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How to Reduce Geometrical Variation in Assembled Products

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Thesis for the Degree of Doctor of Philosophy

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Abstract

Vehicle problems, such as wind noise, water leakage and door closing effort are examples of quality and functionality defects that are controlled by the dimensional accuracy of the structural frame of an auto body.

The aim of this thesis is towards methods for reducing geometrical variation in assembled products in the automotive and other industries. A general approach to these problems, based on the general idea for how rigidly parts are located in their final position using locating schemes, is developed. In particular, a positioning function which relates locating scheme errors to the corresponding displacement of parts is derived.

The positioning function is used to quantify the degree of coupling in a design concept and the geometrical stability provided by a locating scheme. In this way, designers are alerted, during early design phases, to geometrically sensitive and coupled design concepts that are difficult to manufacture and assembly to a proper quality level.

However, even for well designed products and assembly processes, the assembly tools such as positioning fixtures may become worn or broken and cause dimensional variation. The positioning function is combined with methods from multivariate analysis to diagnose fixture errors from routine measurements on parts and products, rather than from special measurements on fixtures. One reason for fixtures being at the centre of interest is that experience from the automotive industry suggests fixture failures as a major reason for dimensional variation in the structural frame of an auto body.

Keywords: Assembled products, body-in-white (BIW), dimensional variation, geometrical variation, fixtures, fixture diagnosis, locating schemes, multivariate analysis, rigid body motion, robust design, root cause, quality.

This thesis consists of an introduction and the following four papers:

Paper A Söderberg, R. and Carlson, J. S. *Locating Scheme Analysis for Robust Assembly and Fixture Design*, Proceedings of the ASME Design Engineering Technical Conferences, Las Vegas September 12–16, 1999.

Paper B Carlson, J. S. *Quadratic Sensitivity Analysis of Fixtures and Locating Schemes for Rigid Parts*, Accepted for publication in ASME Journal of Manufacturing Science and Engineering.

Paper C Carlson, J. S. *Root Cause Analysis for Fixtures and Locating Schemes Using Variation Data*, Global Consistency of Tolerances, Proceedings of the 6th CIRP International Seminar on Computer-Aided Tolerancing, 22-24 March 1999, pp 111–120.

Paper D Carlson, J. S. *Multi-Fixture Assembly System Diagnosis Based on Part and Subassembly Measurement Data*, To appear in Proceedings of the ASME Design Engineering Technical Conferences, Baltimore September 10–13, 2000.

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Chapter 1

Introduction

The introduction starts with a brief survey of general ideas about quality put forward by Deming, Shewhart, Suh, Taguchi and others. Reasons for and effects of geometrical variation in assembled products in the automotive and other industries are discussed. In particular, we explain how parts are located in their final positions using locating schemes. We have adapted these general ideas to the problem of geometrical variation in the project 3D Tolerance Management (3DTM). 3DTM is a joint project between Chalmers University of Technology, The Swedish Institute of Production Engineering Research, IVF and Volvo Car Corporation that was started in 1997. Tools and methods used during design and production aimed at reducing geometrical variation are demonstrated. Some of these tools and methods are traditionally used and others, as will be pointed out, are invented within the project. Finally, a summary of the papers in this thesis[1] is given.

1.1 Ideas of Quality

Products have one or several quality characteristics that determine their performance. The primary quality characteristics are often called performance characteristics, and are the ones that determine the product's fitness for use. With fitness for use we mean the product's ability to meet customer requirements. The ideal state of a performance characteristic is called target value. In a competitive economy the way to stay in business is to continuously reduce the performance characteristics variation about their target values, see Taguchi [19].

Variables affecting the product performance characteristics can be classified into design parameters and noise sources. Design parameters are

[1]This thesis has been written within the project 3D Tolerance Management.

variables controlled by designers or process engineers and noise sources are uncontrollable variables causing variation in the product performance. The latter variables are also called noise factors. Most organisations find it difficult to provide products without quality flaws, since manufacturing imperfections cause variability between different units of the same product. Additionally, during the expected life span of the product, deterioration and variability in environmental variables will cause variability in the product performance.

Statistical Process Control (SPC) is a set of mainly on-line quality tools, first proposed by Shewhart [10], and aimed at bringing and keeping the manufacturing process into a state of statistical control. A process in statistical control performs at its best and should be left alone, since further reduction in variability can only be achieved by system or design parameter changes.

Taguchi [19] proposes that engineering knowledge and designed experiments should be used during design to find product/process concepts that are insensitive to variability in noise factors. Robust design, the approach proposed by Taguchi, can be used off-line as a countermeasure against all noise factors, in contrast to SPC which only can be used as a countermeasure against manufacturing variations.

According to Suh [17] a product/process concept should not only be insensitive to noise but also easy to adjust and control. This can be achieved by striving towards satisfying Suh's independence axiom, which states that in a good uncoupled design each product functional requirement is controlled by one and only one design parameter.

An efficient quality improvement program pays for itself in the form of lower costs for adjustment, rejects and claims. Furthermore, most customers are prepared to pay a little more to get higher quality and therefore a strong quality image is an effective business strategy.

1.1.1 Geometrical Variation in Assembled product

Geometrical variation in the structural frame of an automotive body, Body In White (BIW), can cause quality problems in the final product such as wind noise, water leakage, door closing effort, gap and flush variation. That is to say, any critical assembly dimension on the BIW is a product performance characteristic and should be kept as close as possible to its target value. The major sources of variations in assembly dimensions are component variation and assembly tool related variation, which propagate in accordance with the product/process concept used. This is illustrated in Figure 1.1. By concept we here mean the way parts are located with respect to each other and how positioning tools are used during the assembly process. Next, we discuss general ideas behind how parts are located in their final positions in the assembly.

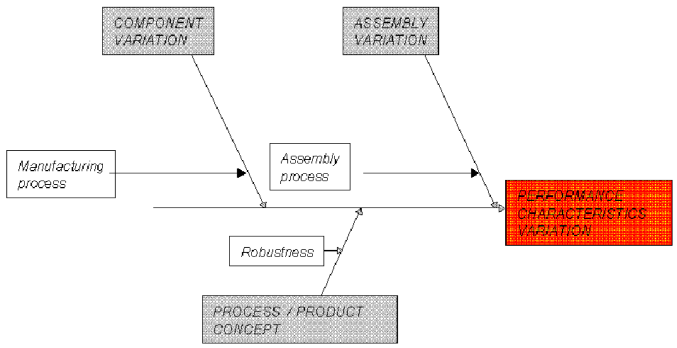


Figure 1.1: *Sources of variations in assembled products, Söderberg [11].*

1.1.2 Locating Schemes for Rigid Parts

A rigid part has six degrees of kinematic freedom. The main purpose of a locating scheme is to position the part by locking these degrees of freedom. A locating scheme is often represented by 6 discrete points such as in the case of the most commonly used class of layouts; the 3-2-1 locating scheme. A 3–2–1 locating scheme has 3 groups of locators which are laid out in mutually orthogonal planes, see Figure 1.2. The first group consists of three locator points, the second group consists of two locators, while the last group consists of a single locator point. In practice the locators are realised by small planes, holes and slots.

Each part/subassembly is located in its final position by bringing its locating scheme, in this work also refered to as the positioning frame (P-frame), in contact with a mating P-frame on a target, see Figure 1.3. The target P-frame points are provided by either mating surfaces from other parts or by assembly tooling elements, or a combination of both. The contact between the local P-frame and target P-frame is inevitable exposed to variation which affects the final position of the part and hence all critical assembly dimensions involving this part. Since locating schemes are used extensively during different phases of assembling a product, see Figure 1.4, it is of obvious importance to find locating schemes which minimise the effect of variation.

1.1.3 3D Tolerance Management

In the future, complex products with short life cycles will be produced near the customer on a global market under high competitive pressure. High

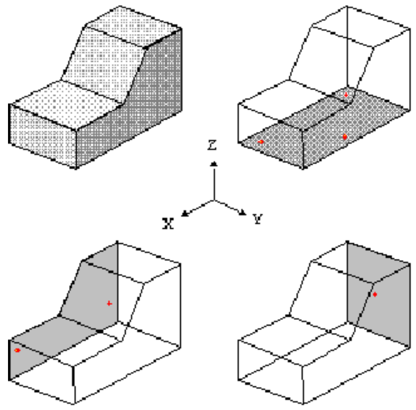


Figure 1.2: *A 3-2-1 locating scheme where the first group of three locators locks three degrees of freedom, translation in Z and rotation in X and Y, the second group of two locators locks two degrees of freedom, translation in Y and rotation in Z, and the last point locks one degree of freedom, translation in X (Söderberg and Lindkvist [14]).*

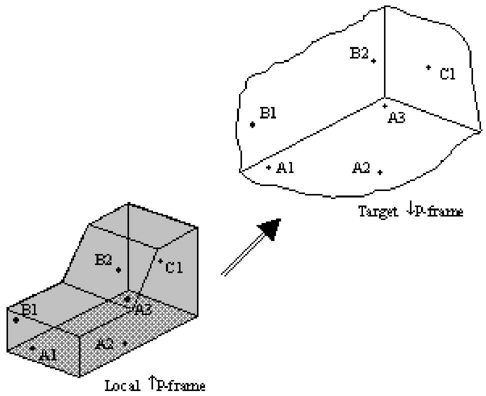


Figure 1.3: *Positioning of a part, Söderberg and Lindkvist [14]*

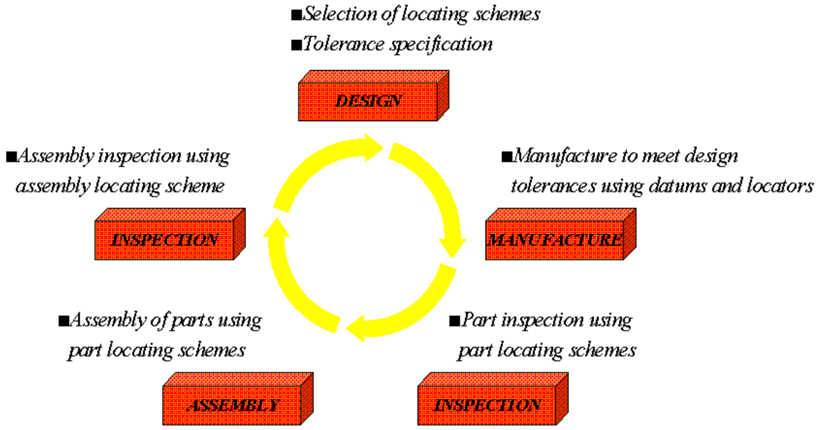


Figure 1.4: *The use of locating schemes in assembled products, Söderberg and Carlson [12]*

quality and short production start up time are critical for business success and is achieved by robust concepts along with a fully digital environment for product/process development and verification.

The 3DTM project aims at finding methods, tools and information flows that allow for better analysis and verification of product/process concepts with respect to geometrical variation and robustness, and to incorporate these methods in a fully digital product/process development environment. The project has three focus areas, (i) robust design and variation simulation, (ii) inspection planning and analysis, and (iii) root cause analysis. These focus areas reflect a product's development cycle, see Figure 1.5. Next, we discuss and demonstrate some of the tools developed in this off-line and on-line quality program, intended for use during the design and production phases.

1.2 Design

Taguchi [18] outlines a 3 step design approach to reduce variation in the performance characteristics in a cost effective way. The first step is system design where engineering and scientific knowledge are used to find product and process concepts that meet both the customer needs and the demands for manufacturability. The second step is parameter design where the settings of design parameters are chosen to make the performance characteris-

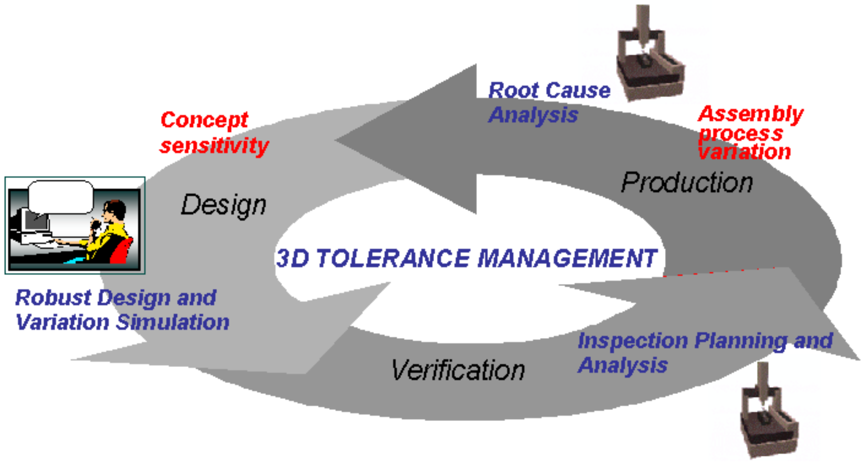


Figure 1.5: *A development cycle of products, with the focus areas of 3D Tolerance Management in blue colour and sources of variation in red colour.*

tics insensitive to sources of variation. Yet, some sources of variation may still affect the performance characteristics and need to be controlled. This is handled in the tolerance design step, where sensitivity is compensated by the selection of tolerances. In this step the trade off between customer's loss and increased manufacturing costs due to tight tolerances should be considered.

System design means in the present case the way parts are located with respect to each other and how positioning tools are used. A vehicle floor assembly is used in Söderberg and Johannesson [13] to illustrate two possible concept solutions in a system design. The floor is built up by a tunnel and a left and right floor panel. One concept solution is to use vertical mating flanges. The total width of the floor is then controlled by the variation in the individual parts (Figure 1.6). An alternative concept solution is to use horizontal flanges and instead control the total floor width with help of fixtures (Figure 1.7).

A way to compare different concepts is to examine how well they satisfy Suh's independence axiom. Remember that a uncoupled concept is easy to adjust and control and hence leads to relaxed tolerances and less problems during the production launch. In this case uncoupled means that each part is controlled by its own P-frame. In Figure 1.8 an uncoupled (parallel) assembly solution and a decoupled (serial) assembly solution are schematically

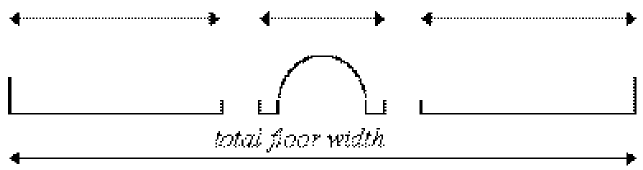


Figure 1.6: *A vehicle floor assembly using vertical flanges, Söderberg and Johannesson [13].*

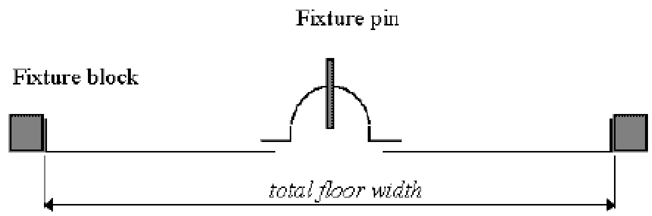
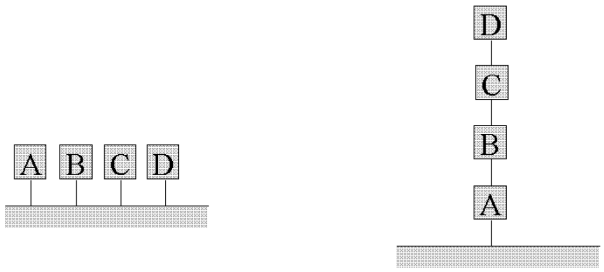


Figure 1.7: *A vehicle floor assembly using horizontal flanges, Söderberg and Johannesson [13].*

illustrated. In a decoupled assembly solution each part is controlled by its own P-frame only if they are adjusted in a particular order. Furthermore, Figure 1.8 shows a matrix relating the linearised functional requirements (position of a part) to the design parameters (P-frame). Such matrices will later be discussed in detail and used to quantify the degree of couplings inherent in a concept.



$$\begin{bmatrix} Part\,A \\ Part\,B \\ Part\,C \\ Part\,D \end{bmatrix} = \begin{bmatrix} \boldsymbol{x} & 0 & 0 & 0 \\ 0 & \boldsymbol{x} & 0 & 0 \\ 0 & 0 & \boldsymbol{x} & 0 \\ 0 & 0 & 0 & \boldsymbol{x} \end{bmatrix} \begin{bmatrix} P-frame\,A \\ P-frame\,B \\ P-frame\,C \\ P-frame\,D \end{bmatrix} \qquad \begin{bmatrix} Part\,A \\ Part\,B \\ Part\,C \\ Part\,D \end{bmatrix} = \begin{bmatrix} \boldsymbol{x} & 0 & 0 & 0 \\ \boldsymbol{x} & \boldsymbol{x} & 0 & 0 \\ \boldsymbol{x} & \boldsymbol{x} & \boldsymbol{x} & 0 \\ \boldsymbol{x} & \boldsymbol{x} & \boldsymbol{x} & \boldsymbol{x} \end{bmatrix} \begin{bmatrix} P-frame\,A \\ P-frame\,B \\ P-frame\,C \\ P-frame\,D \end{bmatrix}$$

Figure 1.8: *Uncoupled assembly and decoupled assembly solution, Söderberg and Lindkvist [14].*

Parameter design aims at selecting locating points which make the assembly insensitive to variation in mating surfaces and tooling elements. This is a nontrivial activity since it often involves a trade-off with other aspects such as manufacturing and inspection requirements. In Figure 1.9 two different possible locating schemes for positioning a part are shown. These schemes provide different degrees of geometrical stability against locator variation.

During tolerance design, geometrical assembly sensitivity is compensated by the selection of manufacturing and assembly tool tolerances. Ideally, the allocation should be done considering both loss associated with deviation from target in critical assembly dimensions and manufacturing costs. However, in practice these costs are not often known to a company.

To sum up, during the design phase methods and tools to determine (i) the degree of coupling in a concept, (ii) the geometrical stability provided by locating schemes, and (iii) adequate tolerances based on assembly sensitivity are needed. The key to our solution of (i)–(iii) is to find and analyse a function which relates P-frame errors to the corresponding displacement of

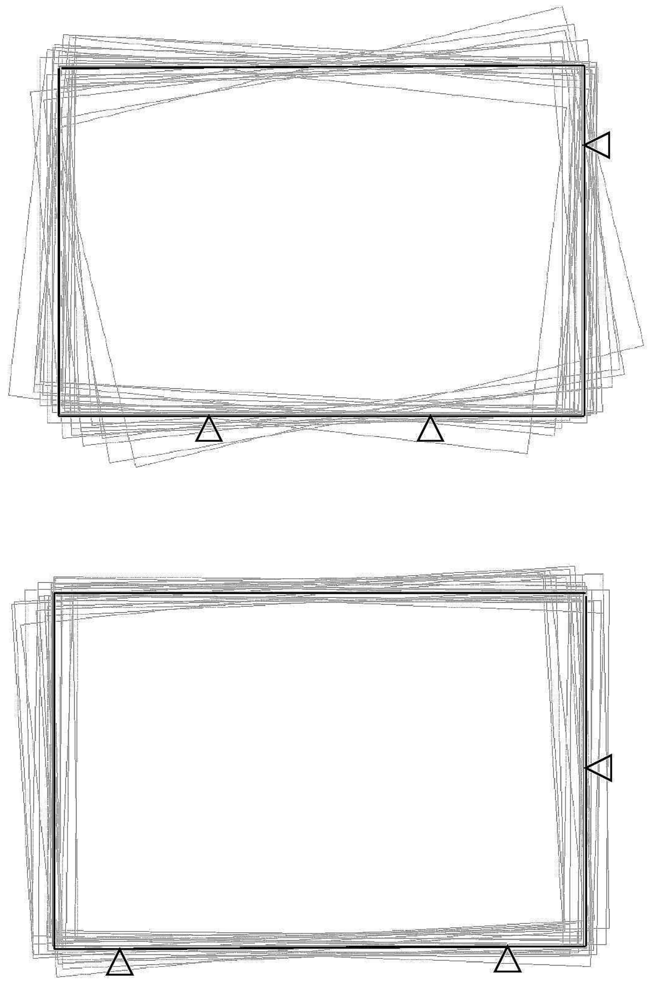


Figure 1.9: *The effect of locator variation on a part located with two different locating schemes.*

parts. Before a detailed discussion of this function a number of tools based on it for managing (i)–(iii) are explained and demonstrated.

1.2.1 Robust Design and Variation Simulation

A function relating P-frame errors to the corresponding displacement of parts for an assembled product will from now on be called a positioning function. A first order Taylor expansion of a positioning function, for an assembled product consisting of N parts, gives

$$\begin{bmatrix} \Delta\text{Position of part 1} \\ \Delta\text{Position of part 2} \\ \cdots \\ \Delta\text{Position of part N} \end{bmatrix} \approx \underbrace{\begin{bmatrix} A_{11} & A_{12} & \dots & A_{1N} \\ A_{21} & A_{22} & \dots & A_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ A_{N1} & A_{N2} & \dots & A_{NN} \end{bmatrix}}_{A} \begin{bmatrix} \Delta\text{P-frame 1} \\ \Delta\text{P-frame 2} \\ \cdots \\ \Delta\text{P-frame N} \end{bmatrix},$$

where the 6 times 6 matrix A_{ij} maps an error, ΔP-frame j, in P-frame j into a displacement, Δposition of part i, of part i. This approximation is often valid, for example in the automotive industry, since the P-frame errors encountered there usually are small and a first order Taylor expansion of the positioning function often gives result close to the exact relationship. The matrix A contains both information about the degree of coupling in the assembly concept and information concerning the geometrical assembly sensitivity. By mapping each P-frame matrix A_{ij} to a scalar a_{ij} we treat each P-frame as a single design parameter and the position of a part as a single functional requirement. This parameter reduction makes it easier to get a general view of assemblies with many parts. Further, inevitable couplings in Aij are removed from the design equation and no longer affect the evaluation of an assembly concept with respect to the degree of coupling. It is important that a_{ij} measures the degree of geometrical stability of part i provided by P-frame j. A useful scalar measure of stability is the root mean squared value of the relative displacement, at a number of points representative for the part i geometry, caused by varying each locator in P-frame j. Details about how to calculate these displacements from the matrix A_{ij} can be found in paper A, B and C.

The N times N matrix obtained by replacing each submatrix A_{ij} with the scalar a_{ij} is called the stability matrix (Söderberg and Lindkvist [14]). From the stability matrix the degree of couplings inherent in the concept solution and the assembly sensitivity can be judged. To demonstrate this the stability matrices for the two vehicle floor assembly concept solutions discussed earlier are calculated and presented in Figure 1.10. The stability matrices show that both concepts suppress variation since all matrix elements are less than 1. Additionally, since the right stability matrix is

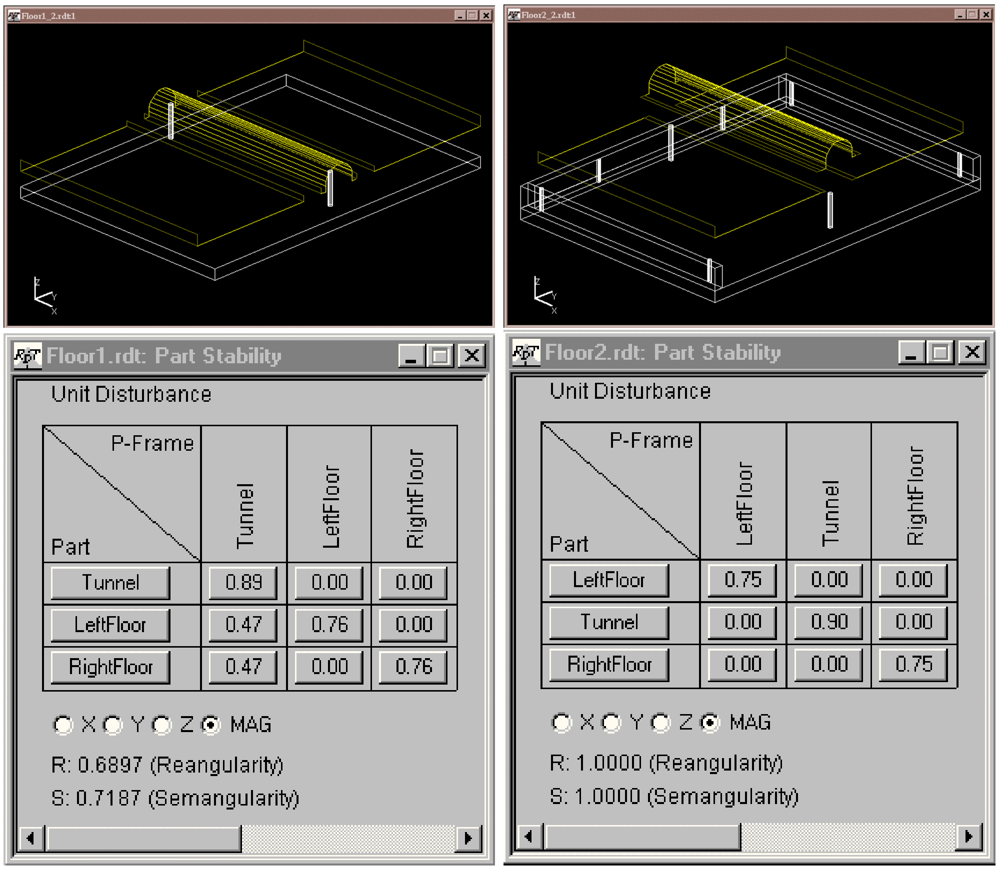


Figure 1.10: *Stability matrices for two floor assembly concept solutions, Lindkvist and Söderberg [8].*

diagonal, the initial decoupled vehicle assembly concept can be made uncoupled with the aid of positioning fixtures.

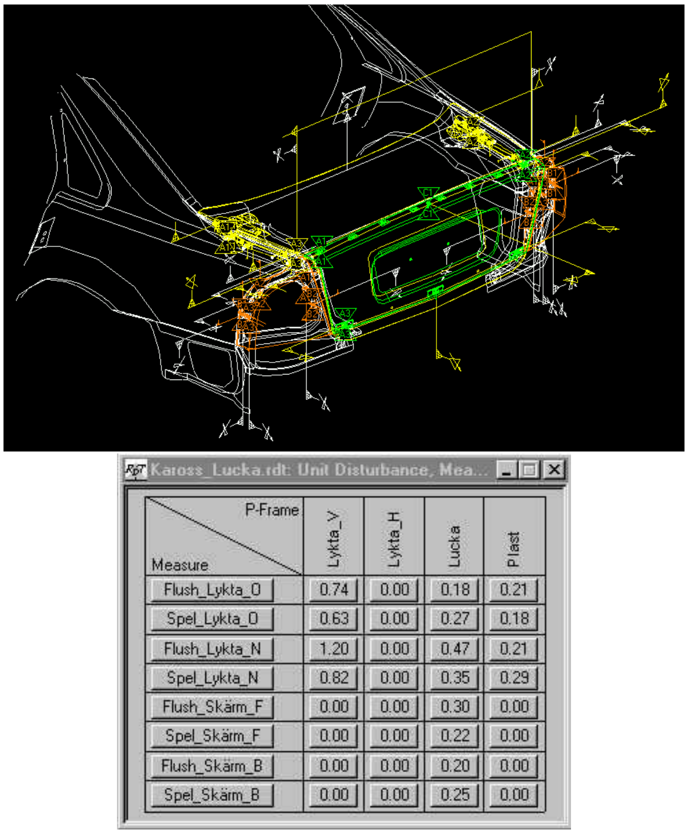
Often, due to overlap of functional requirements, it is impossible to find concepts that completely satisfy Suh's independence axiom. Suh has introduced two quantitative measures called reangularity, R, and semangularity, S, as an aid in the search for the least coupled concept. Reangularity measures the orthogonality between the design parameters while the semangularity measures the alignment of design parameters with their corresponding functional requirements. For more details see Suh [17], pages 115–119. Both measures take on values between 0 and 1, where $S = 1$ and $R = 1$ mean that a concept is completely uncoupled.

Stability analysis may also be carried out for critical assembly dimensions of an assembly. This is done by calculating a stability matrix where the functional requirements are changed from part positions to critical assembly dimensions. In Figure 1.11 we can see how errors in the different P-frames affect the flush between the rear light(lykta) and a plastic part(plast) on the hatch(lucka).

A general idea of the sensitivity of an assembly may be obtained by using colour coding. The colour coding, invented within the 3DTM project, is based on the cumulative effect of errors in all P-frames in every point representing part geometry. In Figure 1.12, the assembly of the doors on the body is colour coded.

Hence, the use of the stability matrix, perhaps complemented with colour coding, during system design and parameter design makes it possible to sort out geometrically sensitive and coupled design concepts that are difficult to manufacture and assembly to a proper quality level. Furthermore, the stability matrix can also be used during tolerance design to point out if some contact features should be manufactured with higher precision than others.

Two other tools traditionally used in computer aided tolerancing, see Söderberg [12], to allocate and evaluate tolerances are variation analysis and contribution analysis. In variation analysis, manufacturing tolerances/distributions of geometrical features are used to calculate important properties, such as mean value and standard deviation, of the corresponding critical assembly dimension distribution. The variation and contribution analysis is often performed by Monte Carlo simulation. This in particular makes it possible to capture nonlinearities in the positioning function. However, also less computer intensive methods are available, see Nigam and Turner [20]. If a critical assembly dimension is outside its specification limits with an unacceptably high probability then some tolerances have to be reassigned. The reassignment process can be facilitated by using a contribution list, where the contribution from each input parameter on a critical



Kaross_Lucka.rdt: Unit Disturbance, Mea...

Measure \ P-Frame	Lykta_V	Lykta_H	Lucka	Plast
Flush_Lykta_O	0.74	0.00	0.18	0.21
Spel_Lykta_O	0.63	0.00	0.27	0.18
Flush_Lykta_N	1.20	0.00	0.47	0.21
Spel_Lykta_N	0.82	0.00	0.35	0.29
Flush_Skärm_F	0.00	0.00	0.30	0.00
Spel_Skärm_F	0.00	0.00	0.22	0.00
Flush_Skärm_B	0.00	0.00	0.20	0.00
Spel_Skärm_B	0.00	0.00	0.25	0.00

Figure 1.11: *Stability matrix with the flush between the rear light and the plastic part on the hatch indicated.*

Figure 1.12: *Sensitive areas of the body side assembly are indicated by colour coding.*

assembly dimension is ranked. A variation and a contribution analysis of the flush between the rear light and the plastic part on the hatch are shown in Figure 1.13. The result from the variation analysis, based on an initial

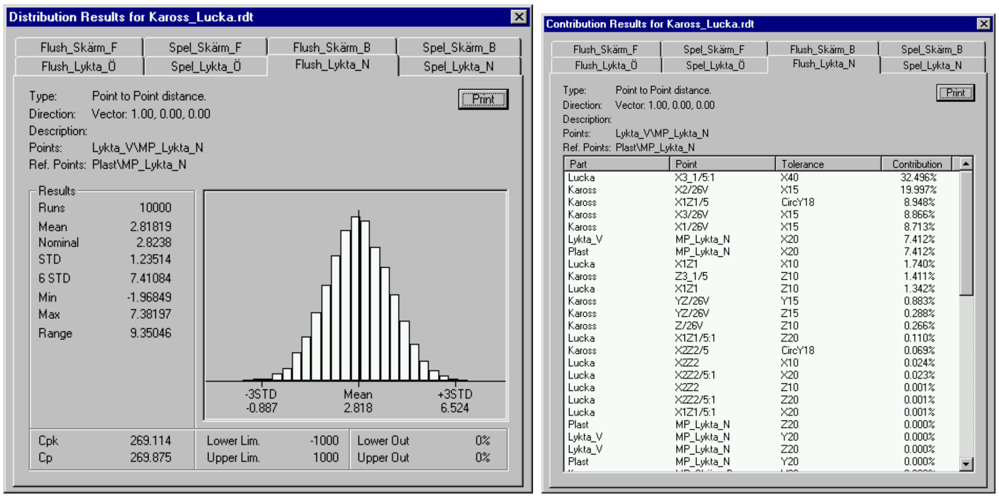


Figure 1.13: *Variation and contribution analysis of the flush between the rear light and the plastic part on the hatch.*

assumed set of design tolerances, is that we can expect 6 standard deviations of the flush to be approximatively equal to 7.4[mm]. From the contribution list we can see that one of the contact points between the hatch and the plastic part causes roughly 32% of the flush variation.

Many geometrical features are manufactured using the same process and therefore we also propose a process contribution list to facilitate key processes identification and change of manufacture process impact estimation. Details can be found in Söderberg and Lindkvist [15]. Before we consider some aspects concerning verification and production it remains to discuss how to calculate the positioning function.

During assembly, as shown in Figure 1.3, each part is located in its final position by bringing its local P-frame to make contact with a mating P-frame on another part or subassembly. The positioning function should be a formula relating errors in these mating P-frames to the resulting displacement of parts. Errors in the target P-frame can be caused by either geometrical variation due to manufacturing imperfections or originate as a result of errors in other target P-frames related to this part. To determine the positioning function it is enough to derive a generally applicable method for finding the rotation and translation that make the part move into contact with a disturbed target P-frame. This method can then be used repeatedly to follow how geometrical variation propagates through the P-frames of the assembly.

The displacement caused by P-frame errors is implicitly described by the part position constraint introduced by the locating scheme. To see this, let the workpiece surface geometry around the locator point with coordinate $\mathbf{p}_i$ be implicitly defined by the $x - y - z$ coordinate points $\mathbf{y}$ satisfying the equation $S_i(\mathbf{y}) = 0$. The geometric constraint equations

$$S_i\left(R_\omega^{-1}(\mathbf{p}_i + \delta_i - \mathbf{t})\right) = 0, \text{ for } i = 1, 2, \dots, 6, \tag{1.1}$$

state that the surface S_i, displaced by the rotation R_w and translation $\mathbf{t}$, should be in contact with the perturbed locator point $\mathbf{p}_i + \delta_i$, see Figure 1.14. The rotation R_w and translation $\mathbf{t}$ caused by locator errors $\{\delta_i\}_{i=1}^{6}$ can be obtained, for example by a numerical routine for solving nonlinear equations by a least squares method. However, in many cases it is useful to have an explicit formula, even if it is only approximate, for calculating the displacement caused by a P-frame error. In paper A and C we derive such a linear formula from these geometric constraint Equations (1.1), whereas a quadratic formula is derived in paper B.

1.3 Production

Today routine measurements in the automotive industry are often made online during the production process. Statistical process control is a set powerful on-line quality tools aimed at reducing variability around target values

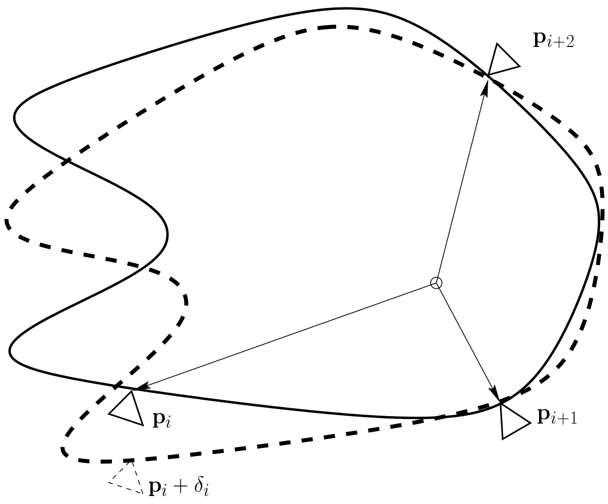


Figure 1.14: *A workpiece translated and rotated from its nominal position due to locator positional error, Carlson [2].*

utilising measurements. A review of the major tools is found in e.g. Montgomery [9]. The most sophisticated SPC tool is the control chart proposed by Shewhart [10]. It is based on his theory of variability in manufactured products. Shewhart divides the reasons for variation in a production process into common causes and assignable causes of variation. The common causes are many and essentially unavoidable since each cause only has a slight effect on the product. The cumulative effect of the common causes give rise to a certain avoidable level of variation inherent in the product and process concepts. In addition, there often exist a few other assignable causes which each has a significant effect on the product. These assignable causes are often operator errors, defects in the raw material and machine/tool errors.

The control chart is an excellent device for distinguishing between common causes and assignable causes. A typical control chart is a graphical display of measurements or a sample key feature, such as sample mean or sample variance, versus sample number or time. A number of horizontal lines on the chart together with a set of rules are used to decide whether assignable causes are present or if the process should be left alone. To change a process when it is operating with only common causes is called tampering. In chapter 11, Deming [6] gives a number of examples where tampering not only increases the product variation but also demoralises the working staff.

If the control chart indicates that a process is out of control then the process engineers must track down and eliminate the assignable cause. For manufacturing processes of simple parts, patterns on the control chart may provide enough diagnostic information to an experienced operator to perform a root cause analysis. However, Gou and Dooley [7] state:

> Experience shows that many SPC attempts fail to produce meaningful results because the lack of diagnostic support for the effort.

Furthermore, in an extensive investigation of dimensional quality problems in the BIW during the launch of a sport vehicle Ceglarek and Shi [5] wrote:

> The complexity of the automotive body prevents measurement data from being sufficient to localise root causes of dimensional variation. It is necessary to include knowledge about the product and the assembly process before the root causes can be determined.

1.3.1 Root Cause Analysis

In the 3DTM project, we have taken note of this problem and developed general methods for diagnosing fixture related errors using routine measurements on parts and products, rather than from special measurements on fixtures. A fixture is a high precision tool used to position parts for assembly and inspection. One reason for fixtures being in the centre of interest is that experience from the automotive industry suggests fixture failures as a major reason for dimensional variation in the BIW. For example, in the above mentioned investigation by Ceglarek and Shi about 70% of all root causes were fixture related.

The two main objectives of root cause analysis for fixtures are to determine if some fixture should be adjusted, and if so, point out which locators to adjust or replace. Reasons for locator variation and offset may be a worn, loose, bent or broken fixture element. Figure 1.15 shows a multi-fixture assembly system which uses a bumper gripper, gripper fixture and a floor fixture to assembly a bumper with a vehicle floor. To control the assembly process 14 inspection points on the bumper are measured after assemblage using a coordinate measuring machine. The result from 35 inspections are shown in Figure 1.16. The 20 initial inspections indicate an unacceptable level of variation. Since the bumpers were known to be close to target before assemblage this suggests an assembly quality problem. The result of the root cause analysis proposed in paper D is shown in the right part of Figure 1.16. The two bar plots show the variation in the contact points (A1, A2, A3) between the floor and the bumper and the variation in a pin/hole

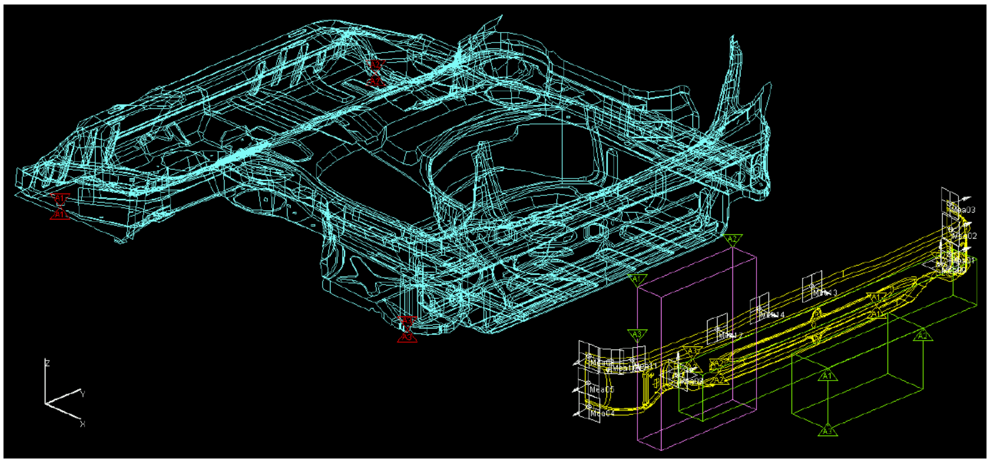


Figure 1.15: *A multi-fixture bumper assembly.*

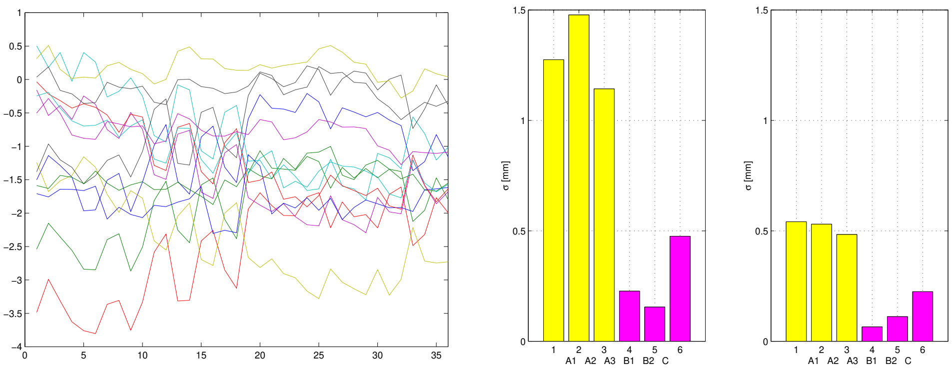


Figure 1.16: *Left plot shows bumper production deviation from target, after assemblage with the floor, in 14 inspection points on the bumper. Right plot shows the standard deviation in the bumper target P-frame for the initial 20 inspections and the remaining 15 inspections.*

(B1, C) and a pin/slot (B2) contact between the gripper fixture and gripper. The left bar plot is for the initial 20 inspections. The right bar plot is for the remaining 15 inspections, which were made after the process engineers had made a change in the gripper fixture to improve the pin/hole contact. As we can see, the change did not only reduce the contact variation in B1 and C1 but also resulted in less variation in the contact between the bumper and the floor. The latter improvement can be explained by realising that when the bumper is less displaced in the $Z - Y$ plane, the bumper makes contact with the floor almost at the intended contact points. These points have controlled dimensional variation.

1.4 Information Needed for 3DTM Tools

We have discussed several tools aimed at reducing geometrical variation in the assembled product. These methods require different level of detail information about the assembly. In this section we specify the information needed for stability analysis, variation analysis, contribution analysis, and root cause analysis. A more general discussion about efficient computer

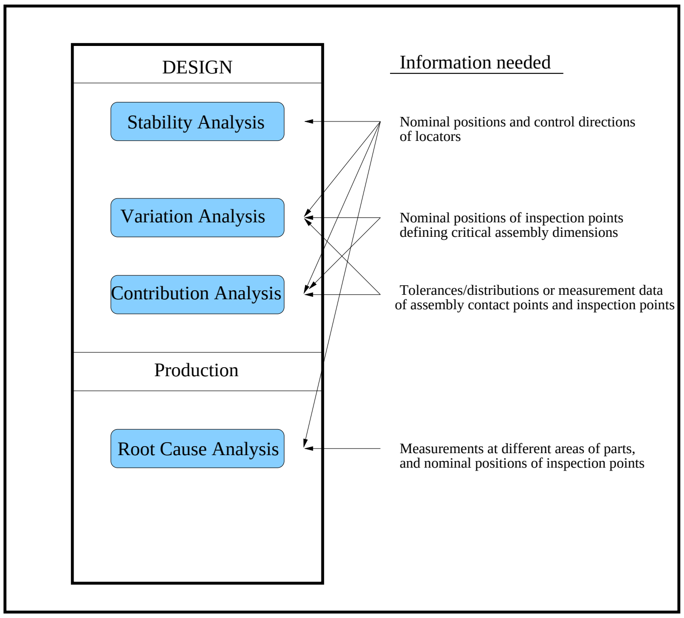


Figure 1.17: *Information needed for tools aimed at reducing geometrical variation in assembled products.*

based information flow and use of measurement data as a mean for reducing lead time in the product/production development process can be found in Wandebäck et al. [21].

The stability analysis only requires the nominal position of locators for parts and fixtures. Hence, the stability analysis can be based on only rough sketches of product/fixture geometry. To make the variation and contribution analysis we need, nominal position for inspection points and specified tolerances/distributions for individual part/fixture geometry at assembly contact and inspection points. Of course, measurement data describing the part/fixture geometry at contact points can be used instead of specified tolerances/distributions. To perform the root cause analysis we need measurements at inspection points localised in such way that all possible displacement can be discovered. This is described in detail in paper C and D.

1.5 Summary of Papers

A summary of contents is made for the papers in this thesis. In each summary, we discuss the subject treated and explain how problems are approached and solved. When applicable, these problems are formulated in terms of mathematics. No literature survey is given in the summaries, since this is done in the introduction of each paper.

1.5.1 Paper A: Locating Scheme Analysis for Robust Assembly Design

Although there exist an abundance of papers on tolerance analysis, relatively little attention has been paid to the problem of how to locate parts and assemblies in a geometrically stable and robust way. Since the selection of datums and locators has a major impact on the geometrical robustness of a component or an assembly, this is the natural step to be taken prior tolerance allocation and tolerance analysis.

The paper highlights the importance of robust locating scheme design and proposes methods and tools for component and assembly robustness design and evaluation. The way datums and locators affect the whole variation control process, from early design stages to inspection of the final product, is discussed. A structured work plan for incorporating robust locating scheme design into embodiment design is proposed. The work plan is shown in Figure 1.18 below. Methods and tools for locating scheme analysis are developed and presented. Sensitivity analysis and variation analysis are exemplified using a small assembly case. In particular, Monte Carlo simulation and the "matrix method" are compared for variation analysis. The methods and tools described support assembly product and process design and are general in the sense that they treat assemblies in the same way, independent of whether components belong to the product or to the assembly process or to a mix of both. The way variation propagates through assembly structures can and should be treated in the same consistent way.

1.5.2 Paper B: Quadratic Sensitivity Analysis of Fixtures and Locating Scheme for Rigid Parts

A linearisation of the positioning function is the basis for sensitivity analysis, whereas Monte Carlo simulation is traditionally used during variation and contribution analysis to capture nonlinear effects in assemblies. In the paper we present an explicit formula that gives a quadratic approximation of the displacement caused by a P-frame error. This quadratic approximation could be used instead of Monte Carlo simulations to save computer time and to make analytic investigations.

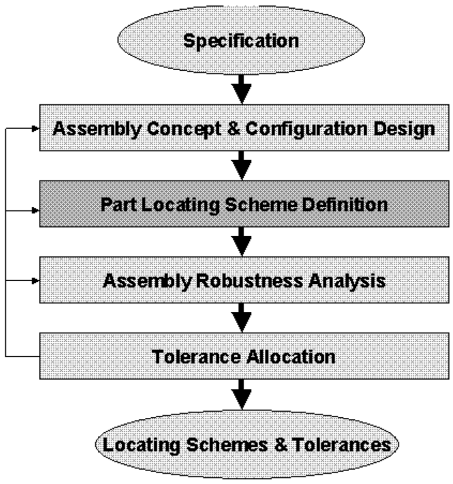


Figure 1.18: *Design process for robust assembly design.*

In particular, the quadratic approximation deals with locator contact at non-prismatic surfaces, non-small errors, locator error interaction effects and locator error in arbitrary directions, while the linear approximation does not. This is investigated through numerical experiments and mathematical analysis. Further, the gain in precision when using the quadratic instead of the linear approximation is examined. This can be used to determine if the linear theory provides enough precision, or if the quadratic theory should be used in the analysis of a specific locating scheme.

The significance of the quadratic approximation in industrial practice is where the linear approximation does not suffice for error evaluation and variation modelling. For small parts, such as the parts encountered in a mobile phone assembly plant, the dimensional errors in locators are relatively large compared to the dimension of the part and the linear approximation may be insufficient. Further, in some subassemblies the locators are realised by contact points from mating parts and these contact points can have relatively large dimensional deviation caused by long tolerance chains. A third situation, where the linear approximation does not suffice, occurs when the locators make contact with non-prismatic geometry. This can happen during the manufacturing of datum features, such as holes and slots, when it can be necessary to hold the part at surfaces with complex geometry. A Turbine airfoil is one example, since it has complex geometry and may be required to be fixtured at specific surface localisation.

Figure 1.20 shows an example of nonlinear effects in locating scheme analysis. The magnitude of the displacement of point **q** has been calculated, using the quadratic approximation, when locator 2 in Figure 1.19 is affected by errors in the Y and Z direction.

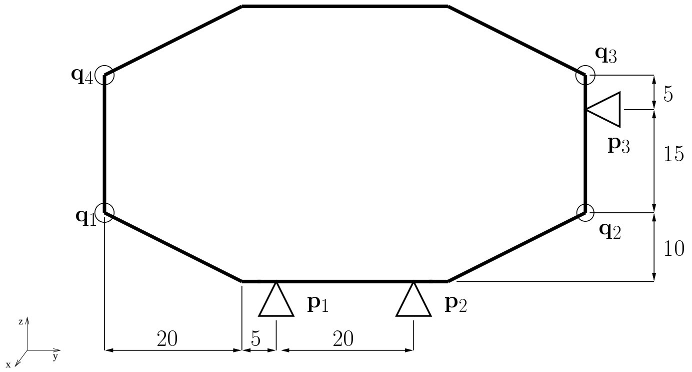


Figure 1.19: *A part positioned by a locating scheme [mm].*

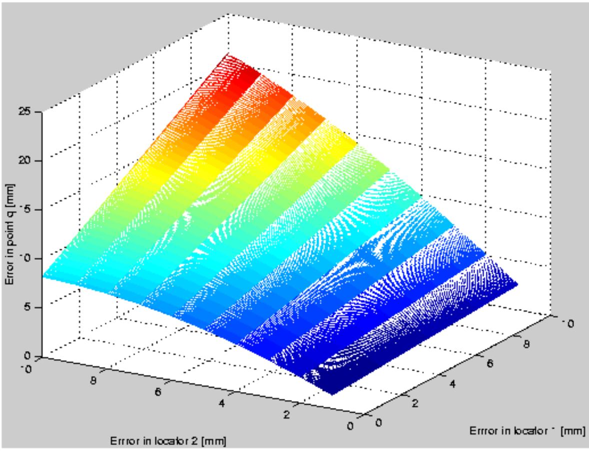


Figure 1.20: *Quadratic approximation of the displacement distance at point* $\mathbf{q}_1$ *caused by displacement of locator* $\mathbf{p}_2$.

Mathematical Framework

A key idea in the derivation of the quadratic approximation is that every rotation matrix can be parametrised by a rotational axis vector. In particular, notation and some calculations are facilitated by this. A function $\mathbf{F}$ is obtained from the geometric constraint Equations (1.1) by treating the rotational axis ω, the translation vector $\mathbf{t}$ and the locator errors ϵ as input variables,

$$F_i(\omega, \mathbf{t}, \epsilon) = S_i\left(R_\omega^{-1}(\mathbf{p}_i + \delta_i - \mathbf{t})\right) = 0, \text{ for } i = 1, 2, \ldots, 6. \tag{1.2}$$

The quadratic approximation is a second order Taylor expansion of the displacement $\mathbf{x}(\epsilon) = \begin{bmatrix} \omega^{\mathrm{T}} & \mathbf{t}^{\mathrm{T}} \end{bmatrix}^{\mathrm{T}}$. The existence of such a displacement function is guaranteed if the locating scheme and part geometry of the part provide a nonsingular Jacobian matrix $\partial\mathbf{F}/\partial\mathbf{x}$ at $(\mathbf{0}, \mathbf{0}, \mathbf{0})$. A locator layout with a nonsingular Jacobian is called a deterministic locating scheme. The Taylor expansion is derived in two steps. First, implicit differentiation of the equations $\mathbf{F}(\mathbf{x}(\epsilon), \epsilon) = \mathbf{0}$ is used to find formulas expressing the displacement derivatives of first and second order in term of derivatives that depend on the nominal locator positions and the nominal geometry of the part. Then some tedious calculations yield these latter derivatives.

A measure of the relative error between the linear and quadratic approximation is presented. It is defined as the mean square error of the difference between the locator error displacement effect at point $\mathbf{q}$ in direction $\mathbf{m}$ calculated with the linear and the quadratic sensitivity equation, divided by the mean square error of the latter. For locator errors that are independent and have a multivariate normal distribution an approximative formula for calculating the relative error is derived. In particular, for the case when locator errors have equal variance and an acceptable relative error is specified, an inequality which specifies whether a specific locating scheme should be analysed using the quadratic approximation rather than with the linear approximation is derived.

1.5.3 Paper C: Root Cause Analysis for Fixtures and Locating Schemes Using Variation Data

The existing literature on fixture diagnosis only considers single locator faults in an effective way. Further, it is limited to fixtures which use a pin/hole and pin/slot contacts. In this paper, a method for diagnosis of multiple coupled locator faults is presented. The method works for an arbitrary deterministic locating scheme, provided that an adequate inspection plan is used. Another advantage is that this method is suitable for theoretical analysis. For example, the effect of increasing the number of inspection points is easily investigated. From inspection data we estimate the variation in the contact points between the target P-frame and the part. By ranking the locator variation estimates, the root cause for part position variability is tracked down.

In practice, the methods based on a single locator fault assumption may confuse the process engineers. This is because, in some cases these methods erroneously point out a locator as the root cause where a multiple locator fault that does not include the locator pointed out is the real reason for position variability.

Mathematical Framework

The aim is to estimate the locator covariance matrix Σ_δ, when it is related to the measurement covariance matrix $\Sigma_{\mathbf{x}}$ in the following way,

$$\Sigma_{\mathbf{x}} = A\Sigma_\delta A^{\mathrm{T}} + \sigma^2 I.$$

The matrix A relates locator errors δ to the resulting displacements at measurement points, and the term $\sigma^2 I$ represents model errors and measurement noise. It is assumed that A is a full rank matrix. Whether this is satisfied or not depends on the number and location of measurement points. We use a three step procedure to find the locator covariance matrix estimator. First, the scalar σ^2 is estimated by using that every vector contained in the null space of A^{T} is an eigenvector of $\Sigma_{\mathbf{x}}$ with corresponding eigenvalue σ^2. Then, this estimate is used to separate out model errors and measurement noise. Finally, by applying the Moore-Penrose inverse the sensitivity matrix A is removed.

Two different methods for diagnosis are presented. Method 1 simply ranks the locator variances. In method 2 the locating failure diagnosis is performed by ranking the locators with respect to the total variation contribution in predefined inspection points. In this way, both locator sensitivity and possible couplings between locators affect the diagnosis.

The estimators derived for diagnosis in this paper, are in fact maximum likelihood estimators (Stoica and Nehoria [16]). However, this has come to the author's knowledge after the paper was written.

1.5.4 Paper D: Multi-Fixture Assembly Diagnosis Based on Part and Subassembly Measurements

In a multi-fixture assembly system, parts are joined using several positioning fixtures. Ideally, a sample of the parts is collected for inspection and the measurements obtained are used for control and adjustment of the manufacturing process. Then, after the parts have been joined in a multi-fixture assembly system a new sample of measurements are collected to control assembly station tools such as fixtures and welding guns.

A method for diagnosing dimensional errors caused by the assembly fixture system is presented in this paper. By a fixture failure control procedure the fixture fault related error is isolated. If the fixture error is significant then the error is explained, by using part and subassembly measurements, to be either a multiple locator fault in a specified fixture or to be a single locator fault in an unspecified fixture.

This methodology is new since it addresses multi-fixture assembly systems in contrast to previous research which has been focused on single fixture diagnosis. Compared to single fixture diagnosis we have to consider the following challenges, (i) it is more complicated to calculate a matrix relating locator errors to the resulting displacement at inspection points, (ii) a multi-fixture assembly system is never fully diagnosable since there exist infinitely many combinations of different locator variation and offsets that can lead to the same subassembly error, and (iii) the statistical knowledge about dimensional deviation is at two inspection levels.

Mathematical Framework

The fixture failure control procedure is carried out by estimating the proportion of disparity in data that originates from the fixture system. This is done by defining two fixture failure indices and deriving asymptotic confidence intervals for these. The fixture failure offset index compares the length of the offset contained in the column space of A with the the total length of the offset, in a metric compensating for different variation in different directions. The fixture failure variation index compares the amount of variation in the column space of A with the total variation. If one or both indices indicate a fixture failure, then the method of maximum likelihood is used for diagnosis.

More specific, we find the mean vector μ_x and the covariance matrix Σ_x that maximise the log likelihood function subject to constraints determined from the failure indices. For example, if only the fixture failure variation index shows evidence of a fixture problem then estimators for diagnosis are obtained by finding the locator covariance matrix Σ_δ and the scalar σ^2 that maximise

$$l(\mathbf{x};\Sigma) = -\frac{n}{2}\log\det(2\pi\Sigma) - \frac{n}{2}\mathrm{Trace}(\Sigma^{-1}S_x), \qquad (1.3)$$

where $\Sigma = A\Sigma_\delta A^{\mathrm{T}} + \Sigma_p + \sigma^2 I_p$. Stoica and Nehoria [16] present a closed form solution to this optimisation problem, assuming that A is a full rank matrix and that the part covariance matrix $\Sigma_p = 0$.

The conditions of the result by Stoica and Nehoria are not completely satisfied for the multi-fixture problem. Yet, the result is useful. To begin with the problem of rank can be solved in two ways. For instance, a priori process engineer knowledge can be used to find a full rank submatrix of A. Secondly, the part covariance matrix is almost removed by using a a linear transformation of the subassembly inspection data.

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Paper A

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Paper B

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Paper C

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Paper D

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