteristic. They are traditionally defined in high-level "frontier" drawings and build philosophy documents which identify the key features and the desired relationship between them. These documents will also define the tolerance that is to be achieved. To assist with the automatic creation of *key_characteristic* relationships, this thesis implements a method of codifying a key characteristic definition into an XML file. This XML format is detailed in Appendix E. Each key characteristic defines its name, type and priority. It may also contain a description. The key characteristic defines the features or geometries which make up the key characteristic. This is achieved by a *component.criteria* style search criteria. Where *component* is the *name* or *ID* of the J_Object in the assembly within which to search for the *feature* or *geometry* object and *criteria* is the *name* or *ID* of the *geometry* or *feature* object. The *static* and *dynamic* attributes identify which part is being assembled to the other. That is, the dynamic component is manipulated and ultimately fastened to the static component. The tolerance and conditions are specified as discussed in the sections above.

Once a nominal data model has been automatically generated, it can be saved to file. Copies of this file can be made for each instance of manufactured product and each copy can be operated in parallel in tandem with its associated physical instance. Therefore, this method need only be run once at the end of a product's engineering design loop before production begins.

To summarise, the method is:

1. Automatically generate *structural* objects and *parent-child* connections from nominal CAD models.

2. Automatically generate *join* connections from analysing the features within each *assembly* object.

3. Automatically generate *key characteristic* connections from XML encoding of assembly requirements.

4. Save data model to file. Generate a copy for each manufactured instance of the product that will be modified (and adapted) with component inspection data.

4.6.4 CAD File Output

Since the data model is defined to be a format capable of modelling a product's entire manufacturing data, it should be possible to derive all other manufacturing formats from it. Of these formats the CAD model is the most useful since everything from engineering drawings to NC machine code can be derived from it. CAD models are be generated from a data model by reading only the network of *parent-child* connections; and the objects they link together. All CAD modelling software applications are proprietary applications. Therefore, a specific interface is required to generate CAD models in an application specific file format. This thesis has implemented an interface for CATIA, generating .CATpart and .CATproduct files [72]. However, the general method is applicable to all.

Using this *Solution/IO* element in combination with the other functions of the data model enables CAD models to be automatically generated which represent the true state of a manufacturing process' output. Chapter 5 will build upon this to integrate an adaptation phase to achieve active variation control in part-to-part assemblies.

Part File Output

```
// Pseudo Code: .CATpart generation
// Usage: CATpartGen(object)

for feature in part:
   #Using feature parameters create data structure via CATIA
      interface...
   #Fill data structure properties and name with object metadata...
```

```
#Generate geometrical set.

for geometry in part:
   #Using geometry parameters create data structure via CATIA
       interface...
   #Fill data structure properties and name with object metadata...

#Save .CATpart to file using same name as part object...

return #reference to file
```

Assembly File Output

```
// Pseudo Code: .CATproduct generation
// Usage: CATproductGen(object)

referenceList = {}
for component in Assembly:
   if component.type == "Assembly":
      ref = CATproductGen(component)
   else:
      ref = CATpartGen(component)

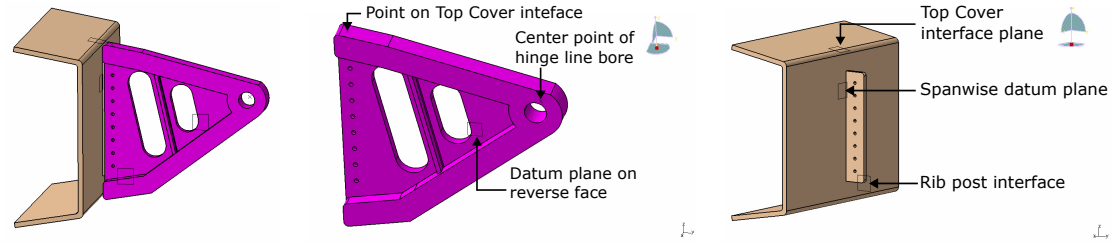
   referenceList[component] = ref

#Create empty .CATproduct
for component, ref in referenceList.items:
   #add file to .CATproduct using reference...
   #locate ref using component.frame object definition via CATIA
       interface...

#Save .CATproduct to file using same name as asssembly object...
return #reference to file
```

4.6.5 Direct Machine Control

Naturally, if the manufacturing resources are automated there may be no reason to translate the information of a data model into another format at all. The manufacturing resource can be controlled directly by an application being driven by an instance of a data model. This approach extends to the gathering of metrology



(a) (b) (c)

Figure 4.12: (a) Simplified example of rear spar to trailing edge rib assembly. (b) Overview of the key geometry for the trailing edge rib. (c) Overview of the key geometry for the rear spar section.

data also. If the metrology device and associated metrology software have an automation interface, the entire data gathering and component production process can be automated with the data model at its core. An example of this is given in Chapter 6. Where a metrology-guided robotic assembly for multiple key characteristic control is delivered. This example features both the robotic assembly device and photogrammetry metrology device being directly controlled. Automating the data gathering, metrology integration, analysis and adaptation, and the assembly operation.

4.7 An Illustrative Example

The above sections have provided a set of classes which are able to model the total manufacturing data of a product in a single machine-readable format. This section will provide an illustrative example. Figure 4.12(a) shows an image of a CAD model representing a section of aerospace spar assembled to a hinge rib. The key items of geometry used to define the key characteristics are presented in Figure 4.12(b) and Figure 4.12(c). For the sake of argument lets assume that the assembly of these two components represents the final product that is delivered elsewhere for other assembly operations. This will simplify the data model to a single assembly and keep the example clear from excessive details. Figure 4.13 shows the typical type of image that would be included in a build philosophy document. It details the key characteristics and tolerances that determine a successful assembly operation. The nominal data model for this product can be generated automatically by using the method detailed in Section 4.6.3.

This nominal data model is visualised in Figure 4.14. All the information and requirements concerning the machining operations of either part can be determined from it's associated *part* object. And, the details and requirements for the assembly operation can be understood from the *key characteristic* and *join* connection between the parts, that are conveniently found in the *assembly* object. From

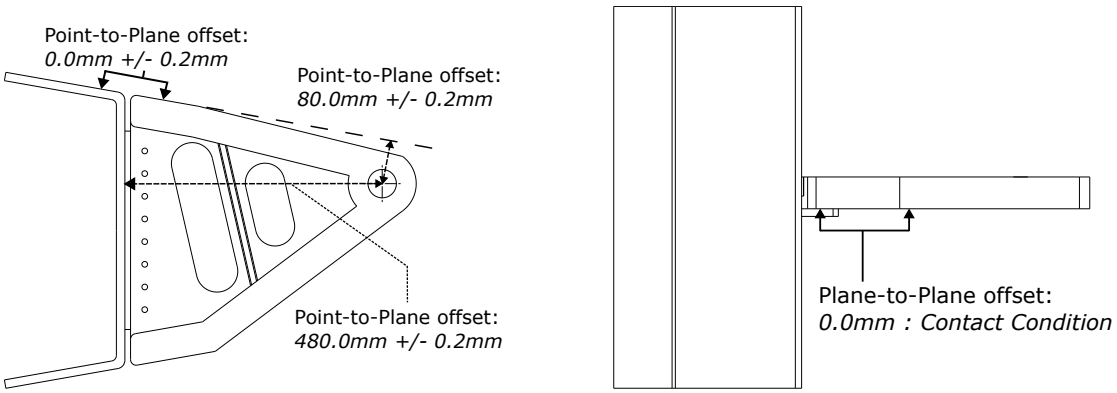


Figure 4.13: Overview of key characteristics and tolerances for the rear spar-to-rib assembly. (a) Key characteristics in the X-Y plane. (b) Key characteristic in the X axis.

this data model it is possible to generate all the CAD models in Figure 4.12 and automatically provide the details for a build philosophy document, implementing the adaptive approach to assembly presented in Figure 4.1(b).

Once production starts for the manufacture of these spar-to-hinge rib products, a copy of the nominal data model can be created and assigned the same serial number as the physical product it is associated with. With reference to Figure 4.1(b) let this be the product with serial number 1. Such that the first copy of the nominal data model has the unique identifier 1 and the physical parts and resulting assembly also have the unique identifier of 1, ensuring a permanent and independent link between the two. At this stage no metrology data has been supplied into the data model so the nominal data model and instance 1 are identical, let this data model state be *state 0*. As the product is produced, part by part and assembly by assembly, it will be measured and inspected to ensure product quality and conformance to tolerances. For example, let the first part manufactured be the spar, see Figure 4.12(c). The spar is inspected by a metrology device to ensure that the design specifications and tolerances have been adhered to and to provide the necessary traceability required of measurements for ISO 9001 compliance [73], a mandatory requirement for the aerospace industry. This data is easily integrated into the data model using the method developed in Section 4.6.2. Referencing Figure 4.1(b) this would be metrology data 1 (the first batch of supplied metrology data). Integrating these measurements into the data model would change its state from *state 0* to *state 1*, more accurately representing the state of the actual product but at the cost of deviating from the nominal design. Since the manufacturing data, in this new paradigm, are derivatives of the data model, changing the state of the data model also changes the state of the manufacturing data to match. However, just copying the true state of the physical product does

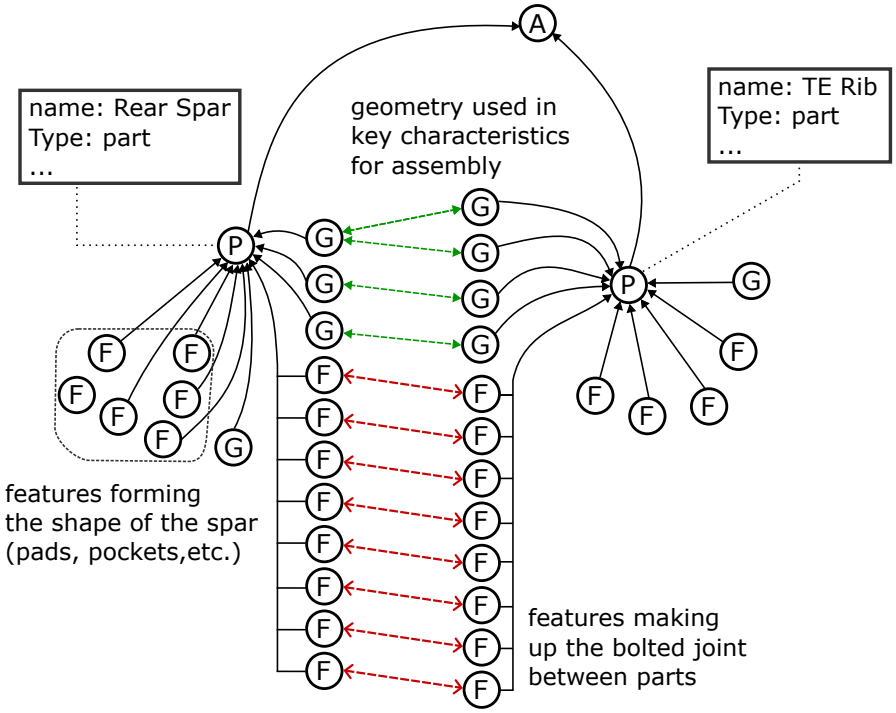


Figure 4.14: Diagram of the data model for the product shown in Figure 4.12(a).

not control manufacturing variation. Therefore, adaptive methodologies need to be integrated into this state changing loop to operate on the data model and intelligently change it to stop the propagation of manufacturing variation. Figure 5.1 and Figure 6.2 detail how the methodologies developed in this thesis integrate into the metrology feedback loop and the data model driven approach detailed in Figure 4.1(b). Once the state of the data model has been changed by the integration of metrology data and one of the two methodologies presented in this thesis, the state of the manufacturing data will also have changed state, minimising the propagation of manufacturing variation when the trailing edge rib is assembled to the spar, see Figure 4.12(a). This will either happen by adaptive changing the design of the trailing edge rib *before* it is manufactured (or by adaptively machining just the key features and assembly features of a stock item just in time for assembly). This is the methodology developed in Chapter 5. Alternatively, it could be done by adapting the assembly process by running through the data model state change loop in near-real time by supplying a live feed of metrology data. This methodology is developed in Chapter 6. Alternately, a combination of the two methods could be used but this is an area for future research. Regardless of the choice of adaptive methodology, once the assembly is complete, it can itself be inspected, or the data from the metrology-guided process (if applicable), and used to update data model again to *state 2*. The state of the data model is incremented each time the metrology data from a manufactured part or sub-assembly operation is completed. Following the completion of the final assembly, the prod-

uct can be shipped/sold and the data model instance stored at whatever iteration it reached during the total production process. It can then be used for inspection or reproduction of parts should the physical instance take some damage during service and need replacement. This approach is followed independently for each serial number of product and their associated independent data model instances (1 to n).

It is foreseen that all measurement data should be supplied to the data model for all parts and assemblies of a product since the data is likely already collected and storing it somewhere is mandatory. Therefore, storing it in an intelligent data model will come at either no, or a small, operational cost. Therefore, any data model should have at least as many iterations as it has parts manufactured and assembly operations. However, this is not mandatory and the variation controlling methodologies in this thesis do not require total inspection, only the inspection of the features involved in the adapted assembly operation; which is a very small subset of the total available features on an aerospace assembly. This leads nicely onto the methodologies themselves, these are more likely to be utilised at key assembly operations in the product's manufacturing progress since operating them for all assemblies reduces the benefits of any particular adapted assembly and will likely be computationally expensive.

4.8 Chapter Summary

This chapter has presented the argument for, and constructing elements of a data model for automatic variation control in product assembly. An overview of the data model was given, followed by a deep investigation of the concepts guiding the implementation of the fundamental classes at the core the data model. This included classes for building data models and for operating on them. The chapter cements these concepts by presenting an illustrative example at the end of the chapter. Ultimately, the data model enables the active variation control methodology of the following chapters, achieving the aim of this thesis. Chapter 5 implements an adaptive methodology to achieve variation propagation control in part-to-part assemblies. It also enables part-to-part assembly techniques to be applied in low tolerance applications in a practical fashion. Chapter 6, however, uses the data model to implement high-precision and mobile robotic assembly. But, most importantly it controls a set of multiple key characteristics simultaneously during the robotic assembly process. The live measurement data of the key characteristics ensures the robotic assembly operation adapts to manufacturing variation present in either component involved in the assembly operation. Together these two methodologies provide a automatic variation control methodology, suitable

for the aerospace industry, for all types of assembly.

This data model exhibits novelty on several different facets. Firstly, the overall manufacturing paradigm suggested here is an alternative to the traditional CAD and engineering drawing driven paradigm. Here, the CAD, drawings and processes change as metrology data is fed back from the live process. In effect the data model becomes the master manufacturing data for a particular product instance and the nominal model the master design reference for a product. The next novel development is the existence and management of closed loops in the spatial network. The mathematics, from which the spatial elements stems, is connective assembly modelling. However, connective assembly techniques can only consider open chains of frames. This was also evident from the literature review which only contains examples of open chains of frames and explicitly states it as a limitation [1, 36]. The last source of novelty is the applications and subsequent implementation. Metrology-adapted processes have been the subject of research for a while but have all largely been bespoke laboratory trials without much consideration for its eventual use in practical industrial environments. This would explain the slow pickup of industry to shift towards metrology-enabled processes. This data model abstracts away a utilisation of metrology data and provides a familiar interfaces to the metrology and manufacturing systems in existing organisations. Ultimately, paving the way for metrology driven manufacturing.

Chapter 5

Automatic Variation Propagation Control in Part-to-Part Assemblies and Technical Demonstrator

5.1 Introduction

This chapter develops an automatic variation control methodology for part-to-part assemblies. It does this by leveraging the production feedback loop enabled by the data model of Chapter 4 and introduces an adaptation phase for both the *key characteristic* and *join* connections. The adaption phase modifies the sections of the data model for the parts that have not been manufactured yet. The adaptation phases ensures that the key characteristics for an assembly in a product's manufacture can be maintained. It also maintains the requirements of part-to-part assembly.

Part-to-part assemblies are one of the two categories of mechanical assembly. They are defined as an assembly that is completely constrained by its assembly features [1]. That is, the assembly is completed by aligning the adjoining hole patterns similar to a set of DIY furniture. It a desirable technique for assembly since no tooling, jigs or gauges are required, making it much cheaper and quicker than fixtured assembly. However, traditional part-to-part assembly does not allow for a variation control method since all manufactured components follow the same manufacturing data. Also, since the assembly is driven by the assembly features the accuracy of the key characteristics suffer. This lack of variation control and accuracy has resulted in part-to-part assembly techniques being overlooked as option for the aerospace industry. The methodology presented in this chapter

removes these limitations and demonstrates a practical means of applying adaptive part-to-part assembly in the assembly of aero-structures.

This chapter begins with a general discussion of the concept behind the automatic variation control methodology in Section 5.2 and what it is intending to achieve. Section 5.3 then details the methodology itself. An illustrative example is provided in Section 5.4. This is then followed by the technical demonstrator in Section 5.5. This discusses the prototype software used to the implement the methodology for the two experimental demonstrators, see Figure 5.11 and Figure 5.13. It also summarises the analytical work completed in Appendix B which provides some useful equations and proofs of achievable accuracy.

5.2 Adaptive Part-to-Part Assembly

This methodology achieves active variation propagation control in part-to-part assemblies by modifying the manufacturing data, usually the CAD data, of components that have not yet been manufactured. This modification uses the measurement data of other components that have already been manufactured and their data has been integrated to into the data model, using the method described in Section 4.6.2. As parts are machined and sub-assemblies are assembled they can be inspected and measured to producing batches of metrology data to update a data model. The updated data model is then adapted by a series of automatic algorithms, restoring to nominal the affected key characteristics and join connections of incomplete and affected assemblies. Affected, here, referring to *assembly* objects which have been partially modified by the inclusion of metrology data to the data model.

This highlights a natural limitation of this approach. It can only be applied on assemblies where one component of the two assembled together is manufactured and measured *before* the other. Alternately, one of the parts or sub-assemblies can be machined in-situ with the aid of sacrificial materials. Fortunately, aero-structures assembly is a much slower industry than most and sacrificial material is already in use in a number of areas. Therefore, either approach is possible to enable this adaptive approach in existing manufacturing facilities.

The next item to discuss is the number of applications of this methodology on a particular product design. Aero-structures are large products with many parts and like most products it is possible to have a combination of the two types of assembly. That is, some of the sub-assemblies use part-to-part techniques and others could use jigs and fixtures. For a product consisting of n parts it must have $n - 1$ assemblies. This assumes that each assembly consists of two components. This is an acceptable assumption since an assembly of more than two components

can be modelled as a series of individual assemblies of two items. Therefore this methodology can potentially be applied a maximum of $n-1$ times. However, measuring every part machined and every sub-assembly assembled can be resource intensive. Fortunately, this process can be applied as little or as much as it is necessary or economical. It is best applied on key assemblies with low tolerances, preferably those which require a lot of gauges. Another advantage is that full inspection is not required, only features involved in the targeted assembly need to be measured. Therefore, it is possible to allow manufacturing variation to build-up until a critical point in the production process and adapt it out when necessary or convenient. This is likely the most practical application of this methodology since using it excessively will likely lengthen the critical path of a production line since every part must be manufactured and measured before the next one can be manufactured and assembled.

5.3 Methodology Overview

This methodology takes the feedback loop in Figure 4.1(b) and introduces an automatic adaptation phase, see Figure 5.1. The figure shows an external programme which operates upon the data model each time metrology information is introduced. This adaption phase consists of two parts: the first analyses the state of the key characteristics for the assembly and modifies the data model to correct any deviation the key characteristics may have to nominal; and, the second analyses the state of the joins in the assembly and modifies the data model to restore them to nominal. Here, a join is what models a single assembly relationship between two components (a pair of bolted holes for example), a collection of joins between the same two components is a joint. Once the adaption phase has concluded, the CAD model extracted for the manufactured of the remaining half of the assembly will be adapted such that upon assembly, the key characteristics will be maintained to within the manufacturing variation of the last part, as proven in Appendix B.

This adaptation phase is associated with the introduction of new metrology information. And, until the final assembly, there will always be an affected *assembly* object where the unfinished component can be adapted. Therefore, the methodology can be summarised as the following for each batch of metrology data from a finished part or sub-assembly.

1. Update the data model with metrology data from finished component (part or sub-assembly). Let this component be called A.

2. Find affected *assembly* object. The assembly object that combines A with component B. Where B has not yet been completed yet.

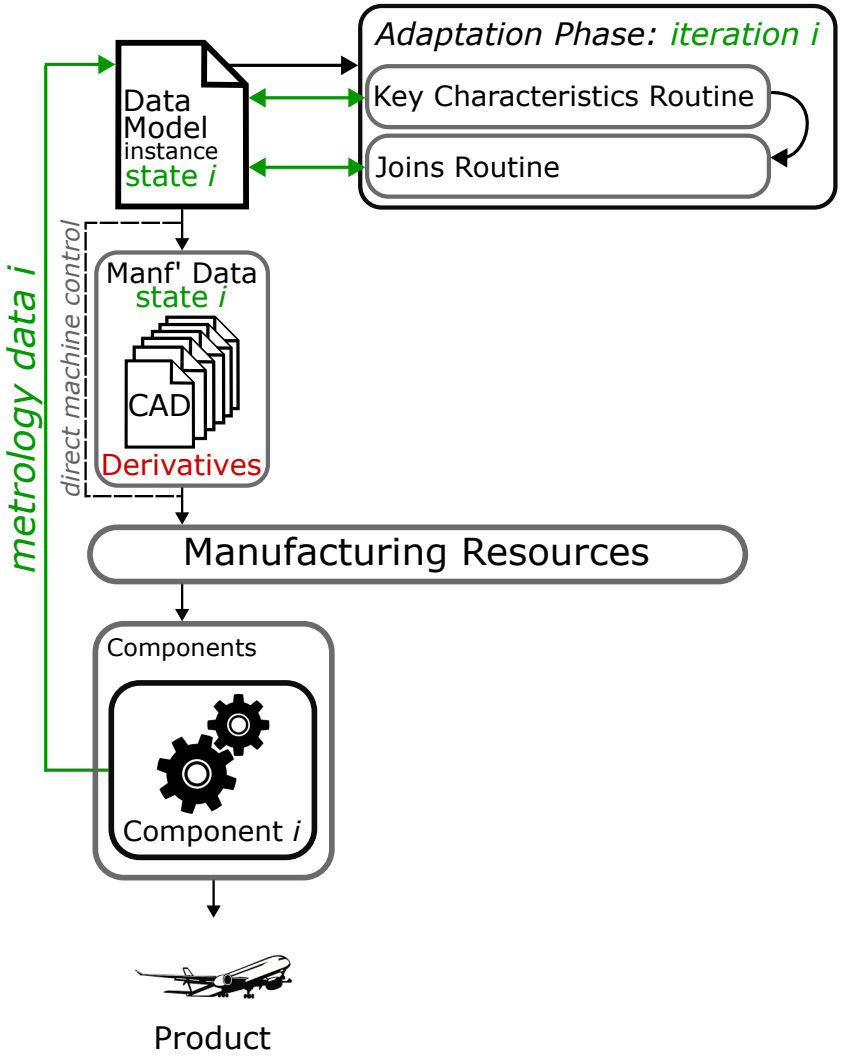


Figure 5.1: Overview of the adaptive variation propagation control methodology.

3. Via the *assembly* object, find the set of *key characteristic* connections for the assembly.

4. Restore the key characteristics to a nominal condition:

   (a) Analyse the deviations of the key characteristic from nominal.

   (b) Solve the set of key characteristic objects, using a key characteristic solution routine, for a transform that restores them to a nominal condition. This transform must be applied to the *parent* connection of component *B*.

   (c) Commit this transform to the data model by modifying the information in the *frame* object of the *parent* connection.

5. Via the *assembly* object, find the set of *join* connections for the assembly.

6. For **each** *join* object:

   (a) Analyse the deviation of the join from nominal.

   (b) Determine the corrective transform to return the *join* to nominal. This transform must be applied to the *parent* connection of *feature* object on component *B*.

   (c) Commit this transform to the data model by modifying the information in the *frame* object of the *parent* connection.

7. Save the state of the data model.

At this point the manufacturing data for component *B* will be modified such that once manufactured and the part-to-part assembly completed, the key characteristics will be nominal to within manufacturing variation of component *B*. This process can then be repeated for the sub-assembly of *A* and *B*.

Following the above methodology, it is possible to stem and remove existing manufacturing variation present in the current state of the product. This is true for a single part or for a sub-assembly that has been aggregating variation across several components. This increase in control and accuracy over the key characteristics of a part-to-part assembly enables its application in low tolerance environments, such as those in the aerospace industry.

5.4 An Illustrative Example

This section walks through the whole methodology using a simple two component part-to-part assembly as an example. Figure 5.2 shows two plates, *A* and *B*,

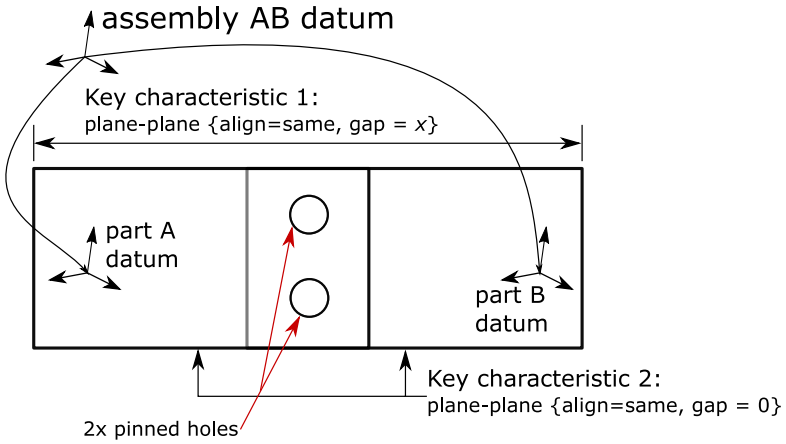


Figure 5.2: Simple assembly example. It is an assembly of two plates. They are joined together by two pairs of dowelled holes.

joined by a lap joint. The lap joint consists of two pairs of assembly holes which are dowelled upon assembly. The requirements for the assembly are detailed by two key characteristics detailing the total width and height of the final product. In this example, only two dimensions will be considered for clarity.

Part A is manufactured first. Its manufacturing data, in whatever form it is needed, is extracted from the data model. This will likely be a machining operation on a CNC machine, a CAD model will be extracted upon which CAM software can generate tooling paths. Once manufactured, the part is then inspected. The metrology device used to complete the inspection could use the CAD model developed to manufacture the item, automatically formatting the data. Alternatively, it could use a metrology integration form (see Section 4.6.2) extracted from the data model.

Using the metrology data from the inspection of part A, the data model is updated. This update is visualised in Figure 5.3(a). It shows that manufacturing variation has produced the plate slightly too large and the assembly holes out of position. The introduction of metrology data into a data model acts as a convenient automatic trigger to launch the adaption phase of the methodology.

5.4.1 Adaptation Phase

The adaption phase for this methodology comes in two phases: the first solves the key characteristics of the assembly by finding a corrective transform for the datum *frame* of part B; the second, locally restores the condition of all the joins between assembly features. This is achieved by determining the corrective transform to apply to the datum *frame* of the features on part B. Both sets of *key characteristic* and *join* connection for any assembly can be found via it corresponding *assembly* object.

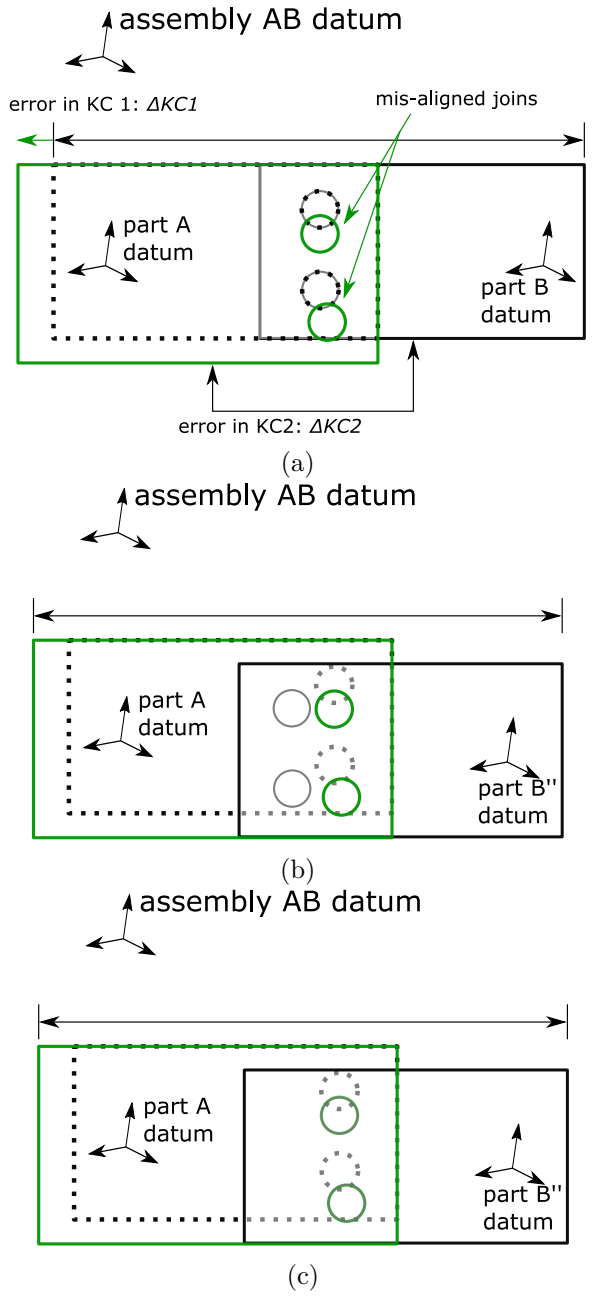


Figure 5.3: Overview of the methodology operating in the assembly upon Figure 5.2. The green lines indicate the measured values of Part A and the dotted lines indicate the nominal values of Part A. (a) State of the data model after the metrology data is imported. (b) State after key characteristics have been adapted to nominal. (c) State at the conclusion of the methodology.

The *key characteristic* connections of an *assembly* object are automatically solved by the creation of a key characteristic solution routine. This routine is created from standard methods called from the *KCsolver* object in the *solution/IO* element group, see Section 4.6. This routine, similar to the nominal data model, only needs to be prescribed once at the initial generation of the nominal data model. The routine details the general format, order that the key characteristic should be solved in, and any projective operations that need to be applied to the results. In this example in Figure 5.3(a), the routine would prescribe the following:

1. Solve KC1: using plane-plane-offset function.
2. Modify data model with resulting transform.
3. Solve KC2: using plane-plane-offset function.
4. Project result onto static geometry of KC1.
5. Modify data model with resulting transform.
6. Commit changes. Figure 5.3(b) visualises the state of the data model following this key characteristic adaptation phase.

This routine is permanently associated with the *assembly* object for which it is prescribed. The above is enough to automatically find the correct *key characteristic* connections, their referenced *geometry/feature* objects, solve them and manipulate the results. For the technical demonstrators of this thesis these routines are created manually and added directly to the *KCsolver* object. However, it is envisaged that they could be automatically generated by building upon the XML approach used to automatically generate the *key characteristic* connections themselves, see Appendix D.

The *join* connections are much simpler to solve since they can be considered in isolation. Each *join* connection can be used to determine the required global position of the hole on part B. This can be compared to its actual global position and a corrective transform generated. This operation is visualised in Figure 5.4. This operation is done for each *join* connection. The aggregate of all these *join* connection correction operations, including the interfacing surfaces discussed in Section 5.5.2, implements the *Joins Routine* in Figure 5.1.

Following these two phases the data model is in a new state where the design of part B has been changed but the important assembly relationships are restored to a nominal condition, see Figure 5.3(c). This successfully implements the variation propagation control required for part-to-part assemblies. This methodology can be repeated for every *assembly* object or just at critical points in a product's manufacture.

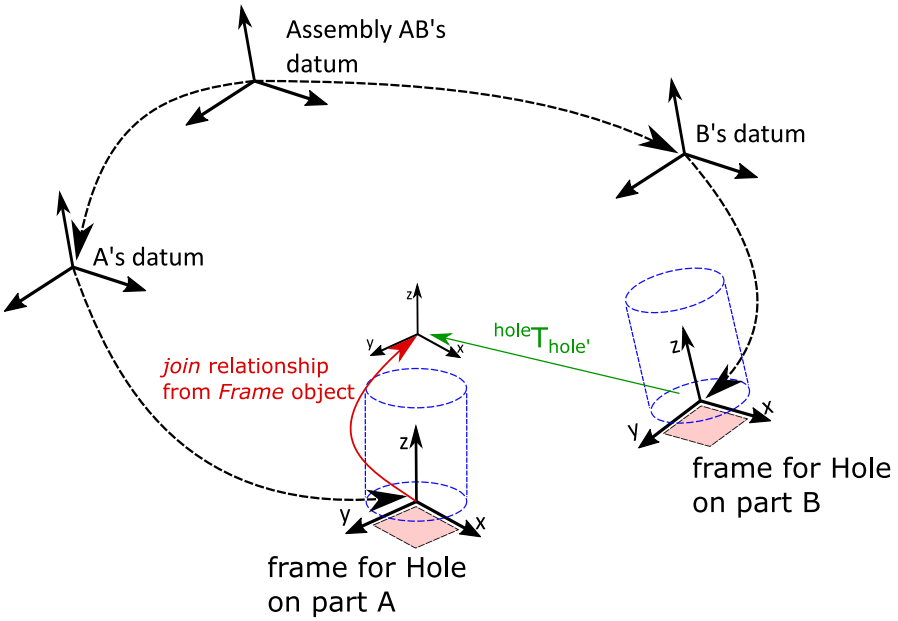


Figure 5.4: Visualisation of the *join* object being used to determine the corrective transform for a hole on part B.

5.4.2 Output

The output of this methodology is technically the new state of the data model. But, as discussed in Chapter 4, the data model is the primary manufacturing data from which all other formats can be derived. Therefore, by changing the data model the CAD models, engineering drawings and instruction sheets for following manufacturing and assembly operations automatically adapt. In this example, the subsection of the data model for part B is modified to reposition the assembly holes such that upon assembly the key characteristics of assembly AB are close to nominal.

More specifically, the key characteristics will be nominal to within the manufacturing variation of the assembly holes and key features on part B. Appendix B analytically proves this is true for any number of accumulated parts or sub-assemblies. The appendix also analytically proves the capability of this process for achieving low tolerance key characteristics and provides an equation for selecting the appropriate manufacturing and metrology equipment to achieve a desired tolerance. Moreover, an analytical consideration coupled with a simulation of an assembled joint similar to that in Figure 5.2 is given to quantify the advantages of this adaptive part-to-part assembly methodology over that of the typical approaches.

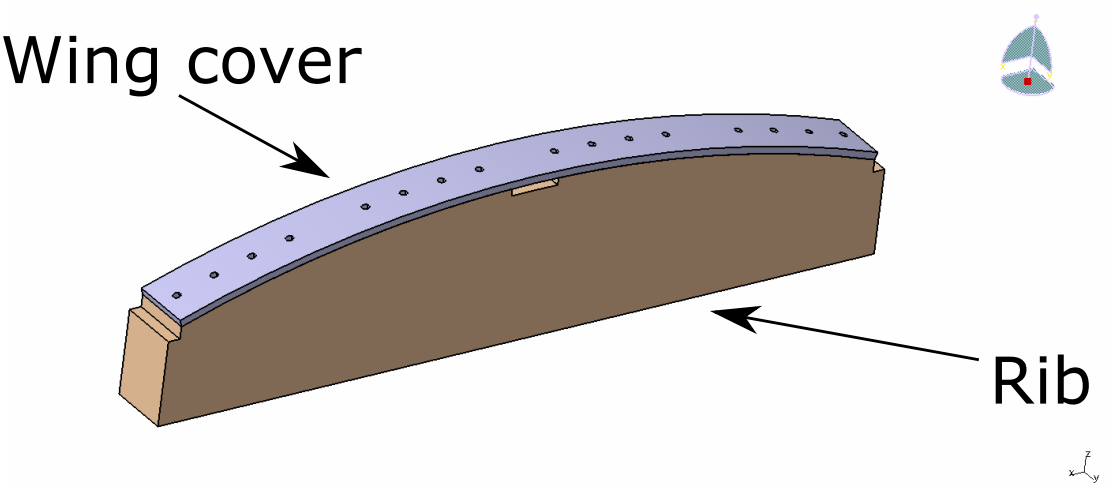


Figure 5.5: Representative case study of a rib to wing cover assembly.

5.5 Technical Demonstrator

In this section, the methodology (see, Figure 5.1 and Section 5.3) and theoretical analysis (Appendix B) will be validated by an experiment on a representative test case. This validation will take the form of a prototype software and the utilisation of this software to complete a process trial. The prototype software validates that the methodology can be suitably automated such that its use is convenient and practical for industrial applications. The process trial will ensure satisfactory key characteristics and part-to-part assembly between two parts using the prototype software. The test case mimics a simplified rib to wing box assembly, see Figure 5.5. Where the major objectives of the assembly are:

- To achieve part-to-part assembly between the two components using representative full-size holes. That is, both holes are of the same size such that there is no subsequent back-drilling operations. Moreover, that leaves very little tolerance of error between the two hole patterns.
- The contact requirement between the interfacing surfaces must not contain gaps larger than 0.5 mm. This is a typical gap condition for commercial aerospace assembly [74]. This will be verified using feeler gauges.
- There is to be a reference surface offset at nominal 6 mm. This will allow post-operation inspections of the amount of sacrificial material left on the component.

In addition to the major features of the assembly, two additional definitions are required to fully constrain the assembly. However, due to the design of the assembly they are not critical since the tolerances are able to washout over both sides of the rib's body. These additional requirements are:

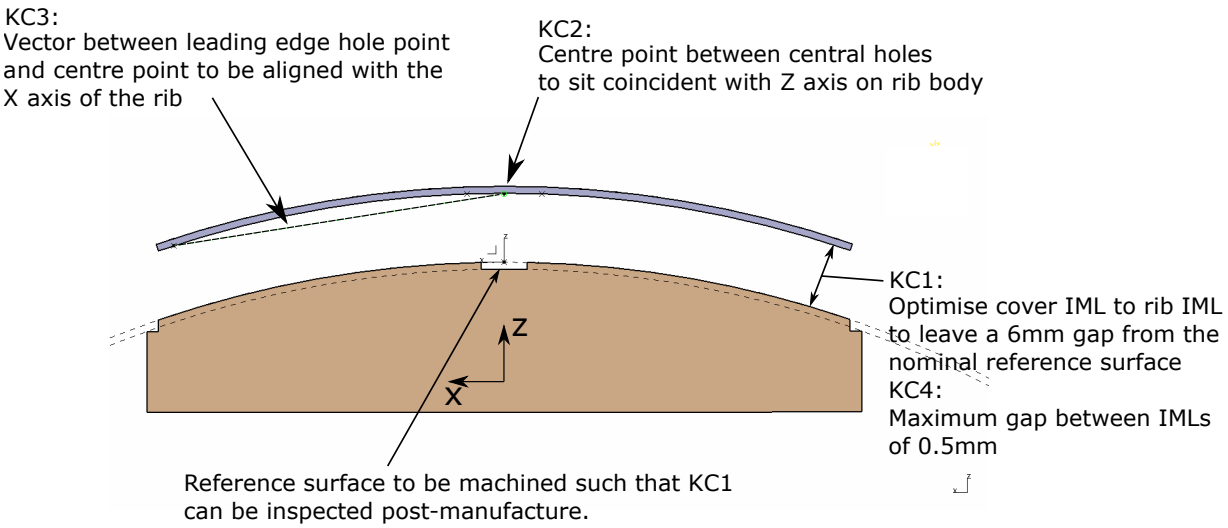


Figure 5.6: Diagram detailing the assembly requirements (key characteristics) for the rib to wing cover assembly. This type of diagram is sometimes referred to as a build philosophy.

- The wing skin is to be centralised on the rib's Z axis by the centre point between the two central holes.
- The wing skin is to be clocked to the rib's X axis using the leading edge hole's central vector.

These assembly requirements are visualised in Figure 5.6. There are four key characteristics that define the success criteria for the assembly. The major key characteristics that will be the focus of this case study are KC1 and KC4. These key characteristics will be inspected after the physical final assembly. A reference surface is added to enable post-assembly inspection of KC1. KC2 and KC3 are required to ensure the assembly is not under-constrained during the adaptation process but, due to their construction, will be difficult to inspect after assembly. That is, the only data available to confirm if these key characteristics have been met is the data fed into the data model which will naturally provide a positive affirmation. However, since the final condition of the assembly depends on the accuracy of all the key characteristics and the accuracy of the part-to-part assembly features, if KC1 and KC3 are acceptable and the part-to-part assembly is successful then it can be safely assumed that KC2 and KC3 are also satisfactory. Otherwise, the rib and cover inner mould lines (IMLs) would not match-up optimally leaving large gaps. It follows then that if the key characteristics are met then the manufacturing variation from the wing cover's manufacture has been successfully adapted out.

5.5.1 Key Characteristic Solution Routine

As discussed in section 5.4.1, a key characteristic routine has to be developed to solve the format of key characteristics the assembly object is constrained by. This section will detail the routine constructed from *KCsolver* object methods to solve the example detailed in Figure 5.6. This implements the *Key Characteristics Routine* in Figure 5.1. The routine consists of three operations: point-line-offset, line-plane-align and then a gap minimisation routine.

The first operation is aligning the centre-point on the wing cover to the rib body's Z axis. Firstly, the geometry is globalised to get both descriptions into the same reference system. Then, the perpendicular vector between the point and the line, $\mathbf{v}$, is calculated and packaged into the transform:

$$^{\mathbf{body}}\mathbf{T}_{\mathbf{body'}} = \begin{bmatrix} 1 & 0 & 0 & \mathbf{v_x} \\ 0 & 1 & 0 & \mathbf{v_y} \\ 0 & 0 & 1 & \mathbf{v_z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.1}$$

This transform is applied the transform describing the global pose of the rib body's *frame* object, $^{\mathbf{global}}\mathbf{T}_{\mathbf{body}}$. To calculate the global adapted position of the rib body which satisfies this key characteristic:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{body'}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{body}}\,{}^{\mathbf{body}}\mathbf{T}_{\mathbf{body'}} \tag{5.2}$$

Once this is understood, the local redefinition of the rib body's *Frame* object in the data model can be calculated from finding it's *parent Frame* object's global transform, $^{\mathbf{global}}\mathbf{T}_{\mathbf{parent}}$:

$$^{\mathbf{parent}}\mathbf{T}_{\mathbf{body'}} = {}^{\mathbf{global}}\mathbf{T}^{-\mathbf{1}}_{\mathbf{parent}}\,{}^{\mathbf{global}}\mathbf{T}_{\mathbf{body'}} \tag{5.3}$$

This transform is then used to modify the data model, virtually setting the key characteristic.

The next operation aligns the vector centre-line of the hole pattern to the X axis of the rib body. Before this can be done the central axis is projected onto the rib body's X-Z plane. following this, the angle, θ, between the two lines can be calculated. The rib body is then rotated about its Z-axis using the matrix transform:

$$^{\mathbf{body'}}\mathbf{T}_{\mathbf{body''}} = \mathbf{Rot}(\theta)_{\mathbf{z}} = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & 0 & 0 \\ \sin(\theta) & \cos(\theta) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.4}$$

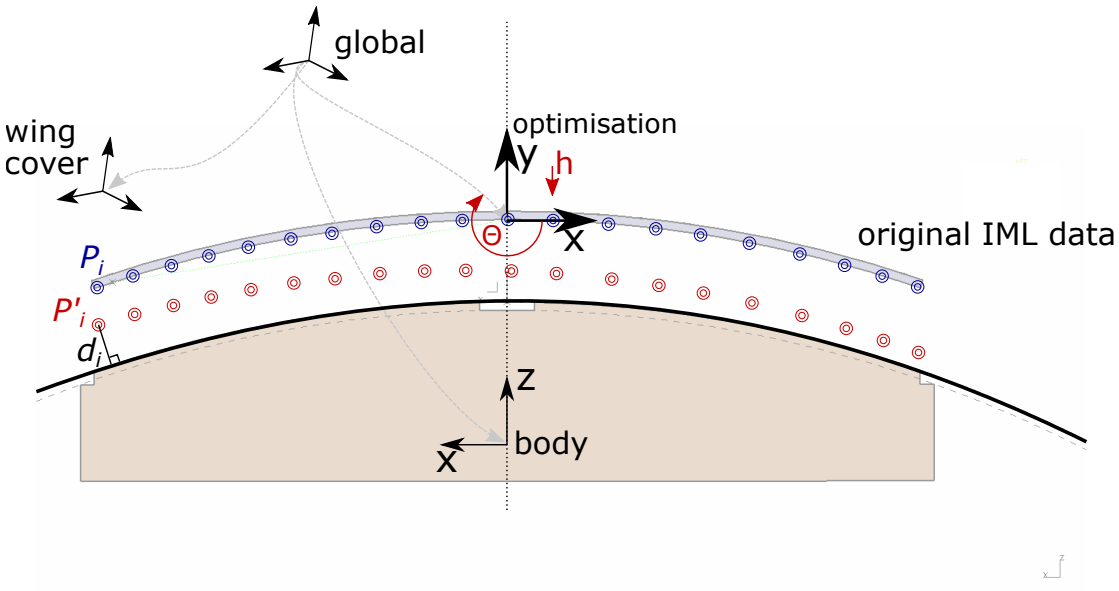


Figure 5.7: Diagram of the optimisation problem for minimising the sacrificial material between the wing cover and the rib body.

The modified global position of the rib body is calculated by:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{body''}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{body'}}{}^{\mathbf{body}}\mathbf{T}_{\mathbf{body''}} \tag{5.5}$$

The resulting modification required for the data model is calculated using the same method as for the previous operation. Once this local transform has been modified in the data model the second key characteristic will be virtually set without unsetting the first.

This final operation is a bit more tricky and has been included in this thesis to show case some of the advantages of having an algorithmically adaptive design. It will run a optimization algorithm to minimize excess sacrificial material and nominally create a zero-gap condition. It does this by first creating an optimisation frame. This optimisation frame simplifies the calculations of the optimization and within this frame a virtual simulation is run to find the best parameters which solve the problem. Instead of all the data being globalised, it is instead all converted into this optimisation reference frame. The data being the point cloud measurements of the wing cover's IML and the nominal 6 mm offset surface inside the CAD data, see Figure 5.7. The optimisation problem is given as:

$$\begin{aligned} \min_{\theta,h} \quad & \textstyle\sum_{i=0}^{n} d_i \\ \text{s.t.} \quad & d_i \geq 0 \end{aligned} \tag{5.6}$$

Where d_i is the tangential distance between the point $\mathbf{p_i'}$, after the driver function has been applied, and the offset surface. The driver function that is used

to modify the set of n points for each iteration is given as:

$$\mathbf{p_i'} = \mathbf{Rot_z}(\theta)\mathbf{p_i} + h \tag{5.7}$$

Since optimisation problems are not the subject of this thesis, this problem is algorithmically solved using a minimisation algorithm provided by the SciPy optimisation package [75]. The function returns the values of θ and h which minimise the function in Equation 5.6 without breaking the stated condition. That is, the wing cover IML must not sink below the rib body's IML. After the optimisation routine has concluded it will return the ideal values which solve the minimisation problem, θ^* and h^*. These can then be used to construct the transform:

$$^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{optimisation'}} = \begin{bmatrix} \cos(\theta^*) & -sin(\theta^*) & 0 & 0 \\ \sin(\theta^*) & \cos(\theta^*) & 0 & h^* \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5.8}$$

Using this modification to the optimisation frame, the effect of this transform on the rib body's datum can be calculated:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{body'}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{body}}{}^{\mathbf{optimisation}}\mathbf{T}^{-1}_{\mathbf{body}}{}^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{optimisation'}}{}^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{body}} \tag{5.9}$$

Where:

$$^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{body}} = {}^{\mathbf{global}}\mathbf{T}^{-1}_{\mathbf{optimisation}}{}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib}} \tag{5.10}$$

As before, $^{\mathbf{global}}\mathbf{T}_{\mathbf{body'}}$ is used to determine the new local definition of the rib's datum and modify the data model.

This final modification to the data model will leave it in a state where all the key characteristics are set.

5.5.2 Interfacing Surfaces

This assembly has the requirement to generate an interfacing surface which is not discussed during the typical use of *join* objects. Fortunately, it behaves in exactly the same way. In this case the *frame* associated with it is always the identity matrix. This ensures that the surface measured on the wing cover is always copied in globally the same place on the rib body, despite the different definition of local part reference systems.

The surface, once copied into the rib body, is used to generate a *feature* object

version of the surface when a CAD model is required of the rib body. This ensures the surface is pickup by the methods that convert the data model into a CAD model format. The surface once inside the CAD model is used to split the sacrificial material, creating the nominally zero-gap interface surface.

5.5.3 Prototype Software

In addition to the requirements for assembly, there also those for the software. The software runs a single cycle of the methodology described in this chapter. It will allow the user to specify the CAD data (*.CATproduct* file) from which the nominal data model is automatically generated. *Key characteristic* objects are also automatically identified using a naming convention for the constituent features involved. *Join* objects are likewise automatically generated by analysing each *Hole* object (subclass of *feature* object) on each part and identifying those whose central vectors align. Next, the user specifies the metrology data set they would like to use to update and adapt the assembly with. Following this the user selects which operations they would like to be performed. That is, the user is able to run a subset of: the metrology update process, the key characteristic adaptation and the joint adaptation sub-methods. Finally, the user then selects the output location for updated and/or adapted CAD files and when to execute the configured process. The user interface for software is shown in Figure 5.8 and it labels these steps in the order described.

To decouple the gathering and processing of the metrology data from its utilisation, the software, and general design for the application of metrology-enabled data model driven systems, accesses metrology data via a data base. In this case, to allow for easy human interrogation, a structured folder system on the users computer was decided as the method of data organisation for the software. This folder structure is summarised in Figure 5.9. Where the XML files codify measurement points and measurement constructs as described in Section 4.6.2. Moreover, a configuration file allows the user to tailor their experience with the software and change the criteria for some of the search algorithms used in operations such as those to kind features involved in the key characteristics of the assembly.

In terms of software architecture, the software is entirely encapsulated in an application object. This manages the run-time of the application and the graphical user interface (GUI). When the user clicks on the application, this object is instantiated and loads in the configuration file. The application then waits for the user to set the options on the GUI and launch the process. The object then generates the data model by instantiating an *assembly* object on the root assembly CAD file and any accompanying XML data. This process is discussed

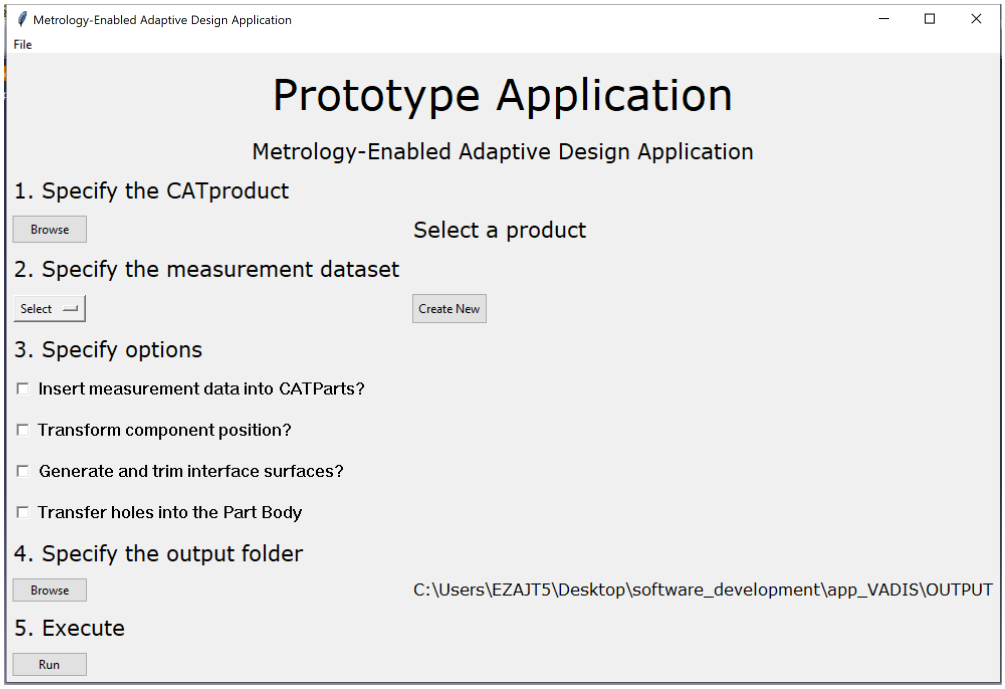


Figure 5.8: Image of the GUI for the prototype software. The prototype software automatically generates a data model and implements the variation control methodology by adapting the data model. It outputs adapted CAD models to achieve variation propagation control.

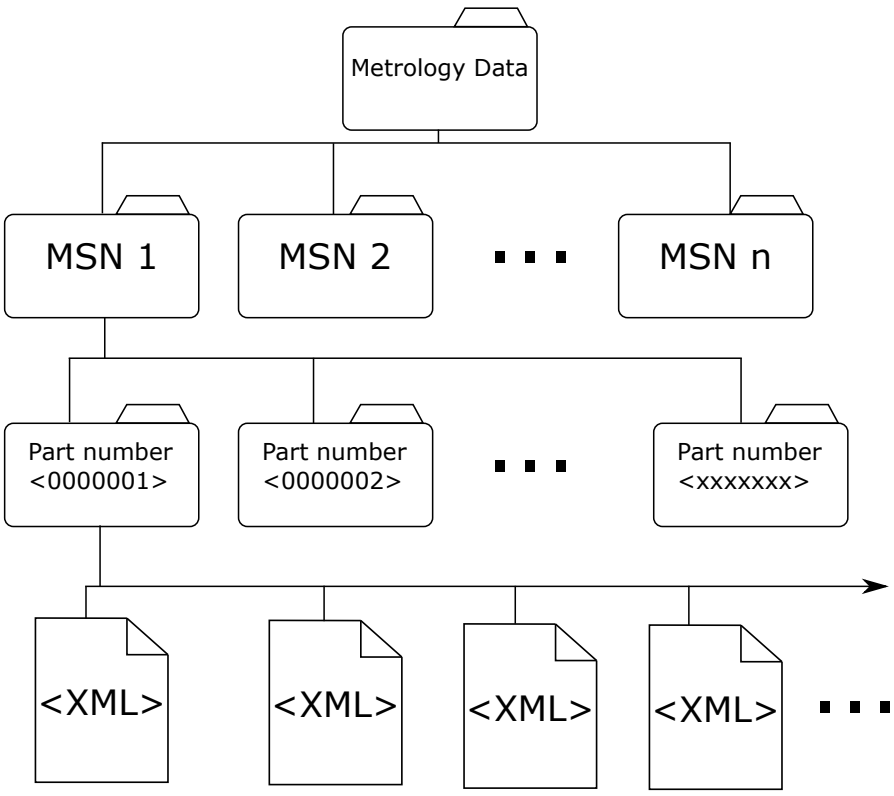


Figure 5.9: Folder structure which takes the places of a traditional database.

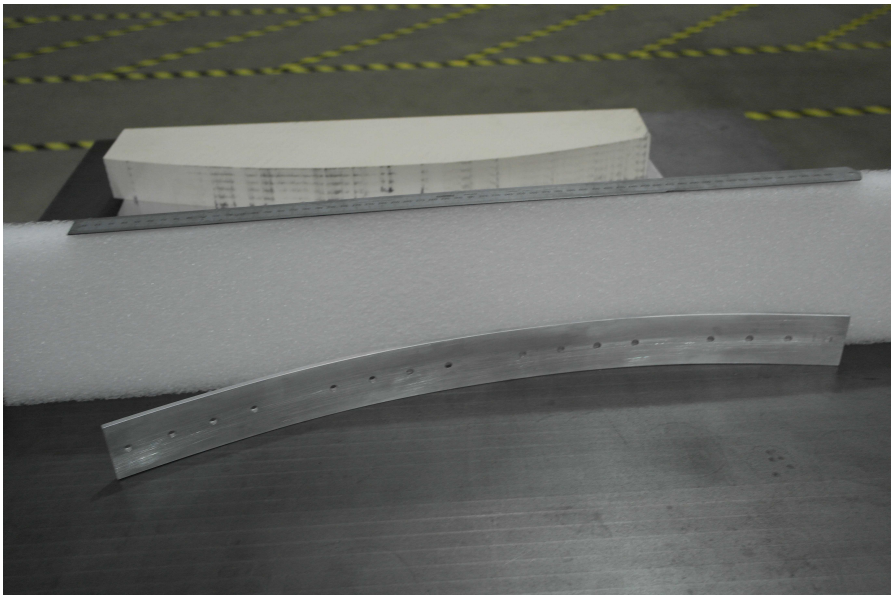


Figure 5.10: Manually fabricated, drilled and reamed rib cover.

in Section 4.6.3. Once the data model has been generated, the process runs as Section 5.3 describes. Finally, the data model is used to generate a modified CAD model, saved in a location of the users choosing, to be used for the manufacture of the remaining component.

5.5.4 Methodology Trial

Firstly, a piece of 5 mm thick aluminium plate was selected and a small drill-start made to indicate where the leading edge and inboard edge meet. Then it was manually bent into a rough aerofoil shape. Once the shape was achieved, the operator marked up the centre line of the skin and pitched in the hole patterns by hand. Following this, they then drilled those hole pitches using a standard pillar drill. Opening them up to 6mm on the final drilling pass with a reamer. The manual approach was key here since inaccuracy and deviation from the CAD nominal is desirable for testing the methodology's capability to stem manufacturing variation. Figure 5.10 shows the finished item.

The component was then placed in a holding fixture and measured with a NIKON MV331 laser radar. Measurements where taken of the interfacing surface, or the inner mould line (IML), and the hole pattern. Since the laser radar records a great deal of data, the metrologist firstly cleans the data of outliers and produces the constructs such as vectors and cylinders to represent the measured holes. Moreover, a point cloud representing the contact surface is created. These final measurement data and constructs where then encoded into files and placed the file structure (database).

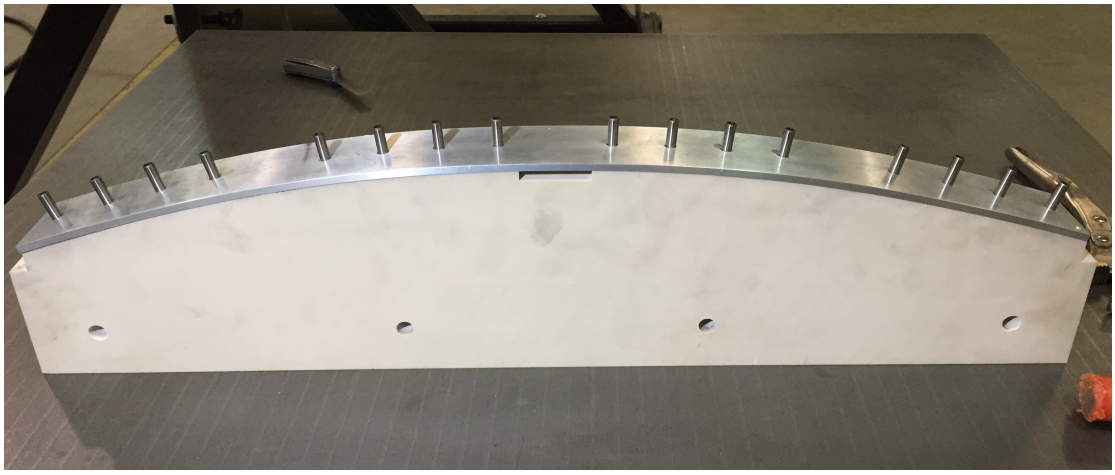


Figure 5.11: Final assembly of the rib cover to the rib body.

The manufacturing user then opens the software and selects both the nominal CAD data and metrology folder populated with the aforementioned data. They then ticked all the boxes and launched the application. After a few minutes, the output location contained three files: the representative wing skin model complete with metrology data (*.CATpart*), the adapted design for the rib body (*.CATpart*) and the new product file capturing the new assembly (*.CATproduct*). CNC code for a Hermle 3+2 milling centre was then generated from the *.CATpart* for the new rib body using MasterCAM CAM software [76].

A block of Raku-Tool was then fixed to the Hermle's machining bed and CNC program run. The finished item was then cleaned off and the two components assembled together using sixteen 6 mm steel dowels. The finished assembly is shown in Figure 5.11.

5.5.5 Results

This demonstrator has three major facets for inspection: the gap condition between the components, the nominal offset reference surface and the part-to-part hole patterns.

The gap condition between the two parts of the assembly was inspected with a set of feeler gauges. Figure 5.12 splits the edges of the assembly into segments and the largest gap measurement taken in that segments labelled against it. It can be seen that all gaps were below 0.4 mm. The largest measurable gaps were at least 0.3 mm in size but in all cases did not extend beyond 10 mm below the surface. The majority of gaps were between 0.1 mm and 0.2 mm in size which is well within aerospace tolerances.

The nominal offset, the main key characteristic under analysis here, was inspected with a digital vernier caliper and all measurements were within 0.1 mm

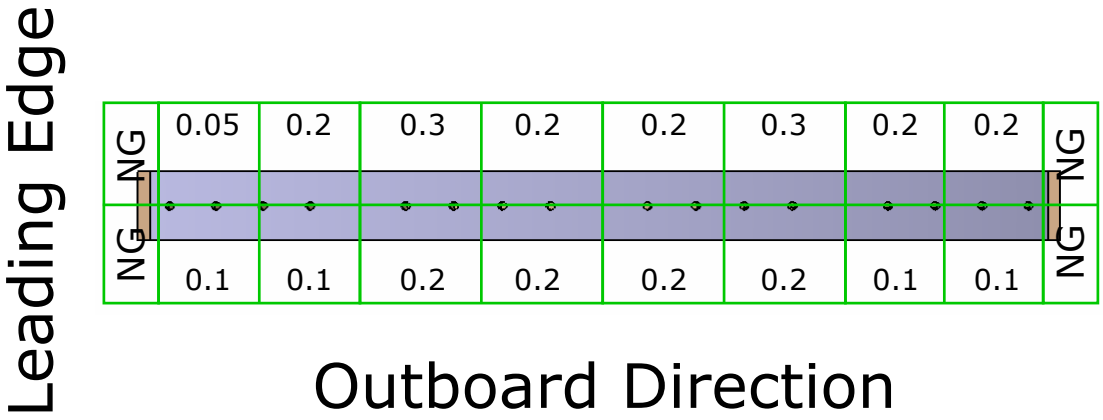


Figure 5.12: Diagram detailing the measured gap and the location of the measurement on the final assembly. Where "NG" refers to no gap or the gap was too small to be measured. All measurements are in millimetres. Each gap is the value presented in the diagram or within +0.05 mm larger than it. Since 0.05 mm was the smallest resolution of measurement available on the feeler gauges.

of the 6 mm nominal dimension. This validates that key characteristics set in the data model can be maintained to within sub-millimetre accuracy despite the part-to-part assembly requirement. This last point is important since in part-to-part assembly it is the assembly features that drive the location of one part to the other and which will ultimately drive the quality of the assembly key characteristics.

The success of the part-to-part assembly is self-evident since all sixteen dowels passed through both components despite the H7-g6 fit. This fit ensures that the nominally 6 mm holes are within the range 6.00 mm and 6.015 mm, and the nominally 6 mm dowels are within the range 5.995 mm and 5.986 mm. Therefore, the centre of each hole in the rib body must have matched its counterpart to within 0.0025 mm at a maximum material condition or 0.029 mm at a minimum material condition.

The results presented here validate the practicality and level of automation of the presented methodology. Moreover, the quantitative analysis of Appendix B has also been validated. But, most importantly, it has demonstrated the capability of the methodology to control the propagation of manufacturing variation in part-to-part assemblies. The methodology can, when given metrology data of a manufactured component; update a representative data model, adapt the model to correct the key characteristics back to nominal and then adapt the joints between those components to ensure part-to-part assembly given this new condition. And, it can do this completely automatically and to an accuracy that is acceptable to the aerospace industry.



Figure 5.13: Full-scale demonstrator for the metrology-enable adaptive assembly methodology.

5.5.6 Full-Scale Demonstrator

Having validated this process on the small-scale demonstrator, this methodology, at the time of writing, has recently been tested on a full-scale demonstrator, see Figure 5.13. The image shows how the methodology and the prototype software is capable of setting the key characteristics and achieving part-to-part assembly with full-scale aerospace components. This demonstrator followed a similar process to that of the small-scale demonstrator, using sacrificial material on the rib feet and achieved similarly successful results. However, a more detailed examination of this full-scale demonstrator will be the subject of future work.

5.6 Chapter Summary

This chapter has presented an automatic methodology for the variation propagation control in part-to-part assemblies. The methodology leverages the data model presented in the preceding chapter to algorithmically update the design of parts. This provides a industrially practical option for part-to-part assembly approaches in the aero-structures industry. A technical demonstrator and associated prototype software validated the methodology and evaluated its capability for aerospace

application.

The methodology differs from those in existing literature in several ways. Firstly, it provides a generalised and automated methodology for controlling variation propagation in part-to-part assemblies. Secondly, it enables practical part-to-part assembly techniques for aerospace application. Thirdly, the methodology is robust to incomplete and patchy data. Achieving the full technical benefits of the process only requires that features involved in the assembly joints and key characteristics be measured. Even if that is not possible, due to production interruptions perhaps, the methodology will provide the nominal manufacturing data. Therefore, the methodology can be applied as much or as little as is necessary for the design of the product and time constraints on the production line. Fourthly, it is an example of multi-key characteristic driven part-to-part assembly. Enabling part-to-part assembly whilst also achieving several key characteristics applied to features other than the assembly holes. Lastly, this methodology abstracts the adaptive process and utilisation of the metrology data from the providers and users of the data by maintaining the traditional interfaces; minimising the disruption of an adaptive design approach.

Chapter 6

A Control Methodology for Setting Multiple Key Characteristics For Robotic Assembly

6.1 Introduction

This chapter develops an automatic variation control methodology for fixtured assemblies. It does this by leveraging the production feedback loop enabled by the data model of Chapter 4 and introduces an adaptation phase for the *key characteristic* connections present in the assembly. The adaption phase modifies the data model such that the ideal adaptive location of a component being robotically assembled is determined. This ideal location, in combination with live measurements of the component's current state, enable the calculation of an ideal transform which solves all key characteristics simultaneously. This transform is used to drive a robotic manipulator. The process is performed iteratively.

Fixtured assemblies are assemblies where some or all of the constraints of the assembly are provided by external equipment. This is typically a fixture, hence the name, but it can also be jigs, tooling or gauges. In this case the external equipment is a serial kinematic robot. Industrial serial kinematic robots do not have the accuracy to achieve aerospace tolerances and are unable to adapt with manufacturing variation propagation. Therefore, metrology equipment is typically employed to provide external measurements to guide the robot to a greater level of accuracy. However, errors within the robot control system, measurement data and the alignment between the two reference systems means that this must be an iterative process; often called a move-measure-correct loop.

As discussed in Chapter 2, the vast majority of the examples focus on machining activities which only a single point is controlled. And, of the examples that consider assemblies activities, they either use a 6 DOF metrology artefact where the key characteristics are set via known tooling relationships between the metrology artefact, the tooling it is mounted upon and the component (also attached to the same tooling); Or, the only control a single key characteristic. The first approach has no method of controlling for manufacturing variation since the features involved in the key characteristics are not directly monitored or controlled. It also makes this process susceptible to variations in the pickup locations between the robot mounted component, the end effector tooling, the metrology artefact. This is also true for the static component involved in the assembly and the fixture it is mounted within. Any errors in these relative positional relationships is directly reflected in the key characteristics. The second approach suffers from a lack of applicability since assemblies seldom have a single key characteristic. Therefore this approach also does not suitably control variation propagation. Another issue present with all instances of metrology guided robotic assembly is that the location of the robot and fixture is static and their relative location to the metrology device is either known via tooling relationships or a manual optimisation procedure which occurs before the assembly operation begins. Both of these approaches preclude automatic mobile robotic assembly applications and they leave the process fragile to variation in these positional locations. The methodology presented in this chapter resolves these issues and enables complete automatic variation propagation control for fixture assemblies.

This chapter begins with a general discussion of the concept behind the automatic variation control methodology in Section 6.2. Section 6.3 then details the methodology itself and its supporting sub-methods. An illustrative example is provided in Section 6.4. This example details the process using an example that is similar to those presented in Chapter 7, which validates the work in this chapter.

6.2 Multiple Key Characteristic Control for Robotic Assembly

The central premise of this methodology is integrating the data model-driven calculation of a single transform which resolves, or minimises, all deviations in a set of key characteristics into an iterative move-measure-correct control loop. Then converting this transform into a movement for a robotic manipulator. Thereby enabling the automatic and simultaneous control of multiple key characteristics for metrology-guided robotic assembly. This is necessary since typical move-measure-

correct loops that solve a single key characteristic would inevitably loose previously set key characteristics if the process was stacked one after another; due to the errors in the robot manipulator and measurement device [39].

The methodology is designed to take an incomplete assembly consisting of two generalised components, A and B, and set A relative to B given a set of key characteristics between them. The starting locations of A and B is arbitrary. One component, A, is rigidly attached to a robotic manipulator and the other B is fixed in location during the assembly operation. The relative location between A and the robot manipulator is also arbitrary and can be changed between assembly operations. Component A is referred to, in this thesis, as the dynamic component and B is referred to as the static component.

One limitation regarding the data model-driven methodologies of this thesis is that to automate their generation a CAD model is used. It is possible that a CAD model is not always available. This may be due to security issues involved with sharing CAD between organisations or lengthy data exchange processes. Regardless, an extension to the data model structural elements enabled the prescription of *Metrology* objects. These are objects which automate the construction of simple data models for use in enabling this methodology when CAD data is not available. Appendix C discusses the details and implementation of the *metrology* object for this thesis. It has been included as an appendix since the specific implementation of this concept does not contribute to the central objective of this chapter. The integration of *metrology* objects into assembly processes can be via tags, along with the other assembly information, in the "job file", see Appendix D for an example of a job file.

This methodology achieves complete manufacturing variation control on two fronts, both of which are enabled by the use of the data model presented in Chapter 4. Firstly, the methodology solves multiple key characteristics simultaneously which has not be previously achieved. Secondly, the *key characteristic solution routine* is driven from actual independent measurements of the features and geometry and not by any known or calibrated relationships of robot end effectors, tooling or metrology facilities. Therefore, manufacturing variations experienced by either components involved in the assembly are automatically adapted out by default across all key characteristics.

6.3 Methodology Overview

This section details the methodology that achieves automatic variation propagation control for multiple key characteristics in robotic assembly operations. At a high-level there are two phases to this methodology the pre-control loop phase and

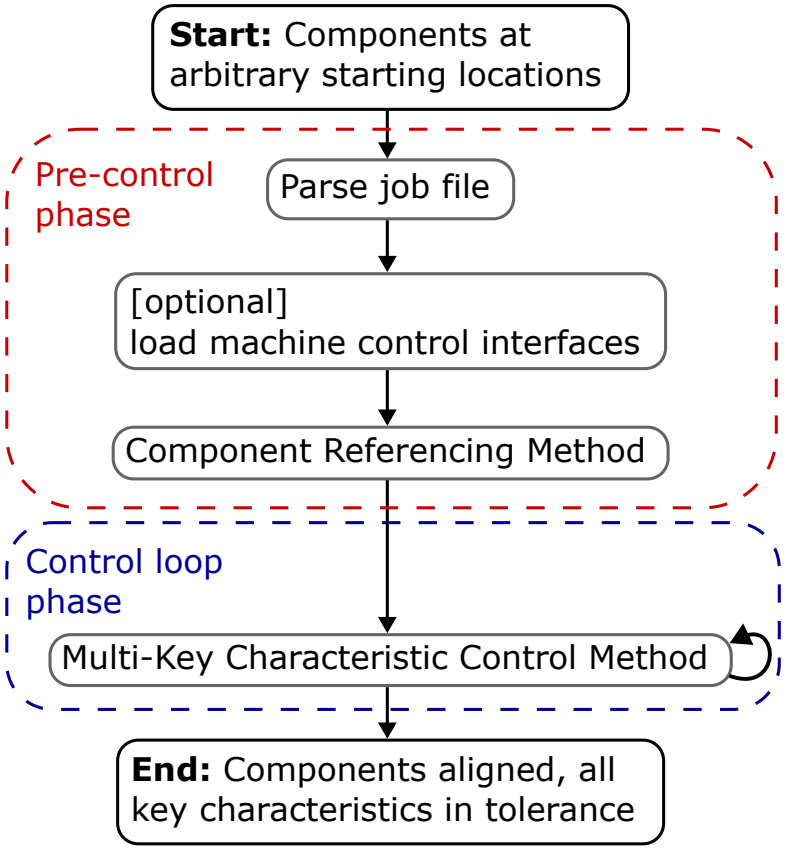


Figure 6.1: Overview of the methodology.

the control loop phase, see Figure 6.1. The pre-control loop phase occurs before the control loop and contains methods which occur only once per assembly operation. These are: parsing the job file (Section 6.3.2), loading the machine control interfaces (if available), and the component referencing routine (Section 6.3.3). These methods determine the prerequisite information and necessary interfaces to enable the following control loop phase of the methodology. The control loop phase is the main method of this methodology and is run iteratively for each assembly (Section 6.3.1). The method ends when all of the key characteristics for the assembly are within tolerance. Therefore, the number of iterations depends largely on the choice of robot and metrology equipment, the quality of the measurement data, and the size and rigidity of the components; to name just a few. To begin, a discussion of core iterative method for controlling multiple key characteristics for robotic assembly is discussed.

6.3.1 Multi-Key Characteristic Control Method

This section details the method used to enable automatic variation propagation control for multiple key characteristics in robotic assembly operations. It takes the feedback loop with production shown in Figure 4.1(b) and introduces an adap-

tation phase, see Figure 6.2. However, unlike the cases in Chapter 5 this feedback loop occurs iteratively during the assembly operation. This is the core of the methodology and is conceptually identical to the key characteristic solution routine presented in Chapter 5. The routine is designed once at the generation of the first data model using methods implemented by the *KCsolver* object, presented in Chapter 4.

This augmented feedback loop, in Figure 6.2, utilises the data model to digitally set all key characteristics systematically and from which the single transform can be extracted and used to control a robotic manipulator directly. The figure shows that since the manufacturing resources are automatable (both robot and metrology device) the data model information need not be translated into a human-readable format and used directly for machine control. To implement this methodology a prototype software was developed that implements both this methodology, a machine control system and an interchangeable approach to direct machine control interfaces for a plethora of manufacturing resource types. This approach is likely to become more common as manufacturing becomes more automated. It has been included as an appendix since it is just one of many possible implementations of this methodology. The data model feedback loop is the primary method of this chapter but to enable it a number of supporting methods are required. Below are a summary of methods covered in this chapter which together enable automatic, high-precision multiple key characteristic control for robotic assembly.

1. Trigger metrology device to measure the current state, i, of components, let these states be called A_i and B. Since component B is static, its state does not change between movements of the robot.

2. Update data model with metrology data.

3. Run *key characteristic solution routine* to adapt the data model, solving all key characteristics. The *key characteristic solution routine* like those in Chapter 5 is constructed of standard sub-methods provided by the *KCsolver* object.

4. Determine the pose of the dynamic object's datum, A_*, given the adapted location of the geometry.

5. Perform frame to frame query between the previous pose of the dynamic object, A_i, and its new adapted pose in the data model, A_*. Let this transform be ${}^{A_i}T_{A_*}$.

6. Convert this transform from the assembly co-ordinate system to the robot co-ordinate system using the transformation matrix, ${}^{A}T_{R}$, provided by the

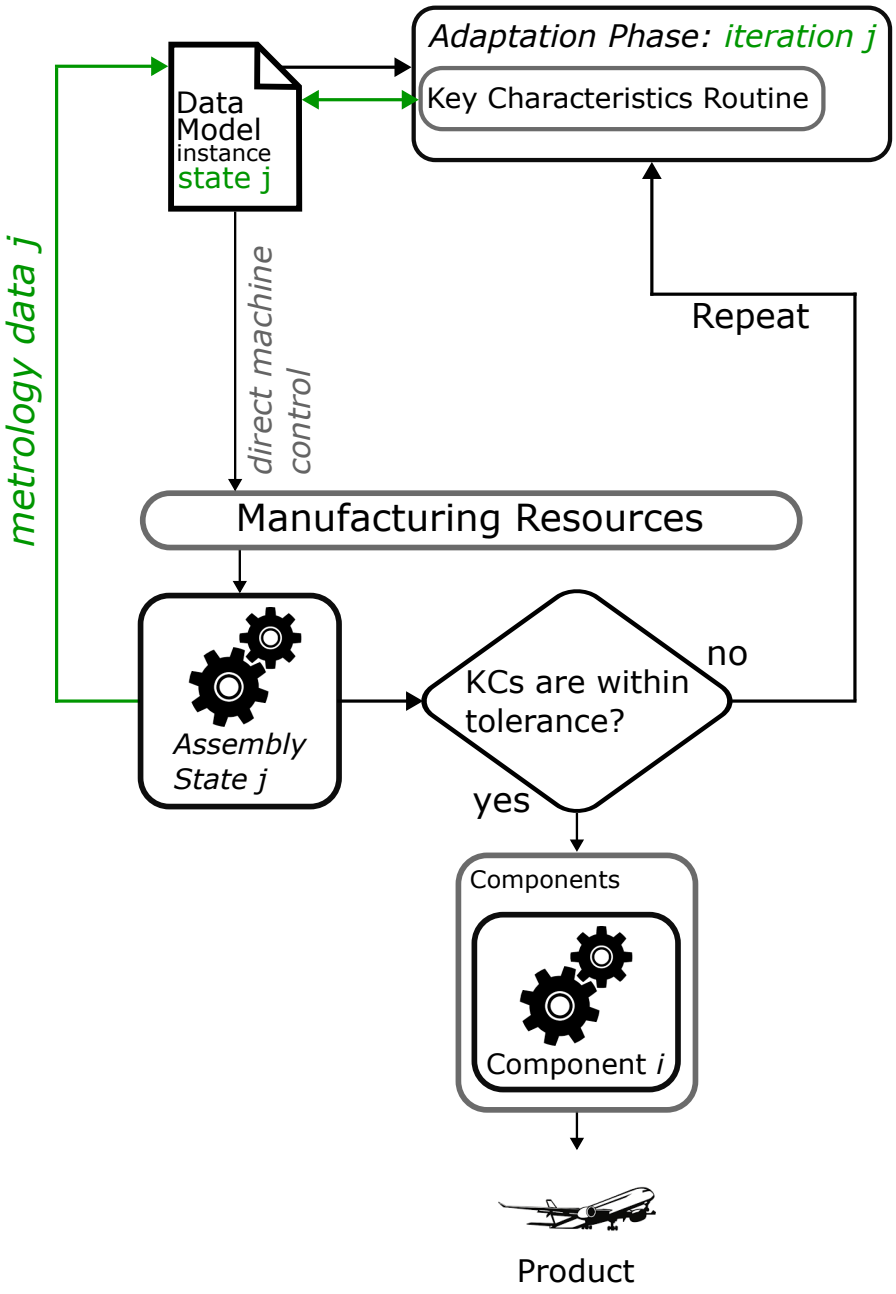


Figure 6.2: Overview of the adaptive variation propagation control method at the focus of this methodology. The "Key Characteristic Routine" here refers to the sequential use of *KCsolver* algorithms to digitally find the solution to the set of key characteristics. This is discussed in detail in Section 6.4.

Component Referencing Routine prior to this iterative operation, see Section 6.3.3.

7. Command robot to perform this movement. That is, R_i goes to R_{i+1} and A_i goes to A_{i+1} using the machine control interface.

8. Re-measure components, A_{i+1} and B

9. Update the data model.

10. Calculate the deviation from nominal for all the key characteristics.

11. If one or more key characteristics are not within tolerance, go to Step 3. Otherwise, the component is set to tolerance and the assembly is in an acceptable state.

At the conclusion of this method, the whole methodology also finishes. The assembly will be in a satisfactory condition, where all the key characteristics are in tolerance. At this point the two components can be joined together in-situ. This locks in the adaptive positioning, stemming the propagation of manufacturing variation. In fixtured assemblies the components are must be set relative to either other using fixtures, tooling and gauges or in this case a metrology-guided robot. It is for this reason that assembly features cannot be produced until this point in the assembly. Otherwise, they would invariably misalign. However, a discussion about the production of these assembly features (the drilling and bolting of holes for example) is out of scope for this methodology. It is enough to know that at this point the components can be fastened together and the dynamic component released and the robot extracted.

6.3.2 Job File Parsing

The job file is a method of easily creating a machine readable format for feeding additional assembly information which cannot (at present) be automatically extracted from existing manufacturing data. It also provides a means for quickly reconfiguring the methodology for different components and key characteristic information. At present the job file is used to encode the following information:

- Supporting and auxiliary metrology software files.
- *Metrology* object definitions, see Appendix C.
- Definition of the set of key characteristics for an assembly.
- Assembly path information, see section 6.3.4.

Two job files are included as Appendix D and Appendix E. These are used to drive the technical demonstrators in Chapter 7.

6.3.3 Component Referencing Routine

This is a quick and automated method to locate the dynamic component relative to the robotic manipulator and the dynamic component relative to the metrology reference system. This also references the metrology reference system and robotic control reference system, relative to the assembly datum *frame* in the data model. It does this by measuring the component as the robot rotates about two of its axis whilst a metrology device measures.

This method measures the position and orientation of the robot's wrist without any prior known tooling or calibration information. It eliminates the need for tight-tolerance tooling or tight-tolerance pick-up locations on the components being assembled. It also ensures that the methodology is robust to errors and manufacturing variations of the interfaces between the robot, the component held by it, and any tooling in between. It is ultimately a quick method for generalising the relationship between the robot and the component it is assembling.

This method assumes that there is at least one measurable point on the dynamic object, and the object is suitably rigid. It also requires that the robot can be controlled relatively to it current pose. The process will be described for a single measurable point on the component but more consistent results can be achieved by averaging the results of this method across several points. The method is as follows:

1. Measure the point, $\mathbf{p}$ at the starting location. Let this be $\mathbf{p_1}$.
2. Command the robot to rotate by angle $+\theta$ about the X axis of its wrist frame.
3. Measure the point, $\mathbf{p}$ at this location. Let this be $\mathbf{p_2}$.
4. Command the robot to rotate by angle -2θ about the X axis of it's wrist frame.
5. Measure the point, $\mathbf{p}$ at this location. Let this be $\mathbf{p_3}$.
6. Using the points, $\mathbf{p_1}, \mathbf{p_2}, \mathbf{p_3}$, calculate the centre point of the circle these point lie on the circumference of. Let this point be $\mathbf{c_x}$.
7. Using the same three points calculate the direction vector of the X axis of the robot wrist frame. Since the sign of the robot rotations is known it is

possible to determine the direction of the axis about which the rotations occurred. In this case: $(\mathbf{p_2} - \mathbf{p_1}) \times (\mathbf{p_3} - \mathbf{p_1}) = \mathbf{v_x}$.

8. Repeat steps 1 to 7 but using rotations of about the Y axis instead of X. This will yield the centre point, $\mathbf{c_y}$ and the directional vector, $\mathbf{v_y}$.

9. At this point we have two points lying on the X and Y axis of the robot wrist frame and we have the directions of those vectors. We can now calculate the remaining directional vector for the Z axis by: $\mathbf{v_x} \times \mathbf{v_y} = \mathbf{v_z}$

10. And the origin, $\mathbf{q}$, of the wrist frame is the solution to this simultaneous equation:

$$\mathbf{q} = \begin{cases} \mathbf{c_x} + \alpha \mathbf{v_x} \\ \mathbf{c_y} + \beta \mathbf{v_y} \end{cases}$$

11. Finally, all this data can be reformatted into a 4 by 4 homogenous transform for converting transformations of the dynamic component, A, into movements of the robot's wrist, R:

$$^{\mathbf{A}}\mathbf{T_R} = \begin{bmatrix} \mathbf{v_{x,x}} & \mathbf{v_{y,x}} & \mathbf{v_{z,x}} & \mathbf{q_x} \\ \mathbf{v_{x,y}} & \mathbf{v_{y,y}} & \mathbf{v_{z,y}} & \mathbf{q_y} \\ \mathbf{v_{x,z}} & \mathbf{v_{y,z}} & \mathbf{v_{z,z}} & \mathbf{q_z} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

This transform is used by the methods in the control phase to convert transformations of the components calculated in the data model into movements of the robot. This method is generalised and can handle any suitably rigid component. This enables quick, robust and automatic referencing for any metrology-guided component manipulation application. It also does not require any high-tolerance tooling or pick-up locations making a cheaper alternative to the methods utilised in the existing research [43, 55, 56].

6.3.4 Assembly Paths

The methods discussed so far achieve the multi-key characteristic control that is the focus of this chapter. However, this method builds upon what has been presented so far to enable prescribable assembly paths. The objective being to ensure that regardless of where the dynamic component is found at the beginning of the methodology, it always follows a designed trajectory. A trajectory that terminates

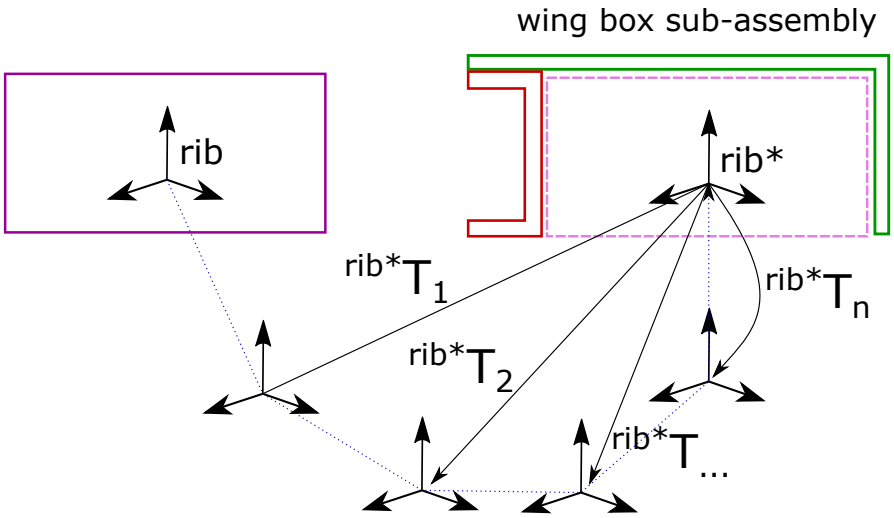


Figure 6.3: Visualisation of the general definition of an adaptive assembly path.

just before the final setting location which uses the method in Section 6.3.1. This method adds an additional layer of practicality to this methodology as a whole.

It does this by generating a series of positions, called path positions, between the arbitrary starting position and the ideal final position via which the component will travel, as shown in Figure 6.3. Each position is associated with its own control loop and forms part of the control loop phase. This offers advantages for the automatic assembly process, such as clash avoidance, greater flexibility on starting position, and greater control on robotic joint configuration in the final location.

This thesis defines two types of path position: loose and offset. Loose path positions are used to apply a loose level of control to the robot path and are used to cover large volumes in the robot working space. And, offset positioning which augments the key characteristic solution routine by applying an offset to one of the key characteristics, this key characteristic is ignored during the conditional check. This enables more accurate path control just before the final setting method in Section 6.3.1 begins.

The assembly path method is as follows:

1. For **each** loose path position defined in the job file:
   (a) Trigger metrology device to measure the current state.
   (b) Update data model.
   (c) Run *key characteristic solution routine* to adapt the data model, solving all key characteristics.
   (d) Determine the pose of the dynamic object's datum, A_*, given the adapted location of the geometry.

(e) Apply offset matrix to A_*.

(f) Perform frame to frame query between the previous pose of the dynamic object and its new offset pose in the data model.

(g) Convert this transform into the robot co-ordinate system.

(h) Command robot to perform this movement.

(i) Re-measure components.

(j) Update the data model.

(k) Calculate absolute distance between current state and .

(l) If it is less than the applied tolerance, go to Step c. Otherwise, move to next offset position

2. For **each** offset path position defined in the job file:

(a) Trigger metrology device to measure the current state.

(b) Update data model.

(c) Generate offset geometry for offset path position using data from the job file.

(d) Run *key characteristic solution routine* to adapt the data model, solving all key characteristics. However, the offset geometry replaces the original element.

(e) Determine the pose of the dynamic object's datum, A', given the adapted location of the geometry.

(f) Perform frame to frame query between the previous pose of the dynamic object and its new offset pose in the data model.

(g) Convert this transform into the robot co-ordinate system.

(h) Command robot to perform this movement.

(i) Re-measure components.

(j) Update the data model.

(k) Calculate absolute distance between current state and .

(l) If all the key characteristics, except the key characteristic with the offset applied, are within tolerance, move to the next position. Otherwise, Go to Step c.

3. End of assembly path, execute Multi-Key Characteristic Control Method.

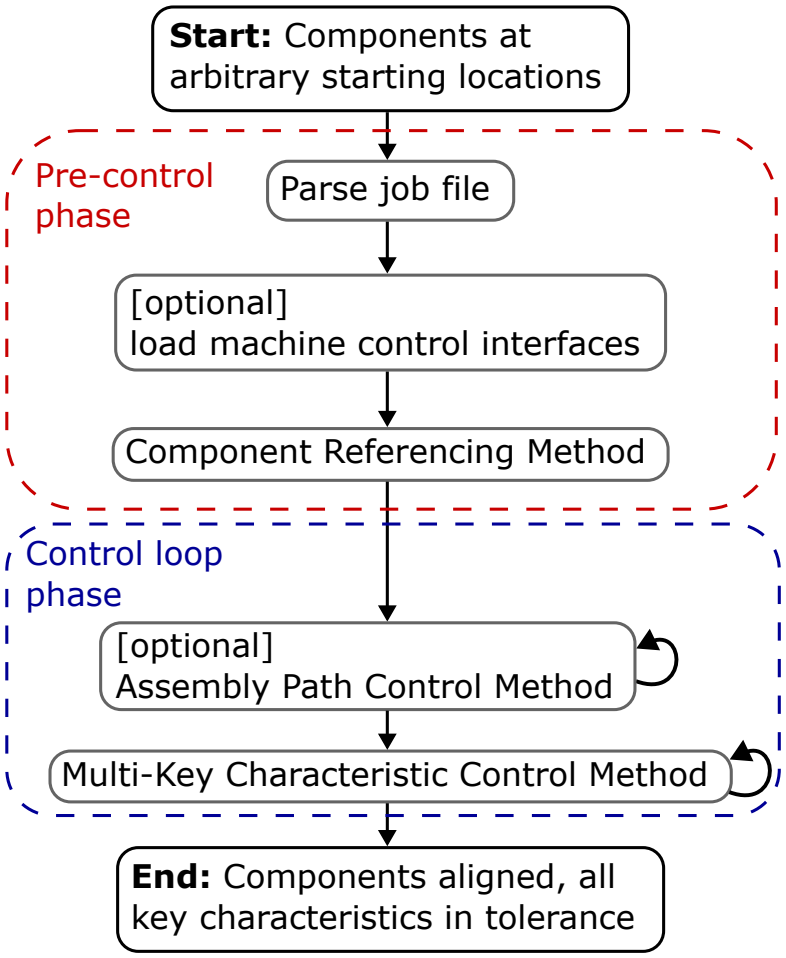


Figure 6.4: Overview of the methodology if an assembly path has been provided in the job file.

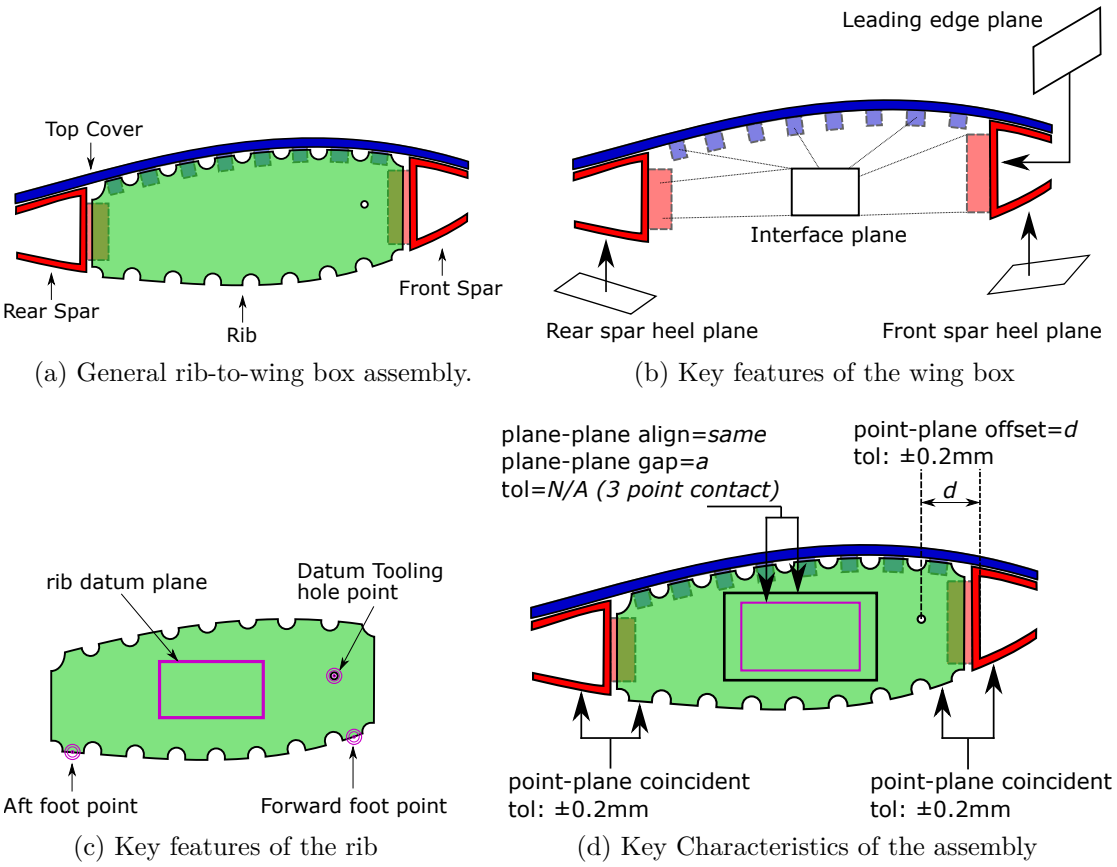
Figure 6.4 shows how the overall methodology is augmented by the addition of an assembly path. The control phase is expanded from that in Figure 6.1 to include the method for navigating the assembly path. The list of loose points is completed before the offset positions. Which is itself completed before the final positioning method. Assembly paths are optional and can be removed by not specifying a path in the job file. In this case the component will take the shortest path, depending on the type of movements commanded to the robot. Assembly paths can include as many positions as is required and can consist of both types or of a single type depending on the requirements of the application.

6.4 An Illustrative Example: Robotic Aerospace Rib Positioning

This section will detail the methodology using an illustrative example that is similar to the technical demonstrators presented in Chapter 7. The steps detailed below is the assembly programme implemented by the prototype software which is used to drive each assembly operation for both technical demonstrators. The details of this software have not been included, since how the methodology is implemented does not directly contribute to the objectives of this thesis. The example is a rib-to-wing box assembly operation, where the rib is attached to a standard industrial robot and the wing box is held in a fixture. The metrology data is provided by a V-STARS photogrammetry system since it has an accuracy acceptable for the aerospace industry and can dynamically track multiple measurements points [77, 78, 79]. It also offers an automation interface which enables it to be controlled in a similar fashion to other automatable manufacturing resources.

A generalised rib to wing box assembly is shown Figure 6.5(a). The wing box is the completed sub-assembly of the top wing cover and the front and rear spars. There is typically over 20+ ribs assembled to a single aisle wing box sub-assembly and there are two wing boxes per aircraft. Its key features for the assembly are; the interface plane that nominally sits upon the contact faces of the rib posts and integrated rib feet, the leading edge spar plane that sits upon the leading edge surface, and the front and rear spar heel planes which sit upon the lower faces of each spar. These are visualised in Figure 6.5(b). The rib's key features consist of the datum plane which sits upon the datum surface, a point on both the front and aft rib feet, and a point located at the centre of the leading edge tooling hole. The key features are visualised in Figure 6.5(c).

The key characteristics for the assembly are shown in Figure 6.5(d). Where the interface plane and the rib's datum plane are to be aligned and have no gap,



(a) General rib-to-wing box assembly.

(b) Key features of the wing box

(c) Key features of the rib

(d) Key Characteristics of the assembly

Figure 6.5: Overview of an general example of a rib-to-wing box assembly. (a) Overview of typical component geometry. (b) Key features on the wing box sub-assembly. (c) Key features on a typical aerospace rib. (d) Key characteristics between the key features.

the rib feet are to sit upon the spar heel planes and the tooling hole is to have an offset from the leading edge plane. All these features are targeted such that they can be measured by V-STARS.

Firstly, the job file parsed and from which, or the sake of argument, the data model is generated using the *metrology* objects defined in Appendix C. Otherwise, the job file would be parsed and a CAD file analysed to generate the initial data model, as defined in Section 4.6.3. This file also contains references for driver and template files that are used by V-STARS, as well as the assembly path for the rib to follow.

The wing box and, if necessary, the fixture holding the wing box is measured by V-STARS in S-mode. The data model is updated using this metrology data. V-STARS is then switched into M-mode and the rib moved into view to be measured.

The rib is picked up by a robotic manipulator, and the relationship between the rib and the robot's control co-ordinate system determined as per the method described in Section 6.3.3, by using the direct machine control interface for the robot. Let this transform be ${}^{\mathbf{rib}}\mathbf{T}_{\mathbf{control}}$.

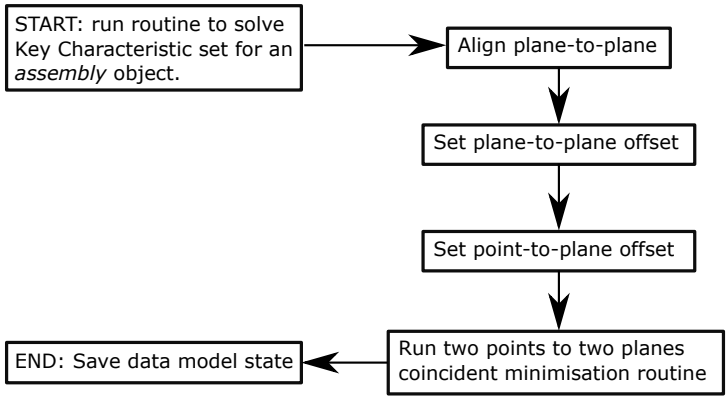


Figure 6.6: Flowchart of the key characteristic solution routine (*Key Characteristic Routine* in Figure 6.2) for the automatic rib positioning application.

The state of the rib is remeasured. And, the state of the data model is updated to reflect the currently unset condition of the rib. The current transform of the rib, ${}^{\mathbf{metrology}}\mathbf{T}_{\mathbf{rib}}$, is read from the data model and then key characteristics of the assembly are then solved digitally within the data model using the key characteristic solution routine.

The routine to solve the key characteristics for this form of rib assembly is summarised in Figure 6.6. Where, in a similar fashion to the previous methodology, a routine is built-up from the building blocks provided by the *KCsolver* object in Chapter 4. Figure 6.6 shows that the primary planes on each component are aligned and the gap between is set first. Following this the rib is translated to set the tooling point at the defined offset to the leading edge plane. And, finally the two points on both rib feet are placed upon the spar heel planes using an optimization routine. Each one of these methods provided by the *KCsolver* object must complete its own lower-level routine to ensure the data model is used and modified correctly. A generalised overview of this lower-level routine is shown in Figure 6.7.

It is worth noting that within the data model, the data for the period of this routine is static. Therefore, setting key characteristics out of order has no consequences. Moreover, using the ribs datum to drive transformations of the geometry also has no consequence since between measurements the data is rigidly locked together.

Plane to Plane Align

The key characteristic to solve is the interface plane to the rib's datum plane. First they must be aligned. Figure 6.8 visualises the problem. First the planes from both the wing box and rib are globalised using their *frame* object's *.getGlobalTransform()* method. The global description of the rib's datum being ${}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib}}$.

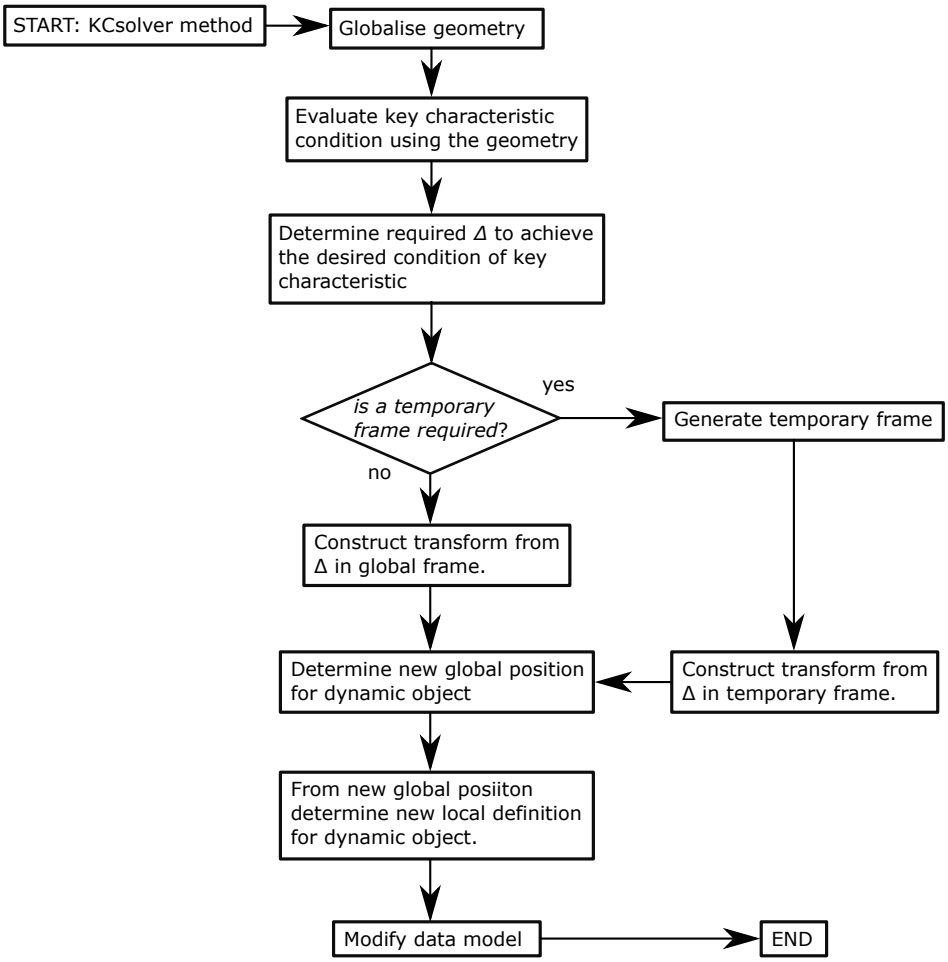


Figure 6.7: Flowchart of the general *KCsolver* method used for setting a single key characteristic.

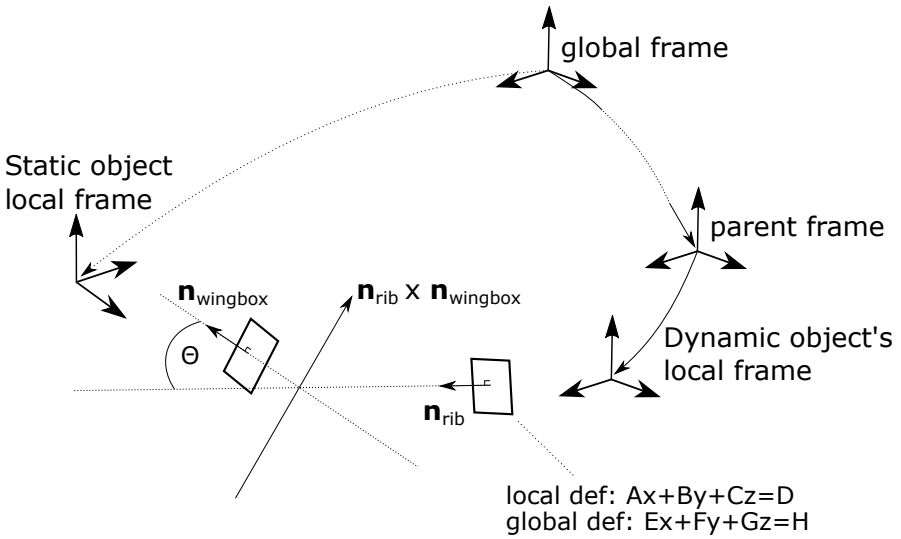


Figure 6.8: Visualisation of the plane to plane align problem within the data model's spatial network.

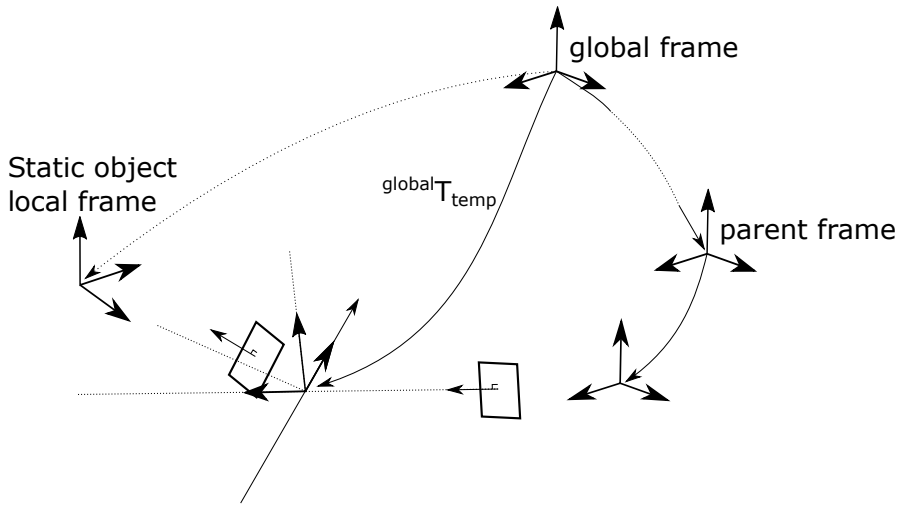


Figure 6.9: Temporary frame generated upon the key characteristic geometry.

Each *geometry* object has a method to generate a globalised copy of itself given an external transform. The angle θ between these planes can now be determined as:

$$\theta = \arccos(\mathbf{n}_{rib} \cdot \mathbf{n}_{wingbox}), \tag{6.1}$$

where $\mathbf{n}_{rib}$ and $\mathbf{n}_{wingbox}$ are the normal vectors to the planes.

This angle is the required rotation about an axis perpendicular to both normal vectors of the planes. Unfortunately, this axis is unlikely to share any convenient relationship to global reference frame the geometry finds itself in. Therefore, a temporary frame is determined to translate this transform into a transformation of the rib's local frame. The cross product of both the normal vectors produces the necessary axis about which the rotation will apply and will serve as the X axis for the temporary frame. The other two axes are largely arbitrary at this point but for convention sake, the Y axis is chosen to be the normal vector of the plane associated with the rib. The Z axis is the cross product of these two vectors. The origin is also arbitrary but to avoid wild translations being introduced into the transform a point is selected from the rib's geometry set to sit the temporary frame upon. Figure 6.9 visualises the situation. Where ${}^{\mathbf{global}}\mathbf{T}_{\mathbf{temp}}$ is the matrix notation for the new temporary frame.

It is known that the X axis of the temporary frame is parallel to the axis about which the rotation needs to be applied. Therefore, a matrix transform for a rotation of θ about the X axis can be constructed:

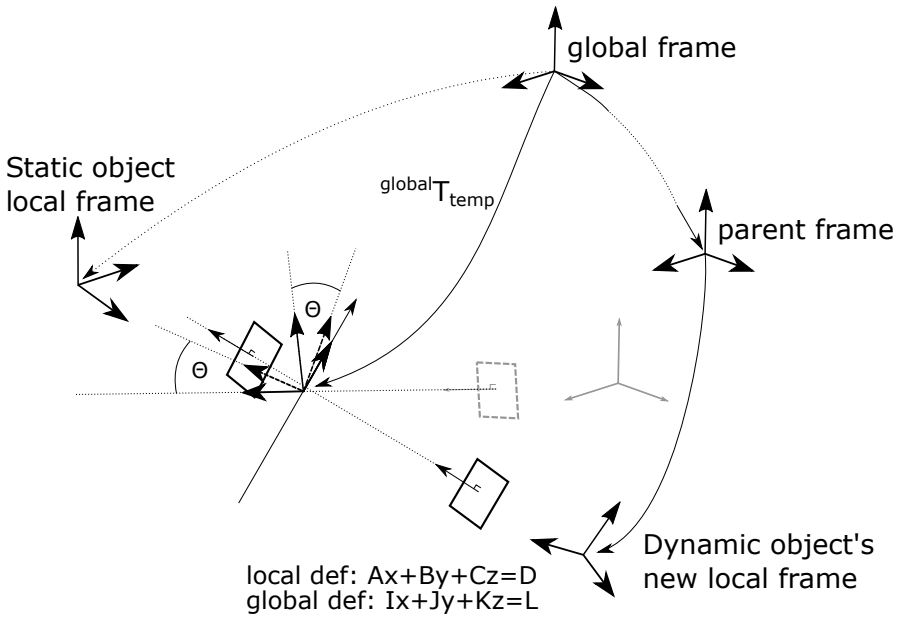


Figure 6.10: Visualisation of the modification to the data model's frame network to correct a key characteristic, using the temporary frame generated from the key feature geometry.

$$\mathbf{Rot}(\theta)_{\mathbf{x}} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & -\sin(\theta) & 0 \\ 0 & \sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6.2}$$

And, this matrix applied after the temporary frame:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{temp'}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{temp}}\mathbf{Rot}(\theta)_{\mathbf{x}} \tag{6.3}$$

Using the relationship the rib datum had with the temporary frame, the rib datum's new location can be found after the rotation about the temporary frame. That is, the ribs datum relative to the temporary frame is:

$$^{\mathbf{temp}}\mathbf{T}_{\mathbf{rib}} = {}^{\mathbf{global}}\mathbf{T}^{-\mathbf{1}}_{\mathbf{temp}}\,{}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib}} \tag{6.4}$$

And, after the rotation, the rib datum's new location is:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{rib'}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{temp'}}\,{}^{\mathbf{temp}}\mathbf{T}_{\mathbf{rib}} \tag{6.5}$$

This motion is visualised in Figure 6.10.

This calculated position of the rib datum now needs to be used to modify the data model. One advantage of this is that all the measurements and geometry currently associated with the rib will be modified to reflect its new virtual location. This will be key to ensuring the next key characteristics calculation and resulting

transformation accumulate logically. The only transform that needs to change is the rib *frame* object which links it to its parent *frame* object; also know as its local definition. The global transform for the rib's parent can be read by calling *.getGlobalTransform()* on it; returning ${}^{\mathbf{global}}\mathbf{T}_{\mathbf{parent}}$. Therefore, the rib's local definition is determined as:

$$ {}^{\mathbf{parent}}\mathbf{T}_{\mathbf{rib'}} = {}^{\mathbf{global}}\mathbf{T}^{-\mathbf{1}}_{\mathbf{parent}} {}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib'}} \tag{6.6} $$

This transform is used to modify the *frame* object for the rib in the data model. Virtually changing is location in space. This also modifies the global location of all *J_Object* subclasses below it, which includes *features* and *geometry* objects; keeping the data model consistent.

Plane to Plane Offset

Now with the planes aligned, the gaps between them can be closed. Again, following the generalised process in Figure 6.7, the geometry is globalised. The call to *.getGlobalTransform()* will now take into account the virtual move completed in the previous step since the parent of the geometry object's *frames* associated with the rib is the rib's datum *Frame* object. Once globalised the gap between two aligned planes is the difference between their D values when the plane is written in the plane equation format:

$$ Ax + By + Cz = D \tag{6.7} $$

Since, the planes were aligned in the previous step, the gap's magnitude is:

$$ D_{gap} = D_{wingbox} - D_{rib} \tag{6.8} $$

Therefore, the vector which moves the rib to a position where the gap is 0 is given by:

$$ \mathbf{v} = -D_{gap} \begin{bmatrix} A_{rib} \\ B_{rib} \\ C_{rib} \end{bmatrix} \tag{6.9} $$

Where, $A_{rib}, B_{rib}, C_{rib}$ are the components of the normal vector of the plane associated with the rib. Since there are no rotations involved the new rib datum, it can be directly calculated by applying the vector to the translational element of the *frame* object:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{rib'}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib}} \begin{bmatrix} 1 & 0 & 0 & \mathbf{v_x} \\ 0 & 1 & 0 & \mathbf{v_y} \\ 0 & 0 & 1 & \mathbf{v_z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6.10}$$

This transform is then converted into its local definition and used to modify the data model as before. It is worth noting that if an offset was applied in the key characteristic definition, it would be used to generate a *plane* object with the appropriate offset from the plane associated with the wing box.

Point to Plane Offset

The next key characteristic to solve is the tooling point on the rib to the leading edge plane. Firstly, if an offset is applied it is used to generate a *plane* object with the specified offset between the leading edge plane and itself. The perpendicular distance between the point and plane is then calculated using the standard equation:

$$distance_{perp} = \frac{AP_x + BP_y + CP_z}{\sqrt{A^2 + B^2 + C^2}} \tag{6.11}$$

Where; A, B, C are the components of the plane's normal vector and P_x, P_y, P_z are the components of the point.

This can then be converted into the vector between the point and plane by scaling the normal vector (assuming its a unit vector) by this scaler value:

$$\mathbf{v_{perp}} = distance_{perp} \cdot \begin{bmatrix} A \\ B \\ C \end{bmatrix} \tag{6.12}$$

However, this is will likely unset the previous gap closure of the primary planes. Before this vector can be applied to the rib's datum, the component of the vector that does not sit upon the interface plane must be removed. However, it must be calculated first. The component of vector $\mathbf{v_{perp}}$ that does not sit upon the interface plane is given by:

$$\mathbf{v_{offplane}} = \frac{\mathbf{v_{perp}} \mathbf{n_{int}}}{|\mathbf{n_{int}}|} \mathbf{n_{int}} \tag{6.13}$$

The component of $\mathbf{v_{perp}}$ which lies on the plane is the resultant vector once the component moving off the plane is deducted:

$$\mathbf{v_{inplane}} = \mathbf{v_{perp}} - \mathbf{v_{offplane}} \tag{6.14}$$

However, it is not guaranteed that this vector is of the correct magnitude. A scaling factor, γ, is calculated with the following equation:

$$\gamma = \frac{D_{wingbox} - \left\{ \begin{bmatrix} A \\ B \\ C \end{bmatrix} \cdot \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} \right\}}{\left\{ \begin{bmatrix} A \\ B \\ C \end{bmatrix} \cdot \mathbf{v_{inplane}} \right\}} \tag{6.15}$$

Finally, the resultant vector which takes the tooling point to the leading edge plane whilst remaining within the interface plane is given by:

$$\mathbf{q} = \gamma \mathbf{v_{inplane}} \tag{6.16}$$

As demonstrated with setting the no gap condition between the two primary planes, this translation is concerted into a matrix and used to determine the rib datums new global position:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{rib'}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib}} \begin{bmatrix} 1 & 0 & 0 & \mathbf{q_x} \\ 0 & 1 & 0 & \mathbf{q_y} \\ 0 & 0 & 1 & \mathbf{q_z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6.17}$$

This global position is then converted into the new local definition and used to modify the data model.

Two Point to Two Plane Coincident Minimization

The final operation is to align the points on the forward and aft rib feet to their plane counterparts on the spar heels. This operation is completed with an optimisation function which minimises the point to plane distances. An analytical function was also derived to set these key characteristics. But, the optimisation method was implemented first, required one less operation, and proved to be fast and robust enough that replacement was unnecessary.

To avoid un-setting the previously solved key characteristics and to simplify the optimisation, the problem is redefined into a convenient co-ordinate system. This co-ordinate system must have an axis that it perpendicular to both the normal vectors of the interface plane and leading edge plane. This will be the axis along which the appropriate amount of translation is searched for. An other axis will be parallel to the normal vector of the interface plane. This is the axis about which the satisfactory amount of rotation will be searched for. To avoid this

rotation from un-setting the previous key characteristics, the optimization frame will sit upon the currently set tooling point on the rib. The required search axis is calculated the cross product of the interface plane and leading edge plane normal vectors:

$$\mathbf{n_3} = \hat{\mathbf{n_1}} \times \hat{\mathbf{n_2}} \tag{6.18}$$

This vector is normalised:

$$\hat{\mathbf{n_3}} = \frac{\mathbf{n_3}}{|\mathbf{n_3}|} \tag{6.19}$$

The final axis is then calculated to complete the axis system:

$$\hat{\mathbf{n_4}} = \frac{\hat{\mathbf{n_3}} \times \hat{\mathbf{n_1}}}{|\hat{\mathbf{n_3}} \times \hat{\mathbf{n_1}}|} \tag{6.20}$$

These vectors are then organised into a matrix transform along with the tooling hole point, $\mathbf{p_h}$, into a matrix transform:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{optimisation}} = \begin{bmatrix} \hat{\mathbf{n_4}} & \hat{\mathbf{n_3}} & \hat{\mathbf{n_1}} & \mathbf{p_h} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6.21}$$

The points and planes are then transformed into this co-ordinate system. Within this coordinate system we are to find the translation in the y axis and rotation about the z axis which minimises the combined point to plane distances. The optimisation function will test different values of Δy and θ until a result within the prescribed deviation is found. It is a simulated setting routine within a simulated setting routine. This optimization is completed by a sequential least squares search algorithm implemented by the SciPy optimisation package [75]. The optimisation problem is written as:

$$\min_{\Delta y, \theta} \quad ||(\mathbf{Rot_z}(\theta)\mathbf{p_{aft}} + \Delta y) \rightarrow \mathbf{pln_{aft}}|| + ||(\mathbf{Rot_z}(\theta)\mathbf{p_{fwd}} + \Delta y) \rightarrow \mathbf{pln_{fwd}}|| \tag{6.22}$$

where $\rightarrow$ denotes the point, $\mathbf{p}$, to plane, $\mathbf{pln}$, distance calculation.

The optimisation function returns the values of θ and Δy that minimises the point to plane distance to $0 \pm 1 \times 10^{-9}$. Let these values be: θ^* and Δy^*. These values can be constructed into a transform which carries the optimisation frame from its current location to one where the points lie upon their counterpart planes:

$$^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{optimisation'}} = \begin{bmatrix} \cos(\theta^*) & -sin(\theta^*) & 0 & 0 \\ \sin(\theta^*) & \cos(\theta^*) & 0 & \Delta y^* \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6.23}$$

And, in a similar fashion to the temporary frame used earlier, the effect of this transform on the rib's datum can be calculated:

$$^{\mathbf{global}}\mathbf{T}_{\mathbf{rib'}} = {}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib}}\,{}^{\mathbf{optimisation}}\mathbf{T}^{-1}_{\mathbf{rib}}\,{}^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{optimisation'}}\,{}^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{rib}} \tag{6.24}$$

where;

$$^{\mathbf{optimisation}}\mathbf{T}_{\mathbf{rib}} = {}^{\mathbf{global}}\mathbf{T}^{-1}_{\mathbf{optimisation}}\,{}^{\mathbf{global}}\mathbf{T}_{\mathbf{rib}} \tag{6.25}$$

As before, $^{\mathbf{global}}\mathbf{T}_{\mathbf{rib'}}$ is used to determine the new local definition of the rib's datum and modify the data model.

This concludes the key characterisation solution routine, at this point the rib's datum and therefore its geometry, will be in a pose where all key characteristics are in their ideal conditions. The ribs datum can be read from the data model and compared to its previous value before the routine; calculating the ideal transform to set all key characteristics simultaneously.

Data Model-Driven Move-Measure-Correct Loop

After the key characteristic solution routine is finished the data model will be in a state where the rib and wing box are set in their ideal position. Therefore, the location of the rib's datum is at a location which solves all key characteristics simultaneously. Reading the rib's datum before and after the key characteristic solution routine allows the transform that takes the rib from where it is physically is to a position where all the key characteristics are solved; namely:

$$^{\mathbf{rib}}\mathbf{T}_{\mathbf{rib'}} = {}^{\mathbf{metrology}}\mathbf{T}^{-1}_{\mathbf{rib}}\,{}^{\mathbf{metrology}}\mathbf{T}_{\mathbf{rib'}} \tag{6.26}$$

This transform is then converted into the coordinate system for the robot's control frame:

$$^{\mathbf{control}}\mathbf{T}_{\mathbf{control'}} = {}^{\mathbf{rib}}\mathbf{T}^{-1}_{\mathbf{control}}\,{}^{\mathbf{rib}}\mathbf{T}_{\mathbf{rib'}}\,{}^{\mathbf{rib}}\mathbf{T}_{\mathbf{control}} \tag{6.27}$$

It is then converted again into the robot's base frame:

$$^{\mathbf{base}}\mathbf{T}_{\mathbf{control'}} = {}^{\mathbf{base}}\mathbf{T}_{\mathbf{control}}\,{}^{\mathbf{control}}\mathbf{T}_{\mathbf{control'}} \tag{6.28}$$

This transform is sent to the robot to physically execute using the device control interface. Once the robot has finished the movement, the state of the assembly is remeasured, the data model updated and the condition of all the key characteristics checked. If all the key characteristics are set then the process finishes since the component is within tolerance. However, this is unlikely to be the case on the first iteration. Therefore the loop repeats again, reading the datum before and after the key characteristic solution routine and determining a robot move. Remeasuring after the robot is finished and checking the condition of the key characteristics until they are eventually within tolerance, as described by Section 6.3.1 and Figure 6.2.

Using the above process any aerospace rib-to-wing box assembly with similar key characteristics can be automatically and adaptively assembled. This process can adapt for manufacturing variation and propagation of the rib or wing box. It can also adapt for variations in the relative locations of the robot, rib, wing box, metrology device and fixture without any consequences or reprogramming. Moreover, with the aid of the machine control interface both the robot and metrology device can be automatically controlled. This enables a programme to fully automate the whole methodology where the data model is directly driving manufacturing resources without requiring the information to be converted to a human-readable format. These conclusions are verified by the technical demonstrators in Chapter 7 which uses this process to assembly two similar but not identical wing boxes.

Automation and Flexibility

One may see the above and believe this to be a bulk mass of calculations which will be difficult to apply to other applications. However, once this routine is defined, it applies to any assembly which has key characteristics of this form. Required offsets and actual geometry involved are modified in the job file. In fact, this same routine was used to locate a plethora of aerospace rib components with varying sizes and shapes and configurations without the need for redefinition outside of the job file. Moreover, the routine is built-up from four standard blocks of code provided by the *KCsolver* object. Other standard functions for positioning geometry relative to other geometry have also been implemented based on the typical key characteristics of Figure A.14. Such that new key characteristic solution routines can be quickly developed for new applications. Future work would see the investigation of automatic generation of these routines or at least a helpful GUI for manually creating them. However, since aerospace rib assembly is suitably covered by the routines developed so far, this work is considered out-of-scope for

this thesis.

6.5 Chapter Summary

This chapter has presented a novel methodology for metrology-guided robotic assembly, where multiple key characteristics are solved simultaneously. Moreover, it does so whilst enabling mobile robotics and avoiding any requirements for high tolerance tooling, prior known relationships, or monolithic automatic approaches. The method leverages the data model developed in Chapter 4. This has enabled a robotic assembly operation to automatically adapt to manufacturing variations in the components across all the key characteristics. It also enables the methodology to adapt to variations in locations on the components relative to the robot, fixture and metrology device which conversely enables mobile high-precision robotic assembly and flexible manufacturing systems. These contributions are verified in Chapter 7.

This methodology differs from existing literature in several ways. Firstly, it solves for multiple generalised key characteristics simultaneously in a move-measure-correct loop. The majority of examples solve for a single key characteristic where conversion of the key characteristic's deviation into a machine transform is very simple. It also drives the move-measure-correct loop from the pure geometry involved in the key characteristics such that there is no need for prior known relationships of the components involved in the assembly. Another advantage of the methodology is that it enables the robot to be mobile which is not a feature of other move-measure-correct methods in the literature. And lastly, it generalises the relationship between the robot control frame and that of the dynamic object such that no expensive tooling is required to understand the relationship between product and robot.

Chapter 7

Technical Demonstrators for Robotic Assembly

7.1 Introduction

This chapter validates and evaluates the methodology presented in Chapter 6 and visualised in Figure 6.2. It does this by building and operating two technical demonstrators that perform an automated robotic assembly operation. Each assembly operation mimics a rib to wing box assembly and is constrained by four key characteristics and aerospace tolerances. Each demonstrator uses the methodology in Chapter 6 to automatically set all the key characteristics to within tolerance simultaneously.

Two technical demonstrators are presented for several reasons. Firstly, it demonstrates how the methodology from Chapter 6 can be easily turned to different assemblies with different key characteristics utilising different equipment. Secondly, it provides a more thorough validation and evaluation of the methodology. And thirdly, it provides a means of testing positional errors in both the robot or fixture/wing box. The first test cell is able to move the location of the demonstrator wing box since it is mounted upon a second robot. Whereas the second test cell has the rib positioning robot mounted upon an AGV such that it can be moved laterally and angularly relative to the demonstrator wing box.

The V-STARS photogrammetry system is the primary source of metrology data and is used to measure the key characteristics [80]. The results of the technical demonstrators is cross-referenced against the robot's internal measurement system, providing greater confidence in the results of the photogrammetry. Finally, capability indices are calculated to find the ratio between the performance of the methodology against the requirements of the assembly.

This chapter begins by explaining each technical demonstrator in Section 7.2.

The section presents the equipment and the requirements of the assembly operation. Section 7.3 shows the results from the demonstrators. This is handled in four steps:

1. The experiment procedure is given.

2. The primary results of the experiment are presented. This is the final measurements of the key characteristics after the multi-key characteristic control methodology has finished, as measured by the photogrammetry system.

3. A cross-reference of the above using the robot's internal measurement during the experiment is given. This provides greater confidence in the results of the photogrammetry system and provides a means of scrutinising the primary metrology device.

4. The capability indices are calculated for each key characteristic and tabulated. This provides convenient ratios of the performance of the system against the requirements of the aerospace assembly in a standard format recognised by industry.

The validation and evaluation work presented in this chapter was also tested for a number of fixture and robot positional deviations. To show that this performance, presented in this chapter, is robust to positional errors (or variance) in the robot, fixture or the components attached to them. This takes a significant step towards enabling mobile high-precision robotic assembly and fast reconfigurable manufacturing systems and fixtures. The details of these experiments have omitted since this robustness is a logical derivative of the methodology itself since it requires no prior information about the robot, the robot's location, the fixture's location or the pickup location on the dynamic component. And, the results are identical to those presented here since the performance of the methodology is invariant with respect to these deviations. That said, it still represents a significant contribution since it validates a major source of novelty and practicality which happens to be a convenient by-product of this methodology. Especially, since flexible and reconfigurable manufacturing systems and mobile robotic manufacturing are currently popular areas of research. Positional deviations of approximately $\pm$ 1 m and angular deviations of $\pm$ 30° for both the robot base and fixture position (with reference to the nominal configurations shown here) were tested with no discernable effect on the capability of the system and methodology. It is likely that the only limit is the reach the robot and the accessibility of the component into the ideal position.

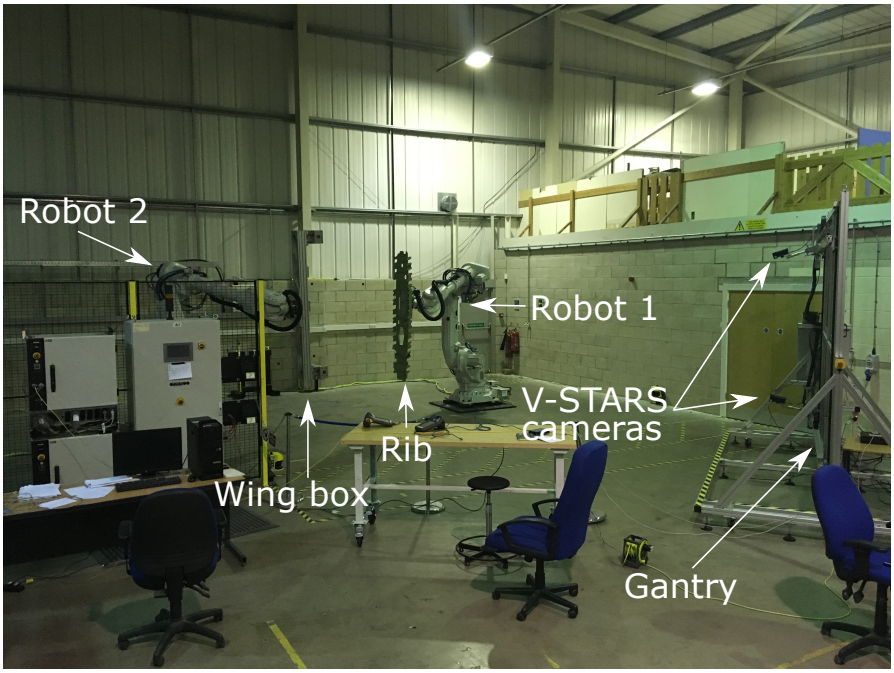


Figure 7.1: Test Cell 1 setup.

7.2 Presentation of Demonstrators

This section discusses the equipment and component setup and the key characteristics for each technical demonstrator. The section discusses each demonstrator in turn, beginning with Test Cell 1. Firstly, the equipment used to implement the demonstrator is presented. This is followed by explaining the details of the assembly operation the demonstrator performs. Details such as what components are involved, what the features and key characteristics are, and their associated tolerances are given in this section. They both perform aerospace rib-to-wing box assembly but their composition of equipment changes substantially. Both demonstrators set four key characteristics simultaneously.

7.2.1 Test Cell 1

Test Cell 1 is a static robotic assembly cell, see Figure 7.1. It has two ABB 6700-150320 serial kinematic robots. The robot on the right in Figure 7.1 is the component positioning robot that will be executing commands from the methodology. The other robot and end effector represents the wing box (static object in the methodology) against which the dynamic component is to be positioned. Since the static object is mounted upon a robot, positional error can be introduced by jogging the left robot to a new pose between assembly operations; demonstrating the methodology's mobility, robustness and flexibility. The cell also has a linear gantry system, controlled by an Omron PLC, to automate the data gathering op-

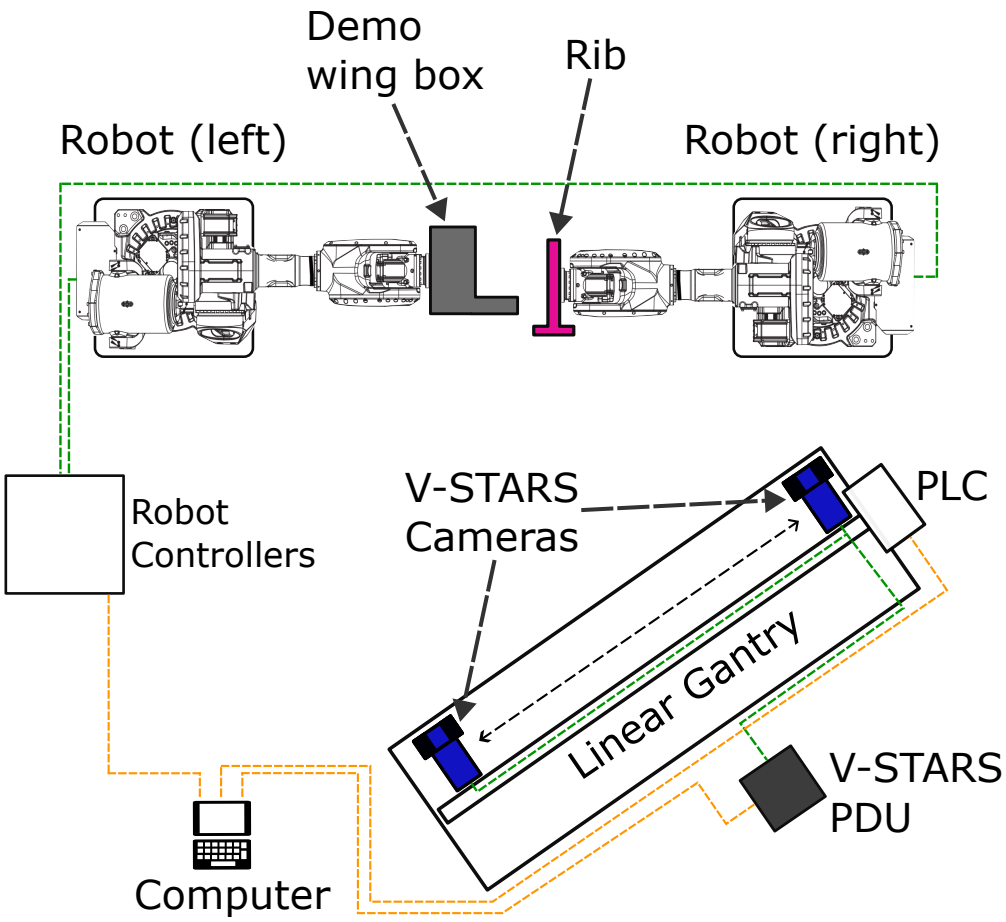


Figure 7.2: Layout of Test Cell 1.

erations of the V-STARS photogrammetry system also integrated into the cell. As mentioned, V-STARS is used as the metrology data source for feeding the data model and subsequent methodologies. Lastly, a number of network targets are placed around the cell to assist with the photogrammetry bundle adjustment. Figure 7.2 provides a schematic detailing the layout of Test Cell 1.

The assembly operation consists of positioning an aerospace rib, see Figure 7.3, against a representative wing box, see Figure 7.4. The key characteristics of the assembly and the key features on each component are annotated in Figure 7.5. It is the key features on both components that are targetted with photogrammetry elements and tooling. And, the key characteristics are encoded into the job file for the assembly operation, see Appendix D.

The rib has four key features: the datum plane, the forward and aft rib foot surfaces, and master tooling hole centre. These key features are annotated in Figure 7.3. The rib feet can be directly probed by applying the photogrammetry stickers directly onto these surfaces. The datum plane is probed via three metrology pins which fasten through tooling holes in the rib's structure. These pins are characterised such that measuring the coded target on the face of the pin

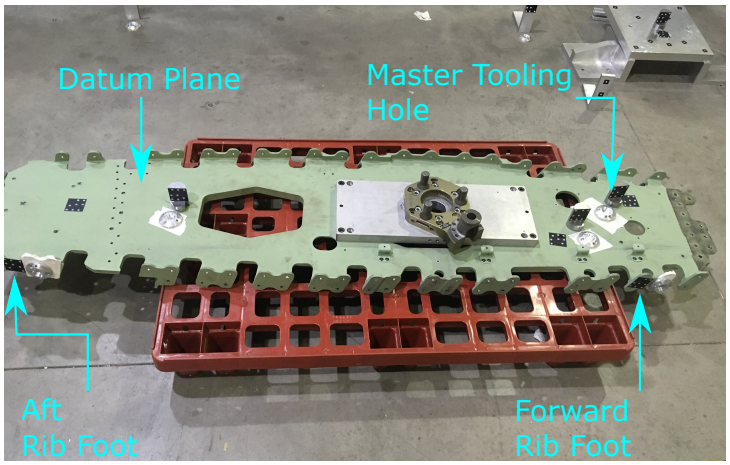


Figure 7.3: The aerospace rib used to demonstrate the assembly operation. The rib has been fitted with metrology facilities and photogrammetry targets for automatic measurement and live tracking. Note: the tooling nests have been fitted for the laser tracker cross-reference experiment and are not necessary for the methodology to function.

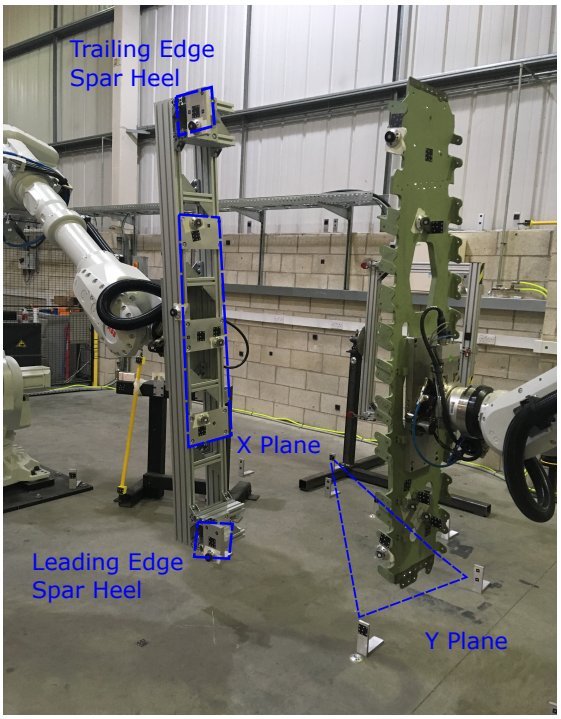


Figure 7.4: The aerospace rib and demonstrator wing box whilst mounted upon the robotic manipulators.

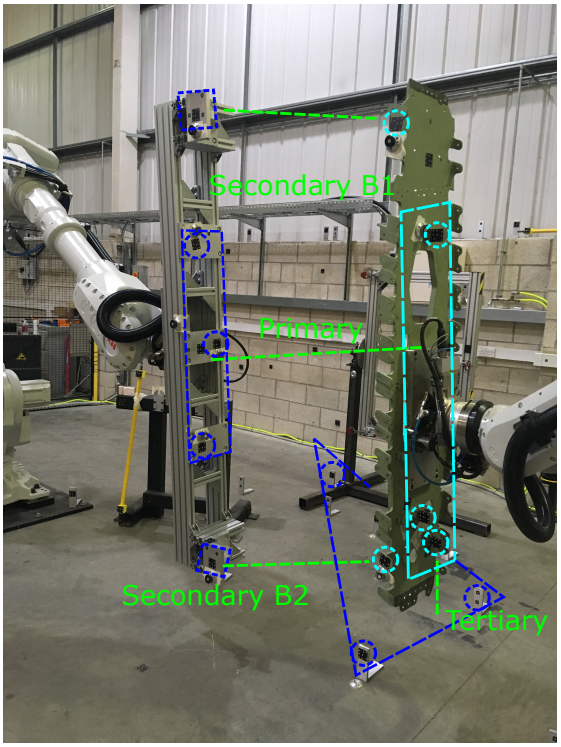


Figure 7.5: Overview of the key characteristics for the assembly operation in Test Cell 1.

creates a virtual point at the intersection of the hole centre and contact surface. Fortunately, one of these tooling holes coincides with the master tooling hole such that a one of the metrology pins used to measure the datum plane can also be used to measure the master tooling hole. An image of one of these metrology pins is shown in Figure 7.6.

The wing box has three key features physically on it: the X plane, and the leading and trailing edge spar heel surfaces. However, to fully constrain the rib, an additional key feature has been taken from the photogrammetry targets on the cell floor. All these surfaces can be directly measured using photogrammetry stickers, except the cell floor where L-shaped brackets were used as probing points.

The four key characteristics between these key features are summarised in Table 7.1 and visualised in Figure 7.5. The first key characteristic is a -350.0 mm offset between the X plane and the rib's datum plane. This naturally implies an alignment condition between the planes for an offset to exist. There are two key characteristics which are similar in definition and constrain the rib feet relative to the spar heels. These are the secondary B1 and secondary B2 key characteristics which are both 0.0 mm offset conditions between the trailing edge plane and the aft rib foot point and the leading edge plane and forward rib foot point; respectively. The final key characteristic is the tertiary key characteristic which is a 600.0 mm offset between the Y plane and the master tooling hole in the rib.

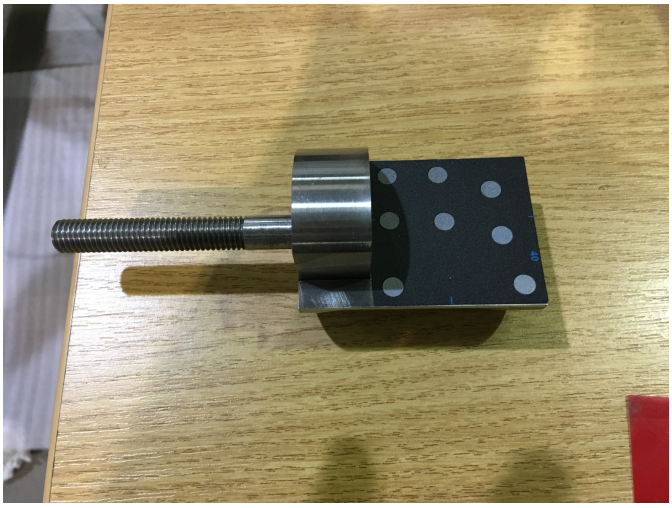


Figure 7.6: Image of a metrology tooling pin used to measure the intersection of the hole vector and the contact surface.

Key Characteristic	Condition	Nominal Value (mm)
Primary	plane-plane offset	-350.0
Secondary B1	plane-point offset	0.0
Secondary B2	plane-point offset	0.0
Tertiary	plane-point offset	600.0

Table 7.1: Summary of the key characteristics for the assembly in Test Cell 1.

7.2.2 Test Cell 2

Test Cell 2 is a mobile assembly machine, see Figure 7.7. It consists of an ABB 6700-245300 serial kinematic robot mounted upon an autonomous guided vehicle (AGV), which positions an aerospace rib against a static fixture. The fixture has photogrammetry targets and metrology facilities fitted to probe the key features of an aerospace wing box. The inclusion of the AGV enables the opposite of the locational error situation in the previous cell. That is, the robot itself is mobile and the product/fixture is stationary. This mobility has been used to introduce positional variation and demonstrate the robustness of the methodology to it. In this instance the V-STARS system is manually moved to gather the data. However, the metrology system itself is still automatically controlled.

The assembly operation consists of positioning an aerospace rib relative to the key features setup on the fixture. The key characteristics for the assembly and corresponding key features are annotated in Figure 7.9. These key characteristics are encoded into the job file associated with this assembly operation, see Appendix E.

The rib is tooled and targeted in an identical fashion to the previous example, see Figure 7.8. The fixture has four key surfaces upon it: the X plane, the leading edge spar heel, the trailing edge spar heel, and the Y plane is the top surface of

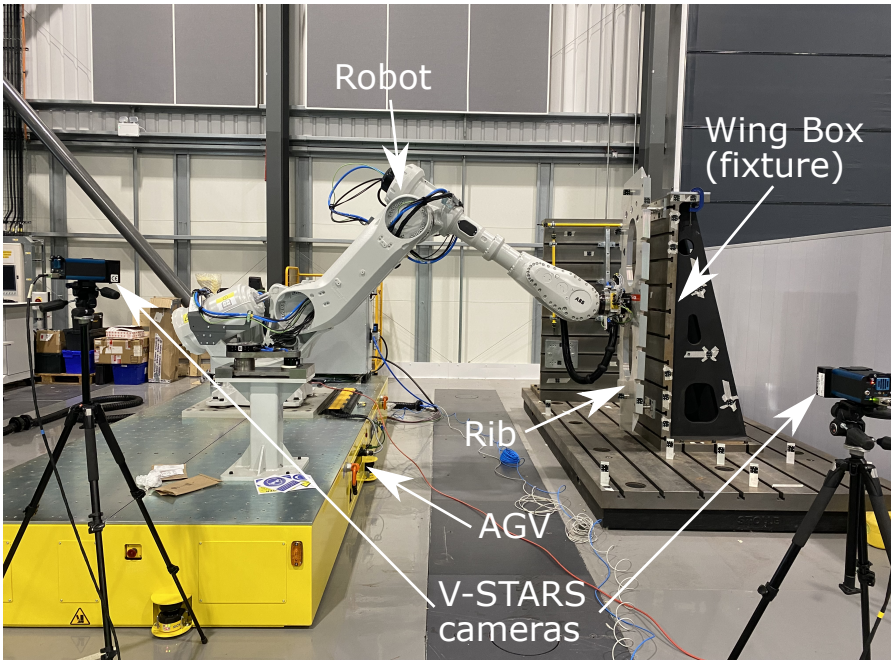


Figure 7.7: Test Cell 2.

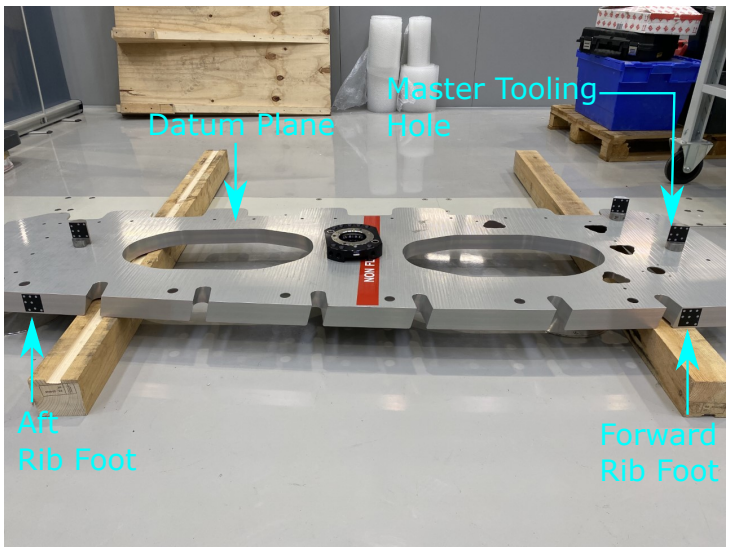


Figure 7.8: The aerospace rib used to demonstrate the assembly operation. The rib has been fitted with metrology facilities and photogrammetry targets for automatic measurement and live tracking.

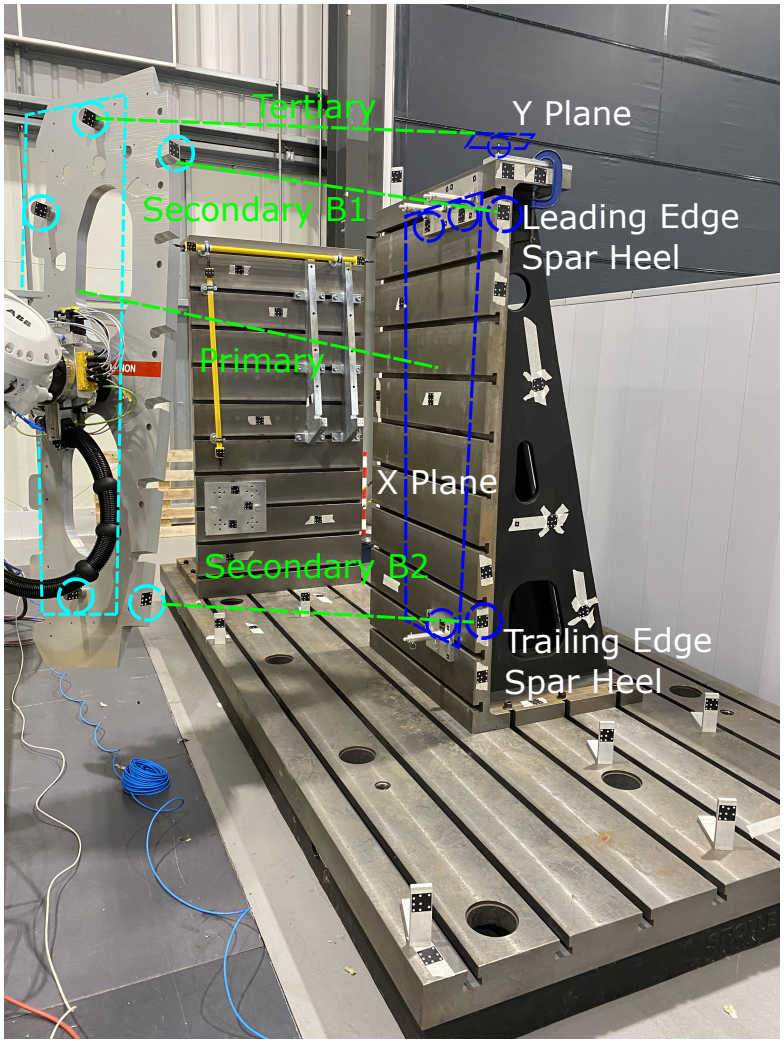


Figure 7.9: Overview of the key characteristics for the assembly operation in Test Cell 2.

the fixture projected onto the vector bar. However, since this surface is typically out of sight of the cameras, it has been characterised in advance using the same technique as the metrology pins.

The key characteristics for Test Cell 2 are summarised in Table 7.2. The primary key characteristic is again a plane to plane offset but now at a value of -220.0 mm between the datum plane of the rib and X plane of the fixture. The secondary B1 and secondary B2 key characteristics are 0.0 mm offset between the representative spar heels and the corresponding rib foot, where leading edge plane is paired with the forward rib foot point and the trailing edge plane is paired with aft rib foot point. The tertiary key characteristic is a 120.0 mm offset between the Y plane on the fixture and the master tooling hole in the rib.

Key Characteristic	Condition	Nominal Value (mm)
Primary	plane-plane offset	-220.0
Secondary B1	plane-point offset	0.0
Secondary B2	plane-point offset	0.0
Tertiary	plane-point offset	120.0

Table 7.2: Summary of the key characteristics for the assembly in Test Cell 2.

7.3 Methodology Validation & Evaluation

These experiments validate and evaluate the multiple key characteristic control methodology presented in Chapter 6. It does this by repeatedly setting the aerospace rib, following the procedure outlined in Figure 6.2 and developed in Sections 6.3 and 6.4, and taking repeat measurements using both the V-STARS photogrammetry system and the robot's internal measurements of itself. The robot internal measurements are taken such that the primary photogrammetry data can be checked. In small volume metrology (<1 m^3) a calibrated artefact is used to check that a metrology device is measuring accurately and repeatedly. However, for large volume metrology, suitable artefacts are not available. However, by measuring the assembly process from two metrology devices simultaneously, it is possible to reason about the quality of the primary metrology data. The data is ultimately used to assess the capability of the methodology against typical aerospace assembly tolerances.

7.3.1 Experimental Procedure

The below process is followed for both test cells and is based on typical process capability studies used to validate manufacturing processes and technologies [20]:

1. S-mode measurement is conducted of the static object(s).

2. Move aerospace rib into camera-shot (an arbitrary location) and take the first M-mode measurement.

3. Execute the multiple key characteristic control methodology (see Section 6.3, Section 6.4 and Figure 6.2), using the associated job file to define the requirements for the assembly operation; Appendix D for Test Cell 1 and Appendix E for Test Cell 2.

4. Once the component is considered set to tolerance by the control methodology, three repeat measurements of the key characteristics are made using the photogrammetry system. In addition to this, the robot internal measurement system records the robot's wrist pose relative to its base.

    - If this is the first trial, then take an additional 30 measurements with the component in position for measurement error analysis.

5. The robot then returns to its arbitrary starting pose.

6. Repeat steps 2 to 5 n times

Where, $n = 30$ for both demonstrators.

It is worth noting that when inspecting the job files and control charts for the assembly operations, a tolerance of ± 0.05 mm is applied to all the key characteristics. However, the actual tolerance desired for each key characteristic is ± 0.2 mm. This is to allow for any measurement error from V-STARS but also to assess the practical limit of this methodology given its physical implementation in this thesis. The value of ± 0.05 mm was found to be the smallest tolerance band that could be consistently achieved by the equipment within a practical time period. The methodology was also able to set to tolerance bands of ± 0.025 mm but the time to achieve such a tolerance for four key characteristics often exceeded 20 minutes without adding much additional accuracy.

7.3.2 Results of Demonstrators

The following are the measurement results and associated data from both test cells. Firstly, the results of Test Cell 1 are discussed which was chronologically the first test cell built and tested. This is followed by a discussion of the results from Test Cell 2. Comparisons and conclusions will be drawn as the results are presented. This section is followed by a further analysis of the data to determine the repeatability and process capability of the methodology.

Test Cell 1

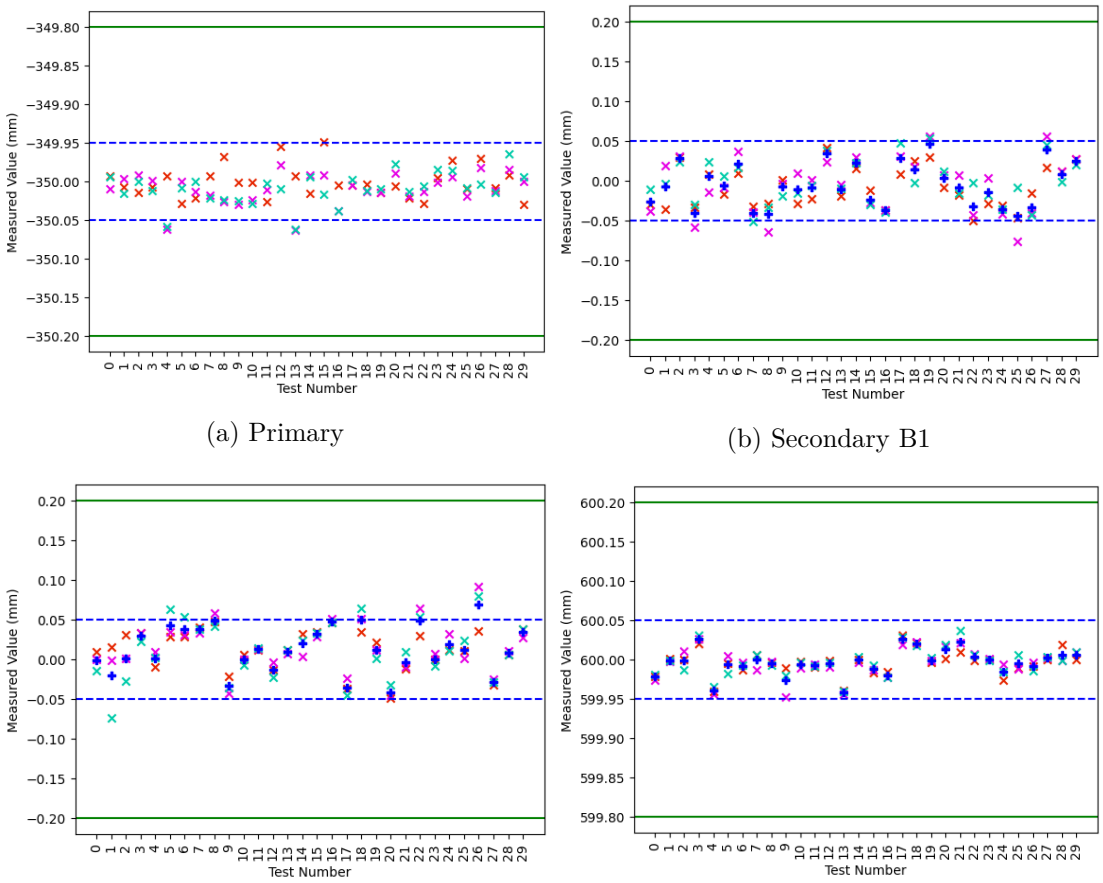
The results of the Test Cell 1 are presented in Figure 7.10. Each graph shows the control chart for each of the four key characteristics. This plots the measured achieved condition of the key characteristic after the control methodology has finished and plots it alongside the aerospace tolerance (horizontal green line) and the control tolerance (horizontal blue dashed line). Figure 7.10 shows that all key characteristics were simultaneously set to within aerospace tolerances consistently across all 30 tests. Moreover, this was done with a comfortable margin leftover. It can also been seen that the vast majority of the measurement data sits within the control tolerances which represents only 25% of the available tolerance range. This demonstrates that the methodology works as intended and does so with accuracies acceptable to the aerospace industry. An image of the rib in a fully set condition is shown in Figure 7.11.

Another aspect that is often pertinent to industry is the speed at which the component can be positioned. The time is not particularly consistent which is to be expected since the methodology is not linear and subject to many sources of error and variation from the implementing equipment. That said, no test exceeded 200 s and the average time to complete the assembly operation was 103.4 s (just over a minute and a half). This is much quicker than manual methods of achieving the same process which typically assign around 45 min per rib.

Test Cell 2

The results of the Test Cell 2 are presented in Figure 7.12. It follows an identical schema to the control charts in Figure 7.10. The results, again, show that all key characteristics were set to within aerospace tolerances simultaneously across all 30 tests. Moreover, in all cases except one, the key characteristics were set to within the control tolerance. This exception exceeded the control tolerance by 4 μm but shows nicely why the control tolerance must be lower than the required tolerance to account for measurement uncertainty. It is shown in a following section that the measurement uncertainty is in the order of 10 to 20 μm at 1σ, which is consistent with this outlier. An image of the rib in a fully set condition is shown in Figure 7.13.

To summarise the major results from this subsection: The methodology developed in Chapter 6 functions as expected. It successfully sets multiple key characteristics to within aerospace tolerances, simultaneously and consistently. It does this without any requirements for accurate equipment or component positioning or prior known relationships. Moreover, it has exhibited its interchangeability and flexibility by being deployed on two separate assembly systems, used to set two



(a) Primary

(b) Secondary B1

(c) Secondary B2

(d) Tertiary

Figure 7.10: The final measurement results of the four key characteristics for Test Cell 1. The green and blue lines are the aerospace tolerance and control tolerance, respectively. (a) The results of the primary key characteristic. The coloured crosses are each associated with the average measurement of one of the points on the datum plane of the rib. (b) The results of the secondary B1 key characteristic. The bold blue cross is the average measurement of the key characteristic, the coloured crosses are the associated measurements. (c) The results of the secondary B2 key characteristic. (d) The results of the tertiary key characteristic.



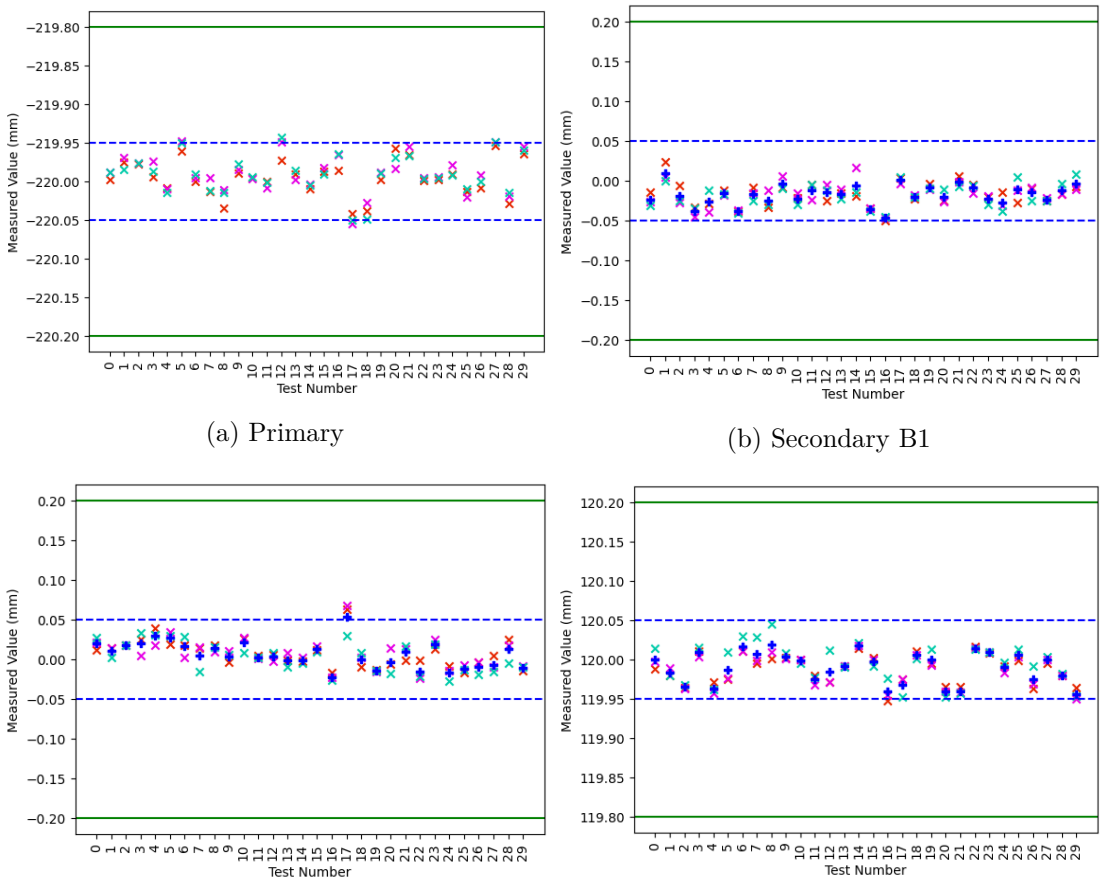
Figure 7.11: Image of the the rib with all key characteristics set in Test Cell 1.

different assemblies.

This data also suggests that the resolution of the robot's movements is smaller than the controlled tolerance of 0.05 mm. Since, had it been larger discrete bands would be visible in the control charts where the robot had been unable to find a joint combination that lay between them. This would also suggest that that robot's internal measurement system has an equally fine resolution to be able to discern between two poses within 0.05 mm of each other.

The movement resolution of the robot was confirmed by experiment. A dial test indicator (DTI) to the robot flange and zeroing it against a fixture surface. The robot then periodically moved towards the surface in progressively smaller increments. The result is that the smallest resolution of movement the robot could reliably perform was at least as small as 10 μm (0.010 mm), the resolution of the DTI itself. It could be observed that the robot was still moving in increments less than 10 μm but without a more precise gauge, a reliable estimate cannot be reported. The resolution of an typical industrial robot was determined to be approximately 5 μm by Kihlman in his thesis [39]. However, he does not elaborate on his method.

Regardless, for the purpose of these test cells, this means that the robot's resolution is not a bottleneck for the capability of the process and it can be used as a useful measurement device to cross-reference the photogrammetry measurements above.



(a) Primary

(b) Secondary B1

(c) Secondary B2

(d) Tertiary

Figure 7.12: The final measurement results of the four key characteristics for Test Cell 2. The green and blue lines are the aerospace tolerance and control tolerance, respectively. (a) The results of the primary key characteristic. The coloured crosses are each associated with the average measurement of one of the points on the datum plane of the rib. (b) The results of the secondary B1 key characteristic. The bold blue cross is the average measurement of the key characteristic, the coloured crosses are the associated measurements. (c) The results of the secondary B2 key characteristic. (d) The results of the tertiary key characteristic.

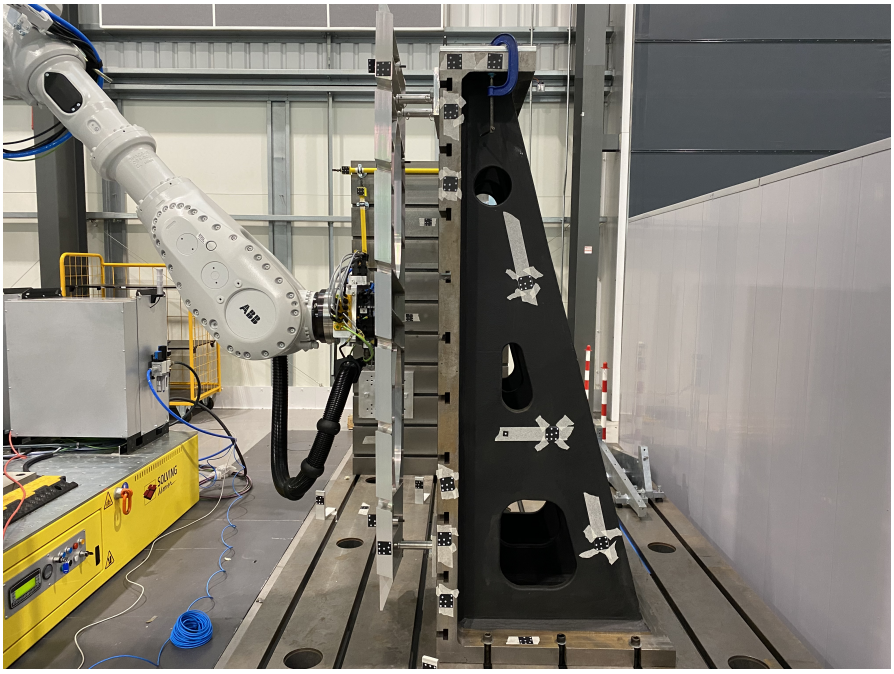


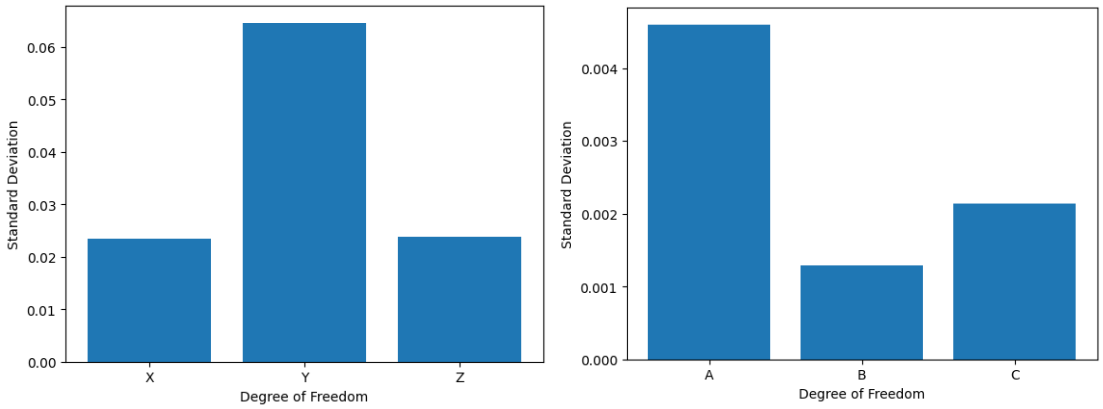
Figure 7.13: Image of the the rib with all key characteristics set in Test Cell 2.

7.3.3 Robot Pose Repeatability

The robotic manipulator internal measurement system is perfectly suitable as a measurement device against which to cross-reference the data from V-STARS. This section analyses the repeatability of the robot measurements of itself during the above testing. The idea here is that the robot measurements should exhibit the same level of consistency as that of the photogrammetry results. Moreover, all the positions should agree with each other to within the same tolerance band.

Beginning first with Test Cell 1, Figure 7.14(a) shows the standard deviations of the translational elements of the robot's wrist pose once all the tolerances had been set. The axes in this figure are those of the robot base coordinate system. Immediately it can be seen that there are two strong axes with one weaker axis. This mirrors the same relationship observed with V-STARS data. In fact, axis Y is roughly aligned with the perspective axis of the cameras. That said, the standard deviations are very small. This proves that the robot was repeatability going, in fact, to the same location; as suggested by the control charts of the previous section. The same is true for the rotational components of robot wrist pose, see Figure 7.14(b). Angle A is the angle between the X axes of the wrist frame and base, as defined in ISO 9283:1998 [81]. Angles B and C are the identical relationship but between the Y and Z axes, respectively.

ISO 9283:1998 also defines a method of calculating the industry accepted measure of pose repeatability [81]. This value quantifies the radius of a sphere within which the robot can be relied upon to achieve. It also goes onto define method for



(a) Translation (b) Rotation

Figure 7.14: Standard deviations for the robot wrist frame in Test Cell 1, as measured from its internal joint encoders. The base frame of the robot is the reference system. (a) Translational standard deviation. (b) Rotational standard deviation.

the repeatability of the poses rotational elements. Since the robot is being driven by the control methodology defined in the preceding chapter, which itself is being supplied data by the V-STARS metrology system, this will be a measure of the capability of the total system. Therefore, this repeatability will be compared to the ±0.2 mm tolerance applied to the key characteristics.

The repeatability for the trials conducted in Test Cell 1 was calculated as 0.149 mm. The sphere associated with this value, along with the data points used to calculate it, are plotted in Figure 7.15. The green sphere shows the ±0.2 mm tolerance. Technically, the tolerance boundary, when translated from the data model's coordinates into the robot's base coordinates, would not be spherical in shape but a polygon whose shape would change depending on the condition of the angular components of the robot. The sphere, however, is a conservative estimate and suitable for showing that the robot is returning to a controlled pose within aerospace tolerances. The repeatabilities values for angles A, B and C where calculated as: 0.014°, 0.004° and 0.007°. Although, there is no tolerance to compare these to, it is comforting to know that a controlled orientation is achievable to within minute fractions of a degree.

Test Cell 2 took measures to improve the metrology bundle to strengthen the weakest axis of measurement. This improvement is evident in the standard deviations calculated for the translational and rotation elements of the robot's wrist pose, see Figure 7.16(a) and Figure 7.16(b). These are measured relative to the robot base co-ordinate system. The magnitudes of these standard deviations are much smaller than those of Test Cell 1. Moreover, a weak axis is much less prevalent. This tighter repeatability is reflected in the ISO 9283:1998 definitions

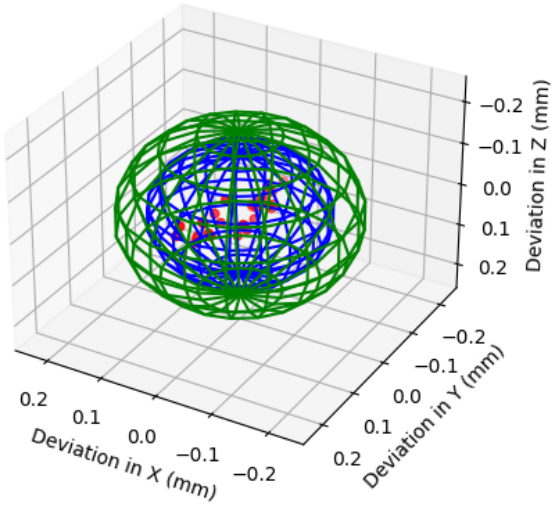


Figure 7.15: Comparison of the process repeatability as measured by the robot against the applied tolerance for Test Cell 1.

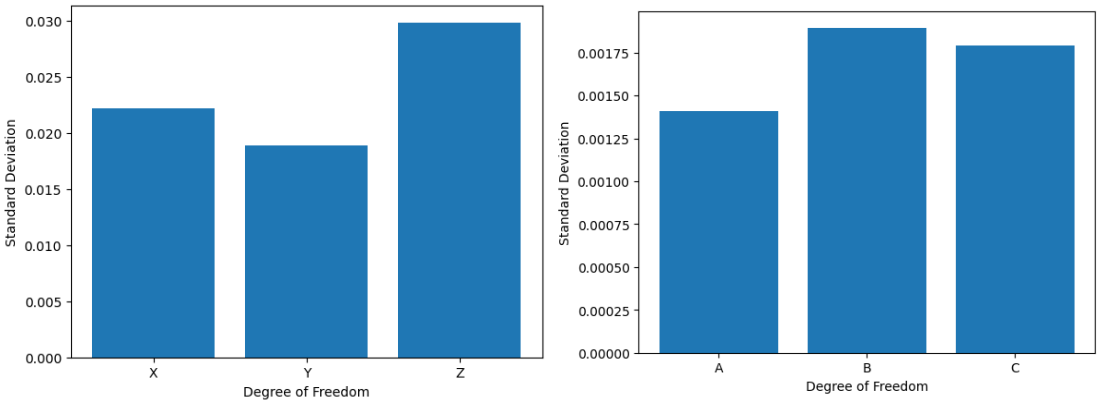
of pose repeatability, Figure 7.17. The size of the repeatability sphere is much smaller than the ±0.2 mm sphere designating the applied aerospace tolerance. However, this improved accuracy is not reflected in the repeatability for the A, B and C angles. These were calculated as 0.005°, 0.012° and 0.012°, respectively. The improved translational repeatability seems to have come at a small cost to the rotational elements. This may be due to improved accuracy allowing for more solutions closer to the extremities of the ±0.05 mm control tolerance.

To summarise, the use of both measurement systems leads to the conclusion that the system implementation and the underlying methodology and data model are able to confidently achieve multiple key characteristics simultaneously and to within aerospace tolerances. Moreover, the method is able to do this repeatedly making it suitable for industrial application. The other major conclusion to draw from this section is that, for the most part, the repeatability of the measurement data from the V-STARS system has been validated.

7.3.4 Process Capability Analysis

Now that the quality of the photogrammetry measurement data has been validated against the robot internal measurement data, conclusions can be drawn about the measurement error, and process capability indices can be calculated with confidence.

Beginning first by quantifying the measurement error associated with V-STARS.



(a) Translation

(b) Rotation

Figure 7.16: Standard deviations for the robot wrist frame in Test Cell 2, as measured from its internal joint encoders. The base frame of the robot is the reference system. (a) Translational standard deviation. (b) Rotational standard deviation.

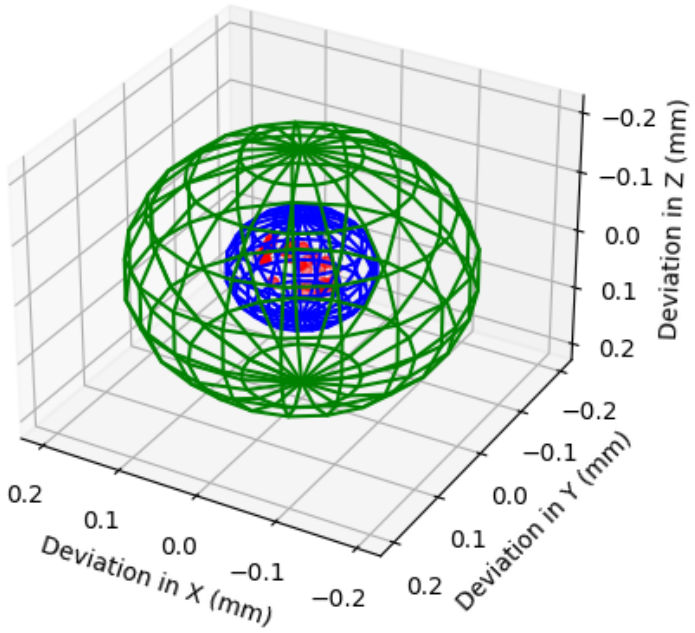


Figure 7.17: Comparison of the process repeatability as measured by the robot against the applied tolerance for Test Cell 2.

The measurement error here being defined as the range about the mean of a set of measurements of a measurand within which the true value is likely to be within [82]. The range, and associated probability that the true value lies inside this range, is typically chosen in scalar multiples of the standard deviation of the data set. Where 1σ corresponds to a probability of 68%, 2σ with 95% and 3σ with 99.7%, assuming a Gaussian distribution. This statement of the likelihood the true values lies between the $\bar{x} \pm k\sigma$ range is referred to as the confidence limit. Where; $\bar{x}$ is the mean of the measurement data set and k is the scaler multiple of standard deviation, σ. This is the traditional approach that is often interpreted from the closest thing metrology has to a globally accepted standard: The Guide to the Expression of Uncertainty in Measurement [83]. It is worth noting that this standard is not totally accepted and has begun to receive criticism along with alternative approaches to quantifying errors in measurements [84]. However, further discussion of this topic is out of scope for this thesis.

The repeat trials for each test cell included a pause where after the first test had concluded 30 repeat measurements are taken. It is these data sets that will be used to quantify the typical measurement error for each test cell. Table 7.3 details the error analysis for Test Cell 1. The table shows that the measurement system is extremely repeatable with even the 99.7% confidence limit sitting well within the ±0.2 mm tolerance range. This was also observed for Test Cell 2, see Table 7.4.

KC	Pri	Sec B1	Sec B2	Tri
Mean	-350.012	-0.023	0.001	599.986
σ_m (68%)	0.008	0.012	0.019	0.007
$2\sigma_m$ (95%)	0.016	0.024	0.045	0.013
$3\sigma_m$ (99.7%)	0.024	0.036	0.058	0.020

Table 7.3: Measurement error analysis for Test Cell 1. All values are in millimetres

KC	Pri	Sec B1	Sec B2	Tri
Mean	-220.009	-0.023	0.022	119.996
σ_m (68%)	0.005	0.008	0.009	0.004
$2\sigma_m$ (95%)	0.0011	0.016	0.017	0.009
$3\sigma_m$ (99.7%)	0.016	0.024	0.026	0.013

Table 7.4: Measurement error analysis for Test Cell 2. All values are in millimetres

The final stage of the analysis is to consider the process capability indices. These consider the variation of the process as a whole against the applied tolerance. The methods for which are taken from the field of statistical process control [20].

The two major indices are C_p and C_{pk} values. The former determines if the process variation could fit within the allowable tolerance band. The latter is similar to the C_p value but it takes into account any bias from the centre of the tolerance band. The C_{pk} value is the minimum of the C_{pku} and C_{pkl} values which are the consideration of the variation of the process relative to the upper and lower tolerance boundaries; respectively. The results of the process capability analysis are summarised in Table 7.5 for Test Cell 1 and Table 7.6 for Test Cell 2.

KC	Pri	Sec B1	Sec B2	Tri
$\sigma_p(mm)$	0.021	0.027	0.029	0.016
C_p	3.2	2.45	2.33	4.08
C_{pk}	3.11	2.39	2.17	4.02
C_{pku}	3.31	2.51	2.17	4.15
C_{pkl}	3.11	2.39	2.49	4.02

Table 7.5: Process capability analysis for Test Cell 1.

KC	Pri	Sec B1	Sec B2	Tri
$\sigma_p(mm)$	0.025	0.012	0.017	0.020
C_p	2.65	5.30	4.02	3.34
C_{pk}	2.50	4.84	3.89	3.18
C_{pku}	2.50	5.75	3.89	3.50
C_{pkl}	2.80	4.84	4.15	3.18

Table 7.6: Process capability analysis for Test Cell 2.

The C_p values of all key characteristics across both test cells reveals that the methodology and equipment is capable of delivering the key characteristic to within aerospace tolerances consistently. This capability follows through into the C_{pk} values which determine if the process is actually contained within the tolerance boundaries.

The methodology and the physical equipment setups are more than capable of delivering multiple key characteristics to within aerospace tolerances; simultaneously. Although, the process capability is largely dependant on the choice of metrology device and the amount of time allotted for setting the component. This is evident from comparing the σ_m values with the σ_p which shows that the majority of the variation comes from the errors in the control of the robotic manipulator and not the variation in the metrology device itself. The error in the robotic control is expected and is why a move-measure-correct process has been employed. This error is proportional to the size of the movement requested of the manipulator and only reduces with the number of iterations of the correction loop, adding time into the process. The repeatability of the metrology also goes

some way to determining the smallest reasonable movement of the robot. If the metrology device is only repeatable to within 0.1 mm it is unreasonable to command the robot to make movements smaller than this. Since, the robot would end up chasing the variation in the measurement itself and not the true value.

7.4 Chapter Summary

This chapter has validated the methodology developed in Chapter 6. Two technical demonstrators have been implemented to test the methodology thoroughly on varying components and equipment. The experimental procedure has largely followed a typical manufacturing process validation procedure but with a caveat to cross-reference the main metrology system against the internal robot measuring system. This circumvents the typical issue with large scale metrology which is a lack of calibrated artefacts.

The results of the technical demonstrators have shown that the methodology is more than capable of adapting and controlling multiple key characteristics simultaneously and repeatedly at aerospace tolerances. Moreover, the process was fully automated via the use of the data model and the associated production feedback loop developed in Chapter 4 and the use of direct machine control interfaces for both the robot, metrology device and supporting equipment. Therefore, this chapter has presented two examples of automatic variation propagation control for fixtured assemblies which are active during production.

In addition to this primary goal, this work also showcases the methodology's robustness, mobility and interchangeability of equipment. Highlighting its potential for enabling flexible, low-cost and reconfigurable assembly systems and factories.

Chapter 8

Conclusions and Future Work

8.1 Introduction

The aim of this thesis has been to develop novel approaches to controlling variation propagation in mechanical assemblies; with a focus on aero-structures assembly. A review of the literature revealed several knowledge gaps concerning active methodologies capable of dealing with manufacturing variation, as it appears within a product's manufacture. It is also clear that the methodologies currently applied in the aerospace industry are neither automated or capable of controlling a sufficient amount of key characteristics to be of practical use. Moreover, there is a lack of methodologies for controlling variation in part-to-part assemblies. Due, in part, to their absence in aero-structures assembly but not for lack of motive. To enable these active variation control methodologies, a data model is developed.

The chapter concludes the thesis by discussing the knowledge contributions delivered for each research objective. Section 8.2 reviews the aim and objectives of the thesis. Section 8.3 summarises all of the knowledge contributions of the thesis. Following this, possible avenues for future work are discussed in Section 8.4.

8.2 Review of Aims and Objectives

This thesis has achieved its aim of automatically controlling variation propagation in aero-structures assembly for all types of assembly, see Section 1.2. It has done this by developing an alternate approach to aero-structures manufacture. Namely, a pair of active and automatic variation control methodologies for both types of assembly, supported by a novel data model. The requirement for these contributions was identified in Chapter 2, where knowledge gaps were identified in the existing literature. And, these knowledge gaps were formulated into actionable objectives in Section 1.3. The following paragraphs review each objective against

the contribution of this thesis.

Develop a data model for the automatic control of variation propagation

The data model developed and formalised in Chapter 4 delivers a novel approach for manufacturing, in contrast to those in the current literature. Firstly, it encapsulates all manufacturing data for a product into a single machine-readable entity, enabling automated feedback loops with production output and automated manufacturing variation management. It also allows a product's design and manufacturing data to be adaptive and flexible to variations experienced during assembly and live production data, creating a platform for adaptive methodologies to be implemented. It combines the functionality of a database, a master manufacturing resource and a connective assembly model into a single machine accessible entity. Moreover, it represents a paradigm change from the traditional approach of manufacturing to human-readable and static CAD models, engineering drawings and build philosophy documents for every assembly and opens up the field to greater adaptive methodologies and novel manufacturing strategies. The data model and its associated manufacturing approach is validated by the methodologies and technical demonstrators that utilise it in Chapters 5, 6 and 7.

Develop and validate an automated methodology for controlling variation propagation in part-to-part assemblies

A methodology has been developed that simultaneously enables part-to-part assembly techniques in aero-structures assembly. It provides a method of automatic control of manufacturing variation propagation in part-to-part assemblies, as demonstrated in Chapter 5. The adaption phase of this methodology is one of the key contributions. It solves the key characteristic sets and corrects the associated part-to-part interfaces to lock-in the adaption for targetted assemblies. Having adapted the data model, the manufacturing data (CAD models, drawings, etc.) will inherently be adapted since the data model drives the manufacturing data and subsequently the manufacturing resources.

Develop and validate an automated methodology for simultaneous control of multiple key characteristics for robotic assembly

A methodology for controlling multiple key characteristics during the automatic assembly of Type 2 assemblies is presented in Chapter 6. Firstly this is a method which controls multiple key characteristics simultaneously for application in automated metrology-guided assembly of aerospace structures. Therefore, it is automating the adaptive variation propagation control across all the key characteristics of the assembly. Secondly, it does this without any prior known

relationships between: the robot, the components involved in the assembly, the fixture, or metrology systems. These relationships are calculated automatically as part of the methodology. This fact is extremely important since it enables precise mobile robotic assembly devices and removes the requirement for expensive locating fixtures, end-effector designs, tooling, or precise factory layouts, and manual teaching, or manual measuring operations. It also ensures assembly programs are robust to locations errors stemming from reconfigurations, exchanges of equipment or component variation or existing accumulations of variation within the product. This capability was validated in Chapter 7.

In summary, this thesis has successfully achieved each of the research objectives laid out in Section 1.3. By completing these objectives the thesis has made a set of knowledge contributions targetting the gaps identified in Section 2.9. The completion of these objectives and knowledge gaps represents a significant step forward in, and example of, research towards automatic manufacturing variation control methods that are active during production; achieving the aim of this thesis, set out in Section 1.2. That is, to develop novel approaches to automatically control and manage manufacturing variation propagation in mechanical assemblies during their production.

8.3 Contributions

During the progress of this research a number of contributions were identified to the field of manufacturing engineering which are not directly related to the aim and objectives set out at the beginning but still worth mentioning here. This section summaries each contribution:

- The data model in Chapter 4 creates a new paradigm for aero-structures manufacturing by creating an object-orientated entity has the following attributes:
  - it combines all the manufacturing data for a product into a single machine-readable and modifiable entity, enabling automation and automated methodologies. Typically the human-readable formats are inaccessible or difficult for a program or automated system to read or modify.
  - It inherently creates a feedback loop between production output and the data driving production. This is not the case in traditional approaches for aero-structures manufacturing.

  - It maintains the traceability of measurement data. The international standard, ISO 9001 [73], requires measurement data to be archived and traceable. As discussed in Chapter 4, each physical instance of a product has its own copy of the nominal data model, into which measurements of it assemblies, parts and features are supplied. The data model structure creates a complete mapping between each feature and geometry on every part involved in every assembly. Such that, so long as the data model is available, the measurement data for any particular feature of a product can be found for each instance of product.
  - The *frame* object network and the associated connections between them allows practical analysis and application of a networked series of connective assembly models. This circumvents the traditional limitation of connective assembly models which is that they must be open-chains [1]. This is a serious limitation since products rarely consist of open chain assemblies, especially in the aerospace industry.

- The methodology and technical demonstrator presented in Chapter 5 delivers the following contributions:

  - It is an example of an automatic manufacturing variation control methodology for part-to-part assemblies during production. The literature review revealed no examples of variation control methodologies maintaining key characteristics in part-to-part assemblies.
  - The methodology itself enables part-to-part assembly to be applied to the aerospace industry and any other low-tolerance industries. Part-to-part assembly is much faster and cheaper than fixtured assembly, since locational fixtures, tooling, and gauges are not required.
  - The methodology is driven by the sets of key characteristics associated with each assembly. Therefore, this is not just another example of measurement-assisted determinant assembly but an intelligent variation control method. Other work has discussed determinant assembly in aerospace application using metrology for enabling part-to-part assembly but they do not implement it as a method of controlling manufacturing variation propagation in key characteristics [60].
  - The methodology is generalised and practical. It is applicable to any mechanical assembly. It is simple utilise. Since, a data model can be automatically generated and adapted using the methods discussed in Chapter 4. Therefore, there is little work required to setup and make

use of this methodology for other applications other than those shown in this thesis.

- The methodology presented in Chapter 6 and validated in Chapter 7 delivers the following contributions:
  - It is an example of an automatic manufacturing variation control methodology for multiple key characteristics during robotic assembly. There are no other examples, in the current literature, of this for metrology-guided robotic assembly. It is therefore a complete variation control methodology for fixtured assemblies during their production.
  - It achieves simultaneous key characteristic control without relying on any prior-known tooling or mechanical relationships. That is, the relationship between the following items are all determined automatically during the methodology:
    * the component being positioned and the robot;
    * the two components involved in the assembly operation;
    * the static component relative to the fixture it is mounted in;
    * the metrology device and the robot.

    This removes any requirement for expensive and high-tolerance end-effector tooling, component pick-up features, or fixturing. And, it make the process robust to variations in these relationships. This was demonstrated in Chapter 7.
  - Since the process is entirely driven by the key characteristics of the components involved in the assembly. The methodology is entirely robust to the relative locations of manufacturing equipment (robot, fixture, metrology device) not just the components therein. Conversely, this enables high-precision mobile robotic assembly, as shown by Test Cell 2 (Chapter 7). And, it enables flexible and reconfigurable manufacturing systems; since fixtures, robots and metrology equipment can be roughly located without high-tolerance floor pick-up locations or lengthy setting procedures, without consequence to the assembly process. This is demonstrated by Test Cell 1 and Test Cell 2 in Chapter 7.
  - The methodology also provides a means of controlling the path the component takes on its approach to the ideal assembly position. This is a practical extension to the existing novelty of methodology.
  - Lastly, the approach is generalised and can be applied to any mechanical assembly that is of Type 2 and suitable for automation. The methodology can be immediately applied to other rib-to-wing box examples by

modifying the job file driving the assembly. And, it can be totally repurposed for other mechanical assemblies using the automatic methods and data model elements described in Chapter 4.

- Chapter 7 itself presents process verification procedure that is a variation on typical manufacturing process validation and capability studies. It is specifically targeted at metrology-guided robotic assembly processes that use large volume metrology. Large volume metrology is difficult to validate since calibrated artefacts do not come is suitably large sizes. In most cases, the work simply assumes the metrology device is accurate and repeatable. The experimental process designed and utilised in this thesis uses the robot internal measurement system to cross-reference the primary metrology device, adding further confidence in the process under investigation.

The other contribution focuses on the automation of this design change loop making the process practical for industrial use, as validated in Chapter 5. The final contribution is the generalisation of the approach. This methodology can be applied to any mechanical assembly and only requires the features involved in the assembly operation to be measured (key features, assembly interfaces); removing any requirement for 100% inspection. The approach minimises disruption by maintaining common interfaces and enables elastic manufacturing approaches. Since, if no metrology data is fed into the data model, the nominal manufacturing data is supplied because the data model is still in its nominal condition. Therefore, this approach can be utilised as much or as little as necessary or desired, subject to production lead times, product requirements and equipment availability.

Other sources of novelty stem from the processes generalisation. The methodology is conveniently turned to other assemblies and key characteristic sets without re-programming. Moreover, a flexible and interchangeable device control platform was developed to support the methodology and further increase the flexibility, robustness and practicality of the approach. The methodology also details other practical additions such as the ability to add assembly paths that adapt to the live assembly operation as variations are measured. These contributions were all validated via the two technical demonstrators detailed in Chapter 7.

8.4 Future Work

This approach is truly a paradigm shift in comparison to the current status-quo in manufacturing and there remains a great deal of untouched ground that is ripe for further research. During the development of the current body of work, a number

of areas have been identified for future development of the presented approach and new avenues for research opportunities:

- **Extend the key characteristics solution algorithm to optimise over-constrained sets**
  It is sometimes the case that key characteristic sets are over-constrained and a mathematically ideal solution cannot be found. In these situations it would be interesting to apply an optimisation or best-fit approach to minimises the error experienced by each key characteristic.

- **Extend the key characteristics solution algorithm to solve over-constrained sets**
  Alternatively, given a part that is over-constrained, it would be possible to achieve all key characteristics, if the features themselves can be adjusted independently of each other (In the same fashion to how the join features were adjusted in Chapter 5). This would enable part designs to achieve several high-precision functions simultaneously without key-characteristic-conflict conditions [1]. Whether this approach or the previous optimisation approach is utilised would depend on the type of assembly and equipment available to the manufacturer.

- **Design for adaptive assembly models**
  As discussed previously, this approach partially decouples the manufacturing variance, experienced early on in the assembly and part manufacturing process, from the achievable tolerances achieved later on in the assembly process. This enables the utilisation of part-to-part assembly techniques where they previously were not possible. Alternatively, it enables cheaper less accurate manufacturing processes to be used without sacrificing later product accuracy. This opens up a number of product and process design opportunities which were previously unavailable for product designers. Moreover, since this approach can adapt features independently from the part they sit upon, it is possible to perfectly solve over-constrained sets of key characteristics; allowing part designs to achieve several high-precision functions simultaneously. Therefore, some research must be done to fully exploit these new opportunities.

8.5 Concluding Remarks

Variation in manufacturing is inevitable. And, a great deal of assembly design and its operation focuses on managing this variation. There are few industries

that suffer more than the aerospace industry with respect to the propagation of variation in assemblies. And despite the efforts of current literature it continues to remain an issue.

This thesis has provided two novel methodologies and an assembly modelling approach which opens new avenues of attack for the problem of controlling variation propagation. It represents a new way of thinking about our manufacturing systems and our methods for controlling manufacturing variation. Choosing to rely less on controlling manufacturing variation at its source and enabling advanced automatic methods for adapting and controlling for it as it inevitably appears on the assemblies and production lines.

The data model developed in Chapter 4 enables assembly representation models and their associate manufacturing data to become automatically adaptive, when given metrology data from production processes. The methodology in Chapter 5 both enables part-to-part assembly in the aero-structures industry and enables an adaptation phase to curb accumulations of variation in key characteristic chains. The methodology in Chapter 6 enables the simultaneous control of several key characteristics for metrology-guided robotic assembly operations. It also enables complete flexibility and mobility of the devices performing the assembly operation. These methodologies and the overall adaptive data model driven approach has been validated and evaluated against aerospace tolerances in several technical demonstrators, see Chapter 7. Moreover, this approach has been developed with practicality and industrial application in mind. Methods have been implemented to automatically generate data models from existing CAD and build-philosophy data, the methodologies are generalised and application bespoke details are either automatically handled by the data model or managed by a simple configuration file (for example the job file and configuration file from Chapter 6), and utility methods have been implemented to enable other aspects of assembly operations such as assembly paths. This approach, although delivered here as research, is practically viable and is ready to be deployed in industry.

References

[1] Daniel E Whitney. *Mechanical assemblies: their design, manufacture, and role in product development*, volume 1. Oxford university press New York, Oxford, 2004. Oxford Series on Advanced Manufacturing.

[2] Oliver Martin. *Metrology Enabled Tooling for the Assembly of Aero-Structures*. PhD thesis, University of Bath, Bath, 2015.

[3] Alison Millar and Henrik Kihlman. Reconfigurable flexible tooling for aerospace wing assembly. In *SAE 2010 Aerospace Manufacturing and Automated Fastening Conference & Exhibition, September 28-30, Wichita, KS, USA*. Society of Automotive Engineers, 2009.

[4] Jonathan Michael Carberry. *Reducing the acquisition cost of the next fighter jet using automation*. PhD thesis, University of Warwick, Warwick, United Kingdom, February 2021.

[5] JE Muelaner, OC Martin, and PG Maropoulos. Achieving low cost and high quality aero structure assembly through integrated digital metrology systems. *Procedia Cirp*, 7:688–693, 2013.

[6] Henrik Kihlman, Raimund Loser, Andrew Cooke, Albin Sunnanbo, and Konrad Von Arb. Metrology-integrated industrial robots: calibration, implementation and testing. In *35th ISR International Symposium on Robotics, 23-26 March, Paris, France*, 2004.

[7] Marco Ryll, Thomas N Papastathis, and Svetan Ratchev. Towards an intelligent fixturing system with rapid reconfiguration and part positioning. *Journal of Materials Processing Technology*, 201(1-3):198–203, 2008.

[8] Marco Ryll. *Towards a software framework for reconfigurable and adaptive fixturing systems*. PhD thesis, University of Nottingham, Nottingham, England, 2011.

[9] Rezia Molfino, Matteo Zoppi, and Dimiter Zlatanov. Reconfigurable swarm fixtures. In *2009 ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots*, pages 730–735. IEEE, 2009.

[10] Marie Jonsson. *On manufacturing technology as an enabler of flexibility: Affordable reconfigurable tooling and force-controlled robotics*. PhD thesis, Linköping University, Linköping, Sweden, 2013.

[11] Joseph Matthew Calkins. *Quantifying coordinate uncertainty fields in coupled spatial measurement systems*. PhD thesis, Virginia Polytechnic Institute and State University, Blacksberg, Virginia, 2002.

[12] Sofia Catalucci, Adam Thompson, Samanta Piano, David T Branson III, and Richard Leach. Optical metrology for digital manufacturing: a review. *The International Journal of Advanced Manufacturing Technology*, 120(7-8):4271–4290, 2022.

[13] Bryan R Fischer. *Mechanical tolerance stackup and analysis*. CRC Press, 2004.

[14] Vincent McKenna, Yan Jin, Adrian Murphy, Michael Morgan, Rao Fu, Xuda Qin, Caroline McClory, Rory Collins, and Colm Higgins. Cost-oriented process optimisation through variation propagation management for aircraft wing spar assembly. *Robotics and Computer-Integrated Manufacturing*, 57:435–451, 2019.

[15] Konstantinos Bacharoudis, Otto Jan Bakker, Atanas Popov, and Svetan Ratchev. Trade-off study of a variation aware determinate wing assembly against a traditional assembly strategy. In *MATEC Web of Conferences*, volume 233. EDP Open, 2020.

[16] Alain Etienne, Jean-Yves Dantan, Jawad Qureshi, and Ali Siadat. Variation management by functional tolerance allocation and manufacturing process selection. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 2(4):207–218, 2008.

[17] Anna C Thornton. A mathematical framework for the key characteristic process. *Research in engineering design*, 11(3):145–157, 1999.

[18] Ramakrishna Mantripragada and Daniel E Whitney. Modeling and controlling variation propagation in mechanical assemblies using state transition models. *IEEE Transactions on Robotics and Automation*, 15(1):124–140, 1999.

[19] Stuart Pugh. *Total design: integrated methods for successful product engineering*. Addison-Wesley, Wokingham, England, 1991.

[20] John Oakland and Robert Oakland. *Statistical Process Control: Seventh Edition*. Routledge, Oxon, England, 09 2019.

[21] Shiyu Zhou, Qiang Huang, and Jianjun Shi. State space modeling of dimensional variation propagation in multistage machining process using differential motion vectors. *IEEE Transactions on robotics and automation*, 19(2):296–309, 2003.

[22] Otto J Bakker, Atanas A Popov, and Svetan M Ratchev. Variation analysis of automated wing box assembly. *Procedia CIRP*, 63:406–411, 2017.

[23] Don J Lee and Anna C Thornton. The identification and use of key characteristics in the product development process. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 4, Irvine, CA, 1996. American Society of Mechanical Engineers.

[24] Anna C Thornton. Variation risk management using modeling and simulation. *Journal of Mechanical Design*, 121(2):297–304, 1999.

[25] Cheryl L Leland. *A cultural analysis of key characteristic section and team problem solving during an automobile launch*. PhD thesis, Massachusetts Institute of Technology, Massachusetts, USA, 1997.

[26] G Thimm, GA Britton, and FS Cheong. Controlling tolerence stacks for efficient manufacturing. *The International Journal of Advanced Manufacturing Technology*, 18(1):44–48, 2001.

[27] Andrew M Terry. *Improving Product Manufacturability Through The Integrated Use of Statistics*. PhD thesis, Massachusetts Institute of Technology, Massachusetts, USA, 2000.

[28] David Jeffreys. *Developing Dimensional Management for the Assembly of Aircraft Structures*. PhD thesis, Wolfson School of Mechanical and Manufacturing Engineering, Loughborough, United Kingdom, 2006.

[29] Stefan Goetz, Benjamin Schleich, and Sandro Wartzack. Integration of robust and tolerance design in early stages of the product development process. *Research in Engineering Design*, 31:157–173, 2020.

[30] Ambre Diet. *An end-to-end approach of statistical tolerancing under industrial constraints: Contribution to the design/industrial virtual twin.* PhD thesis, IMT-Institut de Mathématiques de Toulouse UMR5219, 2021.

[31] Ambre Diet, Nicolas Couellan, Xavier Gendre, Julien Martin, and Jean-Philippe Navarro. A statistical approach for tolerancing from design stage to measurements analysis. *Procedia CIRP*, 92:33–38, 2020.

[32] Daniel E Whitney, Olivier L Gilbert, and Marek Jastrzebski. Representation of geometric variations using matrix transforms for statistical tolerance analysis in assemblies. *Research in engineering design*, 6(4):191–210, 1994.

[33] Z Yang, S McWilliam, AA Popov, and T Hussain. A probabilistic approach to variation propagation control for straight build in mechanical assembly. *The International Journal of Advanced Manufacturing Technology*, 64(5-8):1029–1047, 2013.

[34] Z Yang, S McWilliam, AA Popov, T Hussain, and H Yang. Dimensional variation propagation analysis in straight-build mechanical assemblies using a probabilistic approach. *Journal of Manufacturing Systems*, 32(2):348–356, 2013.

[35] JY Dantan, A Hassan, A Etienne, A Siadat, and P Martin. Information modeling for variation management during the product and manufacturing process design. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 2(2):107–118, 2008.

[36] Tanweer Hussain. *Modelling and controlling variation propagation in mechanical assembly of high speed rotating machines.* PhD thesis, University of Nottingham, Nottingham, England, 2012.

[37] Weimin Wang, Dongbo Li, and Jie Chen. Minimizing assembly variation in selective assembly for complex assemblies using genetic algorithm. In *2011 Second International Conference on Mechanic Automation and Control Engineering*, pages 1401–1406. IEEE, 2011.

[38] Yanfeng Xing and Yansong Wang. Minimizing assembly variation in selective assembly for auto-body parts based on igaot. *International journal of intelligent computing and cybernetics*, 11(2):254–268, 2018.

[39] H. Kihlman. *Affordable Automation for Airframe Assembly: Developing of Key Enabling Technologies.* Linköping studies in science and technology: Dissertations. Linköping University, 2005.

[40] Henrik Kihlman and Magnus Engström. Affordable reconfigurable tooling. *SAE Transactions*, pages 363–372, 2002.

[41] Jonas Herbertsson, Henrik Kihlman, and Magnus Engström. Reconfigurable aircraft assembly: using industrial robots and new tooling to meet future production scenarios. In *33rd International Symposium on Robotics in Stockholm, October 8-10*, 2002.

[42] Henrik Kihlman. Reconfigurable tooling for airframe assembly: a state-of-the-art review of the related literature and a short presentation of a new tooling concept. In *CIRP 1st International Conference on Agile, Reconfigurable Manufacturing, Ann Arbor, Michigan, USA, 21-22 May*. University of Michigan, 2001.

[43] Henrik Kihlman, Gilbert Ossbahr, Magnus Engström, and John Anderson. Low-cost automation for aircraft assembly. In *SAE 2004 Aerospace Manufacturing & Automated Fastening Conference & Exhibition, September 21th 2004, St Louis, Missouri, United States*, 2004.

[44] Henrik Kihlman and Raimund Loser. 6dof metrology-integrated robot control. *SAE transactions*, pages 398–405, 2003.

[45] Marie Jonsson and Gilbert Ossbahr. Aspects of reconfigurable and flexible fixtures. *Production Engineering*, 4(4):333–339, 2010.

[46] Otto Jan Bakker. *Control methodology and modelling of active fixtures*. PhD thesis, University of Nottingham, Nottingham, United Kingdom, December 2010.

[47] Thomas Papastathis. *Modelling and design methodology for fully-active fixtures*. PhD thesis, University of Nottingham, Nottingham, United Kingdom, April 2011.

[48] Ilker Erdem, Gauti Asbjörnsson, and Henrik Kihlman. Workpiece force and position control for active and flexible fixtures in assembly. *The International Journal of Advanced Manufacturing Technology*, 112:333–346, 2021.

[49] Klaus Schricker, Leander Schmidt, Hannes Friedmann, and Jean Pierre Bergmann. Gap and force adjustment during laser beam welding by means of a closed-loop control utilizing fixture-integrated sensors and actuators. *Applied Sciences*, 13(4):2744, 2023.

[50] Jody E Muelaner, Amir Kayani, Oliver Martin, and Paul Maropoulos. Measurement assisted assembly and the roadmap to part-to-part assembly. In *7th*

international conference on digital enterprise technology, pages 11–19, Bath, England, 2011. University of Bath, University of Bath.

[51] Jody E Muelaner and Paul G Maropoulos. Integrated dimensional variation management in the digital factory. In *7th International Conference on Digital Enterprise Technology*, pages 39–46. University of Bath, 2011.

[52] PG Maropoulos, JE Muelaner, MD Summers, and OC Martin. A new paradigm in large-scale assembly—research priorities in measurement assisted assembly. *The International Journal of Advanced Manufacturing Technology*, 70(1-4):621–633, 2014.

[53] Jafar Jamshidi, A Kayani, Pejman Iravani, Paul G Maropoulos, and MD Summers. Manufacturing and assembly automation by integrated metrology systems for aircraft wing fabrication. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 224(1):25–36, 2010.

[54] Dan Vaughan, David Branson, Otto Jan Bakker, and Svetan Ratchev. Towards self-adaptive fixturing systems for aircraft wing assembly. Technical report, SAE Technical Paper, 2015.

[55] Richard Kingston. Metrology assisted robotic automation. Technical report, SAE Technical Paper, 2014.

[56] Jacob Brown. Metrology assisted robotic automation 2. Technical report, SAE Technical Paper, 2019.

[57] Adrien Drouot, Ran Zhao, Lucas Irving, David Sanderson, and Svetan Ratchev. Measurement assisted assembly for high accuracy aerospace manufacturing. *IFAC-PapersOnLine*, 51(11):393–398, 2018.

[58] Gary Williams, Edward Chalupa, Rich Billieu, Jim Murphy, and Dave Swager. Gaugeless tooling. *SAE transactions*, pages 1241–1246, 1998.

[59] Lucas Irving, Svetan Ratchev, Atanas Popov, and Marcus Rafla. Implementing determinate assembly for the leading edge sub-assembly of aircraft wing manufacture. *SAE International Journal of Aerospace*, 7(2014-01-2252):246–254, 2014.

[60] Jody E Muelaner and Paul G Maropoulos. Design for measurement assisted determinate assembly (mada) of large composite structures. In *Journal of the Coordinate Metrology Systems Conference*, Reno, Nevada, 2010.

[61] Michael A. Wesley, Tomas Lozano-Perez, Lawrence I. Lieberman, Mark A. Lavin, and David D. Grossman. A geometric modeling system for automated mechanical assembly. *IBM Journal of Research and Development*, 24(1):64–74, 1980.

[62] Chi-Haur Wu and Myong Gi Kim. Modeling of part-mating strategies for automating assembly operations for robots. *IEEE transactions on systems, man, and cybernetics*, 24(7):1065–1074, 1994.

[63] Jami J Shah and Mary T Rogers. Assembly modeling as an extension of feature-based design. *Research in Engineering Design*, 5(3-4):218–237, 1993.

[64] Sean Callahan and Jeff Heisserman. A product representation to support process automation. *Product modeling for computer integrated design and manufacture*, pages 285–296, 1997.

[65] Göran Adamson, Lihui Wang, and Philip Moore. Feature-based control and information framework for adaptive and distributed manufacturing in cyber physical systems. *Journal of manufacturing systems*, 43:305–315, 2017.

[66] John Craig. *Introduction to Robotics: Mechanics and Control*. Pearson Education Limited, USA, 1989.

[67] Brian Rooks. Automatic wing box assembly developments. *Industrial Robot: An International Journal*, 28(4):297–302, 2001.

[68] Werner Kritzinger, Matthias Karner, Georg Traar, Jan Henjes, and Wilfried Sihn. Digital twin in manufacturing: A categorical literature review and classification. *IFAC-PapersOnLine*, 51(11):1016–1022, 2018. 16th IFAC Symposium on Information Control Problems in Manufacturing INCOM 2018.

[69] Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides. Design patterns: Abstraction and reuse of object-oriented design. In *European Conference on Object-Oriented Programming*, pages 406–431. Springer, 1993.

[70] Erich Gamma, Richard Helm, Ralph Johnson, and John Vlissides. *Design Patterns: Elements of Reusable Object-Oriented Software*. Addison-Wesley Longman Publishing Co., Inc., USA, 1995.

[71] Paul Barry. *Head First Python: A Brain-Friendly Guide*. O'Reilly Media., Inc., USA, 2016.

[72] Dassault Systems. Catia. `https://www.3ds.com/products-services/catia/`. Accessed: 2020-08-22.

[73] International Organization for Standardization. Quality Management Systems – Requirements. Standard, International Organization for Standardization, Geneva, CH, March 2015.

[74] Richard Crossley and Svetan Ratchev. Aerospace assembly gap measurement using low cost smart tools with machine vision. In *International Precision Assembly Seminar*, pages 158–168. Springer, 2018.

[75] SciPy documentation. scipy.optimize.minimize. `https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.minimize.html`. Accessed: 2021-02-08.

[76] MasterCAM. Mastercam. `https://www.mastercam.com/`. Accessed: 2022-03-14.

[77] John Brown. White paper: V-stars / s system accuracy test results. Technical report, Geodetic Systems inc., 1997.

[78] Scott Sandwith and Glen Cork. White paper: V-stars / m system accuracy test results. Technical report, Boeing, 2000.

[79] Giuseppe Ganci and Harry Handley. White paper: Automation in videogrammetry. Technical report, Geodetic Systems inc., 2018. Accessed: 2021-02-09.

[80] Geodetic systems' v-stars d system. `https://www.geodetic.com/products/systems/v-stars-d/`. Accessed: 2021-02-09.

[81] International Standards Organisation. Iso 9283: Performance criteria and related test methods. *Manipulating industrial robots*, 1998.

[82] John Taylor. *An Introduction To Error Analysis: The Study of Uncertainties In Physical Measurment.* University Science Books, USA, 1997.

[83] International Standards Organisation. Iso/iec guide 98-3: Guide to the expression of uncertainty in measurement. *Manipulating industrial robots*, 2008.

[84] Robin Willink. *Measurement Uncertainty and Probability.* Cambridge Univeristy Press, Cambridge, 2013.

[85] Object Management Group. Unified modeling language: Infrastructure. `https://www.omg.org/spec/UML/2.0/Infrastructure/PDF`.

[86] Object Management Group. Unified modeling language: superstructure. `https://www.omg.org/spec/UML/2.0/Superstructure/PDF`.

[87] Oracle Corporation and/or its affiliates. Mysql: The world's most popular open source database. `https://www.omg.org/spec/UML/2.0/Superstructure/PDF`. Accessed: 2020-12-01.

Appendix A

Detail Definitions of Data Model Classes

A.1 Introduction

This appendix discusses in greater detail the implementation of classes described in Chapter 4. It uses the industry standard language for describing object-orientated systems, UML [85, 86]. Greater detail is also provided about what data types and structures exist within each class, some of the methods each class implements and how these classes are associated and related to each other.

The appendix begins with a discussion of the abstract classes which provide a common behaviour throughout a data model (Section A.2). Section A.3 discusses the classes that model the product itself.

A.2 Core Elements of the Data Model

There are three major classes that form the core of the functionality of this data model. The *Frame*, the *J_Object* and the *Connection* class. The *J_Object* and *Connection* class are what are referred to as abstract classes. This means that they are not actually instantiated within the model but are inherited from by more specific subclasses. The *Frame* class on the other hand is instantiated in the model. Every object that exists in the data model has at least one *Frame* object associated with it and every frame object added to the model is linked to every other frame object in it; either directly or indirectly.

The relationships between the core classes is shown in the UML class diagram in Figure A.1. The methods of the classes have been omitted unless otherwise stated. The *CADlink* and *METlink* attributes of the *J_Object* class are interfaces to generate a CAD representation of the model and extract associated metrology

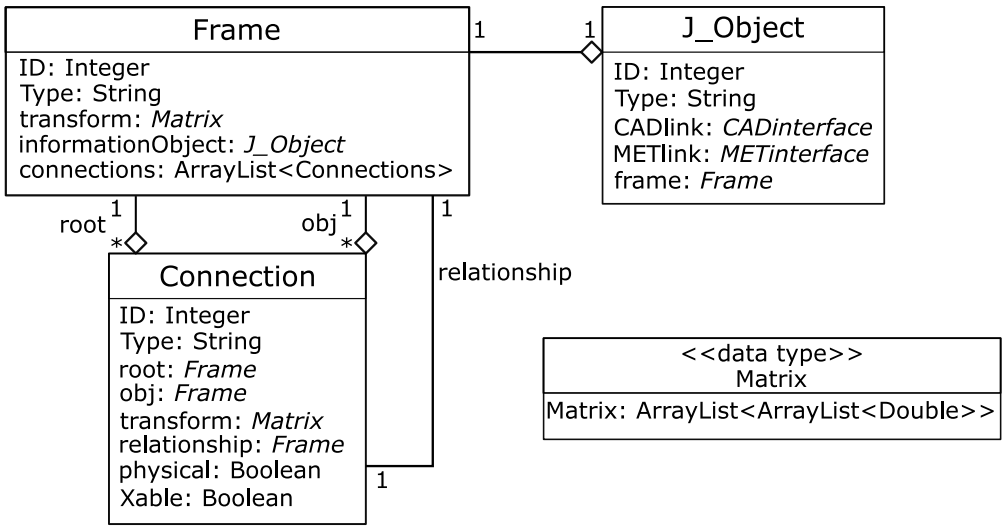


Figure A.1: UML class diagram of the major classes of the data model.

data from a database; respectively.

A.2.1 Data Types

UML defines a number of standard data types such as *Integers*, *Doubles*, *Strings* and *ArrayList <Data Type>*. *Integers* define numerical whole numbers. *Doubles* define numerical numbers with decimal places. *Strings* are arrays of characters, typical used to store text. Lists of data types can be specified using *ArrayList <Data Type>*. Lists can be nested to define multi-dimensional arrays of data.

Complex data structures are typically handled by defining a class. The attributes of the class reference other classes and standard data types. All complex data types eventually decompose into nested sets of standard data types once all references to other classes have been followed and themselves decomposed. The *Matrix* data type is no exception. For the purposes of this thesis, a *Matrix* data type is a $4x4$ array of *Doubles*; unless otherwise stated. They are used to describe a homogenous transform from one reference system to another and have the following form:

$$\mathbf{T} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{A.1}$$

Where $\mathbf{T}$ is the transformation between two reference frames: r_{11} to r_{33} is a rotation matrix and $\mathbf{p_{x,y,z}}$ is a position vector; the bottom row enables matrix multiplication. This is visualised in Figure 4.4.

A.2.2 Frame Class

The *frame* object forms the mathematical backbone of the data model. A *frame* object encapsulates a relative position and orientation, collectively referred to as a pose, and forms a reference node from which other *frame* objects can use it as a datum. Every class in the data model is associated with at least one *frame* object. The structure of a *frame* object is shown in Figure A.1.

The *ID* attribute assigns a unique identification number to the object. *Type* is a text descriptor for the object's type such that algorithms moving through the data model can determine how to utilise the object. The *transform* attribute is a *Matrix* data type which captures the desired homogeneous transform between the *frame* object and its reference *frame* object. The *informationObject* is a reference to the subclass of *J_Object* of which this object describes its spatial location. Lastly, the *connections* attribute is a list of *connection* objects of which the *frame* object has been referenced as either the *root* or the *obj* attribute; the *connection* object is discussed later in this chapter.

That said, it is worth briefly discussing the self-referencing nature of the *frame* object. All *frame* objects must have at least one *connection* subclass of type *parent*. A *frame*'s *parent* connection is the reference to another *frame* object that is the reference system for the *frame*'s *transform* attribute. All frames have a parent except for a single special *frame* object called *Ether*. *Ether* is the data model's default global reference system from which user defined models can be built. This *frame* is generated by default and is not directly accessed by the user. The converse of the *parent* connection is the *child* connection: If a *frame* object A has a *parent* connection to *frame* B, then frame B will have a *child* connection to *frame* A. The *parent* relationship between frames A and B is visualised in Figure A.2; where *frame* A's transform is ${}^{\mathbf{A}}\mathbf{T}_{\mathbf{B}}$ which has a structure of that in Equation A.2. Every *frame* has one, and only one, *parent* connection. This is not true of *child* connections. A *frame* may have none or many *child* connections but for every *parent* connection there is always at least one *child* connection. All frames are either directly or indirect connected to each other by following these *parent-child* connections; creating a network spanning the size of the data model. This network is collectively referred to as the spatial network. An example spatial network is visualised in Figure A.3.

$$ {}^{\mathbf{A}}\mathbf{T}_{\mathbf{B}} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{A.2} $$

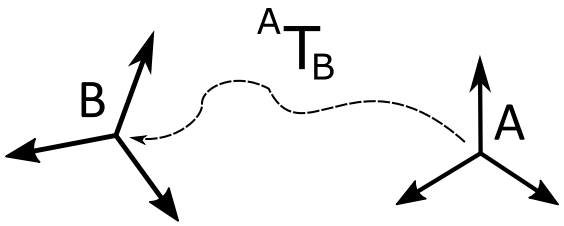


Figure A.2: A visual representation of the transform ${}^{\mathbf{A}}\mathbf{T}_{\mathbf{B}}$ which describes the pose of frame B from frame A.

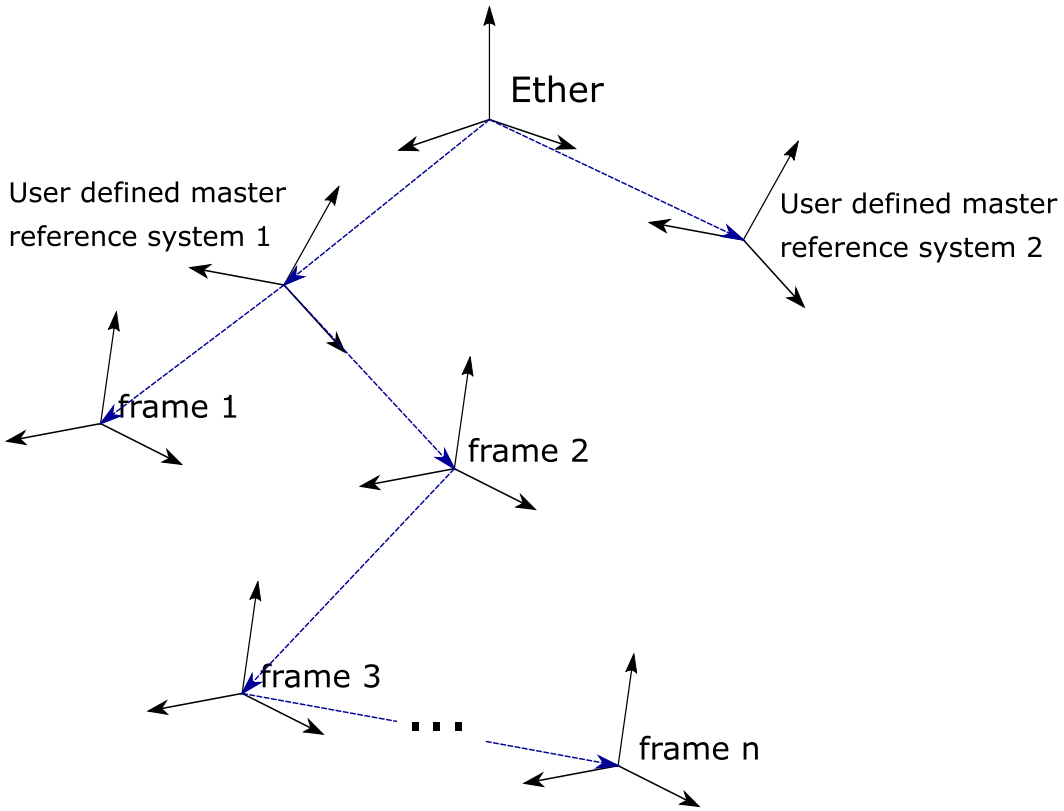


Figure A.3: A visualisation of a spatial domain for an example model. The information domain has been left out for the sake of clarity. However, without querying the information domain, it would be impossible to determine if the figured example is describing a part, product or an entire assembly process.

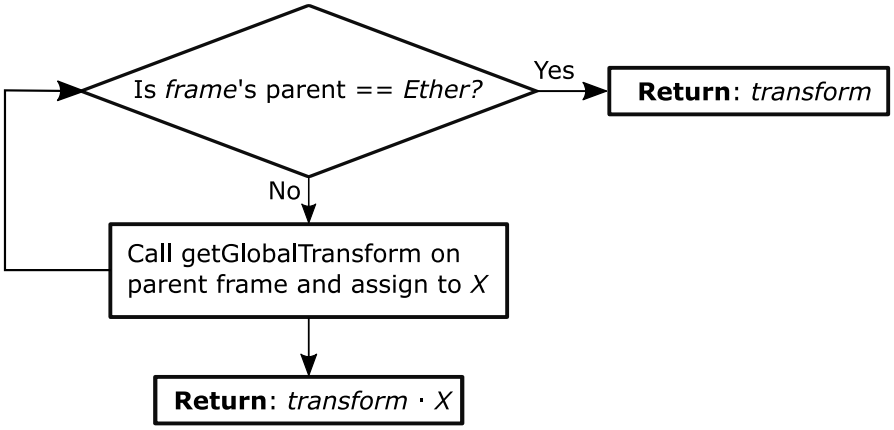


Figure A.4: Flow chart diagram detailing the recursive *getWorldTransform* method used by *frame* objects to calculate their global pose relative to the *Ether* frame.

The network created by the *parent-child* connections between frames allows for a useful property for a *frame* object when combine with its *getGlobalTransform* method. The *getGlobalTransform* method is a recursive algorithm, the flow chart for which is detailed in Figure A.4 and enables any *frame* to return its global pose relative to the *Ether frame*. This property can be utilised to calculate the relative distance between any two frames connected to the spatial network. For example, let *frame A* and *frame B* be two frames connected to a arbitrarily shaped and sized spatial network. Since *frame A* and *frame B* can both return their global pose in the spatial network, an algorithm accessing these frames could get these global transforms, inverse one and multiply them together to calculate the relative pose between the two frames. This operation is detailed in Equations A.5 and A.6 for calculating both the relative pose from *frame A* to *frame B* and *vice versa*.

$$^{\mathbf{Ether}}\mathbf{T_A} = frameA.getGlobalTransform() \tag{A.3}$$

$$^{\mathbf{Ether}}\mathbf{T_B} = frameB.getGlobalTransform() \tag{A.4}$$

$$^{\mathbf{A}}\mathbf{T_B} = {}^{\mathbf{Ether}}\mathbf{T_A^{-1}}\,{}^{\mathbf{Ether}}\mathbf{T_B} \tag{A.5}$$

$$^{\mathbf{B}}\mathbf{T_A} = {}^{\mathbf{Ether}}\mathbf{T_B^{-1}}\,{}^{\mathbf{Ether}}\mathbf{T_A} = {}^{\mathbf{A}}\mathbf{T_B^{-1}} \tag{A.6}$$

A.2.3 J_Object Class

The *J_Object* is the link from the application level to the spatial network. They are often the objects that initiate the methodologies presented in this thesis. That is, the *J_Object* and its subclasses manage the construction, updating, and inputs and outputs of the spatial network. The *J_Object* is an abstract class. An abstract class is never instantiated in the model directly but is inherited from by subclasses of it

which are themselves instanced in the model. Inheritance is a term used in object-orientated programming where a subclass shares the same attributes and methods of the superclass; in addition to the attributes and methods it defines itself [70, 71]. By inheriting from *J_Object* a common set of attributes and behaviours are maintained throughout the information side of the data model.

The *J_Object* class maintains an *ID* and *Type* attribute for unique object identification and class type identification. The *CADlink* is a reference to an programming interface for the CAD application CATIA [72]. The subclasses of *J_Object* implement all the methods required for utilising this interface. However, there are common methods implemented by the *J_Object* itself to ensure all subclasses have access to the methods. These common methods focus on extracting or modifying the existing low-level spatial information from the CAD application. There are also utility methods for controlling the CAD application. The *Metlink* is a reference to a interface for a database; MySQL in this instance [87]. The methods for utilising this interface are implemented by the subclasses of *J_Object*. Lastly, *frame* is a reference to the *frame* object which describes the current location of the *J_Object*.

A.2.4 Connection Class

The *connection* class models the relationship between two frames in the spatial network; creating the arcs between nodes. It references two nodes in the spatial network and the desired transform between them; all three of which are represented by *frame* objects. Just like the *J_Object*, it is an abstract class that is inherited from to maintain common attributes and behaviours throughout the model. A pair of examples, the parent and child connections, have already been discussed but others do exist and will be discussed in context later in the thesis. The class implements a handful of attributes that assist algorithms passing through the spatial network. An example is *Xable*, which is a boolean value which determines if the connection can be crossed by an algorithm. Another important attribute is *physical* which describes if the connection is a physical connection such as a bolted hole between two plates or two holes that exist in the same continuous piece of material.

A.3 Modelling Products

A product here refers to the final output of a manufacturing system. Aircraft, cars, smart phones, hammers and staplers are just some examples of a manufacturing system's product. However, almost everything in the modern environment can

be considered a "product". Mechanical assemblies are the subset of all products that consist of rigid machined or cast parts that are themselves assembled to product a rigid assembly [1]. To limit the scope of the thesis, the data model and methodologies presented are only applicable to mechanical assemblies.

The data model presented here captures: the design intent of the product, the geometrical information required to manufacture the product and the limits of which particular elements of the product can deviate. This allows the model to be used to reproduce the product. However, the major advantage is that the model can be modified during the production process to more accurately represent the current state of a particular instance of a product being manufactured. This enables methodologies to be applied to the model to correct subsequent part designs, assembly data or assembly process commands to correct measured deviations of the key dimensions specified by the product's engineers.

A.3.1 Part Class

A part here refers to a collection of features contained within a continuous material. Take an aircraft rib as an example, it is typically a continuous block of aluminium that is machined to produce: pockets, webs, holes, interface surfaces, profiles and apertures. These details that comprise the physical shape of the part are all subsets of superset "features". It follows that, by defining the position and orientation of a set of features and completing their respective internal data structures we have described all of the data necessary to manufacture the physical shape of the part. This is true since this is exactly the same data that is found in CAD models and machining drawings.

In addition to features, a part can also contain geometry objects. They have a similar structure to features but they describe mathematical objects that are not physically visible on the part but are nonetheless important for a part's manufacture. hole centre points and vectors, points of intersection, ideal planes and interface surfaces are some examples. A UML class diagram is shown Figure A.5 that describes the structure of a part and its relationships to other classes.

The *part* class encloses methods for extracting information from a part's CAD file. It also has methods for populating the *features* and *geometries* arrays with *feature* and *geometry* objects, using this extracted data. Additionally, the *part* class can also, using the existing CAD file, either modify it to reflect the data model's current state or generate a copy of the CAD file and modify that, preserving the nominal file. It can also generate or update *feature* and *geometry* objects from a database containing metrology observations of the part it is intended to represent.

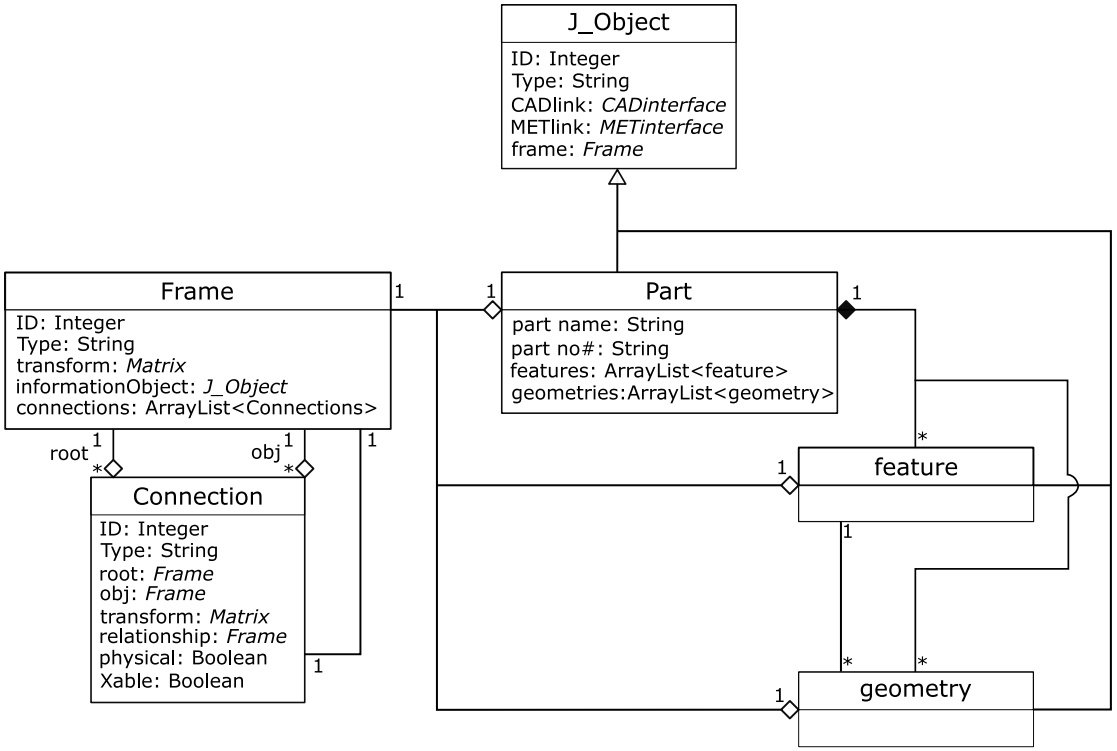


Figure A.5: A UML class diagram detailing a *part* class' relationship to other classes in the data model.

Feature Class

As discussed previously, a feature can be located and oriented from a datum system, using a *frame* object, related to the *part*'s *frame* object. Take a simple hole as an example such as that shown in Figure A.6. In addition to the transform that describes its relative pose, the hole is fully defined by specifying the diameter and depth of the hole. A similar approach can used to model any type of feature. A general pad is modelled in Figure A.7 and added to the same datum as the previous example. This provides an additional example and shows how a part is modelled as a set of features. Where a specific feature can be defined by implementing a subclass from the *feature* superclass and defining in that class a standard data structure; this is detailed in Figure A.8. A *feature* class is an abstract class and usually should not be instantiated in the actual model, only the specific subclasses of it should be generated within the model. However, if a feature in the CAD file is not recognised by the *part* object's generation methods, it will create a *feature* object such that the feature is at least referenced and assigned a unique serial number.

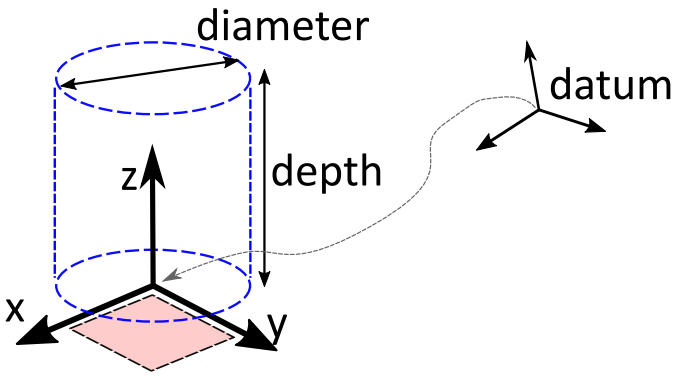


Figure A.6: A general definition of a simple hole.

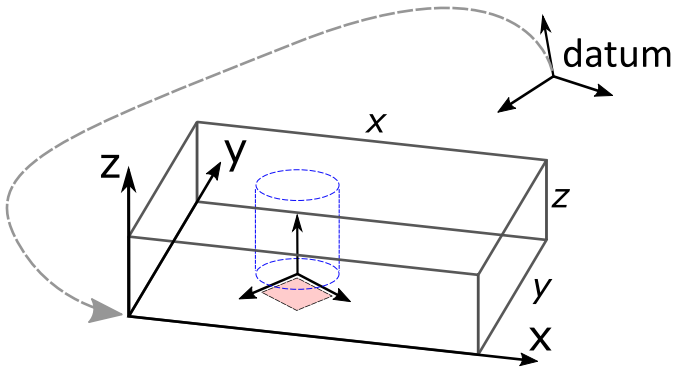


Figure A.7: A general definition of a simple pad. The pad has been defined in the same system as a simple hole.

Geometry Class

A *geometry* class is similar to a *feature* class but, instead of describing a physical detail of a part, it describes a mathematical detail of the part. They are useful for describing details of the part or it's features that are not machined but still important for engineering attention. Hole centres and vectors, intersecting surfaces, and ideal planes, spheres and circles are some examples of geometry that, although are not manufactured, are important for the engineering definition of the part.

The structure of a *geometry* class is shown in Figure A.9. For example; if the geometry object is a point, the structure will contain an x, y, z vector. However, if the object was describing an actual vector in space or a sphere, it would contain a x, y, z, i, j, k or $x, y, z, radius$, vector; respectively. This format allows any geometry to be codified into the model by implementing a subclass of geometry. The transform data type in a *geometry* object's *frame* object is always the identity matrix. This is a decision made by the Author to assume all geometry is defined relative to it's parent part's datum and therefore its *frame* object is always globally identical to the part's *frame* object. This reduces the complexity of the spatial network.

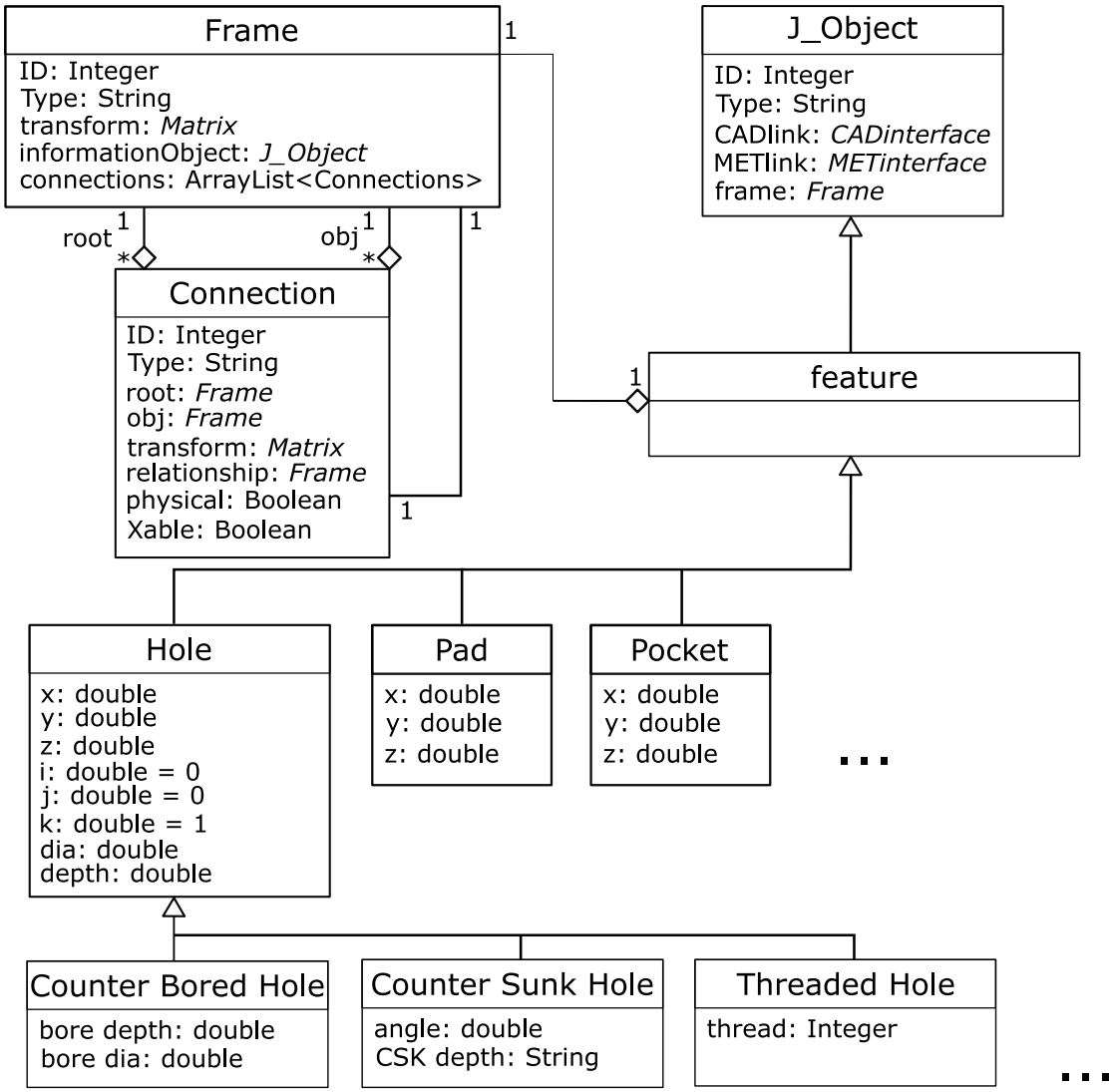


Figure A.8: A UML class diagram detailing the behaviour of the feature class and format of implementing subclasses detailing specific feature information.

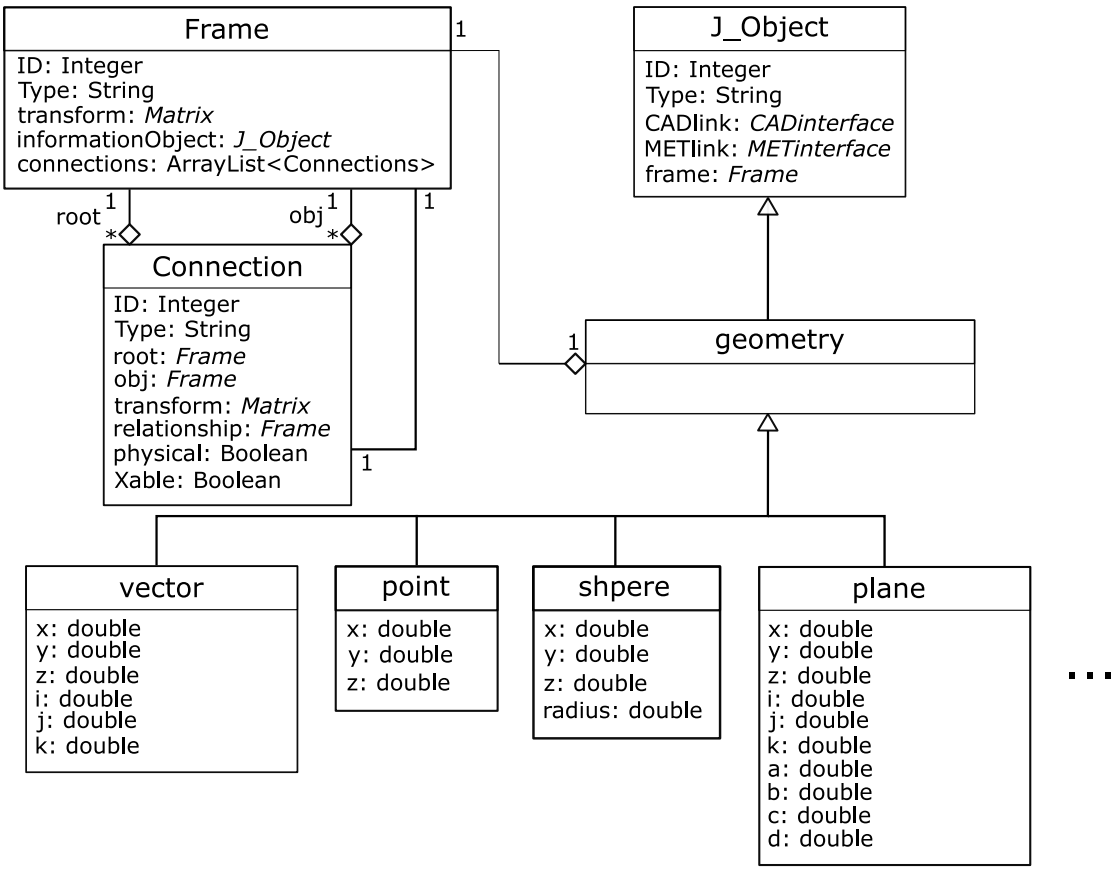


Figure A.9: A UML class diagram detailing the behaviour of the geometry class and the format of implementing subclasses detailing specific geometry information.

Each subclass implements a number of methods that assist with mathematical or geometric operations between two *geometry* objects. These will be discussed, in context, later in the thesis but it is worth discussing the constructor methods. A constructor is a method defined in a class that returns an instance of the class. A good example is the *plane* subclass of *geometry*. When generating a plane object, one can define a plane by a x, y, z, i, j, k vector or its plane equation a, b, c, d. The *plane* class defines a constructor for each definition such that the appropriate method can be used depending on what data has been found during the data models generation algorithm. Once the *plane* object has been instantiated with the correct method, the other values are calculated and stored as attributes such that either format can be utilised by the object itself.

A.3.2 Assembly Class

The *assembly* class, as the name suggests, models an assembly. An *assembly* object models the aggregation of several *part* and/or other *assembly* objects into one entity. An *assembly* object is typically the highest level of the product data model since the final operation of a product's manufacture is ultimately an assembly. It contains an array of references to *part* objects or other *assembly* objects and models the combination of stand-alone parts and sub-assemblies for a particular assembly operation. Moreover, it models the engineering relationships between the features and geometry that define the success criteria for the assembly operation. The *assembly* class also provides a datum frame from which datums of the components are position and orientate themselves. This *frame* is itself positioned and orientated from a higher assembly datum frame, if it is not itself the final assembly. In this case the *frame* is posed from a user defined reference system or *Ether*.

To fully capture the definition, it also models the engineering relationships between the components that form the assembly. The relationships are modelled by subclasses of the *connection* class which are primarily stored by the *assembly* object's *frame* object. However, for completeness of the *assembly* class has an array of references to the *connection* subclasses that represent the key characteristics and the joints between the parts and sub-assemblies referenced within that *assembly* object. The structure, and its relationships with other classes, is detailed in Figure A.10. The root, or top level, of the information domain of the data model is the *assembly* object that represents the final assembly operation of the product. That is, from this root *assembly* object all other *part* and *assembly* objects are directly or indirectly referenced by navigating through the *component* arrays of the *assembly* objects. The search scope in the information can be extended to include

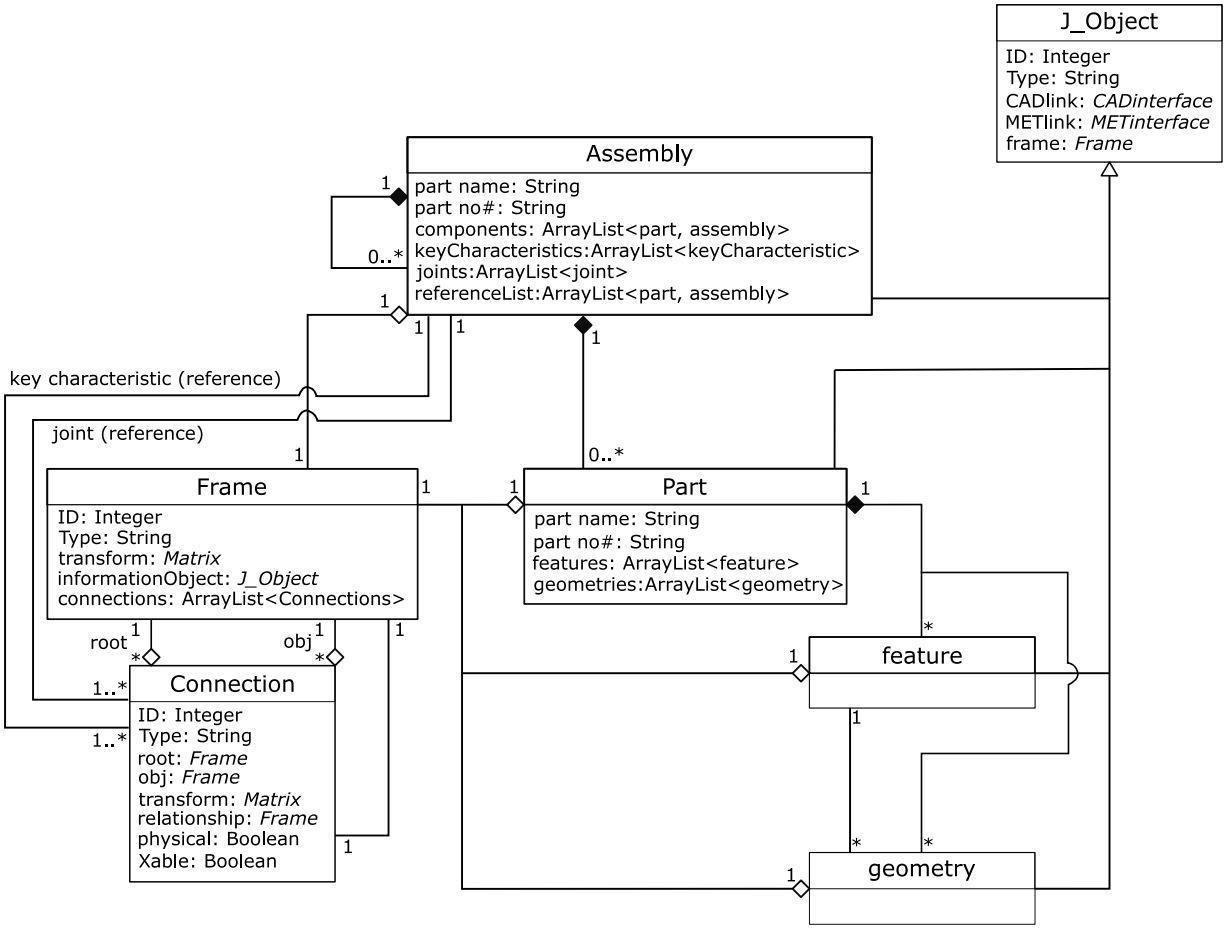


Figure A.10: A UML class diagram detailing the behaviour of the *assembly* class and its relationship with the other classes.

feature and *geometry* objects by searching the *features* and *geometries* reference arrays once a *part* object is found by a search algorithm.

The *assembly* class encloses methods for extracting information from an assembly's CAD file. It also implements methods for modifying, or making a copy and modifying, the reference CAD file. The *product* class also has methods for creating *part* and *assembly* objects for the parts and sub-assemblies referred in the CAD file. There are also a number of search algorithms that enable an number of functionalities. One of functions is a *feature* and *geometry* search algorithm which allows the assembly object to search through all the sub-assemblies and part below it and utilise the feature or geometry as if it where the part that defines it. Another, function is a path finding algorithm which allows an assembly to search through the data model and return the chain of frames between two frame nodes in the spatial network. One additional attribute worth discussion is the *referenceList* array. That is a list of references to all the *part* and *assembly* objects below that instance of *assembly* object. Every *assembly* object has this list but it is only the list held by the root *assembly* object that is used. This allows an

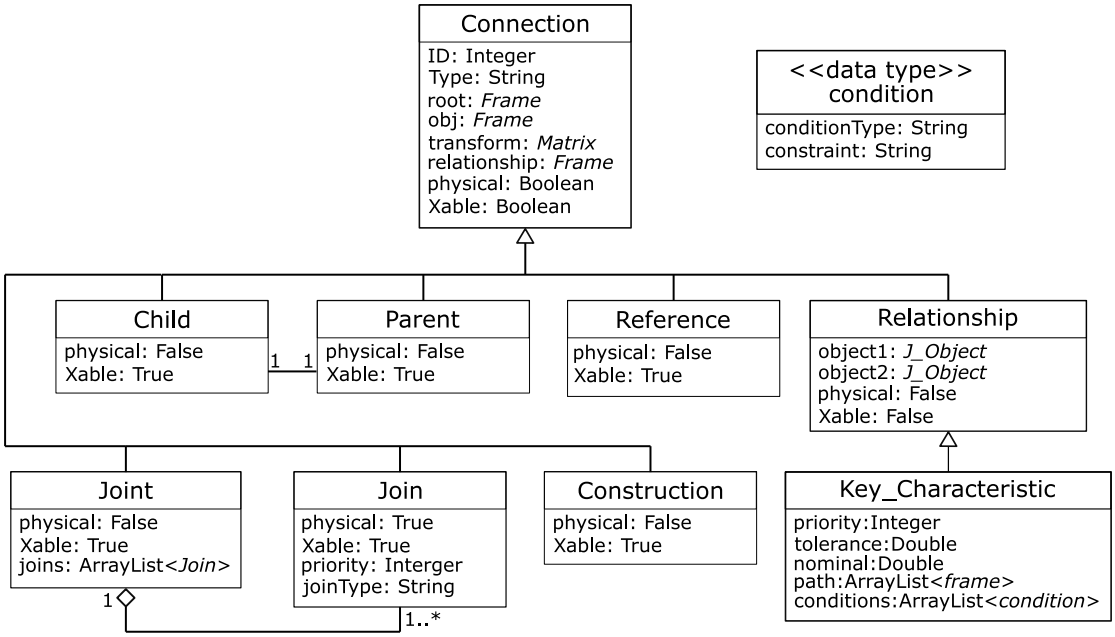


Figure A.11: UML class diagram detailing the subclasses of *connection* and their relationships with each other.

application and its methodologies to access any *part* or *assembly* object without have to recursively search through the information domain tree.

A.3.3 Modelling Assembly Connections

As discussed earlier, the two main relationships that define an assembly are the key characteristic and the join. A key characteristic is a dimension or condition between two features and/or ideal geometry that defines the success criteria for an assembly operation. Ideal geometry here refers to geometry that is probed from the part. Key characteristics are specified by the product's engineering and design team and are often designed to be measurable on the physical product. For example, the mathematical vectors of two holes must be probed from their internal surfaces to confirm if they are aligned. Another example is checking the distance between a hole centre and the edge of a part; where an ideal plane is probed from the part edge surface and the centre point is probed from the hole. A join, here, refers to a physical connection between two features and several of joins between two parts are grouped into a joint. A hole bolted or riveted to another hole for example is a single join connection. Therefore, two parts connected by a lap joint that is fixed with four bolts would be modelled by four *join* connections and a single *joint* connection. In addition to these assembly specific connections, there are also utility connections that assist with the functionality of the model. A UML class diagram detailing the subclasses of *connection* is shown in Figure A.11.

Parent and Child Connections

As discussed previously, the *parent* and *child* connections make-up the primary definitions of the position and orientation of the *frame* objects representing the datums of assemblies, parts, features and geometries. Every *frame* must have at least one *parent* connection but can have none or many *child* connections. A *frame*'s parent is the reference system from which a *frame*'s *transform*, a homogenous matrix, is defined. It is the *parent* and *child* pose information that is needed to generate CAD data from the data model. Moreover, since the *parent-child* sub-network links all the datums of all the parts and assemblies, it essential for booking-in metrology measurements into a common reference system and model-based robotic manipulation of components using product defined coordinate systems and their key characteristics. It is these functionalities that make the *parent-child* connection the master, or primary, definition of a *frame*'s pose. Multiple definitions of the same *frame* do exist in this data model and will be discussed later in this section.

Relationship Connection

The *relationship* class is an abstract class that inherits from *connection*. As an abstract class it is not meant to be instantiated in the model itself but to be inherited from. The *relationship* class is designed to augment the behaviour of *connection* to include two *J_Objects*, or its subclasses, and more accurately model a relationship between features and geometries in an assembly. The purpose here being to define a mathematical constraint between the two elements without over constraining the data model. That is, a connection between two frames fully defines all 6 degrees of freedom which is not always helpful when specifying engineering relationships. For example, if an engineering assembly drawing specifies that a pin slots into a hole, this constraint can be satisfied with the pin in infinitely many orientations about its major axis. Another example is specifying that two plates make contact, which again leads to infinitely many solutions. Therefore, the *relationship* class changes the focus from two frames linked together by a homogeneous transform to two features or geometries linked together by some defined constraint specified by the subclass of *relationship*. That said, the decision was made to leave the *frame* to *frame* connection attributes in the *relationship* class with the attributes *Xable* and *physical* set to *False*. This ensures consistency in the spatial network such that a search algorithm moving through the frames can read that a relationship, such as a key characteristic for example, exists between the two frames but it cannot cross the connection without accessing the *J_Object*s and solving, or taking into account, the defined constraint between them.

Key_Characteristic Connection

Naturally, the *key characteristic* class models a key characteristic in an assembly. Thorton's definition of a key characteristic is useful and the most widely cited in literature [17]:
"Key characteristics are the product, sub-assembly, part and process features whose variation from nominal significantly impacts the final cost, performance, or safety of a product. Special control should be applied to those key characteristics if the cost of variation justifies the cost of control".
This thesis focuses on key characteristics that are applied to assemblies and sub-assemblies. An assembly key characteristic, hereafter referred to as just a key characteristic, typically takes the form of a linear measurement between features and/or ideal geometry on the two components involved in the assembly. The trick to a good key characteristic is that is easily confirmed on the physical product. This is why they typically take the form of linear measurements. These measurements are usually gaps, steps, alignments and intersects. An example is shown in Figure A.12. It shows two ideal planes on the from and rear spares constrained to ensure alignment and size of the cord-wise box section. Moreover, each assembly usually has several key characteristics defined for each assembly operation. Sometimes these are defined to perfectly constrain the pose of one part to the other. However, a set of key characteristics can be defined which over-constrain the assembly if each relationship is critical. In these cases a priority ranking is assigned to the key characteristics.

The *key characteristic* class inherits from the *relationship* class and as such is designed to model the specific mathematical conditions between two features and/or geometry. However, a connection is still created between the frames to whom the features or geometry are associated with. This ensures a complete spatial model with the caveat that key characteristic connection must be considered at the *relationship* level. The class defines the priority of the key characteristic, where lower integers are prioritised before higher integers. Key characteristics sharing the same value of priority must be solved at the same time. The class also defines three attributes: *nominal*, *tolerance* and *measurement*. The *nominal* attribute records the desired measurement value of the key characteristic as specified by the designer at the product's nominal, or ideal, condition. The *tolerance* attribute is the value representing the allowable deviation of the *measurement* from this *nominal* condition. This deviation is a symmetric tolerance such that if a value of y is specified on nominal condition x then the satisfactory condition of the key characteristic is $x-y < measurement < x+y$; where *measurement* is the current, either physical or simulated, condition of the key characteristic. nonsym-

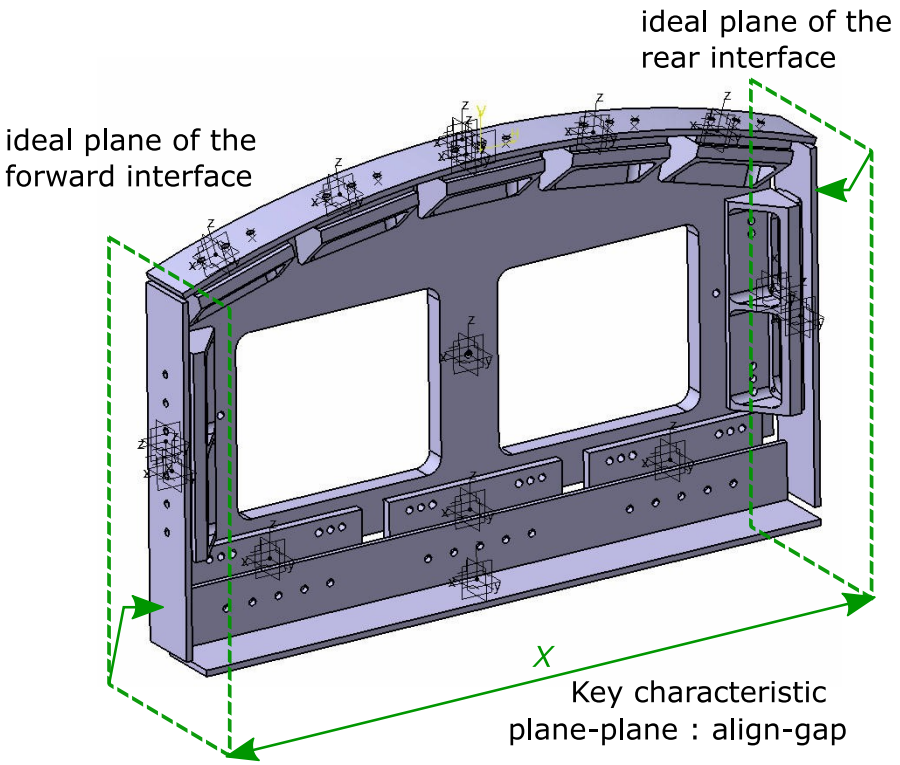


Figure A.12: Typical example of an assembly key characteristic. The image figures a mechanical assembly where the forward and rear interface surfaces must have a specific gap of X which implies that the two planes must also be aligned. Other key characteristics would also exist for this assembly but have been omitted for clarity.

metric tolerances can always be converted into a symmetric tolerances. Finally, class defines a list of *condition* data structures. A *condition* describes the conditions of the key characteristic which assist the evaluation of the key characteristic. For example, consider a key characteristic that stipulates that two ideal planes measured from a surface on two parts are to be aligned. A plane can be aligned, that is no angle between the normal vectors of the two planes, in two conditions: either the normal vectors are in the same direction or they are in opposite directions. To resolve this issue, the alignment condition is defined as either "same" or "opposite". Additional conditions can be combined such as the "offset" condition which can be added to achieve a specific gap between the planes, or a "concentric" condition could be applied to ensure that the normal vectors occupy the same line. This example is visualised in Figure A.13 but other conditions do exist and are typically specific to the object types involved in the key characteristic. New conditions will be discussed in context.

The next major elements of the *key characteristic* class is the methods it implements and its position as an abstract class. The main method that the class implements is the *evaluate* method which is assigns the value of *measurement*. The actual algorithm employed to calculate *measurement* is implemented by the subclasses of *key_characteristic*; where each subclass represents a specific type of key characteristic. The UML class diagram in Figure A.14 shows the major key characteristics used in this thesis. However, any assembly key characteristic can be similarly modelled by extending this format. Taking the *point-plane* class as an example, the evaluation method is implemented by the algorithm described in Figure A.15. Since every subclass of *key_characteristic* implements its specific method of *evaluate*, a user or algorithm accessing the set of key characteristics of an assembly can always utilise them even if the key characteristic is unrecognised by the user or algorithm. The other major method is *set* which is detailed in Figure A.16 and returns a boolean value to indicate if the key characteristic is satisfied or not.

Join and Joint Connections

The *join* connection models a mechanical connection such as a two hole's bolted or riveted together, two pieces joined by a tack weld or any other form of rigid assembly operation. The *join* connection exists between the *frame* objects of the two *feature* objects involved in the mechanical connection. An example is provided in Figure A.17, it models two holes joined by a bolt or rivet. It does this by positioning its *frame* object in the identical pose to the secondary object in the connection but as defined as a relative pose from the first object in the connection.

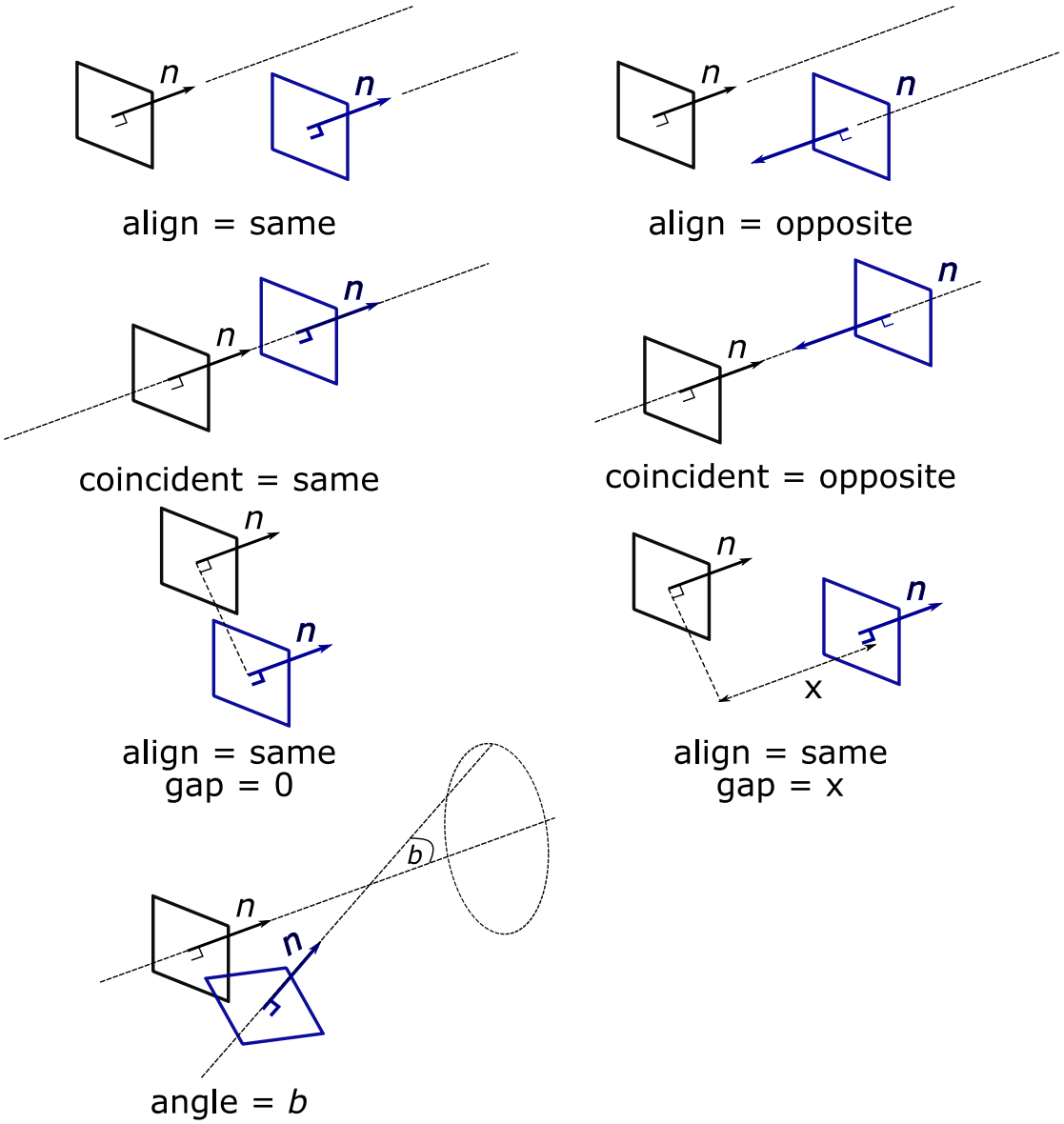


Figure A.13: Visualisations of the conditions that can be applied to a plane-plane key characteristic. Some of these conditions require other conditions to be applied. The gap condition is one such example where a gap distance can only exist if the planes are parallel. The condition always applies to the primary object. For example, if two planes are have a gap of $-X$ then the secondary plane will be a distance X in the opposite direction to the primary plane's normal vector, n. Some conditions cannot be combined; such as the gap and the angle condition.

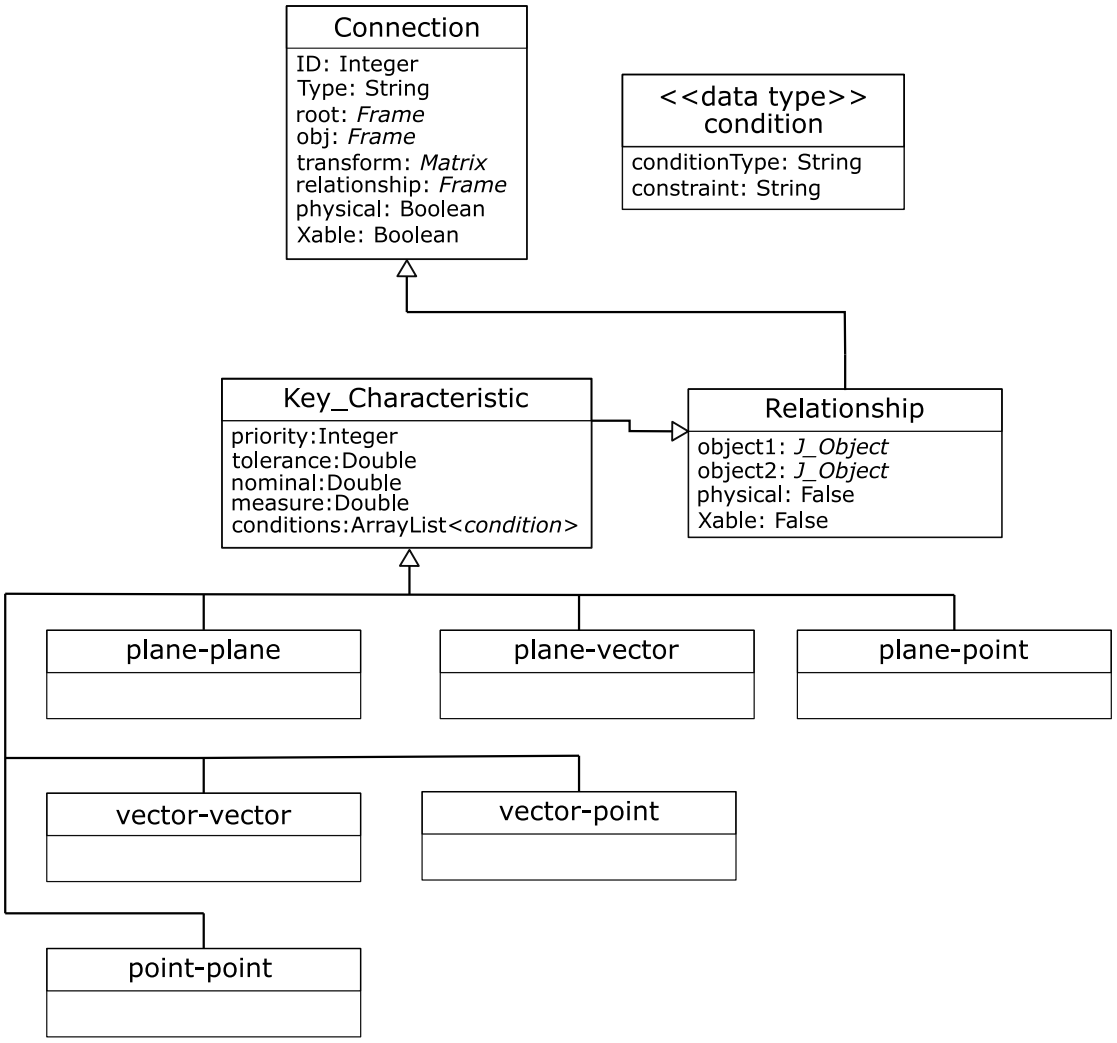


Figure A.14: A UML class diagram detailing the major key characteristic classes implemented during this thesis. All the key characteristics involve geometry objects and no features. This is due to all the work in this thesis involving metrology data which often produce points and geometry constructs such as vector/lines and planes. Therefore, if two features are to have a particular relationship to each other, the key characteristic is often applied to the supportive geometry that underpins the feature. An example is two holes which must be concentric. In this case the holes would be probed to measure the central axes of each hole (modelled as a *vector* object) and the angle and gap, if one exists, between them calculated.

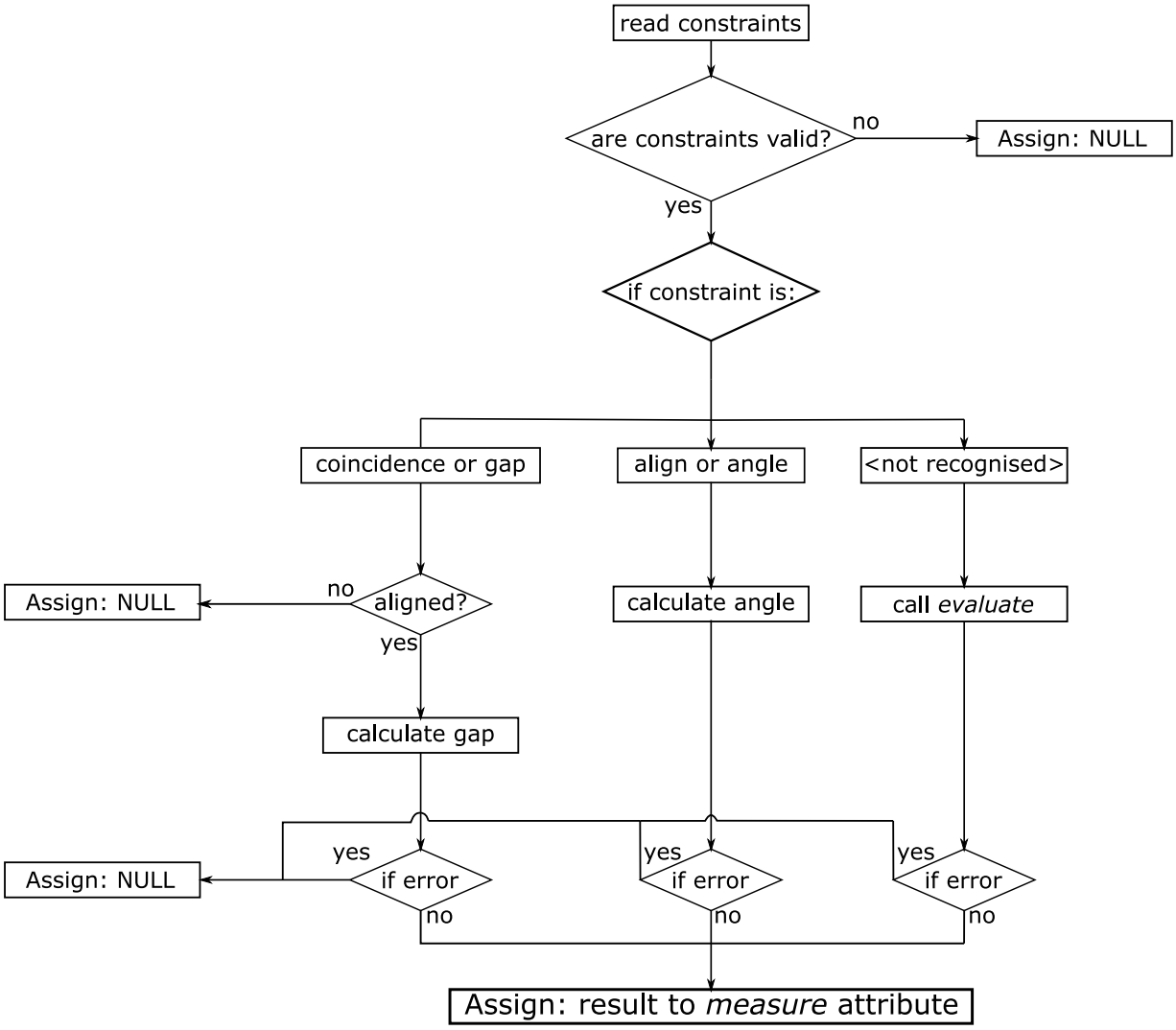


Figure A.15: An overview of the *plane-plane* key characteristic object's *evaluate* method. Other subclasses of the *key_characteristic* superclass would implement their own version of this method, where the result of the algorithm is always assigned the *measure* attribute.

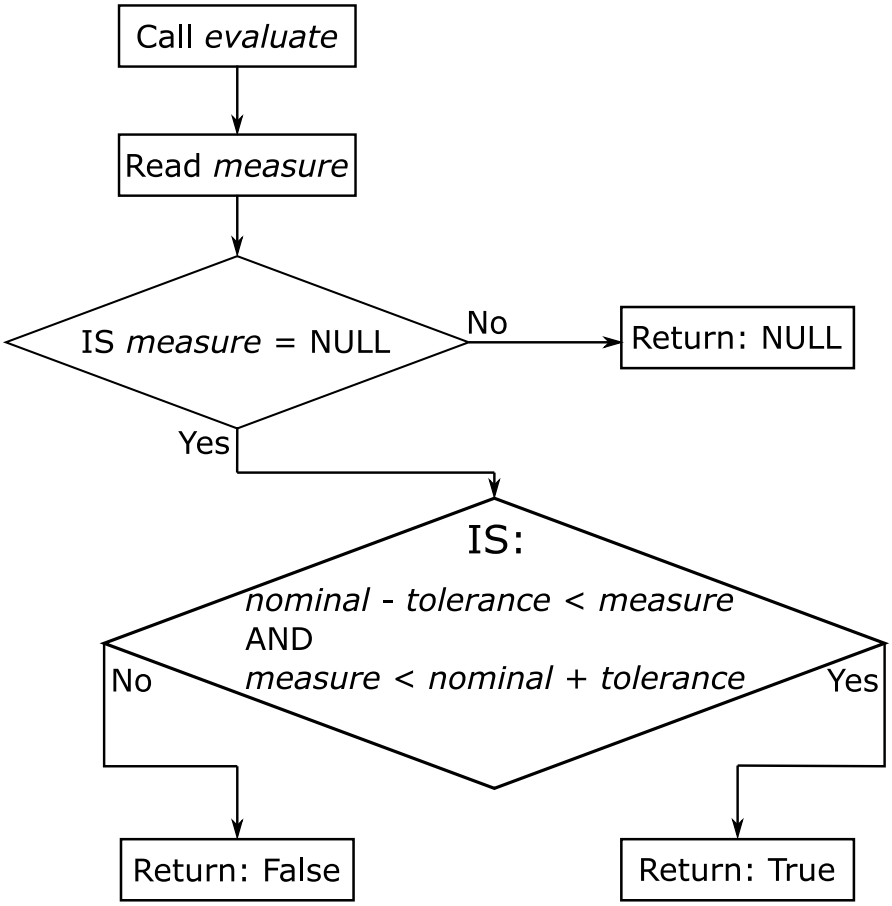


Figure A.16: An overview of the *set* method used by all subclasses of *key_characteristic* object to determine if a key characteristic in the data model is currently within tolerance or not.

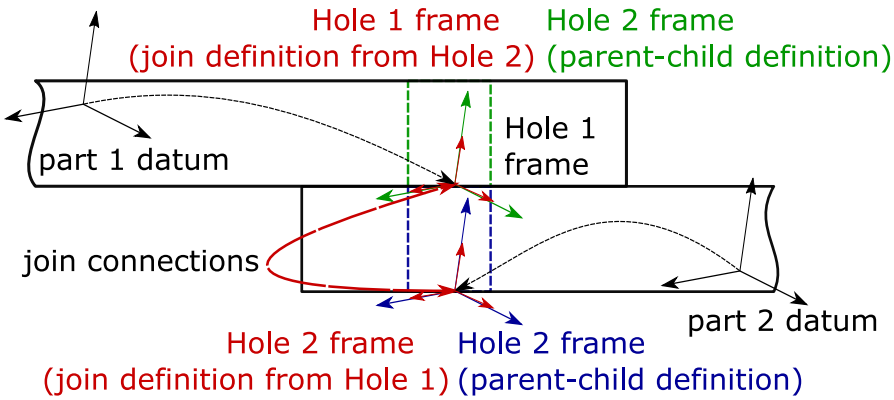


Figure A.17: A visualisation of the join connection. Two holes on two separate parts are bolted together. The mechanical connection provided by the bolted joint is modelled via a join connection.

That is, if two holes are to be bolted together then the *join* connection that goes from the first hole to the second would contain a *frame* object that defines the second holes *frame* relative to the first hole's *frame*. This leads to the *join* connection's reciprocal behaviour: for every *join* that models feature 1 connected to feature 2, there exists a reciprocal *join* that connects feature 2 to feature 1. A *joint* connection models the total mechanical connection between two components in an assembly such as a bolted hole pattern or an entire seam of tack welds. It exists between the *frame* objects that represent the *part* object and/or *assembly* object involved an higher *assembly* and this object itself is stored in that higher *assembly* object. The *joint* connection is largely an organisational tool. It groups *join* connections into one object if they contribute to connecting the same two components together.

The main concept here is, if a *join* connection is maintained at the nominal condition then the physical mechanical connection is also maintained as per the designer's specification. That is, if the data model is modified in some way but a *join* connection still connects the two features together, as defined by the *parent-child* network, then the two holes can be successfully bolted together. This example is visualised in Figure A.18, where two plates are bolted together. One plate has been rotated about the axis of the hole and the hole's *frame* object has been fixed globally; maintaining the join connection and by extension the bolting operation is possible. Another example in Figure A.19 shows a join connection which has been broken and therefore the bolting operation cannot be completed.

Joins should be modelled as a subclass of relationship since most mechanical joints do not provide constraint of all 6 degrees of freedom. For example, a single nut and bolt connecting two plates still, theoretically, allows the plates to rotate about the axis of the bolt. However, this thesis is focused on the analysis and satisfaction of key characteristics and assumes that if the original transform between

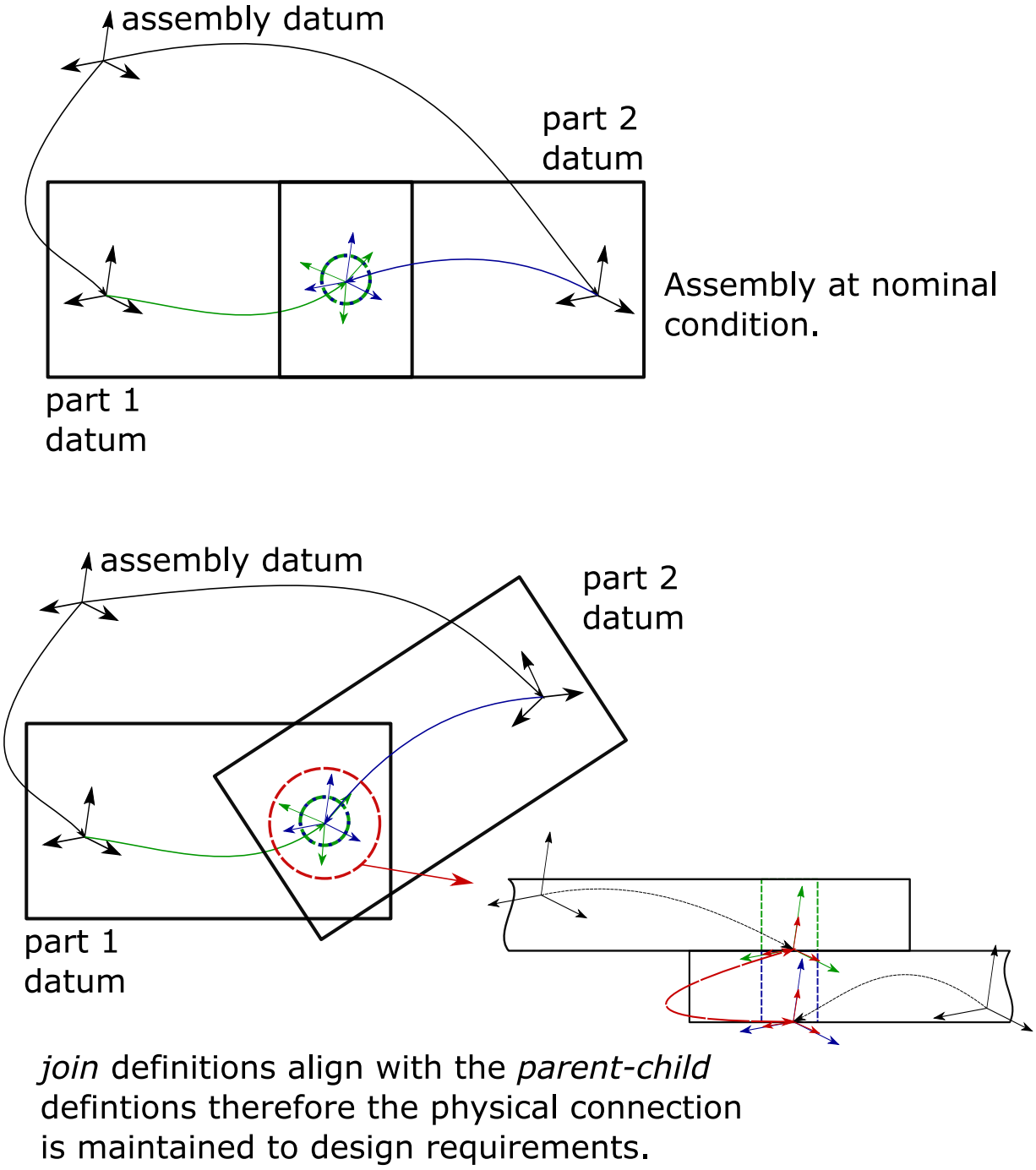


Figure A.18: A visualisation of the *join* connection under a global transform of one of the parts involved in the assembly. The *join* connection allows for the user or application to test if the mechanical join is still valid and therefore is physically able to be completed. The example shows that despite the global transform the hole positions as defined by the *join* and the *parent-child* connections match. Therefore, the definitions of the holes maintain the designers original specification for that hole-to-hole joint.

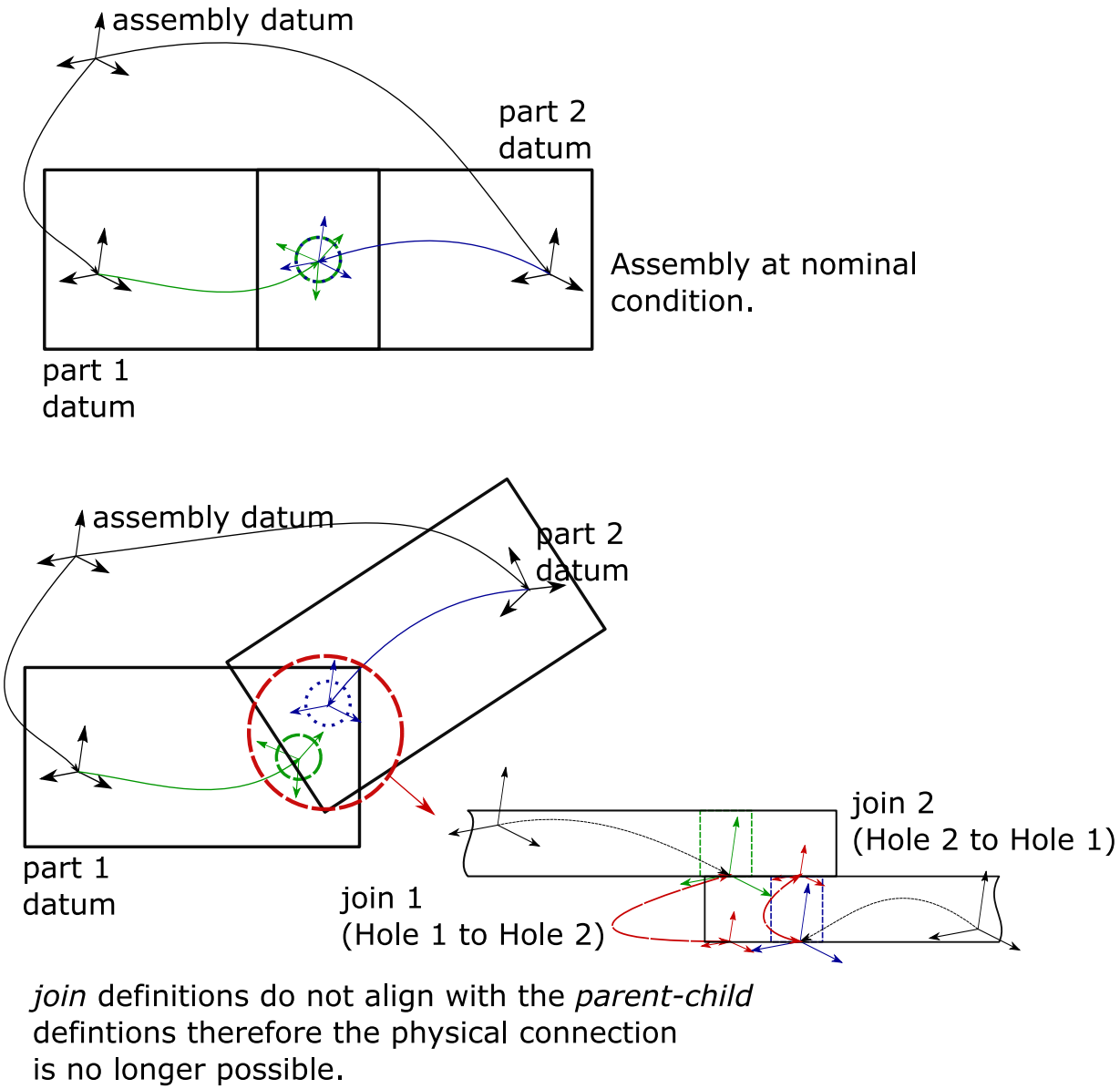


Figure A.19: In this counter example, the global rotation has misaligned the *join* and *parent-child* definitions of Hole 1 and Hole 2. Therefore, a user or application testing the *join* connection, say from Hole 1 to Hole 2, would find a error transform between Hole 2's join definition and its parent-child definition. Since tolerances are not considered for *join* objects in this thesis, any error can be equated to a mechanical connection that is not longer possible in the physical build; unless it is subsequently corrected for as will be discussed later in the thesis.

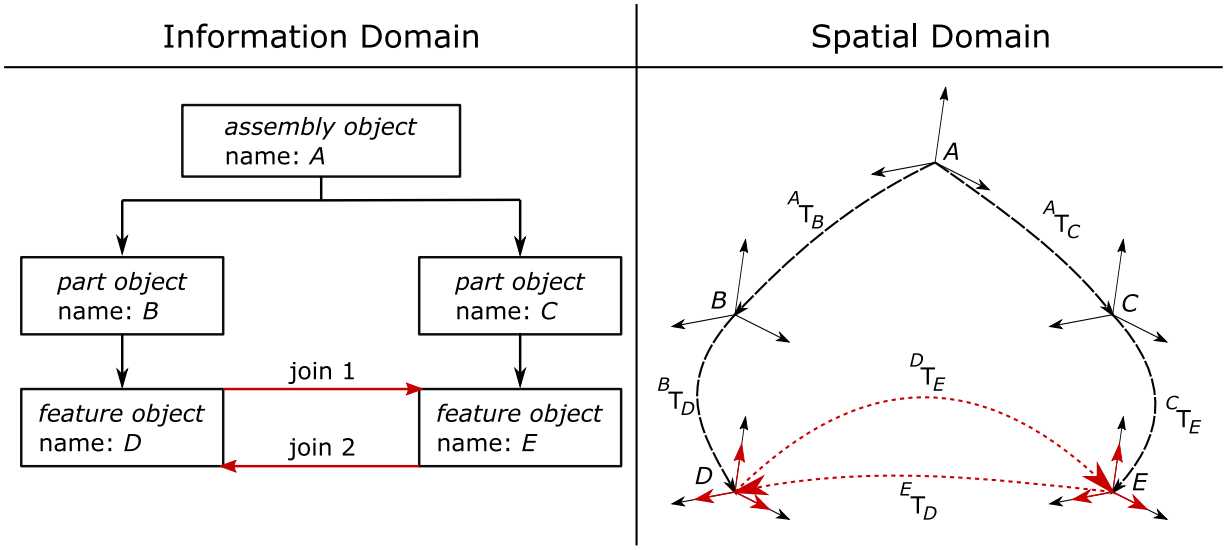


Figure A.20: The information and spatial domain for a simple two part assembly. The *join* connection between the two features creates two pairs of duplicate global definitions for the features involved in the *join* connections.

the two *frame* objects that represent features involved in a join is preserved, then the conditions required to achieve a mechanical joint between the features is also preserved. That is, if the *join* connection is maintained between two frames then the actual mechanical assembly of the features is achieved since conditions such as tolerances, manufacturing variability and full constraint between the parts has been considered by the product designer. Therefore, the CAD model, from which the data model was generated, implicitly achieved these conditions at a nominal condition. Therefore, to limit the scope of this thesis and to reduce the complexity of the data model, joins will not be modelled as a subclass of relationship. The caveat is that future requiring the analysis and perhaps algorithmic definition of mechanical joins and joints could, and should, implement this joins and a subclass of *relationship*.

Reference Connection

The spatial network generated from the connections described so far oftens leads to multiple *frame* definitions for *feature* or *geometry* objects involved in joins and key characteristics. An example of this has already been discussed in the previous section. Where the definition of a *join* between two features results in two separate global definitions for both features involved since each connection carries a *frame* object. This is visualised in Figure A.20; where feature *D*'s global pose can be calculated from the *parent-child* connections:

$$^{\mathbf{A}}\mathbf{T}_{\mathbf{D}} = {}^{\mathbf{A}}\mathbf{T}_{\mathbf{B}}\,{}^{\mathbf{B}}\mathbf{T}_{\mathbf{D}} \tag{A.7}$$

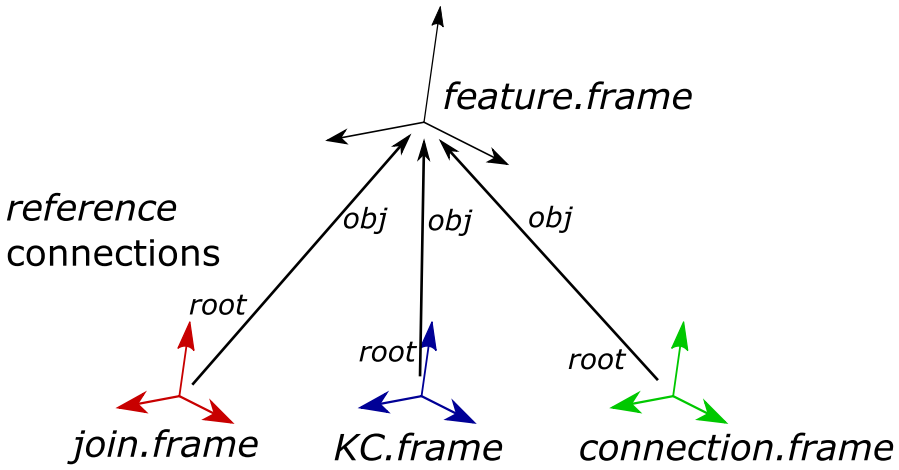


Figure A.21: The *reference* connection always links the duplicate definition to the primary definition. duplicate definitions stem from an object's involvement in engineering connections such as joins and key characteristics (referred to as KC in the image). All the frames in this figure define the same object in space and therefore are, when the data model is in a nominal condition, globally identical. That is, when these frames are measured from a global reference frame they are the same pose despite there own local definitions and frames of reference being different from each other.

Alternately, feature D's global pose can be found using the *join* from feature E to feature D:

$$^{\mathbf{A}}\mathbf{T}_{\mathbf{D}} = {}^{\mathbf{A}}\mathbf{T}_{\mathbf{C}}\,{}^{\mathbf{C}}\mathbf{T}_{\mathbf{E}}\,{}^{\mathbf{E}}\mathbf{T}_{\mathbf{D}} \tag{A.8}$$

To avoid confusion in the model, the *reference* connection is defined.

The *reference* connection provides a link from duplicate definitions to the primary definition. The primary definition is the tree-like subnetwork generated by the *parent-child* connections. The *reference* connection always goes from the duplicate to the primary reference, see Figure A.21. That is, *root* is linked to the *frame* object generated in a *join* connection, for example, and *obj* links to the *frame* object involved in the *parent-child* subnetwork. The *frame* object for the reference connection itself is identity. The *reference* connection allows an application to check if the current object it is accessing is a duplicate definition. If it is using a duplicate and this is not expected, the *reference* connection provides an easy link to the primary definition of the object. This ensures that applications always use the same primary definitions for extracting information out of the data model.

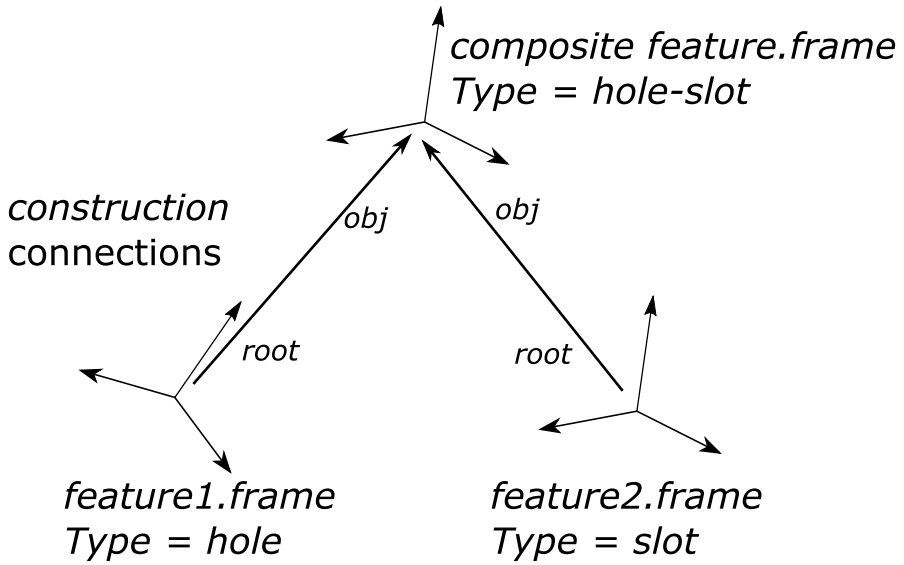


Figure A.22: The *construction* connection links the *frame* objects of features involved in a composite feature to that composite feature's *frame* object. This enables an algorithm to test a feature to determine if it is part of a composite feature. The algorithm can then access the composite feature utilising the *construction* connection.

Construction Connection

The *construction* connection has a similar behaviour to the *reference* connection. It is used to link the *frame* objects of features to the *frame* object of the composite feature they are involved in, see Figure A.22. A composite feature is an imaginary feature that is added to the data model to enable the mathematical modelling of the positional properties of a mechanical joint. The UML class diagram for a composite feature is given in Figure A.23 and shows how the *Type* attribute changes, so does the methods used to calculate the *frame* object associated with it. Composite features behave like any other feature and are linked together by *join* connections, as detailed in Figure A.24. They are used in the data model, and this thesis, for simulating the effect of manufacturing variation across realistic assembly joints and will be discussed in more detail in the next chapter. However, Figure A.25 illustrates the model behaviour achieved using this approach. The *construction*, to get back to it, allows an algorithm to determine if a feature is involved in a composite feature and if necessary access the composite feature and it *frame* using the references contained within it.

A.3.4 Data Model Summary

This concludes the required objects to build the data model utilised in this thesis. With these tools it is possible to model any assembly, capturing both the engi-

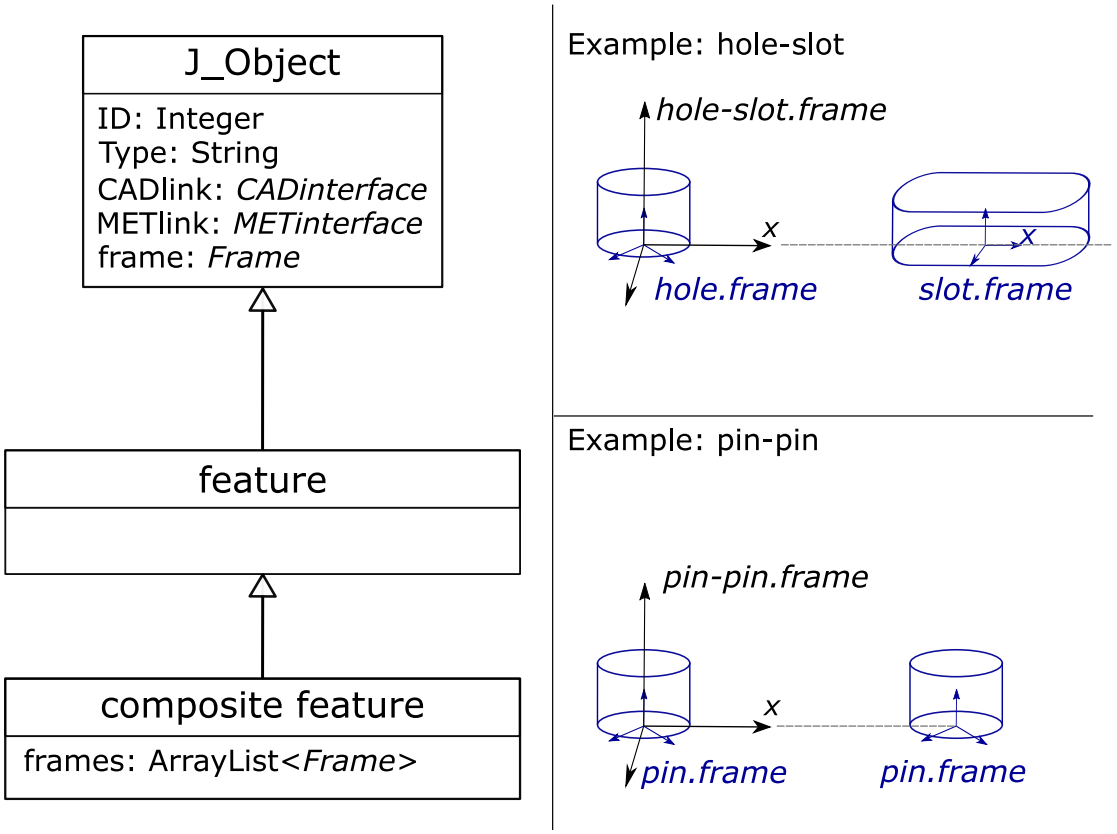


Figure A.23: UML class diagram for a composite feature object and some diagrams depicting how a composite feature's frame is constructed from its constituent features. In the first example, the pin-slot feature takes its origin and z axis from the primary hole feature but the x axis is parallel to the x axis of the slot feature. In the second example, the origin and z axis are taken from the primary, or master, pin but the x axis is parallel to the vector that intersects the origins of both features. The methods for computing these poses is implemented in the composite feature object and the method chosen depends on the *Type* attribute assigned to the composite feature.

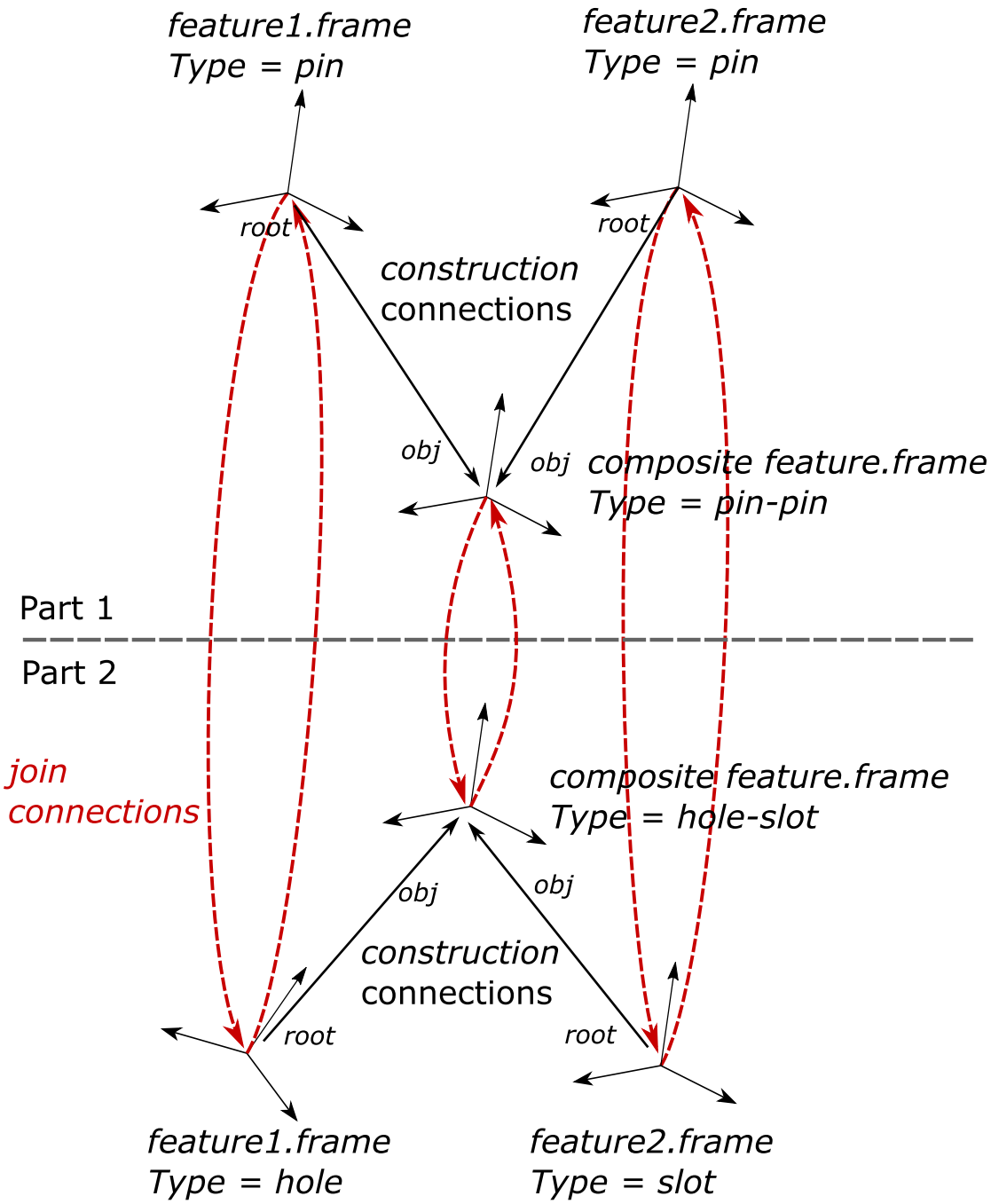


Figure A.24: composite features, and their *frame* objects, are us utilised in an identical fashion to typical features. The use of composite features does not replace the requirement of there being *join* connections between the features involved in the composite feature.

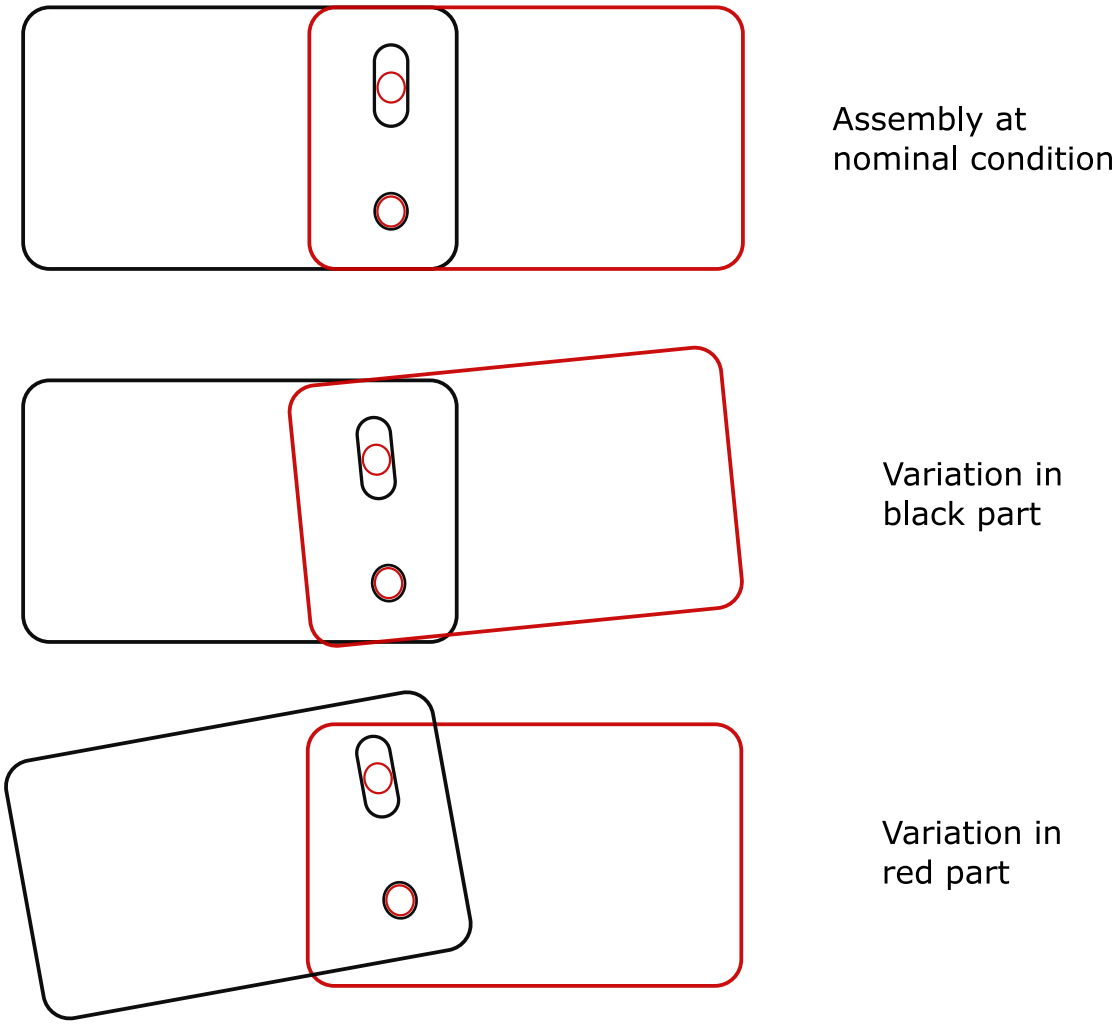


Figure A.25: A diagram visualising realistic joint variation behaviour enabled by the composite feature frames which are themselves enabled by the *construction* connection.

neering connections at the assembly level and the machining requirements at the part level. Moreover, due to the extensible nature of the objects in this model it is possible to implement additional features, geometry and engineering connections to suit other applications which are not covered in this thesis.

Appendix B

Quantitative Analysis and Simulation of Adaptive Part-to-Part Assembly

B.1 Introduction

This section will quantify the advantages of the data model driven methodology presented in Chapter 5 over the traditional static design approach. It also goes onto analytically determine the capability of this methodology for achieving low tolerances. It will begin with a theoretical consideration of simple assemblies considering a single degree of freedom, extending from the connective assembly analysis detailed by Whitney [1]. Representative aerospace joints are simulated using a modified version of the prototype software presented in the thesis. Random manufacturing variation is applied to the features in the simple mechanical assembly (Figure B.1), these variations are updated into a data model representing this that understands these deviations to within a simulated uncertainty of a typical metrology device and adjusts the data model as described above. The deviation between the datum frames constituting *KC1* is used to compare the benefits between an adapted and un-adapted part-to-part assembly. This simulation is followed by an analysis of assemblies containing more than two parts. Finally, a discussion about the more significant benefits of this metrology-enabled adaptive assembly model and associated methodology is given.

The simple assembly that will be used for this discussion and simulation is visualised in Figure B.1 which shows a 3D CAD model of the assembly in CATIA. Moreover, the major key characteristic, *KC1*, has been set between these new features. Figure B.2 shows an exploded view of the assembly and applies a naming convention that will be useful for discussion in this section. This nominal CAD

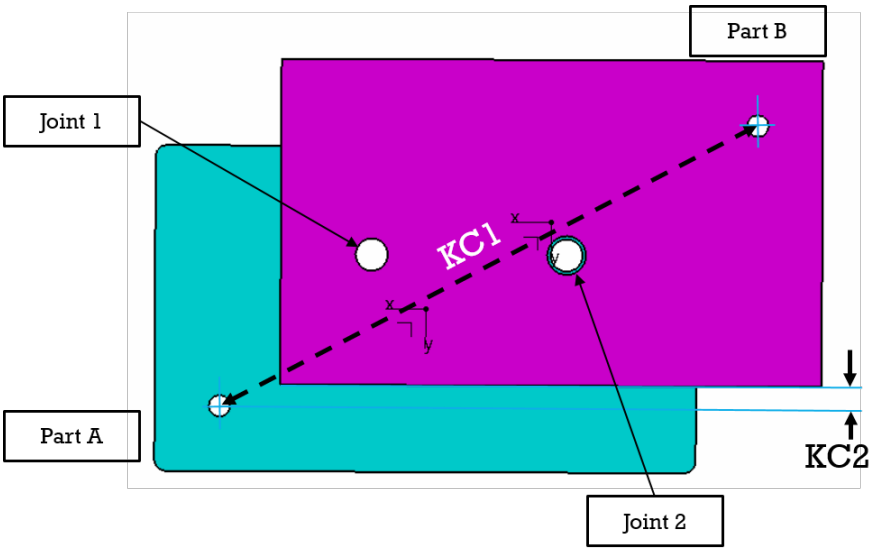


Figure B.1: CATIA model of a simple mechanical assembly.

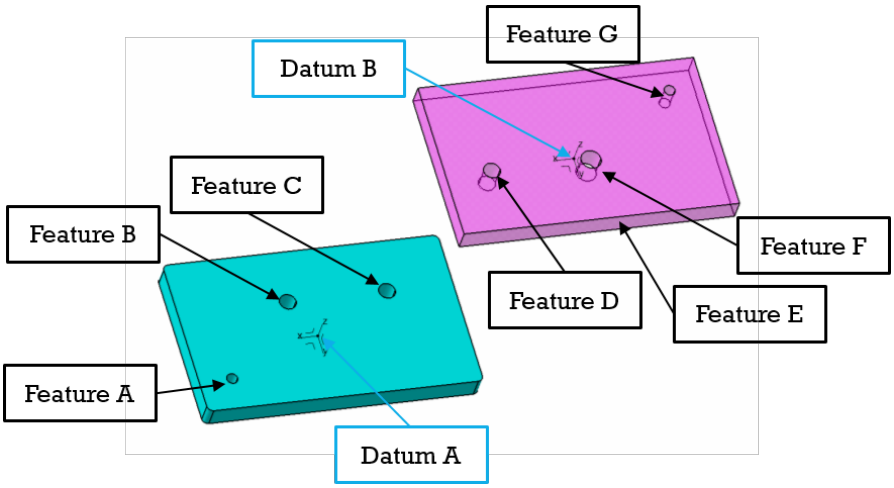


Figure B.2: Detailed exploded view of the simple assembly in Figure B.1. It shows the naming convention applied to the elements involved for ease of discussion.

model, in Figure B.1, was used to automatically generate the initial data model as discussed in Chapter 4.

The following sections will begin to apply an analytical consideration of manufacturing variation in the key characteristics of adaptive part-to-part assemblies. The analysis begins with the smallest example of two parts in Section B.2 in a single degree-of-freedom. Section B.3 goes onto consider more complex and representative assembly conditions using the data model to drive simulation. The simulation determines the variation experienced by key characteristics spanning across an adaptive part-to-part assembly joint by computation and then compares this to the same design under traditional approaches to assembly. The analysis then goes onto consider products consisting on n components in Section B.4.

B.2 Analysis in a Single Degree of Freedom

It is the case that the variance of a typical manufacturing resource is at least an order of magnitude greater than the uncertainty of a typical industrial metrology device, if not more. And, variance accumulates linearly (when considered in a single degree of freedom in isolation) [1]. Let the ratio of the metrology variation and the manufacturing variation be defined as k. Where;

$$k = \frac{\sigma^2_{met}}{\sigma^2_{manf}} \tag{B.1}$$

and typically k is much less than one.

Taking the simplest case first, two parts connected by a single feature present on both parts which fully constrains the assembly; a square peg in a square hole for example. The key characteristic is the distance between two arbitrary features on the components and can be modelled as a chain of frames; see Figure B.3 and Equation B.2.

$$\mathbf{{}^{A}T_{D}} = \mathbf{{}^{1}T_{A}^{-1}\ {}^{1}T_{B}\ {}^{B}T_{C}\ {}^{2}T_{C}^{-1}\ {}^{2}T_{D}} \tag{B.2}$$

Deviation of this key characteristic due to manufacturing variation is modelled as a post-multiplied error matrix applied to each manufactured feature; see Figure B.4 and Equation B.3. The dash above the frame designation indicates that it the modelled error of a nominal frame.

$$\mathbf{{}^{A'}T_{D'}} = \mathbf{{}^{A}T_{A'}^{-1}\ {}^{1}T_{A}^{-1}\ {}^{1}T_{B}\ {}^{B}T_{B'}\ {}^{B}T_{C}\ {}^{C}T_{C'}^{-1}\ {}^{2}T_{C}^{-1}\ {}^{2}T_{D}\ {}^{D}T_{D'}} \tag{B.3}$$

Assuming the manufacturing variation has a zero mean and only considering variation in a single degree of freedom then a key characteristic consisting of a

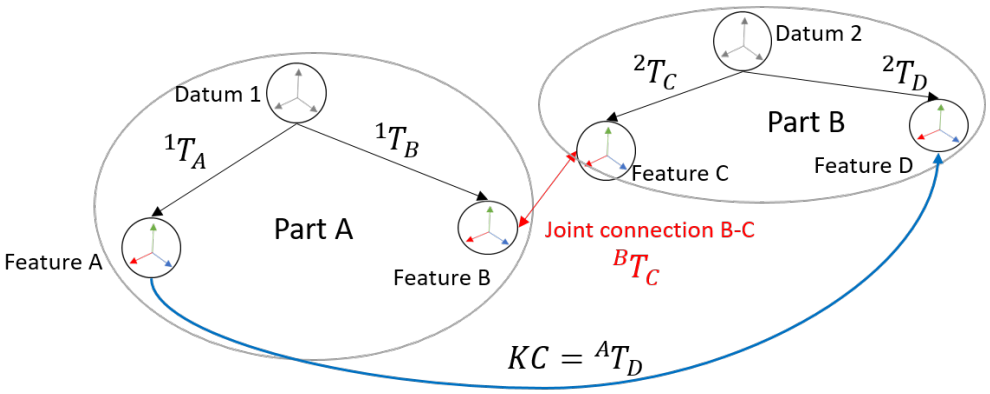


Figure B.3: A connective assembly model detailing the chain of frames constituting a key characteristic, typical of those extracted from the data model for analysis of key characteristics during the update procedure, see [1] for a complete explanation of notations and theory.

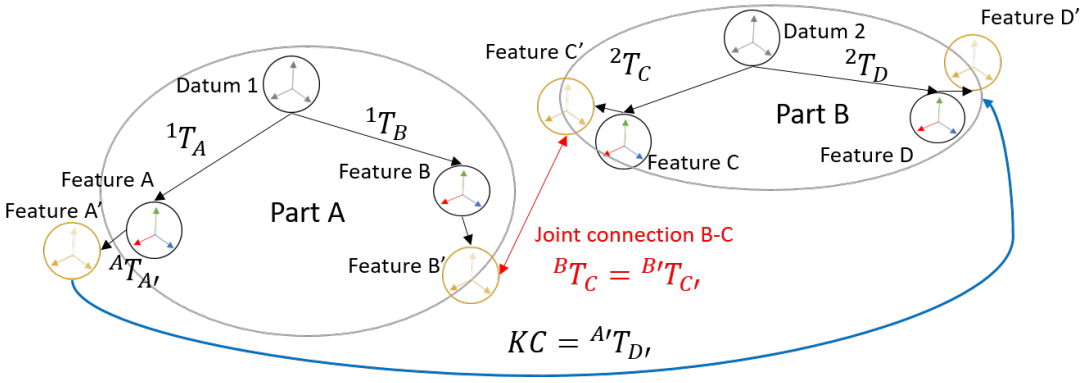


Figure B.4: Chain of frames extended with modelled variance of the manufactured features.

chain of N features would show a variation of:

$$\sigma^2_{KC} = \sum_{i=1}^{i=N} [\sigma^2_{manf,i}] \tag{B.4}$$

where; σ^2_{manf} is the manufacturing variation, and N is the number of features in the key characteristic chain.

Assuming that the manufacturing variation is the same for all produced features, the above equation becomes;

$$\sigma^2_{KC} = N\sigma^2_{manf} \tag{B.5}$$

Which evaluates to $4\sigma^2_{manf}$ for the example in Figure B.3.

Since the data model takes metrology observations of manufactured features and adjusts subsequent geometry to eliminate variation, the manufacturing variation present in Part A can be substituted for the uncertainty of the metrology device. Then the expression for the variation of the key characteristic shown in Figure B.3 is as follows:

$$\sigma^2_{KC_{(AAM)}} = 2\sigma^2_{metrology} + 2\sigma^2_{manf} \tag{B.6}$$

Using Equation B.1 simplifies Equation B.6 to:

$$\sigma^2_{KC_{(AAM)}} = (2 + 2k)\sigma^2_{manf} \tag{B.7}$$

Comparing the traditional approach with that presented in this chapter, the following expression for the relative reduction in variance experienced by the KC in a two part mechanical assembly is:

$$\frac{\sigma^2_{KC_{(AAM)}}}{\sigma^2_{KC}} = \frac{(1 + k)}{2} \tag{B.8}$$

Since k is in all practical circumstances much less than 1 and greater than zero, industry can expect reductions in key characteristic variance of up to 50%; depending on their choice of manufacturing resources and metrology equipment.

However, aerospace assemblies are seldom this simple. Joints between parts typically contain at least two features, usually a pin-hole and pin-slot combination or a master hole and clocking position. A joint may contain more than two holes however only two of these carry the locational properties and the rest only reinforce the joint [1].

B.3 Analysis of Representative Assembly Joints

To quantify the benefits of this methodology in more representative part-to-part joints (i.e. joints consisting of more than a single feature, otherwise known as a composite feature), a simulation was run to apply manufacturing variation to the features of the parts in Figure B.5. Figure B.6 presents a simplified visualisation of the data model sub-network responsible for the key characteristic in Figure B.5 and is the subject of this variation simulation. This manufacturing variation was in two degrees of freedom (Z and Y directions) for each feature and was sampled from a zero mean normal distribution (with a variance of σ_{manf}). Once the manufacturing variance was applied to all features the key characteristic was evaluated, representing the result of a traditional manufacturing approach to be used as a comparison. The methodology presented here however can adapt to the manufacturing variance in Part A by adjusting part B. This is modelled by taking the varied location of Part A's features and applying an additional error modelled by a zero mean normal distribution (where the variance is σ_{met}). This allows the data model to understand where Part A's features have moved to but with an error determined by the uncertainty of the metrology device. Once the data model has simulated it metrology observations of the features of Part A, it will adapt Part B to remove the propagation of variation. It is worth stating clearly that the data model does not adapt for the simulated manufacturing error in Part B since this would not be known at the time. The key characteristic is then evaluated for the data model driven process. This is then repeated such that the variance of the key characteristic under this novel methodology and the traditional approach can be compared.

The simulation evaluated 1000 samples and considered the deviation of the key characteristic's degrees of freedom linearly in Z and Y and the angular variance has also be calculated. In both cases the manufacturing variation has been assumed to be that of a CNC milling centre; $\sigma_{manf} = 0.2\ mm$. In the data model's analysis, Part A's variation has been adjusted for to within the uncertainty of a laser radar metrology device ($\sigma_{met} = 0.02\ mm$).

The results of the linear variation of the KC shows a 43.9% reduction which is consistent with our previous single degree of freedom analysis, if k is set to the values of σ_{met} and σ_{manf} used for the simulation; see Figure B.7. However, the reduction in the angular variation is far more compelling, Figure B.8 shows that the methodology reduces the angular variation by 66.6%. This is an important advantage in the aero-structures industry where the components are large and small angular errors can lead to large deviations elsewhere in the assembly.

This simulation validates the application of the analysis in Section B.2 and also

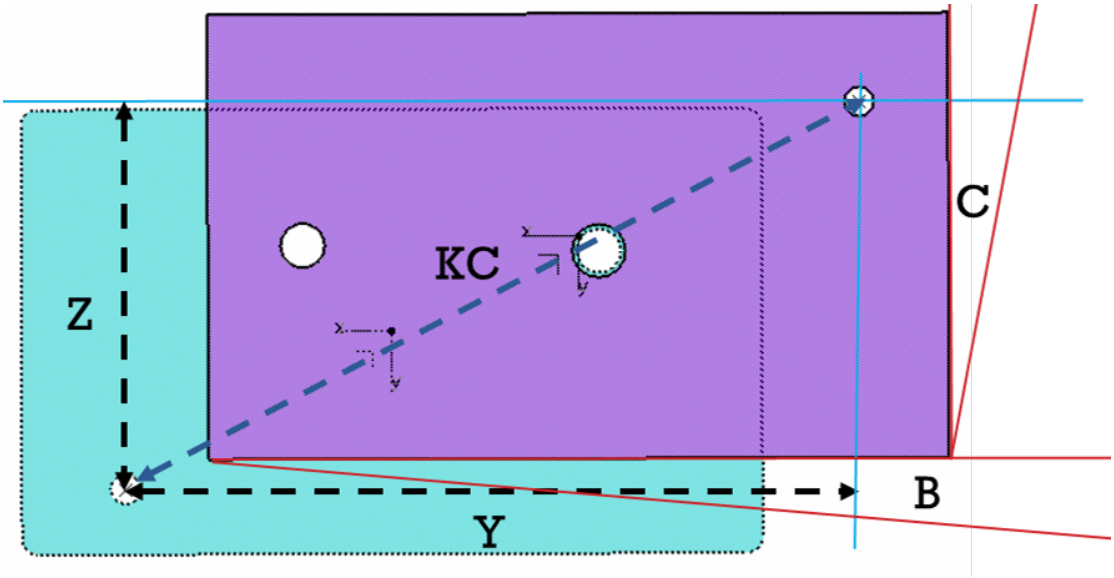


Figure B.5: Simulated composite feature joint considering only *KC1* from the example shown in Figure B.1.

shows the advantages this data model driven methodology has over traditional "make-to-nominal" approaches; especially for large components where angular deviation needs to be tightly controlled. However, assemblies rarely consist of two parts. Section B.4 will quantify the advantages for assemblies consisting of greater than two parts.

B.4 Analysis of Larger Assemblies

The major advantage of this approach is revealed as the number of parts and features present in the chain increases above two. Consider the example in Figure B.9 where a key characteristic chain consists of r parts and N features, where each part has two contributing features to the key characteristic chain ($N = 2r$).

Since Section B.3 validated the equations in Section B.2, the variance of the key characteristic in each translational degree of freedom is given by Equation B.4. Every key characteristic will have a tolerance applied to it to determine the acceptable deviation from nominal of the assemblies major dimensions. Let this tolerance be $nominal \pm tol$. Therefore, if the business wants to have a 99.7% confidence that the assembly will be produced correctly then the variance of the key characteristic must be:

$$\sigma_{KC}^2 = \frac{tol^2}{9} \tag{B.9}$$

And, since variation accumulates linearly, then for a key characteristic consisting of N features then and assuming the tolerance is to be shared equally then

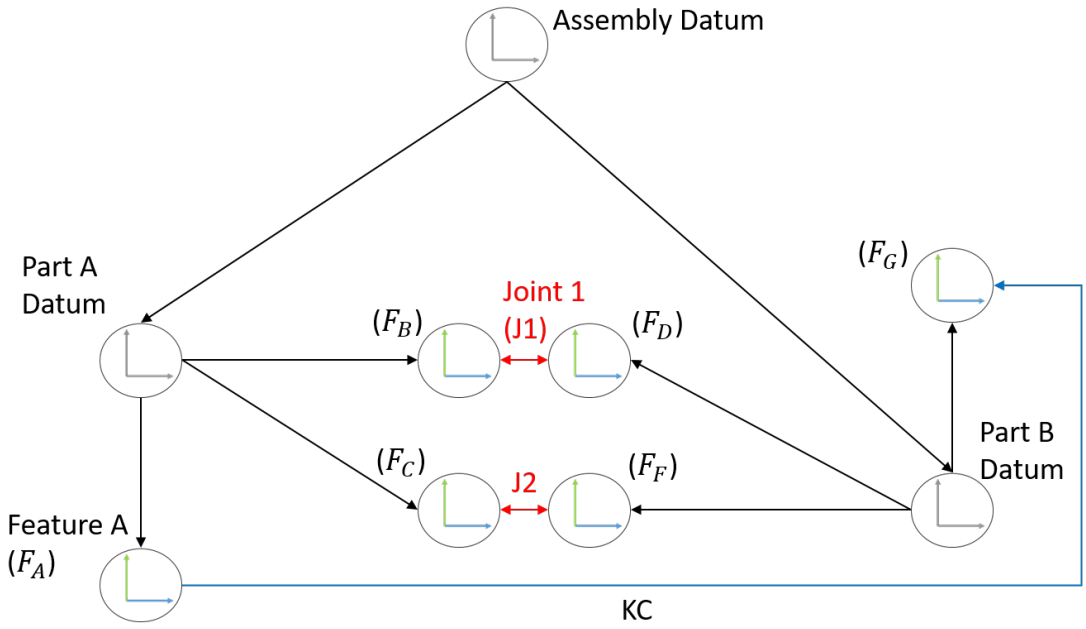


Figure B.6: A simplified view of the sub-network responsible for delivering the key characteristic identified in Figure B.5. Only two dimensions are considered to simplify the analysis and add clarity to the discussion.

the tolerance for each feature is:

$$\sigma_{feauture,i} \leq \frac{\sigma_{KC}^2}{N} = \frac{tol^2}{9N} \tag{B.10}$$

If required tolerances are sub-millimetre, as they are in the aero-structures industry, then the allowable variance is very small for each feature. Fortunately, the data model driven methodology presented here is able to bypass this issue, since its use of metrology inspection allows it to skip features in the chain and adapt Part r to suit the variation observed in the sub-assembly (Part 1 to Part r-1), returning the key characteristic to nominal; as shown in Figure B.10. Equation B.6 evaluates the resulting variance the key characteristic will exhibit despite there being more parts in the key characteristic chain. Moreover, it follows from Equation B.10 that the allowable variance for each feature is limited to:

$$\sigma_{feauture,r-1.B}, \sigma_{feauture,1.A}, \sigma_{feauture,r.A}, \sigma_{feauture,r.B} \leq \frac{\sigma_{KC}^2}{4} = \frac{tol^2}{28} \tag{B.11}$$

where $N = 4$.

This places even sub-millimetre tolerances within the manufacturing capability of CNC manufacturing centres. Moreover, if the manufacturing variance, or more likely the metrology uncertainty is less than their share of the total variance then this frees up additional allowable variation for the remaining features. Therefore,

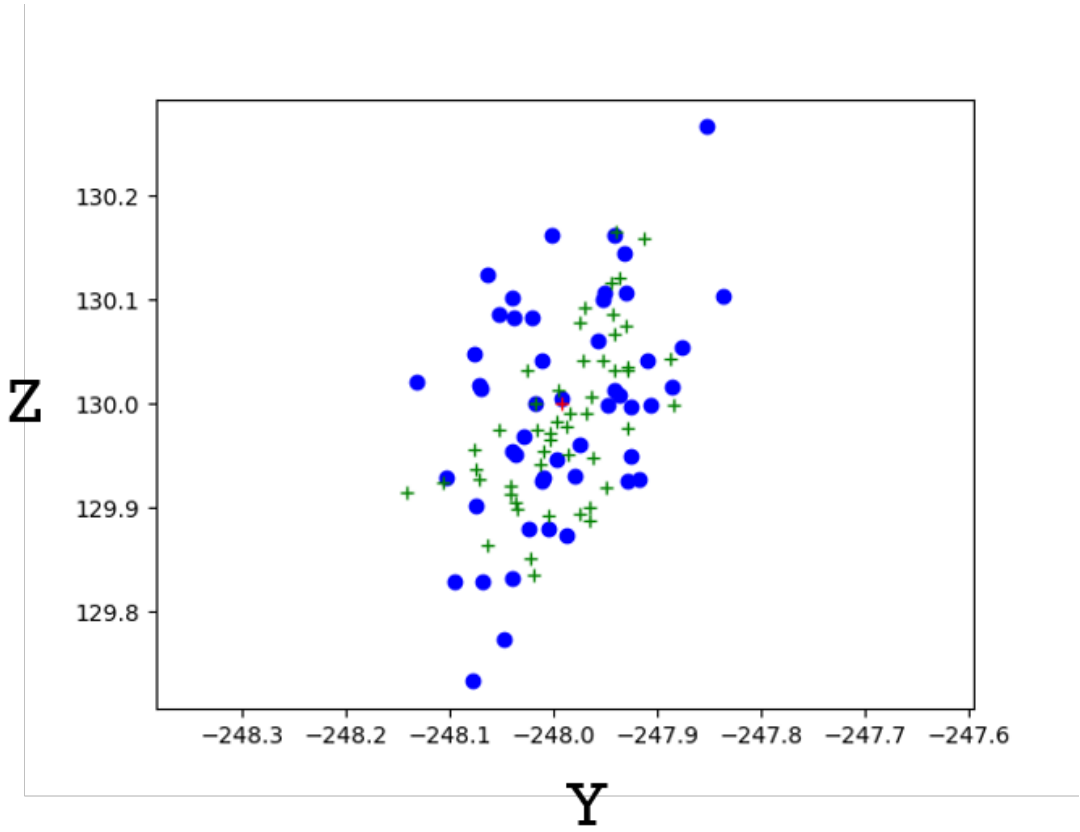


Figure B.7: Linear variations in the Z and Y axis, as detailed in Figure B.5. Blue dots are the un-adapted results, green crosses are the metrology-enabled data model driven results and the red cross indicates the nominal value. Number of samples shown reduced for clarity

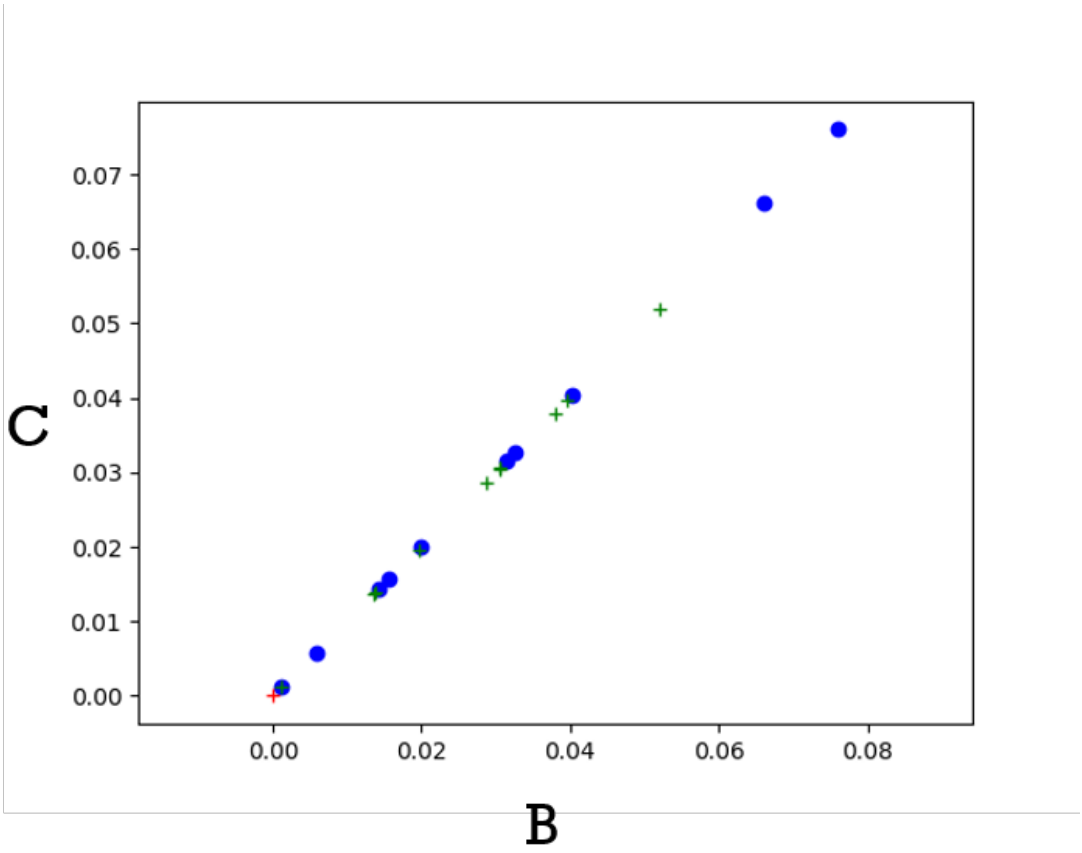


Figure B.8: Angular deviations measured as B and C in Figure B.5. Values are in radians and are identical as they both related to the angular deviation about X. Naturally the nominal value is 0. Number of samples shown reduced for clarity

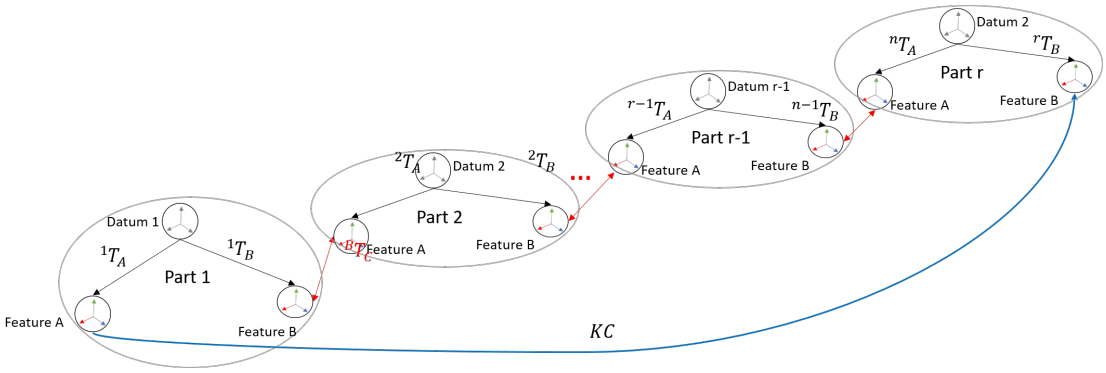


Figure B.9: Abstract KC chain consisting of r parts and N features, where each part has two contributing features to the key characteristic chain ($N = 2r$)

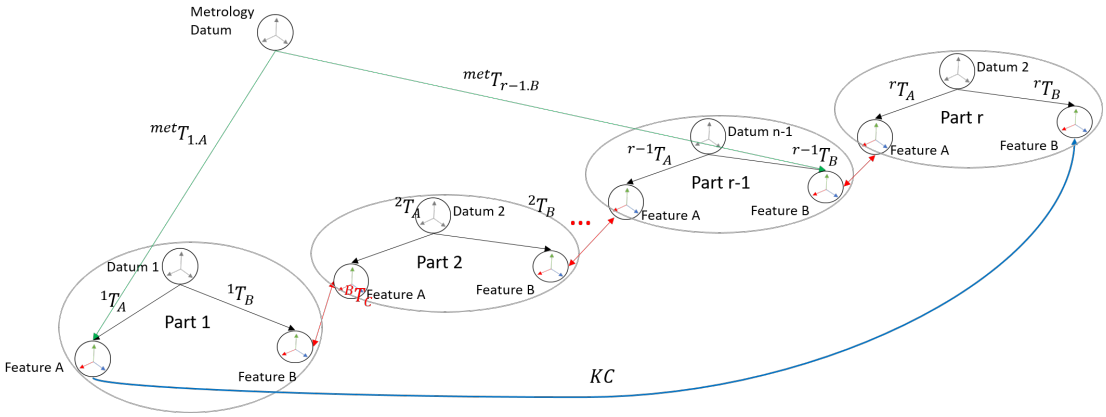


Figure B.10: data model driven methodology utilises metrology devices to evaluate the current state of variation present within sub-assemblies and adapts Part r to return the key characteristic back to design nominal.

the features $\sigma_{feauture,r-1.B}$ and $\sigma_{feauture,1.A}$ both of which are measured and the variation between cancelled out will only consume a fraction (k) of the allowable variance; allowing far more allowable deviation for the features of Part r.

This ability to skip features and consider whole sub-assemblies as a single sub-network is essential for application within industry since the metrology device may only be deployed at a sub-set of all available manufacturing and assembly processes. For example, consider the application in Figure B.11, the two locating features that mate with the rib are on two separate spar posts. The manufacturing variation between these two features is contributed to by at least five large and complex parts making accurate part-to-part assembly implausible. However, a metrology device can observe both these features (and others) on the sub-assembly within the same metrology operation such that the relationship between them can be understood two within the accuracy of the device. This metrology data for the sub-assembly can be added to the data model's network in an identical fashion to the simple example given earlier in the chapter; allowing the data model to produce the new hole locations on the rib's manufacturing data. Such that when it is manufactured/post-processed, part-to-part assembly is assured and the key characteristics between the rib and sub-assembly are maintained to within the variation predicted by Equation B.7.

The expression for the relative improvement of the methodology presented in this chapter over the traditional methodology for part-to-part assemblies as the number of components grows above 2 in a single degree of freedom is given as:

$$\frac{\sigma^2_{KC_{(AAM)}}}{\sigma^2_{KC}} = \frac{2(1+k)}{N} \tag{B.12}$$

As the number of parts N increases, the methodology presented here increasingly

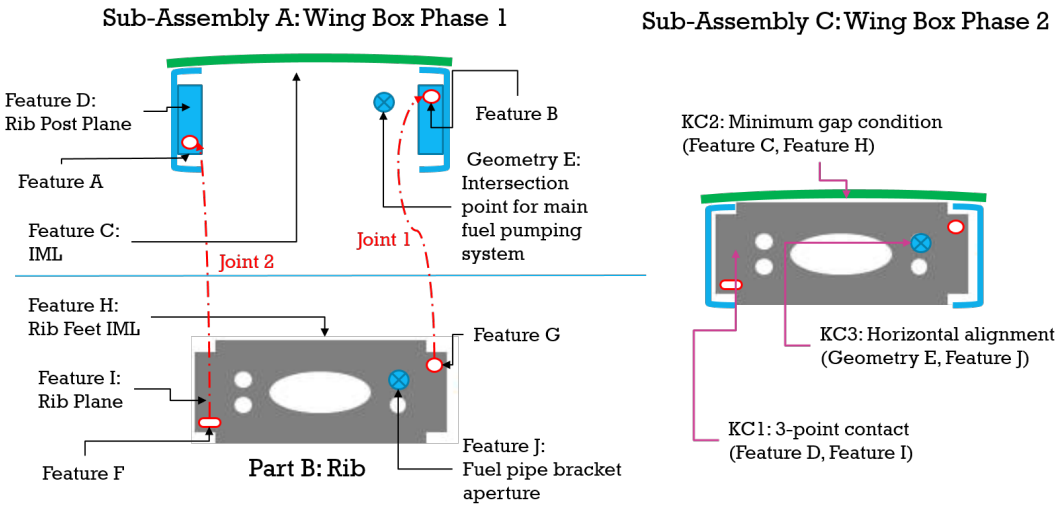


Figure B.11: Potential application of the methodology enabling part-to-part assembly for a process that has typically used fixtures, tooling and gauges to achieve successful assembly.

becomes the superior method.

From the above quantification, it becomes clear that the metrology-enabled adaptive assembly methodology can deliver significant benefits for lower quantity assemblies; especially if angular variation needs to be controlled. However, the process becomes unarguably superior if several features are present in the assembly chain; as is often the case in the aero-structures industry. An example of this was shown briefly in Figure B.11 where the features and geometry required to adapt the rib's location and joints relative to the wing box sub-assembly were measured together negating the variance stack-ups present within the parts themselves. The data model driven approach, when given metrology information of the features involved in the key characteristics and locating joints of an assembly operation, can reduce the variation of the key characteristics to within that predicted in Equation B.7. Therefore, if the manufacturing resources and metrology equipment are chosen appropriately the key characteristic variation can be controlled to with the sub-millimetre range. This enables the part-to-part assembly for aero-structures applications where sub-millimetre tolerances are expected. Moreover, it is suitably automated such that it is almost indistinguishable from the traditional approach with respect to the interface with the manufacturing organisation.

Appendix C

Data Model Extension: Metrology Objects

C.1 Introduction

This appendix defines the *metrology* object. This is a class which enables the easy generation of data models for which a CAD model is either not available, accessible or does not exist. This is some times the case if the part is very simple or designed by someone unfamiliar with CAD software packages. It is also not uncommon in the aerospace industry that CAD information is withheld on the grounds of national security and economic protection. *Metrology* objects are defined, if they are required, within the job file, see Appendices D and E for some examples.

C.1.1 Data Model Extension: Metrology Objects

A *metrology* object acts in exactly the same way as a *part* object. That is, they can be added to the *components* attribute of an *assembly* object. They have a *name* and *geometries* list containing a list of *geometry* objects but they have no *features* array. This is because a *metrology* object has no physical shape, it simply exists in the data model as a set of points with geometry generated from those points. The UML class diagram for the *metrology* object is shown in Figure C.1.

Metrology objects are generated from simple XML file which, for the purposes of this methodology, can be added to the job file. The XML only needs to define the name, the set of point names and the set of geometry "schematics". The name is just used to name the *metrology* object in the data model. The set of point names is the mapping between the metrology object and the database containing live metrology measurement data. Where each name is used to find the co-ordinate data from the database. Geometry schematics allow the user to define any important geometry for the assembly operations key characteristics.

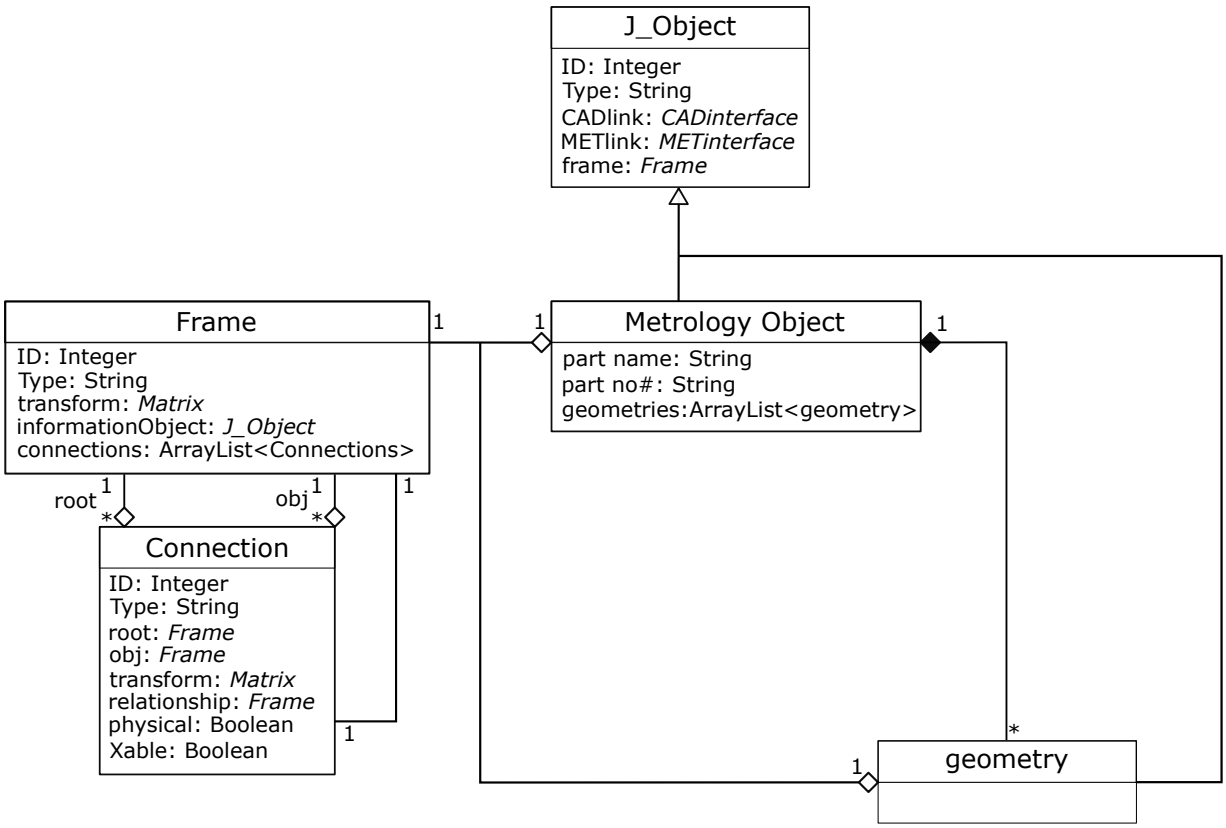


Figure C.1: UML class diagram for the Metrology Object. This is an extension to the original set of objects that construct the data model described in Chapter 4. It enables data models to be constructed without requiring a CAD model.

The schematic must specify the name and type of geometry and the point names involved such that a *geometry* object can be appended to the *metrology* object. There is no nominal data defined here, since none exists, the metrology object is simply a mapping to the metrology data and a set of instructs on what to do with that data.

Since a *metrology* object is a subclass of a *J_Object* it must have a *Frame* object which represents its datum and to make the objects mathematical link to the rest of the spatial network. However, since this methodology is driven by the geometry of the key characteristics the actual information in this *Frame* object is arbitrary. Therefore, when a *metrology* object is created its *Frame* object is just the identity matrix.

When the *metrology* objects are generated from a job file, and the first batch of metrology data has been used to actually populate them, they the added into an *assembly* object. As discussed previously, the *key_characteristic* objects are added to the data model using the *"KC"* tags in the job file. At this point the data model is ready to be operated upon just like any other; despite no CAD data existing. In fact, since *metrology* objects are very simple, consisting only of live point data and geometry, it is possible to utilise some of the methods developed in the previous chapter to both simulate this process and generate CAD models to visualise the *metrology* objects within the *assembly* object, see Figure C.2.

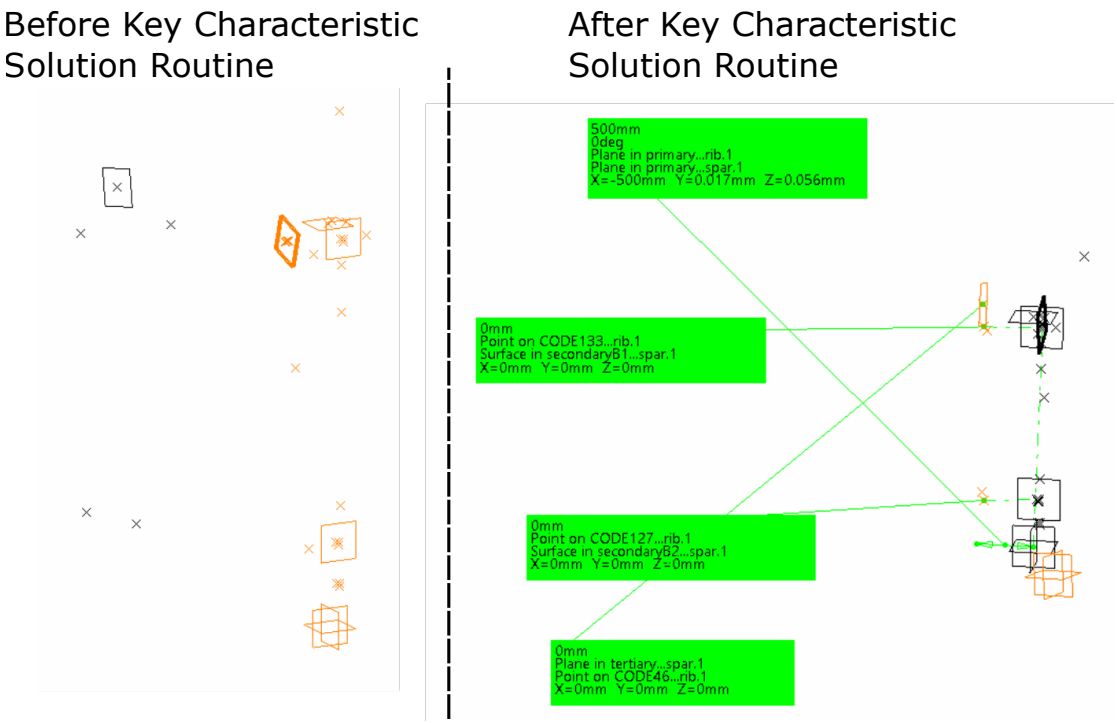


Figure C.2: CATIA simulation of the key characteristic solution routine. The geometry in black is associated with the rib and the data in orange is associated with the fixture. Data for this simulation was derived from the live measurement test for the 2nd test cell.

Appendix D

Job File for Test Cell 1

```
<?xml version = "1.0"?>
<job name="test setting job">
<VSTARS>
<driver>Jig_Sys_ph5.3D</driver>
<templates>
<template>FT_PIN28.3D</template>
<template>FT_PIN34.3D</template>
<template>FT_PIN40.3D</template>
<template>FT_PIN46.3D</template>
</templates>
</VSTARS>
<metObjects>
<metObject name="rib" component="rib">
<labels>
<label>CODE46</label>
<label>CODE28</label>
<label>CODE34</label>
<label>CODE47</label>
<label>CODE41</label>
</labels>
<geometrySchematics>
<schematic name="primary" type="plane">CODE46,CODE28,CODE34
</schematic>
</geometrySchematics>
</metObject>
<metObject name="spar" component="product">
<labels>
<label>CODE27</label>
```

```
<label>NUGGET27_B</label>
<label>NUGGET27_C</label>
<label>NUGGET27_D</label>
<label>CODE25</label>
<label>NUGGET25_1</label>
<label>NUGGET25_5</label>
<label>NUGGET25_8</label>
<label>NUGGET25_A</label>
<label>NUGGET25_B</label>
<label>NUGGET25_C</label>
<label>NUGGET25_D</label>
<label>CODE71</label>
<label>CODE33</label>
<label>CODE38</label>
<label>CODE31</label>
<label>CODE32</label>
<label>CODE28</label>
<label>CODE35</label>
</labels>
<geometrySchematics>
<schematic name="primary" type="plane">CODE31,CODE35,CODE32
</schematic>
<schematic name="tertiary" type="plane">CODE38,CODE33,CODE71
</schematic>
<schematic name="secondaryB1" type="plane">CODE27,NUGGET27_C,
NUGGET27_D</schematic>
<schematic name="secondaryB2" type="plane">CODE25,NUGGET25_A,
NUGGET25_D</schematic>
<schematic name = "primary_offset1" type="plane_offset">
primary,-5</schematic>
<schematic name = "primary_offset2" type="plane_offset">
primary,-10</schematic>
<schematic name = "primary_offset3" type="plane_offset">
primary,-15</schematic>
<schematic name = "primary_offset4" type="plane_offset">
primary,-20</schematic>
</geometrySchematics>
</metObject>
</metObjects>
```

```
<KCs>

<KC name="primaryKC" type="plane_plane_offset"
description="plane_plane_offset" priority="1">
<features>
<feature type="static" ref="1" >spar.primary</feature>
<feature type="dynamic" ref="1" >rib.primary</feature>
</features>
<tolerance ref="1">0.05</tolerance>
<conditions>
<condition ref="1" type="offset">-350.0</condition>
</conditions>
</KC>

<KC name="secondaryKC_1" type="plane_point_offset"
description="two point - two plane optimisation" priority="2">
<features>
<feature type="static" ref="1" >spar.secondaryB1</feature>
<feature type="dynamic" ref="1" >rib.CODE47</feature>
</features>
<tolerance ref="1">0.05</tolerance>
<conditions>
<condition ref="1" type="offset">0.0</condition>
</conditions>
</KC>

<KC name="secondaryKC_2" type="plane_point_offset"
description="two point - two plane optimisation" priority="2">
<features>
<feature type="static" ref="2" >spar.secondaryB2</feature>
<feature type="dynamic" ref="2" >rib.CODE41</feature>
</features>
<tolerance ref="2">0.05</tolerance>
<conditions>
<condition ref="2" type="offset">0.0</condition>
</conditions>
</KC>

<KC name="tertiaryKC" type="plane_point_offset" priority="3">
```

```
<features>
<feature type="static" ref="1" >spar.tertiary</feature>
<feature type="dynamic" ref="1" >rib.CODE34</feature>
</features>
<tolerance>0.05</tolerance>
<conditions>
<condition type="offset">-600</condition>
</conditions>
</KC>
</KCs>
<path def="MAJ">
<matrix order="0">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,500</row>
<row>0,0,0,1</row>
</matrix>
<matrix order="1">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,1000</row>
<row>0,0,0,1</row>
</matrix>
<matrix order="2">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,1500</row>
<row>0,0,0,1</row>
</matrix>
<matrix order="3">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,2000</row>
<row>0,0,0,1</row>
</matrix>
</path>
</job>
```

Appendix E

Job File for Test Cell 2

```
<?xml version = "1.0"?>
<job name="test setting job @ TEST CELL 2">
<VSTARS>
<driver>quickDriverFixtureCiss.3d</driver>
<templates>
<template>YKCtemplateV2.3d</template>
<template>FT_PIN28.3d</template>
<template>FT_PIN46.3d</template>
<template>FT_PIN40.3d</template>
<template>FT_PIN34.3d</template>
</templates>
</VSTARS>
<metObjects>
<metObject name="rib" component="rib">
<labels>
<label>CODE46</label>
<label>CODE28</label>
<label>CODE34</label>
<label>CODE133</label>
<label>CODE127</label>
</labels>
<geometrySchematics>
<schematic name="primary" type="plane">CODE46,CODE28,CODE34
</schematic>
</geometrySchematics>
</metObject>
<metObject name="spar" component="product">
<labels>
```

```
<label>CODE98</label>
<label>NUGGET98_B</label>
<label>NUGGET98_D</label>
<label>CODE104</label>
<label>NUGGET104_B</label>
<label>NUGGET104_D</label>
<label>CODE116</label>
<label>CODE97</label>
<label>CODE103</label>
<label>CODE109</label>
<label>NUGGET109_B</label>
<label>NUGGET109_D</label>
<label>CODE121</label>
<label>CODE128</label>
<label>CODE122</label>
<label>CODE134</label>
<label>YPP1</label>
<label>YPP2</label>
<label>YPP3</label>
</labels>
<geometrySchematics>
<schematic name="primary" type="plane">CODE128,CODE121,CODE122
</schematic>
<schematic name="tertiary" type="plane">YPP1,YPP2,YPP3
</schematic>
<schematic name="secondaryB1" type="plane">CODE109,
NUGGET109_B,NUGGET109_D</schematic>
<schematic name="secondaryB2" type="plane">CODE104,NUGGET104_B,
NUGGET104_D</schematic>
<schematic name = "primary_offset1" type="plane_offset">
primary,-5</schematic>
<schematic name = "primary_offset2" type="plane_offset">
primary,-10</schematic>
<schematic name = "primary_offset3" type="plane_offset">
primary,-15</schematic>
<schematic name = "primary_offset4" type="plane_offset">
primary,-20</schematic>
<schematic name = "norm" type="point_offset">YPP3,-300,400,500
</schematic>
```

```
</geometrySchematics>
</metObject>
</metObjects>
<KCs>
<KC name="primaryKC" type="plane_plane_offset" priority="1">
<features>
<feature type="static" ref="1" >spar.primary</feature>
<feature type="dynamic" ref="1" >rib.primary</feature>
</features>
<tolerance ref="1">0.05</tolerance>
<conditions>
<condition ref="1" type="offset">-220.0</condition>
</conditions>
</KC>

<KC name="secondaryKC_1" type="plane_point_offset"
description="two point - two plane optimisation" priority="2">
<features>
<feature type="static" ref="1" >spar.secondaryB1</feature>
<feature type="dynamic" ref="1" >rib.CODE133</feature>
</features>
<tolerance ref="1">0.05</tolerance>
<conditions>
<condition ref="1" type="offset">0.0</condition>
</conditions>
</KC>

<KC name="secondaryKC_2" type="plane_point_offset"
description="two point - two plane optimisation" priority="2">
<features>
<feature type="static" ref="2" >spar.secondaryB2</feature>
<feature type="dynamic" ref="2" >rib.CODE127</feature>
</features>
<tolerance ref="2">0.05</tolerance>
<conditions>
<condition ref="2" type="offset">0.0</condition>
</conditions>
</KC>
```

```
<KC name="tertiaryKC" type="plane_point_offset" priority="3">
<features>
<feature type="static" ref="1" >spar.tertiary</feature>
<feature type="dynamic" ref="1" >rib.CODE46</feature>
</features>
<tolerance>0.05</tolerance>
<conditions>
<condition type="offset">120</condition>
</conditions>
</KC>
</KCs>
<path def="MAJ">
<matrix order="0">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,500</row>
<row>0,0,0,1</row>
</matrix>
<matrix order="1">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,1000</row>
<row>0,0,0,1</row>
</matrix>
<matrix order="2">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,1500</row>
<row>0,0,0,1</row>
</matrix>
<matrix order="3">
<row>1,0,0,0</row>
<row>0,1,0,0</row>
<row>0,0,1,2000</row>
<row>0,0,0,1</row>
</matrix>
</path>
</job>
```