An Investigation of the Measurement, Fixturing, and Trimming of Large Sheet Metal Parts

by

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ABSTRACT

Stretchformed sheet metal part production offers many challenges in process improvement such as increasing flexibility and part accuracy while decreasing cost and cycle time. The Reconfigurable Tooling for Flexible Fabrication (RTFF) project addresses these issues.

This thesis investigates the measurement, fixturing, and trimming of large sheet metal parts. The objective of the thesis is to first present the current and alternative methods of three-dimensional measurement, fixturing, and trimming, especially for the RTFF project. Then, recommendations on the appropriate technology depending on the desired outcome can be made. Research show there are many potential technological changes that can be made to improve these current operations that encompass the sheet metal forming process.

Three-dimensional shape measurement is investigated in detail. The current technologies are able to measure large sheet metal parts but have many disadvantages. A promising method of three-dimensional shape measurement is being researched and developed using laser speckle wavelength decorrelation. This method is still in development but initial results show that this method will decrease measurement time, decrease the amount of precision hardware needed, and decouple accuracy with the range of the object. Many of these factors are disadvantages of current measurement systems.

A critical component of the promising measurement system is a precision linear actuator. A proposed design, consisting of cascaded solenoids and mechanical stops, is evaluated and shown to be unacceptable since commercial linear actuators perform the function more accurately and for lower cost.

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Chapter 1

Introduction[1]

The commercial aerospace industry produces many aluminum airframe skin components using the sheet metal stretchforming process. This process stretches a sheet metal blank to its yield point while forming, or after forming the part over a die. Conventional stretchforming requires a solid die for each unique part produced, resulting in large tooling inventories. The current process is inflexible, time consuming, and expensive.

The forces driving improvement of the stretchforming industry are lean manufacturing and precision assembly principles. Companies are cutting costs by reducing cycle times and the predominantly fixed costs associated with tooling. These fixed costs include tool design, fabrication, and material costs. Unnecessary tooling is being eliminated in an attempt to create lean processes. Moreover, the tooling requires considerable factory floor and storage space (Flinn, 1997).

Die design and development time add directly to new part lead time because the finished part drawing is needed to begin the die development phase. The average time required to produce an airframe panel die is 850 hours (J. Boivin, personal communication with R. Boas, 1996). This time consists of design, machining, trial, and

[1] Much of this chapter was derived from Boas (1997) due to the similar background of our two theses.

rework times and can extend new part lead time a few months past the final part design stage.

Along with reducing costs and lead times, there is a drive to increase quality. Aircraft manufacturers are becoming intolerant of part variations as they move away from trimming and shimming to reduce assembly variation and cost. Parts can no longer be forced into place; they must be as close to the desired shape as possible. Inaccurate components can actually cause slight warping of airframe structures, such as wings. Increasing part accuracy is also important for precision assembly implementation (Parris, 1996).

The Reconfigurable Tooling for Flexible Fabrication (RTFF) Project is a proposed improvement to these issues. This thesis is supported by and is part of the RTFF project. RTFF will increase the flexibility and precision of the stretchforming process while decreasing cost, cycle time, batch time, and lead time. The project's main thrusts are the development of a reconfigurable tool (discrete die), model-based tool design method, and closed-loop shape control system. The reconfigurable tool is a discrete die composed of many pins that can be moved independently to approximate a continuous surface. The tool design and control system consists of finite element simulation software coupled with a system identification control algorithm.

The RTFF program is also researching other supporting topics that will improve the quality of the final product. One topic is three-dimensional (3D), rapid shape measurement. Shape measurement is used to close the loop in the shape control system and to inspect the final product. Other topics include operations performed after forming such as fixturing, trimming, and chemical milling.

Airframe skin manufacturing was selected as a reconfigurable tooling test bed for two main reasons. First, a discrete die has limited shape resolution capabilities. Many outer skin components have mild single or bi-directional curvatures that meet this tooling constraint. Second, the tool offers the greatest potential cost reduction when implemented in small batch (less than 20 parts) production environments, like the aerospace industry. Commercial aerospace companies typically produce planes at the rate of 20 to 200 per year, typically toward the smaller end of this range (Parris, 1996). Targeting small batch production allows for maximum realization of reductions in part cycle time, batch cycle time, and die development time.

The objective of this thesis is to present the current and alternative methods for the 3D measurement, fixturing, and trimming of large sheet metal parts, especially for the RTFF program. The thesis begins with an overview of the stretchforming process and then describes the RTFF program and reconfigurable tooling. Afterwards, Chapters 4, 5, and 6 discuss 3D shape measurement methods and alternatives for the RTFF project are described. Alternative methods of 3D shape measurement will be presented to understand the capabilities and limitations of each method and of large-scale shape measurement in general. Sheet metal fixturing, drilling and trimming methods are then presented in Chapters 7 and 8, followed by a chapter on system integration. That chapter describes how the previous processes fit in a manufacturing system or facility. Finally, conclusions and recommendations will end the main body of the thesis.

Then there is a discussion in Appendix A of the design issues and analysis involved with the stepper, a device that is critical for the operation of a potential measurement system for RTFF. First there is a description of the design problem and then the proposed solution.

This document will be useful since it will be similar to an encyclopedia by listing potential solutions and issues related to large–scale, shape measurement problems. When the research began, it was difficult to find a comparison of the different methods of shape measurement. There are many sources of in-depth information on specific measurement methods. This thesis provides a survey of the different methods of measurement and underlying physics. The basic physics gives a picture of the advantages and limitations of each method. This, in turn, gives the engineer a foundation to continue his own investigation for his specific problem. Jais (1997) and City University (1998) are other sources of general information about shape measurement methods.

Similarly, the thesis will report on current solutions to the fixturing, drilling, and trimming problems for sheet metal. The section on the stepper design can be used as a starting point for further work on precision positioning devices.

Chapter 2

Current Stretchforming Practices[1]

2.1 The Stretchforming Process and Mechanics

Stretchforming refers to a process whereby a piece of sheet metal is clamped at its edges and stretched or pulled over a single tool or die. This is shown schematically in Figure 2–1 and Figure 2–2. The stretchforming process is well suited to part geometries having mild contours and no sharp edges. Double curvature parts can be formed if the part curvature is convex in the longitudinal axis while the curvature in the transverse direction can be either convex or concave. There can be no local maxima or minima in any longitudinal or transverse part section. This constraint is necessary to eliminate parts with pockets or islands, since those features can not be created with stretchforming. Acceptable part geometries include cylindrical, spherical, elliptical, and saddle shapes.

[1] Much of this chapter was derived from Boas (1997) due to the similar background of our two theses.

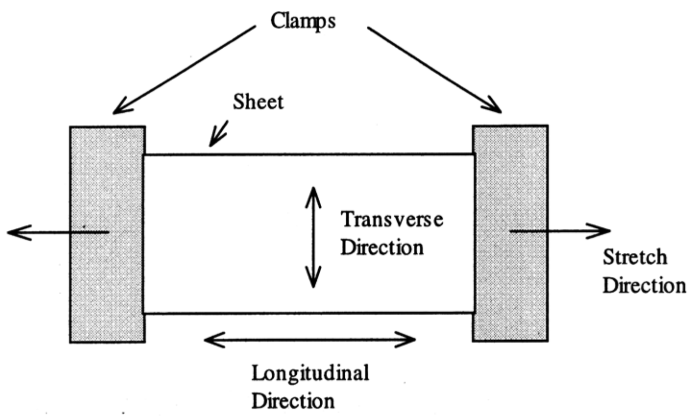


Figure 2–1: Top view of clamped sheet metal blank showing part directions (Boas, 1997)

Stretchforming offers the advantages of lower springback in formed parts, the use of one die instead of a matched set (as in stamping), and improved part material properties through strain hardening over other forming methods. Springback is the change in shape caused by elastic unloading of the part when the forming forces are released. It is difficult to control since springback depends on material properties, such as yield strength and thickness that can vary from sheet to sheet or lot to lot. Therefore, one goal is to minimize springback even when properties are unknown. Section 2.2 will discuss springback in more detail.

There are two basic types of stretchforming processes: drape forming and stretch–wrap forming. Drape forming pushes the die into a piece of sheet metal and then stretches the sheet to a predetermined stress state (a “post–stretch”). This stress state is nonuniform along the longitudinal the sheet because of friction between the sheet and die. For an axisymmetric part shape, there is actually a significant stress gradient, which adds to springback, in the longitudinal sheet direction with a minimum value at the center of the die.

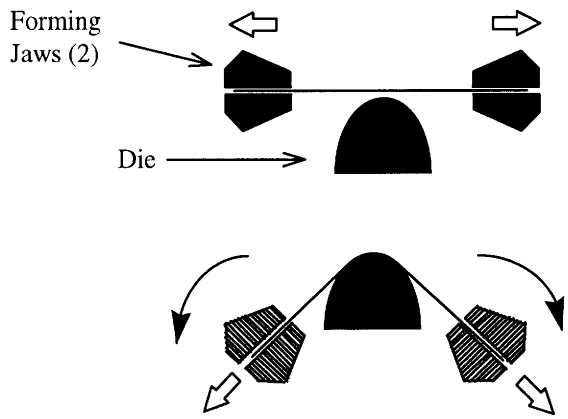


Figure 2–2: Stretch–wrap forming process (drawing by Valjavec)

Stretch–wrap forming places an initial tensile stress in the sheet before moving the die into the sheet (a "pre–stretch"). This state of stress (at or near the material's yield point) is maintained throughout the forming cycle. After the die has been moved to its final position, the forming force is normally increased to provide a post–stretch. The stretch–wrap forming process is illustrated in Figure 2–2.

The main advantage of stretch–wrap forming over drape forming is the use of a pre–stretch. The pre–stretch leads to a more uniform stress distribution throughout the sheet and less springback. Pre-stretching first reduces the effect of friction between the part and die (Parris, 1996). Drape forming wraps the sheet completely over the die at essentially zero axial stress creating a stress gradient based on the post–stretch load only. Stretch–wrap forming, on the other hand, wraps the sheet under the pre–stretch load, producing a stress gradient based on the difference between the post- and pre–stretch loads. For any nonzero pre–stretch load, the stretch–wrap gradient is reduced significantly, providing a more uniform stress distribution throughout the sheet.

Post–stretching a sheet introduces an additional tensile plastic strain in the already stretched sheet metal part when more force is applied. The resulting strain further deforms the part, thereby eliminating plastic bending strains, which translates into a reduction of springback when the part is released from the forming jaws.

2.2 Springback in Stretchforming

Springback refers to the change in shape caused by elastic unloading of the part when the forming forces are released. For stretchforming, the part curvature is decreased from a stretched condition (die shape) to the final condition. The effect of springback on a simple part can be seen in Figure 2–3.

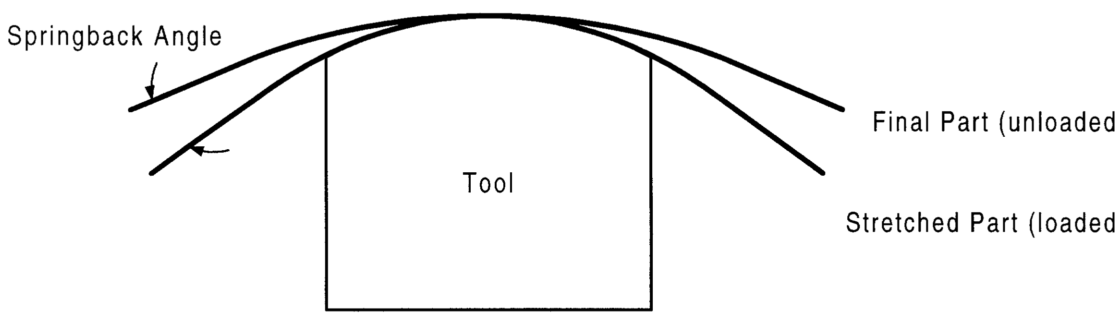


Figure 2–3: Springback in a simple sheet metal part

A brief explanation of springback mechanics is given below. For a detailed analysis refer to Parris (1996). This explanation assumes an elastic, perfectly plastic stress–strain relationship for the material (shown in Figure 2–4) and a cylindrical die shape with no friction. If the sheet blank is formed using the drape forming process, it will be wrapped with a stretch force of almost zero, creating a pure bending strain distribution in the sheet after bending as shown in Figure 2–5. The stresses caused by these strains will create a moment on the sheet metal. When released, the part springs

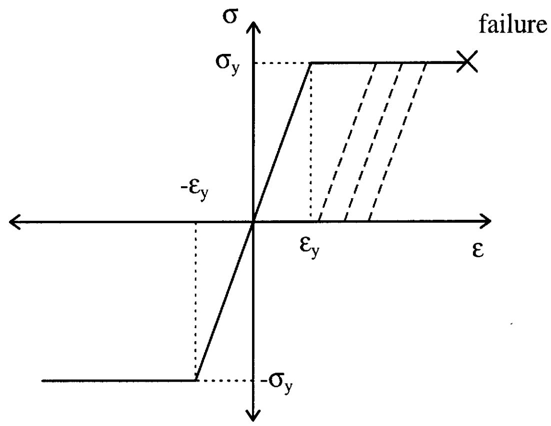


Figure 2–4: Generalized elastic, perfectly plastic stress–strain curve (Parris, 1996)

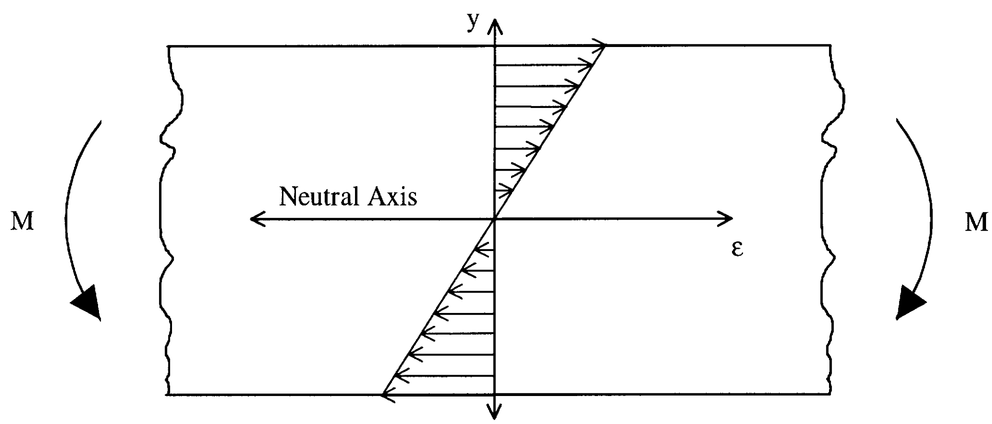


Figure 2–5: Strain distribution in a beam after pure bending (Parris, 1996)

back, this moment returns to zero, and the part returns to equilibrium. If the deformation incurred during forming is completely elastic, the part will return to its original shape, a flat sheet.

The post–stretch operation is an attempt to counteract the effects of the resulting bending moment. If the moment can be forced to zero in the loaded condition (part loaded and formed over die), springback is totally eliminated. Ideally, a strain equal to two times the yield strain, $2\varepsilon_y$, will be applied to the part after it has been wrapped over the die. This forces all stresses in the sheet after the post-stretch to be equal to the yield stress, σ_y, thereby eliminating the moment. This is shown in Figure 2–6.

For the idealized elastic, perfectly plastic stress–strain curve, springback can be totally eliminated by straining all areas of the part to ε_y. However, this is not the case in actuality. The actual stress–strain curve only approaches the perfectly plastic (flat) region. Moreover, the individual stress–strain curve for each piece of sheet metal will be different. Therefore, there will always be a varying combination of elastic and plastic deformation, resulting in a moment that causes the part to springback. To minimize springback, the part must be strained as close to its breaking strain as possible. The stretch press operator is constantly trying to approach the breaking strain of the part. His experience and some visual cues are the only insurance against breaking parts.

Most forming processes control the force applied to the part, which can result in problems because of the nature of stress-strain behavior. Referring back to the elastic, perfectly plastic curve, yield stress does not correspond to a unique value of strain as shown in Figure 2–7. After the yield point is exceeded, the applied force has no control over strain. If the stress is greater than σ_y, the sheet will elongate until it breaks, while a stress lower than σ_y will not deform the part plastically. The true stress-strain curve has

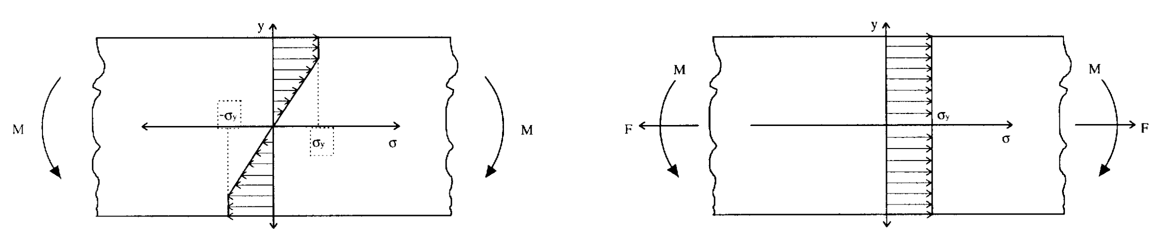


Figure 2–6: Pure bending stress and post-stress distribution in sheet (Parris, 1996)

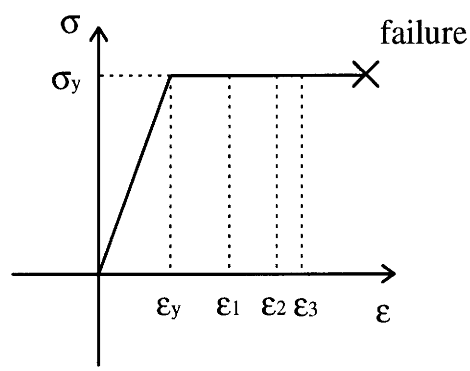


Figure 2–7: Beyond σ_y, no unique value of strain corresponds to yield stress

an asymptotic region after the yield point instead of the level region depicted in Figure 2–7. The actual material behavior after reaching yield is not as severe as in the idealized case, but the relationship is still extremely sensitive to slight changes in stress. For this reason, strain is the proper process variable to control.

Strain control research has been conducted with noticeable improvements in part precision (Parris, 1996). Strain control requires the placement of strain gages on the part surface, creating a new feedback loop and, therefore, a more complex system. Manufacturing processes continue to use force or displacement as the stretchforming input because it is easier to control and implement.

2.3 Part Design

Stretchformed parts are usually designed for performance first, then for manufacturability. The part is represented by a series of drawings, some electronically in CAD, others simply by detailed drawings.

In recent years, parts are being designed with certain key characteristics (KCs). "KCs are the critical features on the parts and assemblies that most affect the function, safety, or customer satisfaction of the product" (Cunningham, Mantripragada, Lee, Thornton, & Whitney, 1996). These characteristics must be accurate since they are usually used in assembly. The other areas of the part do not have to be as accurate since they are non-critical. A standard "tolerance" for stretchformed parts is ±0.030" but the real accuracy needed highly depends on the assembly method and design philosophy (Parris, 1996). "Tolerance" is actually an ambiguous term and will be discussed in more detail in Section 4.3.

2.4 The Stretchforming Phase of Part Production

Figure 2–8 is a typical process flow diagram for stretchforming of sheet metal parts. Many of the operations are stretch press operator dependent, including the actual forming cycle. The operator decides how much forming force or displacement to apply based on previous experience. Visual inspection of the sheet surface during forming is used to adjust these parameters. Many times, the forming cycle is a series of iterations. The operator visually inspects the part after each iteration to determine if the part has sprung back too much. If so, another forming iteration is performed.

While operator judgment errors affect part quality and consistency, they can also cause catastrophic sheet failure. Breaking a sheet causes equipment damage and the potential for operator injury. Unfortunately, the ideal stopping point for the forming cycle is just before part failure. The operator is constantly trying to strain the part as much as possible to reduce springback, making adjustments that make the difference between breaking a sheet and forming a good part.

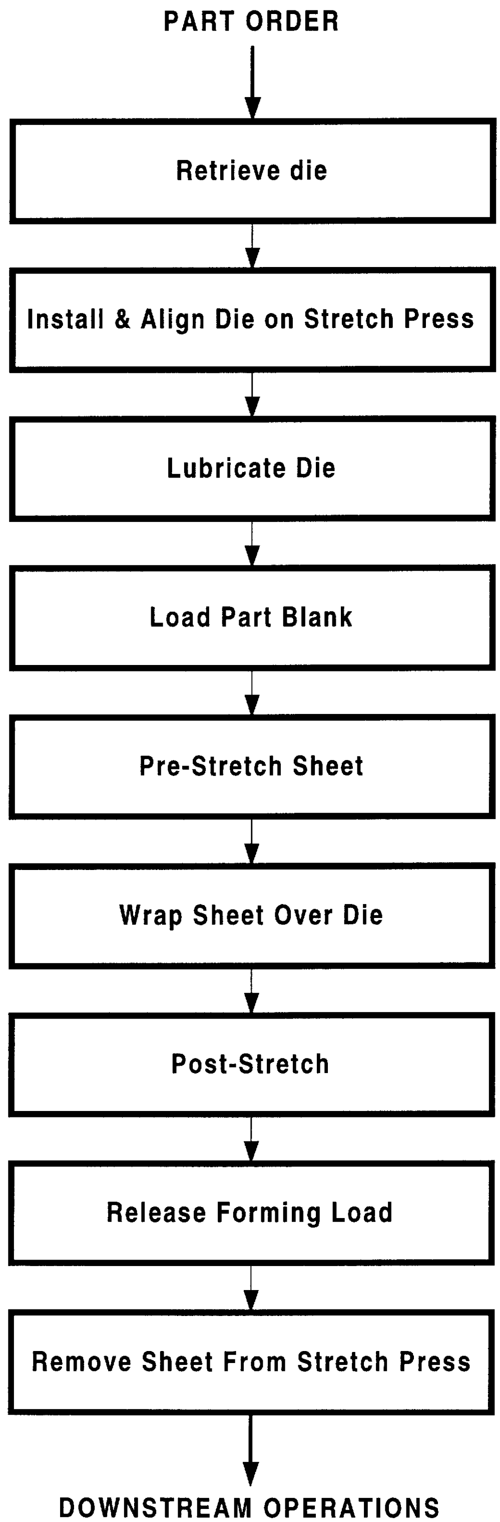


Figure 2–8: Typical stretchforming phase of part production with post-stretch

2.5 Die Design and Construction

Inability to accurately model springback effects in the stretchforming process and downstream operations has made die design an art based on designer experience. Figure 2–9 depicts the typical die design procedure. The die designer generates machining toolpaths directly from the part drawing. In other words, the resulting die will be the net part shape when finished. A net shape die only serves as a reasonable die design starting point and will never create a proper part due to the effects of springback, friction between the die and part, and processes outside the forming cycle such as chemical milling, trimming, and drilling.

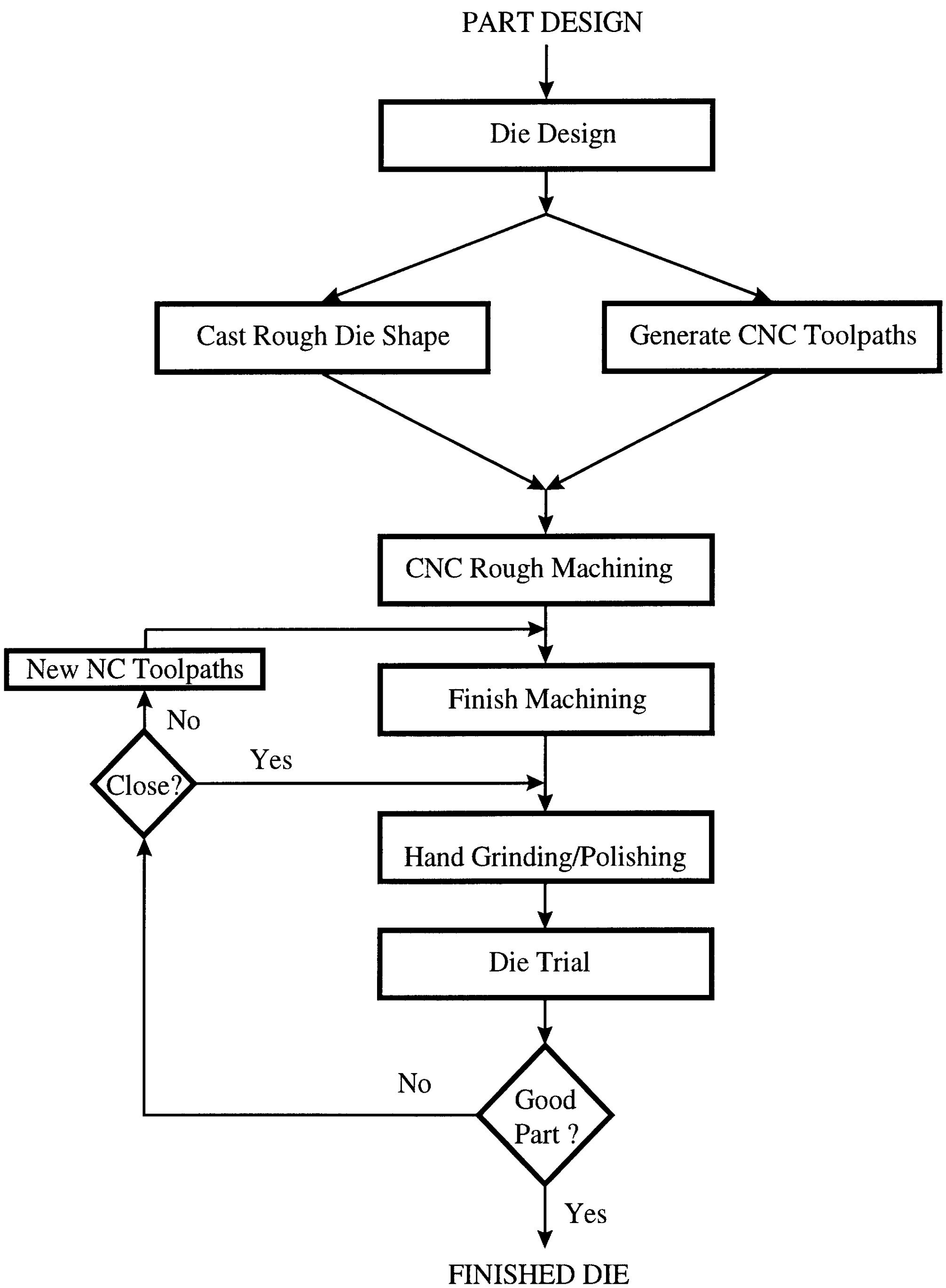


Figure 2–9: The die design process (Boas, 1997)

After creating an initial design, the die is typically CNC machined from a block of kirksite, an easily machinable material. Due to the low volume requirements of the aerospace industry, this will be the final die used for production. Mass production industries will machine the die out of a harder material such as tool steel, alloy steel, or carbide when the die design stage has been completed. The harder die will resist the wear of high volume production. For instance, cemented carbide tooling can be used for up to one million cycles (Walczyk, 1996).

The machined die is then taken to the stretchforming press and used to form a part. The part is then compared to the desired part or a check fixture. The die designer uses this comparison to generate new toolpaths to modify the die. The die will be re-machined and tried again. The important rule in die development is to always undercut the die. "Undercutting" is the procedure of removing less than the expected amount of metal from the die. This act of conservative machining prevents the destruction of a die during the development phase. This process is repeated until good part is created. In some cases, if too much material is removed, the die can be salvaged by welding extra material to the die.

2.6 Fixturing, Drilling, and Trimming

After the forming is complete, the operator unloads the part from the stretch press grips and inspects it visually. Since the die was lubricated, the part needs to be degreased to remove the residual lubricant. If the part needs to be heat treated, the appropriate steps are performed. Afterwards, the part is ready for fixturing, drilling, and trimming.

The basic tool used is the Hand Routing Fixture (HRF). One is shown in Figure 2–10. The HRF is a dedicated fixture for each unique part. It consists of a holding fixture and a drilling guide that perfectly mate with a perfect part. The formed part is placed on the HRF (or the holding fixture on the figure) and the part is drilled and

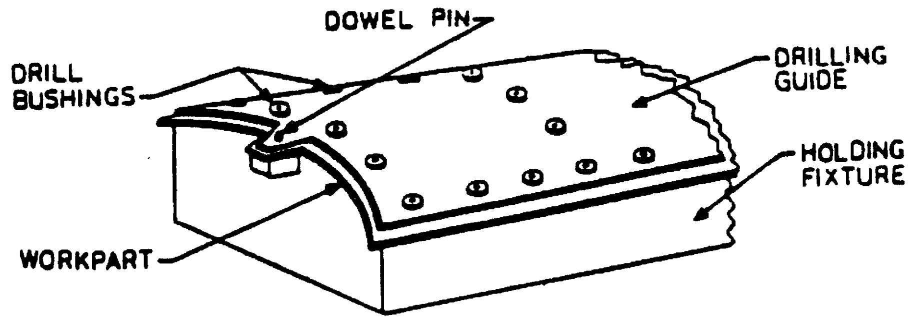


Figure 2–10: A hand routing fixture

trimmed. The HRF also is used as a check fixture. If the part fits on the fixture, then the part is acceptable.

The first step in creating a HRF is to use the die to create two perfect parts. A part is subjectively considered perfect if it conforms to the drawing and fits well in downstream assembly operations. One part, the master, is stored in archives, and the other is a sample that follows the HRF and is used for comparison. Plaster is splashed onto the master. The plaster "splash" is used to create the HRF, which is made by composite layup. Therefore, if the part fits snuggly over the HRF, which is the same shape are the plaster "splash," the part is the correct shape. No more measurement is required but a dedicated check fixture (the HRF) is required for each part.

The HRF has a few extra features to assist in manufacturing. The HRF has holes to accept dowel pins. These dowel pins go through the drilling guide, workpart, and the holding fixture. The dowel pins go though the “dog ears” that added onto the part geometry. “Dog ears” are simply two tabs that are used for positioning. They are

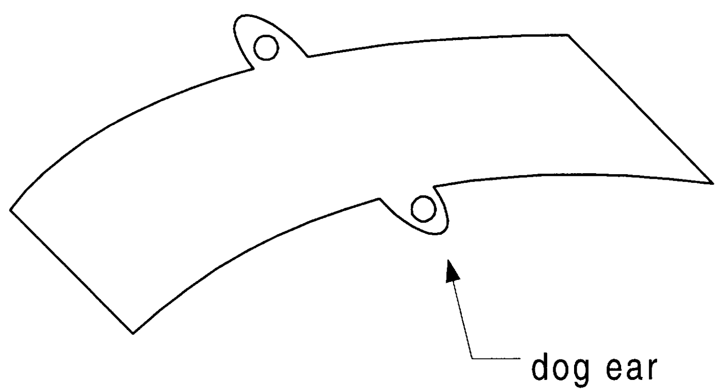


Figure 2–11: Part with "dog ears"

removed for final assembly. “Dog ears” on a part are shown in Figure 2–11

Once the drilling guide, workpart, and holding fixture are aligned, holes can be drilled by using a hand drill. The operator uses the drill bushings as guides.

The driling guide also has an offset on the perimeter. This allows the operator to use a hand router to trim the part while using the HRF as a guide. This offset takes into account the geometry of the router bit and guide.

2.7 Final Inspection

Final part inspection is based on the force needed to conform the part to the HRF or the assembly since the part rarely fits perfectly without applying some assembly stress. Usually, sandbags of known weights provide this force. They are placed on top of the part, and the weight corresponds to an allowable assembly stress for the part. Operators have been known to use a mallet to manually force the part into compliance.

Chapter 3

Overview of RTFF[1]

3.1 Description of the RTFF Project

The Reconfigurable Tooling for Flexible Fabrication (RTFF) project combines a reconfigurable tool with a model-based tool design and closed-loop shape control system. RTFF improves forming process flexibility and accuracy, while reducing cost and time. For a general interest article about RTFF, please refer to Flinn (1997).

Figure 3–1 shows the process layout of the RTFF system. The tool design and

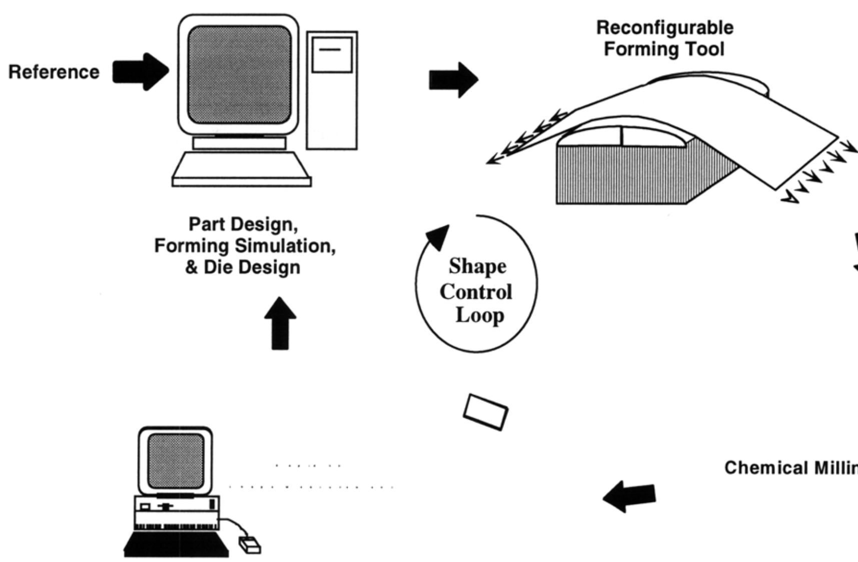


Figure 3–1: Flexible stretchforming process as defined by RTFF (drawing by Valjavec)

[1]Much of this chapter was derived from Boas (1997) due to the similar background of our two theses.

control loop starts in the upper left corner of the drawing.

For a given desired part shape, the initial die shape is produced by a forming process simulation, instead of using the conventional net shape die as a starting point. This model is an ABAQUS™ based finite element simulation that uses a "springforward" algorithm (Boyce & Karafillis, 1995). Model inputs are the desired part shape, sheet metal material properties, interpolator (described in brief below) material properties, forming loads, and stretch press motion trajectories. The model output is an initial die shape that should produce the correct part shape.

After an initial die shape is generated, it is decomposed into a discrete pin height matrix and sent to the reconfigurable tool for a forming trial. This tool has a 4x6 foot plan form and uses a 42x64 matrix of independently movable discrete pins, of 1.125x1.125" cross section and hemisperical ends, to approximate the desired 3D die surface. The key word is "approximate." Ideally, this die is to replicate a conventional die exactly. To do this, the discrete pins need to be infinitely small. Practical size limits and cost requirements place a lower limit on the size of the discrete die pins.

The finite pin size (1.125x1.125" cross section) means that the sheet metal contacts discrete pin locations during the forming process, creating an uneven pressure distribution over the sheet. A sheet of polymer-based interpolator is used to prevent dimpling and tearing of the sheet metal part by more uniformly distributing the discrete pin forces. Currently, this layer is Elvax 360, a high durometer material, with two layers of Teflon between the sheet metal and interpolator. The Teflon sheets are used to reduce friction between the part and die. The lowest coefficient of friction exists between the two sheets of Teflon, meaning relative motion between the die and part will occur at this interface. Eigen (1992) conducted initial research on interpolator materials. He found that Elvax is a much better interpolator than neoprene. Elvax is tougher, harder, and can be softened and formed to the discrete die surface, if necessary.

To ensure an accurate final part at assembly, operations subsequent to forming are included in the RTFF shape control loop (described below). After forming, the part is trimmed and drilled on a separate, reconfigurable fixture. This fixture ensures maximum process flexibility by totally eliminating hard tooling in the RTFF concept.

The part is then chemical milled (Narisaranukul, 1997), which is a process of removing metal from the part with the aid of etching chemicals. Masks are placed on the part to protect areas that are not to be milled. The exposed areas are etched at a rate determined by part material properties, the chemical solution tank composition, and temperature.

Next, the part is measured using a rapid shape measurement system. Currently, CMM's are used to measure parts, with measurement times on the order of hours. A new rapid measurement system is being developed as part of RTFF. This system is optics–based and has a part measurement time goal of under ten minutes. Speed is important because the data is used to close the shape control loop.

If the forming simulation were perfect and input properties were constant, good part production would start with the first part made. Unfortunately, this is not the case. Material properties vary from batch to batch. Also, the current springforward algorithm does not include the effects of the chemical milling, trimming, and drilling operations. The shape control loop is needed for this reason. The forming simulation produces a die shape that is very close to the correct shape, then the shape control algorithm fine tunes the die shape to account for model discrepancies and in–process variation.

The actual shape control algorithm is a system or model identification approach and is termed the Deformation Transfer Function (Figure 3–2). The Deformation Transfer Function (DFT) estimates the system transfer function by comparing two parts in the spatial frequency domain.

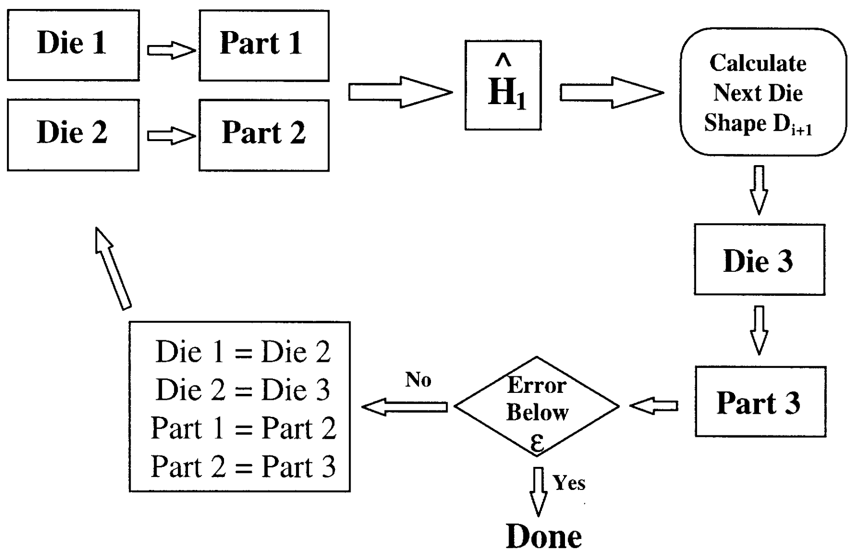


Figure 3–2: Deformation Transfer Function (drawing by Valjavec)

The spatial frequency based control system (Webb & Hardt, 1991) uses two previous forming iterations with different die shapes to predict the next die. Currently, Die 1, D_{i-1}, is the desired part shape (adjusted for the interpolator thickness) and Die 2, D_i, is the initial die shape generated by the forming simulation. The two measured parts produced by these die shapes are Part 1 and Part 2, denoted as P_{i-1} and P_i. The two die and part shapes are transformed into the frequency domain using a Discrete Fourier Transformation. The next (new) die shape, $D_{i+1}(\omega_1, \omega_2)$ is then produced using Equation

3.1. This equation sums the current die shape, $D_i(\varpi_1,\varpi_2)$, with the shape error, $R(\omega_1,\omega_2)-P_i(D_i(\varpi_1,\varpi_2))$, multiplied by the DTF. The shape error is the difference between the reference or desired shape and the part shape obtained using the current die shape. An Inverse Fourier Transformation is used to convert the new die shape from the frequency domain back to the spatial domain.

$$D_{i+1}(\omega,\omega_2)=D_i(\varpi_1,\varpi_2)+(R(\omega_1,\omega_2)-P_i(D_i(\varpi_1,\varpi_2)))\left(\frac{D_i(\omega,\omega_2)-D_{i-1}(\omega,\omega_2)}{P_i(\omega,\omega_2)-P_{i-1}(\omega,\omega_2)}\right) \tag{3.1}$$

A part will be formed with the new die shape, D_{i+1}, and then measured. The error between the new part, P_{i+1}, and the reference part, R, is computed and compared to the stopping criterion, ε. If the error is less than ε, the die design process stops and D_{i+1} is the correct die shape. If the error is larger than ε, a new die will be calculated. The two "newest" dies and their associated parts are used for each subsequent iteration of the controller (bottom left of Figure 3–2).

Initial convergence tests (Grodzinsky, 1996) show the shape control loop to converge in four forming cycles for a simple curvature part. The first and second dies were 90% and 110% of the reference shape. The springforward algorithm can make a better initial estimate, which has been shown to reduce the necessary number of iterations performed by the DTF (RTFF 12th Quarterly Meeting, February 6, 1998).

3.2 Advantages of RTFF

RTFF offers many improvements to sheet metal manufacturing. The discrete die reduces fixed tooling costs by eliminating hard tooling; creating a savings in material, machining costs, storage space, and labor. Physical operations are replaced by computer technology. Simulation software and a closed-loop control system replace an experience-based die development and machining phase. Development time reduces to the time required to run simulation software, stretchform a small number of parts, and measure parts between iterations of the controller. The die shape is now stored in a data file rather than being embodied in a block of metal that must be stored and handled manually.

While reducing cycle times, lead times and costs, reconfigurable tooling also has the potential to significantly improve part accuracy and repeatability through a reduction of in–process variation. Unlike the manual die development and part production methods currently employed in industry, the DTF creates a true closed-loop process. Closing the loop around die design allows for improved part accuracy. The DTF can also be used as a genuine process control tool. For example, batch to batch material property variations can be rejected. Rapid (almost "in–process") part measurement allows tooling offsets to compensate for process variable changes, similar to tool offsets used to compensate for tooling wear on a lathe or milling machine.

One of the needs of RTFF will drive a quality improvement in the airframe skin industry: the need for numerical tolerances on sheet metal part shapes. The DTF requires quantitative rather than qualitative part inspection. A true measure of the necessary part conformance is needed to determine the shape control loop's stopping criterion. This will be discussed further in Section 4.3.

RTFF technology also offers potential advantages in solid die construction. Similar to reconfigurable die shape development, the simulation software will allow for rapid die development, reducing costs and associated times. Unfortunately, the inherent inflexibility of the conventional process will still remain since the die can not be altered in–process to account for process variations.

3.3 Limitations of RTFF

While reconfigurable tooling offers many advantages and improvements to conventional stretchforming, it also has a serious limitation, forming resolution (Ousterhout, 1991). Parts with high frequency content can not be formed because of the discrete nature of the tool. A car door panel is one example of an impossible stretchformed part. The resolution problem exists for any discrete die, not just for stretchforming operations. This means that a RTFF version of matched discrete die forming (stamping) will have resolution problems and would not be well suited to automotive industry applications. As mentioned previously, the resolution issue is the primary reason for targeting airframe skin components.

Ideally, one tool would be capable of manufacturing every stretchformed part. Again, because of limited resolution and the wide geometrical variation in part characteristics, a small number of reconfigurable tools are needed to cover a large number of parts. A specific reconfigurable tool targets part families. For example, the first RTFF prototype tool is not able to form leading edge parts due to their radical geometry (high pull-off angle or end slope). With the current discrete pin configuration, the high frequency components of these edges would require extremely small die pins to achieve the required shape fidelity. However, applying RTFF technology to other part families is a natural extension of the research.

Chapter 4

Three-Dimensional Shape Measurement Overview

4.1 Differences Between 2D and 3D Measurement

There are many differences between 2D and 3D measurement. The basic vocabulary is the same but there are new terms when using non–contact methods that are described in Section 4.2. There is a different method of determining acceptable parts and many of the principles used in 2D measurement are not relevant in 3D measurment. Therefore, this Chapter attempts to explain some of the basics of 3D shape measurement.

4.2 Imaging and Gaging Vocabulary

In metrology, there are many terms that are often misused or cause confusion. To start, "gage" is the correct incorrect spelling of "gauge." A gage is a standard for measurement or instrument for measuring or testing. The next three terms, accuracy, repeatability, and resolution are related. Accuracy is the ability to tell the "truth" or the maximum error between any two points being measured. Repeatability or precision is the ability to tell the same "story" over and over again. It is also the maximum error between measurements or moving to the same point. Resolution is the minimum discernible difference or the lower bound on repeatability (Slocum, 1992).

Most vendors quote the accuracy of their system and "high accuracy" is valued. For example, sensor A might be quoted to be accurate to ±1 inch and might be considered better than sensor B, quoted to be accurate to ±1.5 inches. However, the meaning of those specifications is ambiguous. Often people believe the accuracy range is how far the measurement can be from the actual value. For example, let a sensor, with an accuracy of ±1 inch, measure an object. If the sensor outputs a value of 100 inches, the general assumption is the object can be anywhere from 99 to 101 inches or 100±1 inch.

The previous assumptions are incorrect. Usually, the sensor output is a normal (bell–shaped or Gaussian) distribution centered about the actual value. The sigma represents the standard deviation or the amount of spreading of the bell curve. A higher value of sigma implies there is more variability of values. Likewise, if sigma is low, the sensor output is very tightly grouped around the actual value and gives data that is more certain.

Generally, vendors quote the "one–sigma" (1σ) accuracy, which means 68% of all measured points will be accurate to that specification, under the best conditions. These are the normal assumptions. Others quote "two–sigma" (2σ) accuracy, which generally is twice the 1σ accuracy and means 95% of all measured points will be accurate to that specification. Therefore, sensors A and B can not be properly compared without more information. Strangely enough, many vendors either do not know or will not reveal how they measure accuracy.

In our previous example, if the ±1 inch accuracy is a one–sigma accuracy, we are 68% confident the actual length of the object is between 99 and 101 inches and 95% confident the actual length is between 98 and 102. However, there still is a probability that actual length is not within the 98 to 102 inch range. One can only be 100% sure the length is between zero and infinity, but that information is not very useful. So, as the confidence level goes up, so does the range of the possible lengths. Therefore, the end result is that sensors with "higher accuracy" (or a smaller value of sigma) give data that is more certain or often called "more accurate."

As a side note, even if the sensor output is not normal, the same analysis can be applied. However, many sensor outputs must be taken and analyzed. Generally five to twenty data points can be considered "many," but that number is dependent on the distribution of the sensor itself. That is because the Central Limit Theorem states that as many individual outputs are taken, though the individual outputs many not be from a normal distribution, the data as a group will tend to follow a normal distribution.

Normally gages are valued for their high accuracy. However, repeatability should also be valued. For example, a gage may not be accurate, but can be very repeatable and useful. One example is a force sensor that is always reads 10% higher than actual. Though there is a consistent error, the error can be isolated and be taken into account.

If the sensor is neither accurate nor repeatable, there are more problems. These errors can be either systematic or random. A systematic (or bias) error is like the error with the force sensor above. Generally, these errors occur the same way each time a measurement is made and therefore are predictable. These errors bias the results in one direction. These errors can not be minimized with statistical techniques but are often resolved with calibration.

Random errors are precision errors. They are caused by a variety of sources, are different each time, and can be minimized, but usually never eliminated. Random errors are unpredictable. Therefore, the probability distribution of these errors are important since the errors may be averaged out.

Three-dimensional optical imaging techniques have a set of terms that describe some of the characteristics of the sensor. The definitions are found in Table 4–1 and illustrated in Figure 4–1.

Table 4–1: Terms used in 3D imaging

Term	**Definition**
Range	Direction parallel to the measurement axis of the sensor
Cross range	Direction normal to the measurement axis of the sensor
Standoff	Minimum range from the sensor at which objects can be measured
Depth of field (DOF)	Distance between the standoff and the maximum measurable range of an object
Field of view (FOV)	Maximum cross range extent of the object

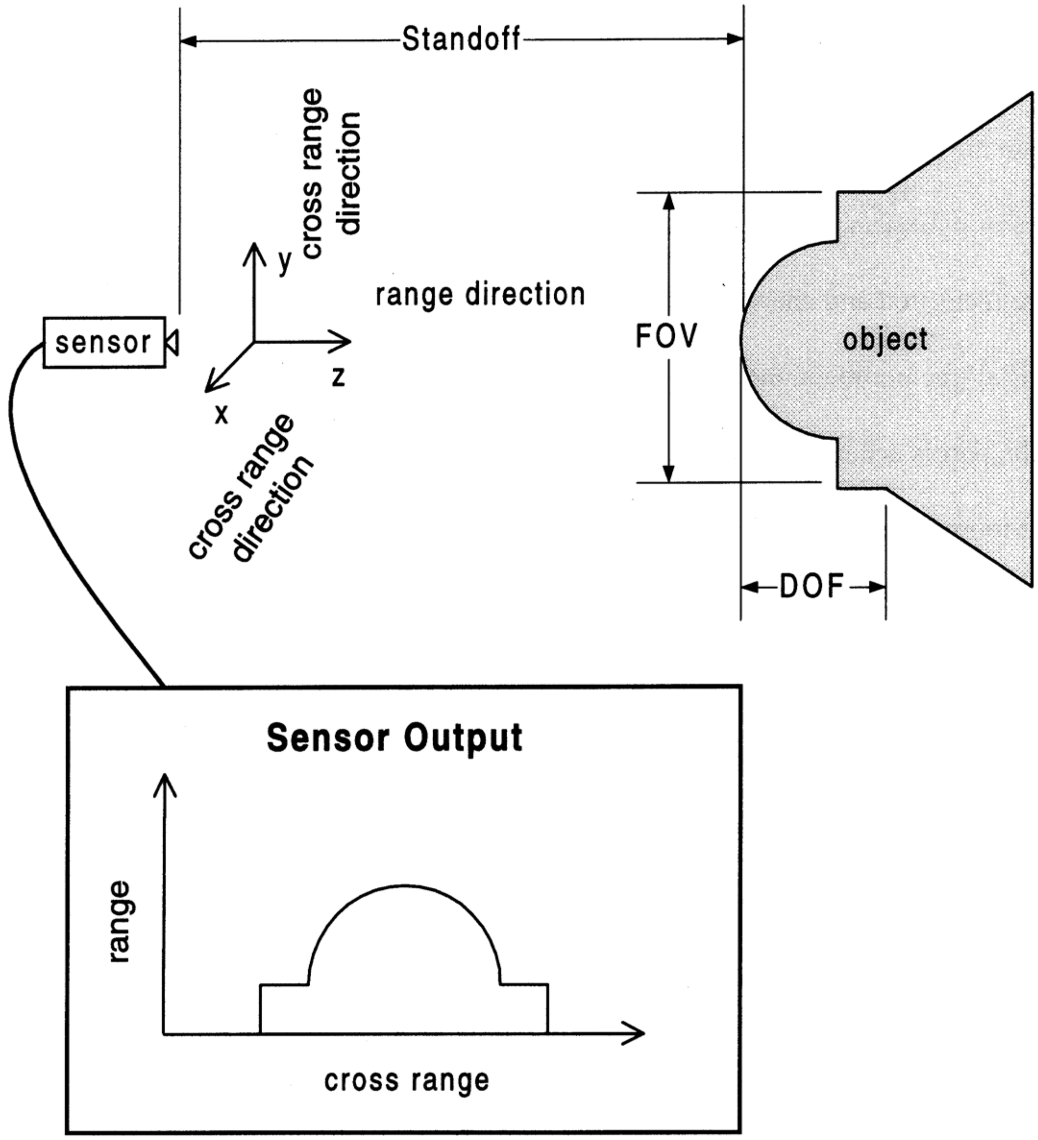


Figure 4–1: Illustration of terms used in 3D imaging

4.3 Tolerances, Accuracy, and Acceptable Parts

As described at the end of Section 3.2, RTFF is attempting to apply some type of numerical tolerances on sheet metals parts to define an acceptable part. This is critical since the DTF requires a quantitative rather than qualitative measure of “acceptable.” This determines the shape control loop’s stopping criterion.

4.3.1 Prismatic Part Gaging

Conventional gaging works well with prismatic parts and not so well for sheet metal parts. Prismatic parts are typical of most machined parts. They generally contain prism–type shapes or cylinders. Lengths of sides, locations of holes, angles of surfaces, or other features are measured and characterized by a number that can be compared with the part drawing. If all the numbers, the measurements, are within the tolerances specified in the drawing, the part is acceptable.

For more demanding applications, geometric tolerancing (ANSI Y14.5M-1982, R1988) can be used. Geometric tolerancing provides a "comprehensive system for the accurate transmission of design specifications" (Green, 1992). Actually, geometric tolerancing does not properly apply to sheet metal but is excellent for prismatic parts. The designer can convey his design intent, such as parallelism, on the drawing and have the part gaged for that feature. At the end, there still is a numerical metric that is used to compare the actual part with the drawing.

4.3.2 Matching Sheet Metal Parts with Drawings

This next section is about matching sheet metal parts with drawings. In other words, how is a perfect part compared with its drawing?

In some applications, certain critical points are the only features of the part and the drawing that are compared. These points are key characteristics (KCs), or critical features on the part and assemblies that most affect the function, safety, or customer satisfaction of the product (Cunningham et al., 1996). The number of these checkpoints can vary from a few to dozens. If these KCs are being measured, the part can often be treated as a prismatic part and standard tolerancing and gaging can be used.

However, the situation is more difficult if there are contours to measure. This problem is prevalent in boats, planes, cars, and even consumer products. Historically, shipbuilders represented their hulls with a series of cross sections down the length of the hull and a side view of the hull. This method is being used today as well but comparing the formed part with the drawing is still difficult.

Direct comparison, of course, works but normally only a few points are measured and compared to check points on the drawing. This is similar to the KC concept. Ideally, the entire curve should be measured, but problem now is converting a continuous curve into a set of discrete points that accurately describe the curve. This is similar to A/D (analog to digital) conversion with signals. Practically, the contours are characterized by measuring or sampling at a discrete point spacing, or a n x m grid of points. The density of the grid is a critical factor in accuracy. More data is generally better since more data allows for averaging and gives more raw information. At the same time, too much data can be impractical to acquire and handle.

For example, some tool and die makers require a 0.004" grid spacing to reverse engineer their product. Some aerospace application require a similar level of details, and other applications only require a few check points to be measured. There does not seem to be a standard for determining a proper grid spacing.

The raw data is usually some form of ordered triplets in some coordinate system. That data can then be converted and surfaced (if needed) in many ways. NURB surfaces, polygonal meshes, and n^{th} order polynomial curve fitting are a few of the methods used.

The data can then be referenced and compared with the drawing or the CAD representation. A simple metric is the vertical error between the part and model, where vertical is the normal direction with respect to the base plane of the parts. In that case, simple numerical tolerances can be applied. For example, one can reject a part if any point is more than a certain deviation for the model. This method provides a way of seeing if the part matches the model.

4.3.3 Defining Acceptable Parts

Lets assume an appropriate choice of grid spacing was chosen, there is an accurate 3D representation of the actual part, and a 3D representation of the ideal part. Understanding tolerances, accuracies, and acceptable parts is still difficult. According to members of the aerospace industry working on the RTFF project, the "industry standard" tolerance is ±0.030" tolerance for formed sheet metal parts. It is important to note that the tolerance does not specify on which dimensions should there be a ±0.030" limit. Therefore, that number is a poor indication of what an acceptable part might be.

If the part matched the model perfectly, or with even a slight deviation, one might consider the part acceptable. However, there has not been much work in developing a standard for parts that do not conform closely to the model. A part that does not conform to the model might still be an acceptable part.

For simplicity, assume all the parts are 3D extrusions of 2D curves and Figure 4–2 to Figure 4–6 are simply showing the cross section normal to the direction of extrusion. Also assume that the error between the part and the model is some measure of the quality or acceptability for the part. That is what the ±0.030" tolerance seems to imply; any product within a ±0.030" is acceptable. A possible interpretation is shown in Figure 4–2. With this standard, the parts shown in Figure 4–3 and Figure 4–4 would be acceptable. However, by inspection, these parts do not seem like "good" parts.

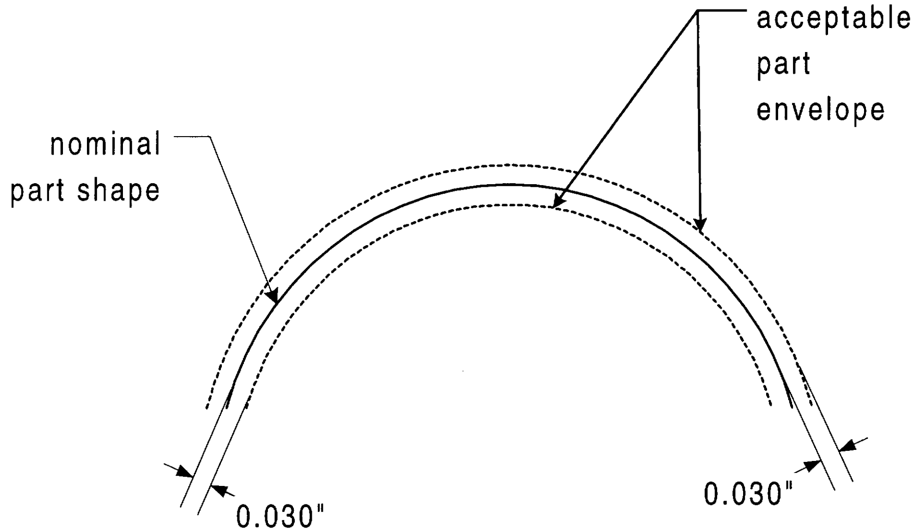


Figure 4–2: A part with the conventional view of tolerances

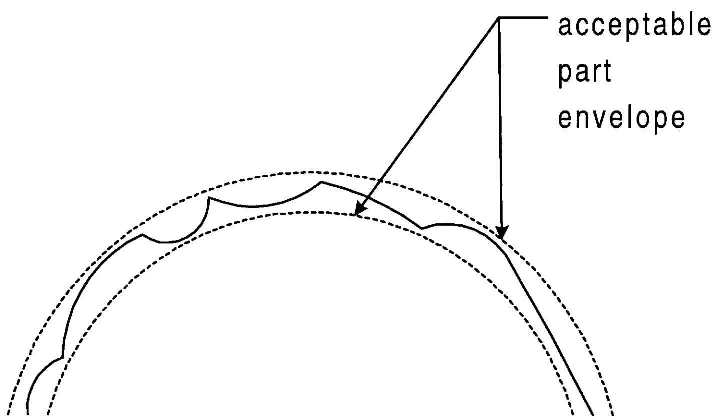


Figure 4–3: An acceptable part by conventional terms

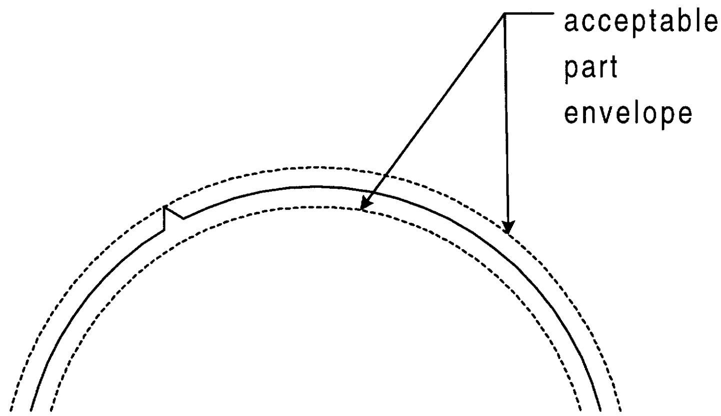


Figure 4–4: Another acceptable part by conventional terms

On the other hand, the part in Figure 4–5 might not be considered acceptable. The only difference between the part and the ideal part are the radii (or curvature) since the arclength has remained the same. In many cases, it is allowable to use extra force to

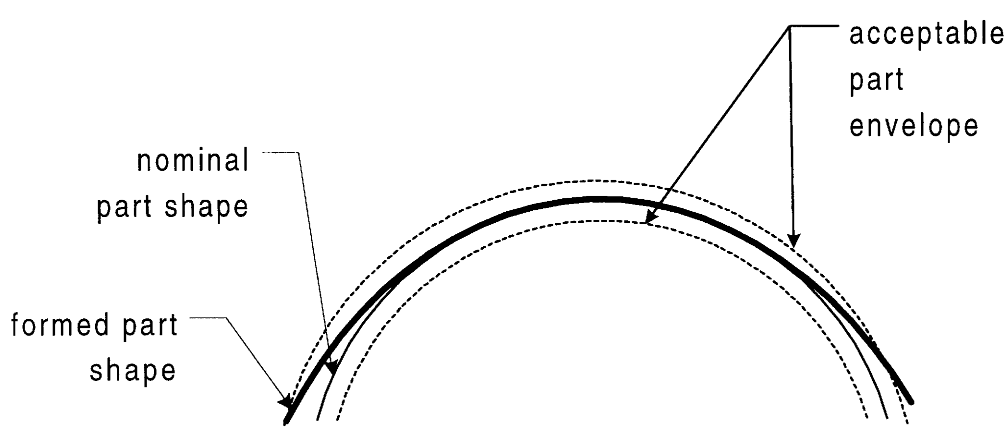


Figure 4–5: An unacceptable part by conventional terms

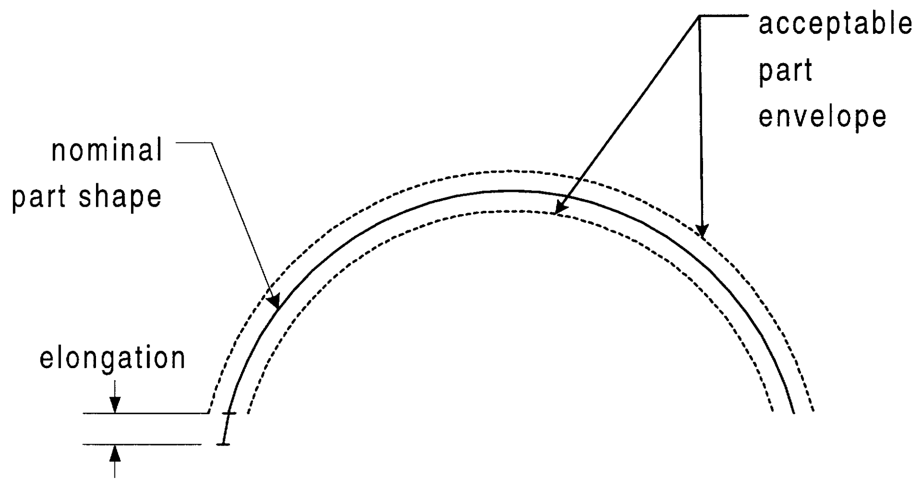


Figure 4–6: Another unacceptable part by conventional terms

conform the part to the correct shape or curvature since the metal deflects and the resulting assembly stresses are within limits. Figure 4–6 shows another interesting case. The part perfectly conforms to the model, except it has a slight elongation. That can be because of improper trimming or thermal expansion, for example. In this case, the curvature is the same but the arc lengths are different. During assembly, one may find that the elongated part matches the curvature but is too long, and therefore requires rework for the part to be acceptable. From these two examples, we see how geometric features (arc length or curvature) can help determine acceptable parts. To generalize, the curvature is not as critical as arc length. Perhaps the arc length should be the feature with the tolerance specification.

There are also other factors that determine if a part is acceptable. For example, these can include surface features such as waviness or scratches. Ideally, the sheets are to be free of all scratches, abrasions, pits, blisters, stains, or other defects.

In summary, human operators are useful in determining acceptable parts since many of the features are best determined qualitatively or by trial and error. The challenge in automation is to determine a robust quantitative method for the computer to decide if the part is acceptable. The choice of this method will influence how the part is measured and data interpreted.

Chapter 5

Three-Dimensional Shape Measurement Methods

There are many ways of measuring objects, though not all will be presented in this section. This section will focus on methods with commercial implementations or promising research and that are able to measure large sheet metal parts.

The two broad categories of acquiring data for 3D measurement are contact and non–contact methods. All these sensors have limited range so translation devices may be needed to move the sensor. A common translation device is the CMM. Connecting a series of 2D images or patching together a series of 3D images or points then creates the 3D image.

5.1 Coordinate Measuring Machines

Coordinate measuring machines (CMMs) are translation devices that move a sensor. The sensor is connected to the CMM at the probe mount, which is the translation device/probe interface. A milling machine and end mill are analogous to the CMM and sensor. Traditionally CMMs are based on Cartesian coordinates as shown in Figure 5–1.

However, CMMs can also be based on other coordinate frames or even have fully

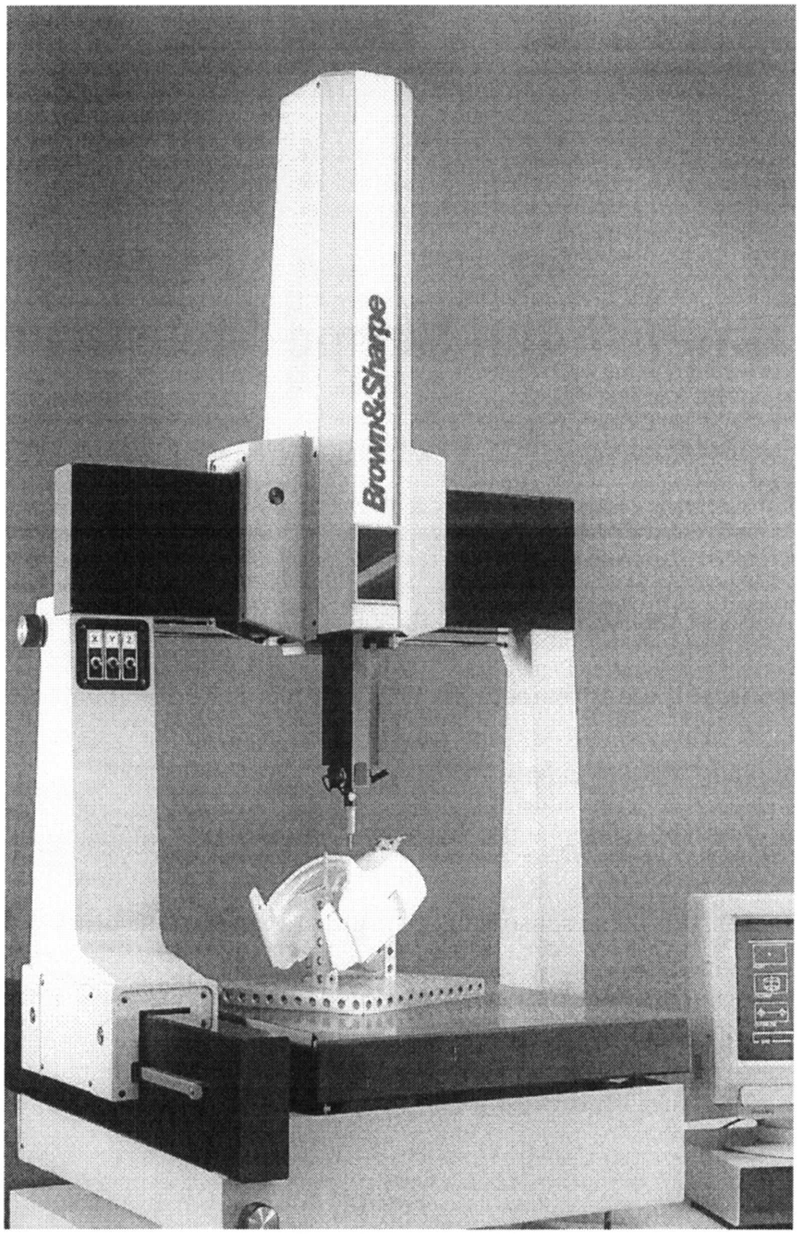


Figure 5–1: Basic CMM

articulated joints to provide six degrees of freedom as shown in Figure 5–2. The scan volume is constrained by the size of the CMM Therefore, to measure large parts, a large and, usually more expensive, CMM must be used.

The CMM becomes a measuring device when the CMM is used with a sensor. When data is collected, the location of the translation device (with respect to a system

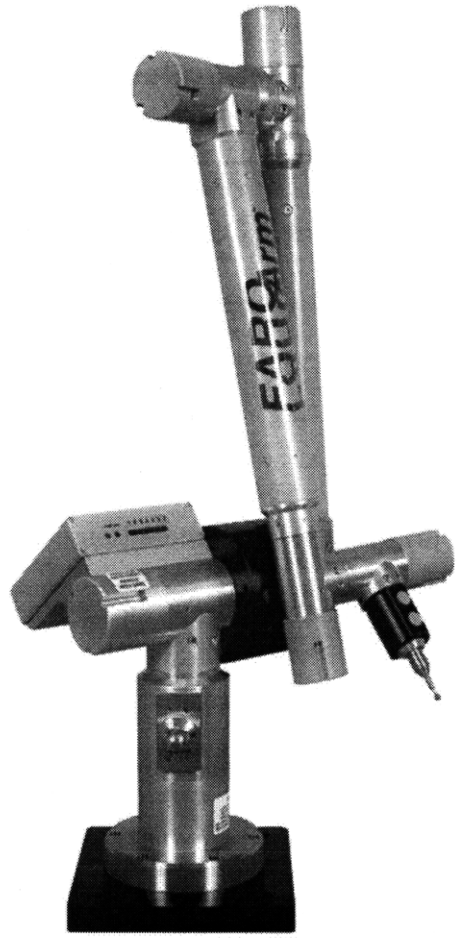


Figure 5–2: Portable CMM

coordinate system) is recorded as well as the location or output of the probe (with respect to the probe mount). The location of the data point is then transformed to the system coordinate system. Therefore, the accuracy and performance is dependent on both the translation device, as well as the sensor.

5.1.1 Frame CMMs

Most CMMs are based on a Cartesian coordinate frame. These frame CMMs are stiff, precision machines with x,y,z linear slides that move to sensor around the part, very much like milling machines. A picture of one can be seen in Figure 5–1. The linear slides have encoders to feedback position. The linear slides move the sensor to provide access to the workpiece features and determine position information.

CMMs can be programmed to move like CNC machines. They need to be programmed to move through desired path or can be controlled manually by the operator, usually by an interface like a joystick. Controlled motion is needed to prevent the probe from crashing into the part. This can be very time consuming and is usually part specific.

Later in this Chapter, there will be sections on sensors that are attached to the CMM. An important factor is the depth of field or range of a sensor. That is, a sensor with a low DOF must follow the surface of the part closely to stay within the DOF. This means the CMM must be programmed carefully to follow the shape of each part to be measured. This can be a problem is the part is very different from the ideal shape. Therefore, high DOFs in sensors are valued since it allows a CMM program to be used for a variety of parts (perhaps of the same ideal part or of several similar ideal parts). This will be discussed in more detail in Section 5.5.4.

Advantages

These CMMs are valuable because of their positioning precision. Also, since they can be programmed, performing repeated measurements on many parts is an ideal application. They are often used to gage parts from a mature process for SPC-type analysis. In this case, the part shape is well known and the range of variation is limited.

Disadvantages

However, CMMs do have many disadvantages. One problem with all of these machines is the need for a temperature–controlled environment for highest accuracy since they are precision machines. Moreover, a clean environment will decrease preventative maintenance schedules and costs. Calibration can be time consuming and result in days or weeks of downtime. Vibrations from the environment also cause problems with CMMs since vibrations will disrupt the sensor and lead to inaccurate results. Passive vibration isolators and special foundations can be used to isolate the CMM from the rest of the environment. If passive means are not adequate, active control may be needed to improve the CMMs accuracy and repeatability. A metrology room is an ideal location for a CMM and a factory floor can be a troublesome location for the CMM.

These machines move slowly, which may limit measurement speed. Lastly, these machines are not expandable. The part must fit in the CMM. If a part is larger than the current CMM, a larger, usually more expensive, CMM must be used. Therefore using a CMM to measure buildings and whole aircraft would be impractical. Also, as mentioned earlier, programming the CMM can be time consuming, especially if the sensor has a small DOF or range.

Conventional CMM Example

Brown & Sharpe have frame CMMs that measure objects larger than 2.5x2x1 meters and position with an accuracy of better than 0.001" if the temperature is controlled to 20±2°C. Some machines large enough for cars to drive through. One large machine is the Beta 25.20.10 SPM which costs around $280,000 and is shown in Figure 5–3. For larger and more accurate machines, costs can be greater than $500,000.

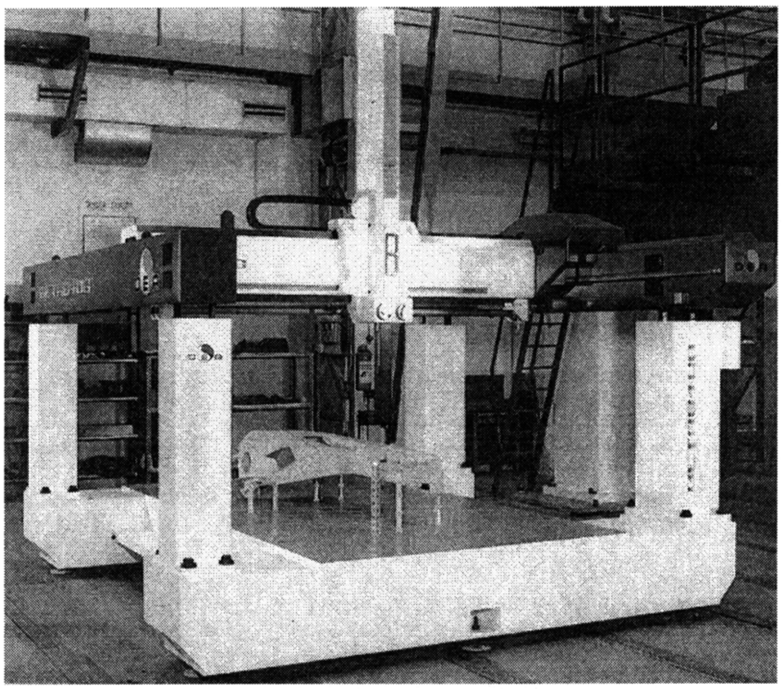


Figure 5–3: Brown & Sharpe Beta series CMM

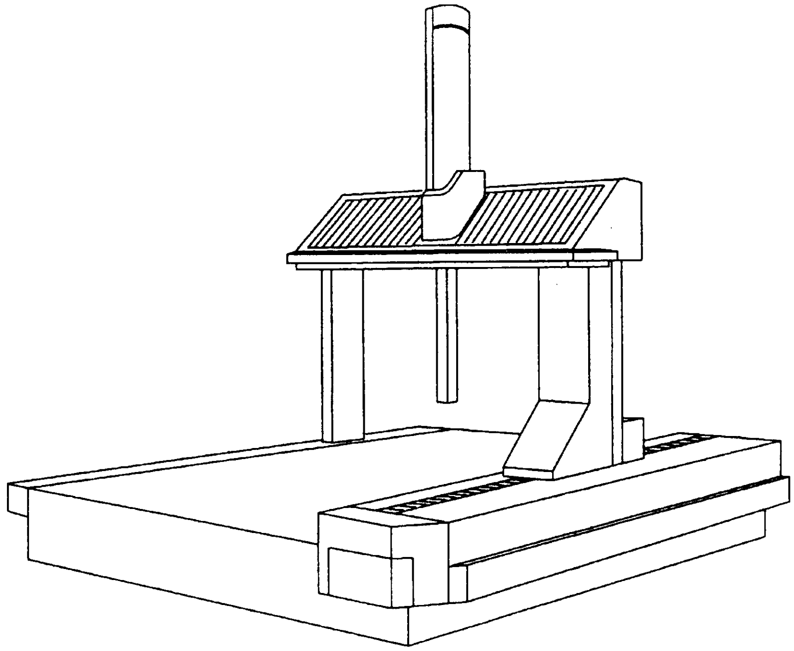


Figure 5–4: Brown & Sharpe Typoon CMM

Another machine available from Brown & Sharpe is the Typoon. This machine is shown in Figure 5–4. These machines are similar to the Betas but are designed to used on the shop floor. These robust machines are about half as accurate but can tolerate the shop environment much better than the Betas. The prices are also 30% less. However, the Typoons are smaller than the Betas.

Alternative CMM Example

Tarus Products, Inc. has a new type of CMM. The structure is similar to frame CMMs but instead of being made of steel, it is made of graphite. This decreases the weight of the machine and allows for faster scanning rates and motion. The quoted traversing rate is up to 1000 inches per minute. Moreover, this machine is designed to function on the shop floor. A machine similar to the Beta mentioned in would cost $250,000. However, Tarus does not have official specifications on this machine.

5.1.2 Portable CMMs

Another type of CMM is the portable CMM. They look like an "arm" with the probe on the end and can be seen in Figure 5–2 on page 57. Figure 5–5 and Figure 5–6 show two of the main competitors in the portable CMM market. Figure 5–7 shows the Romer portable CMM being used to measure an auto body. These have articulated joints to provide six degrees of freedom. The articulated joints have angular encoders to provide position information. These machines are grounded to provide a local reference frame. Then the operator manually moves the probe to measure the part.

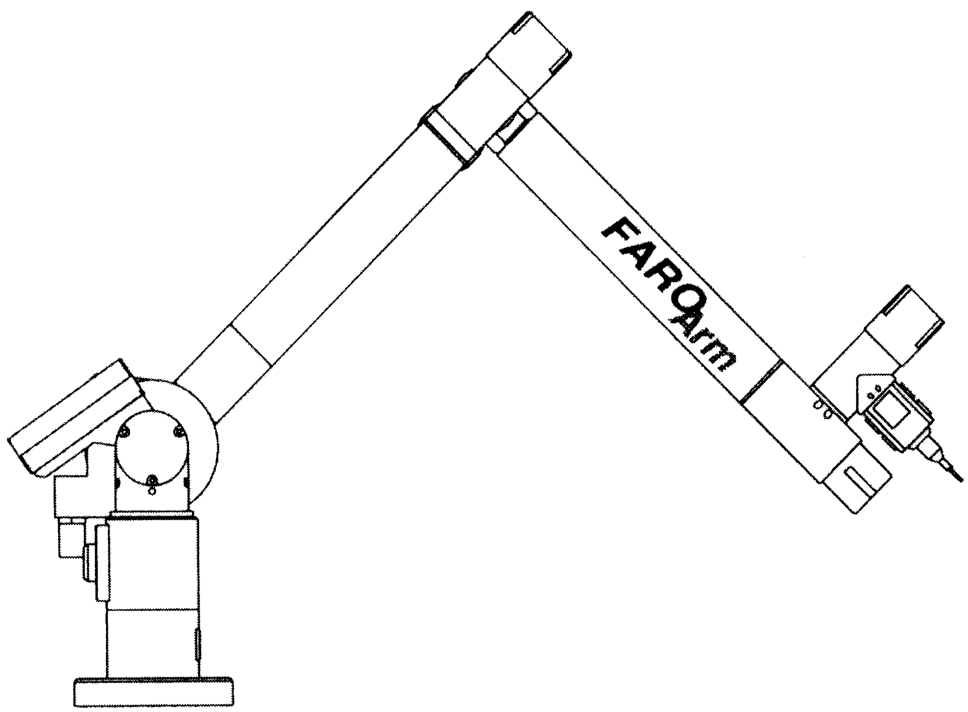


Figure 5–5: Schematic of the Faro Arm

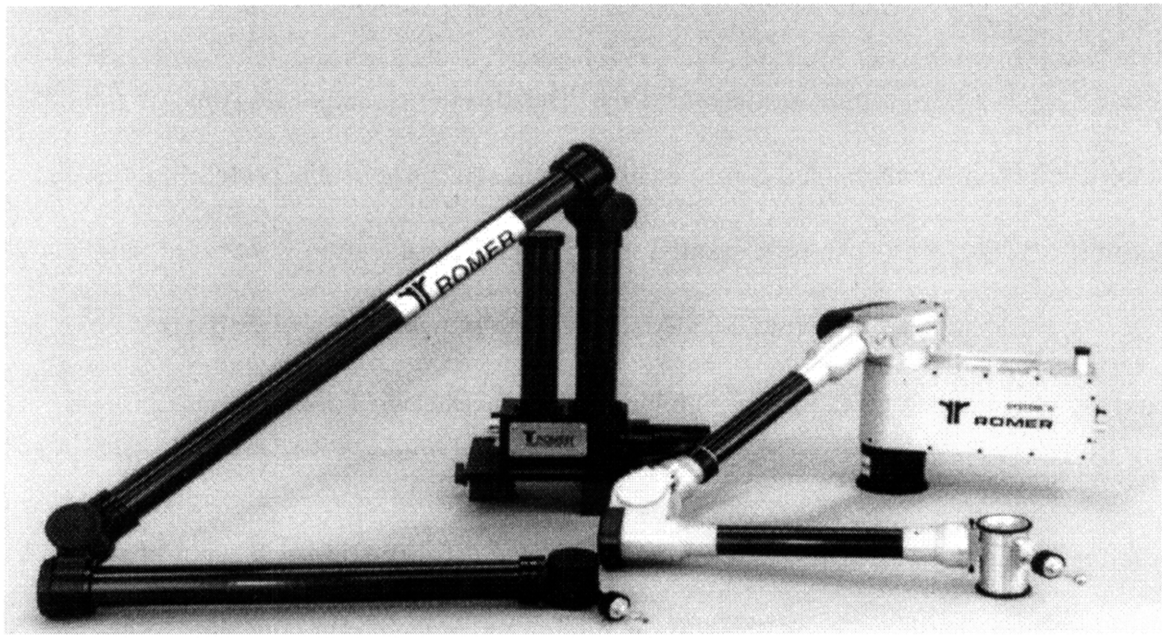


Figure 5–6: The Romer portable CMM

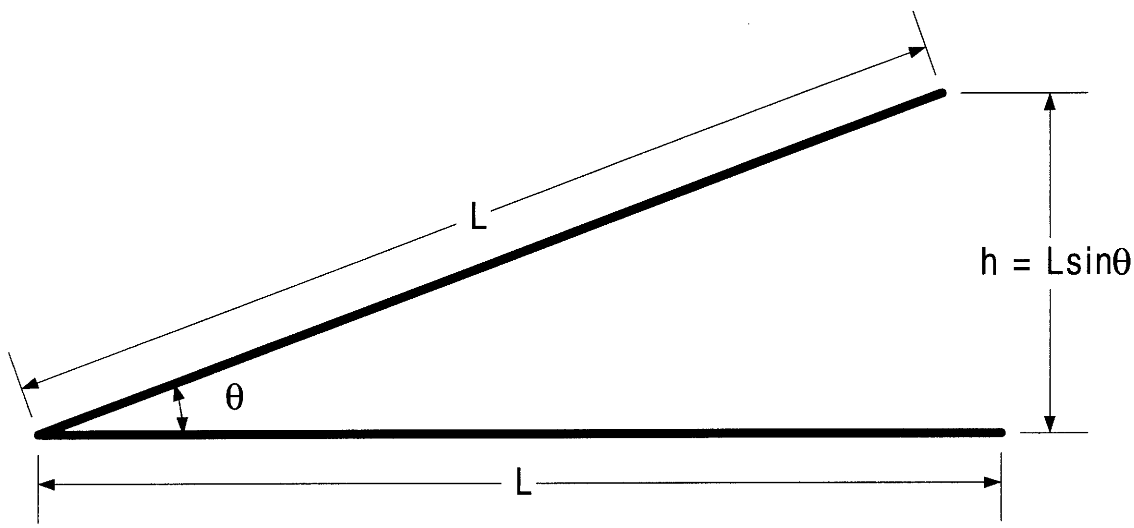
Figure 5–7: The Romer in use

Advantages

Portability is a key features of these CMMs. These systems weight less than 35 pounds, can fit into two suitcases, and can be easily moved. Because of this portability, there is extra flexibility. Parts can be measured in a lab, on the production floor, or at the client's site. Another advantage to frame CMMs is the ease of use. The probe attaches to the end and the operator moves the probe to the part to be measured. There is no need for programming.

This makes using portable CMMs ideal for measuring different types of parts. An arbitrary part can by measured by simply moving the probe around the part. When coupled with software, this method can be extremely powerful. For example, there is a mode that allows data to be taken at a regular rate per unit time. Another mode is called "stitch" mode where a point of data is taken every unit length of travel on the part. Another mode allows the operator to define planes. Then he can scan the part and only data on that plane will be recorded. This can be used to create data files with loci of points at a constant elevation, much like a typographical map and contour lines.

The range is unlimited in that the CMM can be located on the ground and moved to other locations. Then the data for each of the different locations (and coordinate systems) can be transformed to a global coordinate system.



L, length of the lever arm

θ, angular error

h, Abbe error

Figure 5–8: Illustration of Abbe error

Disadvantages

Because of the portability, the CMM sacrifices some accuracy and are not as accurate as frame CMMs. Frame CMMs are built to be extremely stiff and rarely have long cantilevers that can result in Abbe errors. An Abbe error is when an angular error is manifested in a linear form. This error the product of the lever arm's length and the sine of the angle. This is often also called a sine error and is very common in cantilevers (Slocum, 1992). This is illustrated in Figure 5–8. Portable CMMs are essentially a series of levers and angle sensors that make them prone to Abbe errors. These potentially large errors are prevalent throughout the entire work volume of the portable CMM. This error is included in the "accuracy" specification of the tool. However, any decrease in accuracy of the angle sensor will be amplified by the long lever arms too decrease the accuracy of the system.

Since the movement is entirely manual, portable CMMs are not as repeatable or stable as the closed–loop, computer controlled frame CMMs. If a sensor needs to be fixed in space for some time to measure data, portable CMMs may be inadequate. However, this is not a problem for scanning contact probes where data collection is nearly instantaneous. Since portable CMMs are not repeatable, the data files for different measurements of the same part may be substantially different, though describe the same part. It is difficult to manually ensure one is measuring the same way from part to part. However, often the data is surfaced and so long as sufficient data is collected, having the identical measurement pattern is not critical.

Examples

Faro Technologies and Romer both make portable CMMs. Both systems are essentially the same. These CMMs are available in different sizes and accuracies, with the largest and subsequently least accurate the most expensive. Romer claims 2σ accuracies range from 0.0012–0.0040", scan volumes from 5–12 feet spheres, and prices under $100,000. Faro Technologies is not available to provide formal technical specifications on their accuracies.

Romer also offers extended measurement solutions. These systems basically allow the portable CMM unit to move within the workplace while the support systems keep track of the location of the device.

5.2 Mechanical Contact Measurement

5.2.1 Operating Principles

Mechanical contact measurement requires the sensor to physically touch the part with some force. Normally, mechanical contact sensors or probes are used to determine the location of a point in space. The probe can be attached to a translation device that moves about the measuring volume. The probe tip touches the surface for each data point. Normally the probe is brought close to the surface (fixing two orthogonal coordinates) and is linearly translated until probe contacts the part (completely locates the probe).

Contact Probes and the CMM

A contact probe is a common mechanical contact sensor usually used with CMMs. These probes have attached styli that usually either touch the surface at discrete points, touch trigger probes, or scan the surface by continuously contacting the object and acquiring data, scanning contact probes. One can compare the probe and stylus on a CMM to a tool holder and milling bit (or any tool) on a CNC machining center.

The most common type of styli are ruby ball styli. These look like a “finger” with a ruby ball on the end. Ruby is used since it can be made to highly spherical shapes that are extremely hard, and hence have low wear. The stylus should be stiff and able to reach or resolve the relevant features to be measured.

The probe connects with the stylus. The probe has a “range” which is like the “range” of a dial indicator or LVDT or the DOF of an optical sensor. The stylus tip can move slightly and output data throughout that range. The range of these probes varies widely. Strain gage sensor is often used to measure displacement and springs to allow the range of motion. A typical probe and stylus is shown in Figure 5–9.

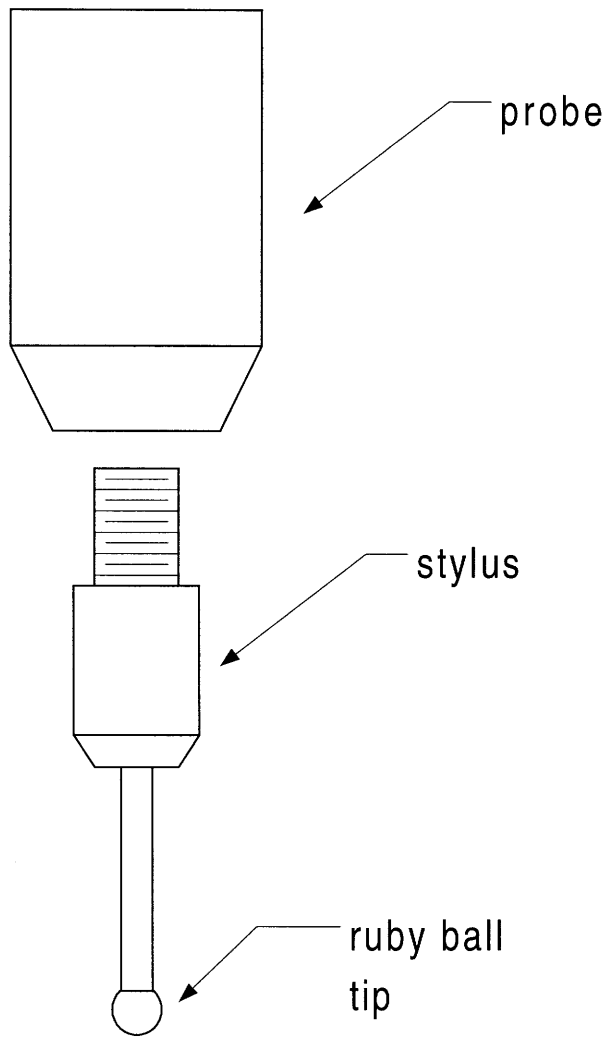


Figure 5–9: CMM touch probe

A touch probe is usually used on large machines and in applications where data is needed at specific locations. A scanning probe is useful when one needs to continuously scan the surface and collect data. These probes are not as common and usually require an extra, more expensive controller to operate.

Targets and Optical Sensors

Mechanical contact measurement can also be used with non–contact, optical sensors, instead of a translation device. In this case, a target physically touches the part and the optical sensor determines the position of the target. These methods are often incorrectly considered "non-contact" methods. These targets are often LEDs or retroreflectors. LEDs are light emitting diodes that behave as light sources that can be easily spotted against the part to be measured. Retroreflectors are optical elements that reflect light directly back to the source. Optical sensors determine the position of the target, and by the geometry of the target, one can determine the position of the part. The actual methods will be explained when discussing the different optical sensors.

LED targets can be placed on the object like stickers to measure arbitrary locations. LEDs and retroreflectors can also be placed in holes or slots to determine hole, slot, or surface location. These targets are often in a shape of a sphere with a retroreflector or LED inside. The operator moves the sphere around the target and the optical sensor measures the position of that target.

Targets can also be mounted on a rigid, handheld mechanical touch probe. The operator can probe the part with manually with the touch probe. The measurement is taken and given the locations of the targets on the handheld probe, one can determine the location of the probe tip.

5.2.2 Features of Using Mechanical Contact Sensors

Since the probe tip much touch the object, the surface qualities and fixturing are important for accurate measurements. The part must not elasticity or plastically deform or translate under the force exerted by the probe. When the probe is continuously touching the surface or being "dragged," the probe may damage the part by leaving grooves on the surface, especially on softer materials. Moreover, dragging the probe over a surface with a high coefficient of friction, such as rubber, will cause difficulties. Probing locations can be difficult as well if the material deforms elasticity at the point of measurement. For touch probes, the part should not deflect under the applied forces. However, for most hard surfaces, there should be no problem with making contact between the part and sensor.

Since the probe must touch the point to measure that point, the probe must be able to detect and reach every point of interest. The ball radius limits the smallest feature detectable. The radius filters out the high frequency components found on the part such as surface finish. However, this may result in the omission of critical features in the part such as scratches. Reaching features can be difficult if the features are deep holes, overhangs, hidden geometries, or similar hard to access features.

An illustration of a potential problem with using mechanical contract sensors is shown in Figure 5–10. The surface is a perfectly flat surface, except for a minor concave depression. We will assume that the probe tip scans the surface and collects data at the shown locations. This probe tip has a finite radius and the points are measured from the center of the tip. Notice how the probe tip detects the divet in surface. However, the tip radius is larger than the feature radius. In that case, the tip can not fit in the divet to further investigate that feature. Also, as the points are connected with straight lines (or even splines), the resulting curve is not the same as the surface profile. Even if the points accurate, the limited sampling and probe size limits the overall accuracy of the measurement.

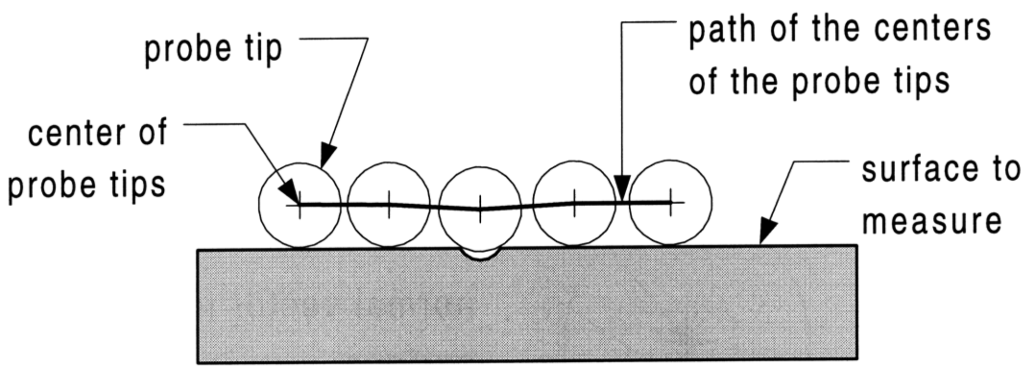


Figure 5–10: Mechanical contact probe measuring a surface

Contact Probe Features

There are slight errors because the CMM does not necessarily keep track of the actual point of contact between the ball surface and the part. The CMM usually tracks the location of the center of the ball as shown in Figure 5–10. With this method, the raw output is at an offset from the actual surface. The points are then projected normally towards the surface by the offset (ball or probe tip radii). This is shown in Figure 5–11. The adjusted point is the actual tangent point of the tip to the surface. However, this adjustment can lead to errors in position on the order of fractions of the radius of the ball if the assumed normal vector is not actually normal to the part surface. This is shown in Figure 5–12. In this case, the assumed normal vector is not normal to the actual surface. Therefore, when the center of the probe tip is offset in the incorrect normal direction, the assumed contact point is a point on the probe tip that is not in contact with the surface. The figure shows the actual contact point as well. Notice how there is an error, but it is minor. This is usually insignificant since the actual measurement error dominates the surface angular error (Greenwood, 1993).

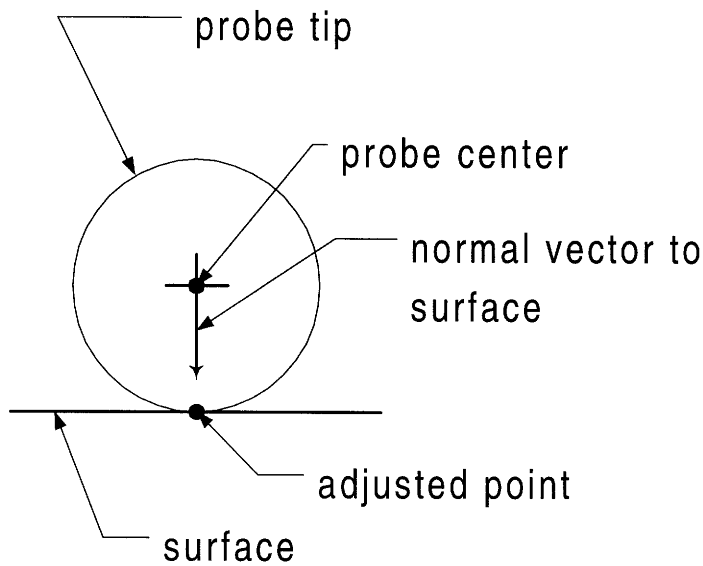


Figure 5–11: A surface point correctly offset from measured point

As mentioned earlier, frame CMMs are usually programmed. Programming a CMM to measure a part with a probe tip can be challenging in many ways. However, with modern software, the process is much easier. The operator can use software that works off the CAD file. The probe is set to take data only within certain limits, perhaps ±1 inch from the part surface. Then the probe automatically moves around at a set grid spacing and measures the part automatically. Since portable CMMs are not programmed, the feature is not applicable. The operator simply has to move the probe to the surface and takes measurements.

The measurement speed is low since the probe tip must move to and touch every point data is taken. Measurement speed is on the order of one point a second, or even less. Measurement times of several hours is not uncommon for complex parts. However, to gage a few critical points, the measurement can be completed in minutes (Karlin, 1995).

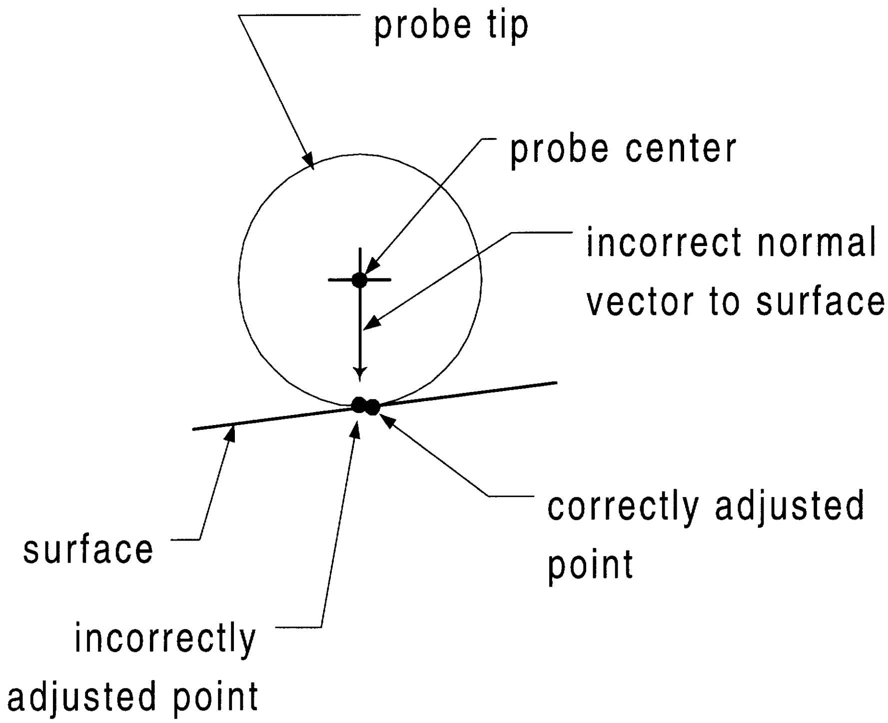


Figure 5–12: A surface point incorrectly offset from measured point

Despite these problems, CMMs and scanning probes are very common in industry. They are commonly used for measuring a few check points on a sheet metal part or measuring a few parts features an hour for SPC. They are also used for dense mapping of dies and molds if a measuring time of hours is acceptable. In general, CMMs and scanning probes are useful since they can measure a variety of parts. Their largest drawback is their slow measuring time.

Target Features

An optical sensor is measuring the position where the optics and the target interact. For retroreflectors, the optics are measuring the location of reflection. Once that location is known, one can estimate the position of the point of contact if the retroreflector's geometry is known. This is similar with scanning contact probes and the unknown point of contact with the part. Normally, the data must be offset to estimate where the part surface is.

The optical sensor scanning rate limits the measuring speed. However, positioning and moving the targets may be time consuming and can be the limited factor. Other issues relating to specific optical sensors will be discussed in their respective sections.

5.3 Non–contact Measurement

Non–contact measurement is the other broad category of acquiring data for 3D measurement. Non–contact methods do not physically touch the part. Some methods are incorrectly called "non-contact" methods. These methods use targets, as described in the previous section, and rely on non-contact methods to determine the position of the target. However, the target still is physically contacting the part.

5.3.1 Attributes of Non–contact Methods

The main advantage of non–contact methods is that the sensor does not make physical contact with the part. Therefore, there is little potential for damage to the part. For example, the sensor does not drag on the surface, as with mechanical contact probes. This allows these methods to measure soft materials like clay, fabric, human skin or fragile parts. Moreover, since heat can damage or reduce the accuracy of mechanical contact probes, hot parts can be measured. The disadvantages of non–contact methods will be described separately for each method.

5.3.2 Types of Non–contact Methods

The majority of non–contact methods are optical methods. The rest of the Chapter discusses non–contact methods, and all methods except for the laser radar described in Section 5.13, can be considered to be optical methods. Though laser radar does not rely on optics, it does rely on lasers. The laser can interact optically with the part and therefore, cause the sensor behave like an optical sensor. Therefore, "non–contact" and "optical" methods are often used, incorrectly, as synonyms.

5.4 Optical Measurement Methods

Optical gages rely on light and vision to determine location. Though the fundamental physics differ with each optical method, there are many similarities between them. The following section describes some generalizations about non–contact measurement and optical gages. Harding (1996) was especially useful in providing the framework for this section.

5.4.1 Attributes of Optical Methods

Optical methods are often characterized as "fast" since optical systems can collect data thousands of times faster than mechanical contact probes. Practically, this speed difference allows for high–density surface mapping at reasonable speeds. For parts that would normally take hours to measure with a mechanical contact probe, optical methods would take minutes instead.

As with mechanical contact probes, part access is also a limitation. Since these systems use optics, there must be a line–of–sight path from the source to the part, and back. The areas of the part in shadows can not be measured. Basically, the sensor has to be able to “see” a part to measure it. Therefore, these methods might need to take several views of the same part. Most systems require a normal view of the part for best accuracy as well.

Another benefit is that it is a non–contact technique. Attributes of non–contact methods are detailed in Section 5.3.1.

For each sensor, there is a standoff distance from the sensor and part surface. The standoff is the minimum range from the sensor at which objects can be measured. The “range” of a sensor is described by its depth of field (DOF) and field of view (FOV). The DOF is the distance between the standoff and the maximum measurable range of an object. The FOV is maximum cross range extent of the object. Please see Section 4.2 for a review of terminology.

With mechanical contact probes, features smaller than the probe tip radius will be filtered out. However, some optical probes can measure small features like the micro–structure of the material.

Many optical methods use lasers. These lasers may need special attention for safety. Lastly, since the probe interacts optically with the surface, the surface properties are important.

5.4.2 Part Surface Properties

Just as mechanical contact sensors require a certain type of surface qualities, so do optical sensors. The light needs to interact predictably with the part surface. Therefore, the air should be free of large contaminants and the part should have a consistent surface finish.

The surface finish is very important and is often the limiting factor with these optical sensors. There usually are problems if the part is reflective like a mirror or even sheet metal. Translucent (backlit plastic) or transparent (glass) parts also make measuring very difficult. Also, the large random shapes of a rough surface finish may cause the light to be reflected in unpredictable ways. The roughness also causes speckle in lasers, which can decrease the accuracy of the measurement.

For best results, the surface should be uniform, dull, matte, light colored, and have diffuse reflecting properties. Deviations from the ideal surface can lead to noisy data (Jais, 1997). There are many ways to make a reflective or transparent surface into diffuse reflecting and light surface. One method is to cover the part with "Spot Check" by Magnaflux. This product sprays, from the can, on clear and wet. When it dries, it is a powder that is good for optical applications. Then, it can be washed off with water. The problem is that the thickness averages around 0.008"-0.010" and can vary substantially. Similarly, one can treat the part with chalk dust. Another method is to spray on water–soluble paint. This requires special equipment to spray the paint. All these methods are effective but require extra work and preparation.

5.5 Laser Point Triangulation

Triangulation is an optical method that constructs triangles to compute geometrically the location of the target. There are many forms of triangulation but the simplest form is laser point triangulation.

5.5.1 Operating Principles

In laser point triangulation, a focused laser is projected normal to the target. The spot is viewed by a photodetector, usually a CCD. There is an angular separation between the light source and detector. A lens is used to focus scattered light from the target onto the

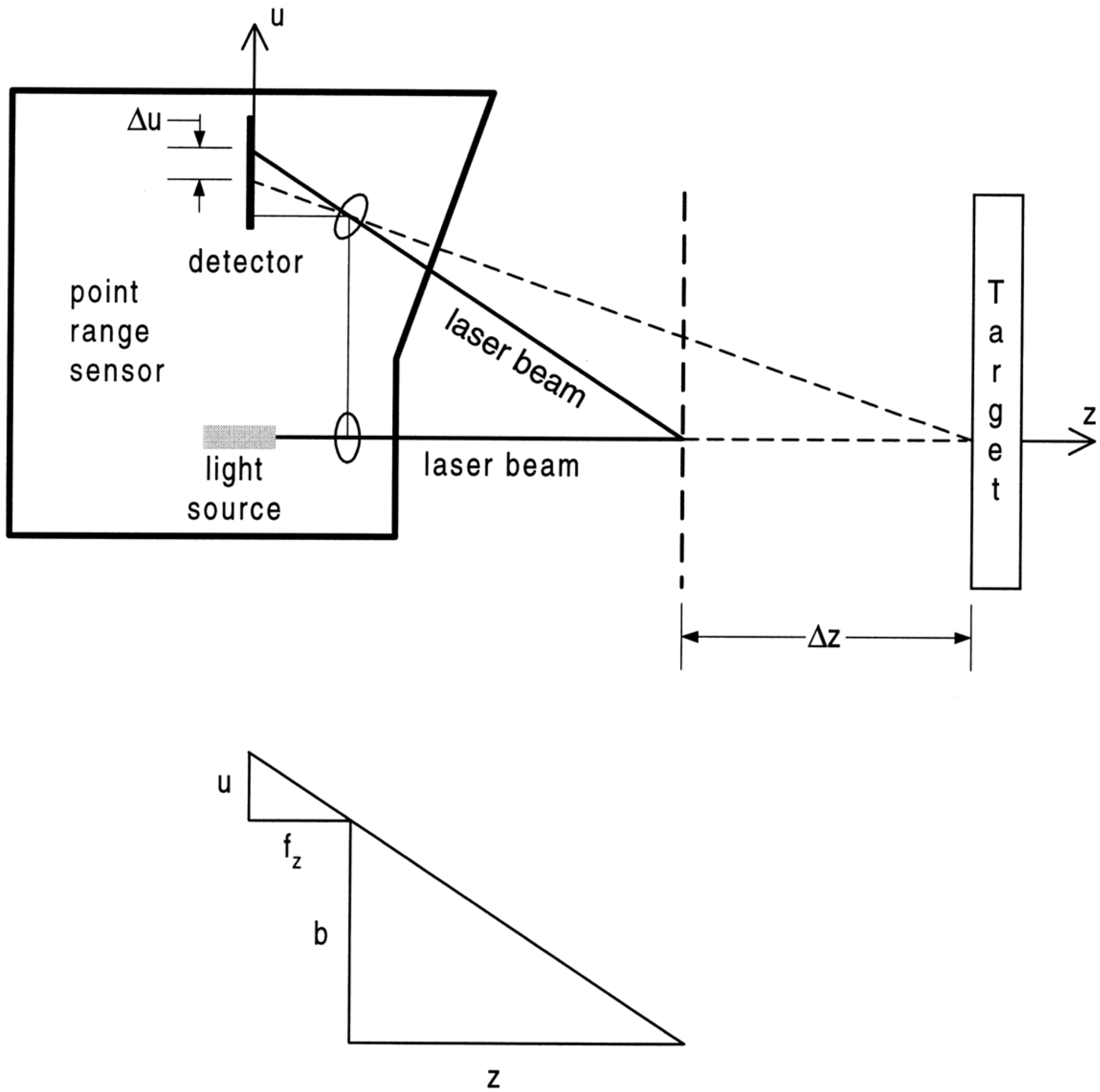


Figure 5–13: A schematic of triangulation

surface of the photodetector (Slocum,1992). The range to the target is calculated with simple geometric relations. This is diagrammed in Figure 5–13.

As the range, z, changes, the position of the detected light on the CCD changes as well. This change is measured by the value u. When the object is closer, the value of u is larger and if the object was further, u is smaller. The dimensions of f_z and b are accurately measured and known for the specific sensor. The absolute range is calculated with the equation:

$$z = \frac{bf_z}{u}.$$

5.5.2 Sources of Error

There are many sources of error and variation in the system. The lengths, b and f_z need to be known accurately and should be a constant during measurement. A change in temperature or vibrations can change these values without operator knowledge. Moreover, since triangulation is an optical method of measurement, the laser needs to act uniformly and predictably on the surface of the part. Ideally, the spot on the surface would be tightly focused and small to avoid speckle noise. Speckle is the resultant interference pattern generated by the coherent light source, the reflecting waves, and a surface roughness on the order of the wavelength of light. This noise spreads out the originally tightly focused laser beam. When this spread–out return beam is detected on the CCD, there are difficulties in determining the location of the original projected spot from the detected spot. Non-uniform surface color will have a similar effect.

The uncertainly in the actual location of u is symbolized by v. The two–sided range of z is

$$z_{error} = \frac{bf_z}{u-v} - \frac{bf_z}{u+v}$$

or more compactly

$$z_{error} = \pm \frac{bf_z v}{u^2 - v^2}.$$

An interesting result is that z_{error} is not constant, even if v is constant. u is normally larger than v, the uncertainly. As the object gets further, u gets smaller. At the same time, the contribution of the quantity v^2 becomes more significant. These two factors decrease the denominator, hence increasing z_{error}, thus the accuracy of a triangulation system is range dependent and non-linear. Moreover, the sensor's overall resolution is limited by resolution of the detector.

5.5.3 Usage Issues

Again, laser point triangulation is an optical method and has the benefits and restrictions of optical methods. Especially for this method, there must be wide part access to allow the return light to be detected since the return light is viewed at an angle relative to the projected light. This would make measuring deep pockets or steep slopes difficult. Moreover, this sensor should articulated to be kept as close to normal to the surface for best results. If the angle of incidence is greater than around 60°, there can be difficulties and can lead to inaccurate measurement.

It is important to notice how much geometry is involved in this method. One simply can not increase the depth of field since the detector might not be large enough. If the angle of incidence becomes too great there may not be clear optical path to view the projected spot. All these factors will affect triangulation sensors.

5.5.4 Laser Point Triangulation and a CMM

This type of sensor is very common and can be easily added to a CMM to be used instead of the mechanical contact probe. This sensor can be comparably accurate and is orders of magnitude faster.

Laser point triangulation sensors can have different DOVs (range in which the sensor can operate) and can vary from 0.01 inches to several yards. That is, the sensor has a "tolerance" of one DOV from the part. If the sensor is in that range, it can still output data about the part. Having a large DOV is generally desirable though usually inversely related to the resolution of the sensor. For our applications, the DOV is usually less than one foot.

The need to program CMMs to move a mechanical scanning probe around the part is one reason it may be difficult to use when measuring various different parts, especially if the CAD file is not available. The CMM must be programmed for each part as described in Section 5.1.

When using laser point triangulation probes, or other non–contact probes with larger DOVs or "ranges," the CMM still must be programmed. However, the larger DOV gives more tolerance in programming. When gaging a part, the dimensions may deviate from the ideal on the order of fractions of an inch, but not on the order of inches. If the DOV is three inches with a standoff of one inch, the sensor can be anywhere from one to four inches away from the part and still output data. Therefore, for programming the CMM, the operator can set the probe to move on a path three inches away the ideal surface of the part. With fairly high confidence, one can say the part will be within the sensor's range and data can be collected. For a mechanical scanning probe, "range" is smaller than non–contact sensors. The range often can be only fractions of an inch, which makes the programming more difficult.

5.6 Scanning Point Triangulation

Scanning point is the another level of complexity when using triangulation. When a point triangulation device needs to scan a line, the CMM would have to move the sensor linearly to take data. In other words, point triangulation is a 0D sensor since it measure the location of a point, a zero dimensional object. To gather data about a 1D object, a line, the sensor must be moved and data is taken in a line as the sensor moves.

5.6.1 Operating Principles

With scanning point triangulation, the CMM could stay fixed as the internal optics redirect the laser point to scan a line. Therefore, as the internal optics sweep a point to scan a line, this line can be moved normal to the line to scan a 2D patch of data. The fundamental technology is the same as point triangulation, but the scanning rate is increased. Despite this benefit, if one does not need the added point density, laser point triangulation may be adequate and faster.

5.6.2 Example

The Hymarc Hyscan sensor is a scanning point triangulation system. A picture of the Hyscan sensor is shown in Figure 5–14. It projects a point and scans a 2.4 inch line to measure a line of the object. This is illustrated in Figure 5–15. The internal optics sweep the laser point while also collecting and focusing the scattered light of the spot onto a

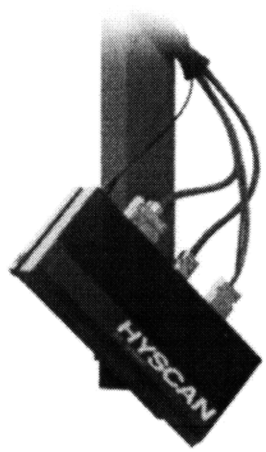


Figure 5–14: Hymarc Hyscan

CCD. The geometry is different than the one shown in Figure 5–13 but fundamentally, it is the same. The scanning rate is exceptionally high and can digitize 10,000 points a second.

To measure a 2D patch, the sensor must be moved and easily attaches to a CMM frame. To measure parts wider than 2.4 inches, the CMM would move normal to the 2.4 inch line to scan a 2.4 inch path. Then the CMM could index 2.4 inches normal to its last direction of motion to prepare to scan the next 2.4 inch path. One can imagine this technique as a sensor "painting" a part.

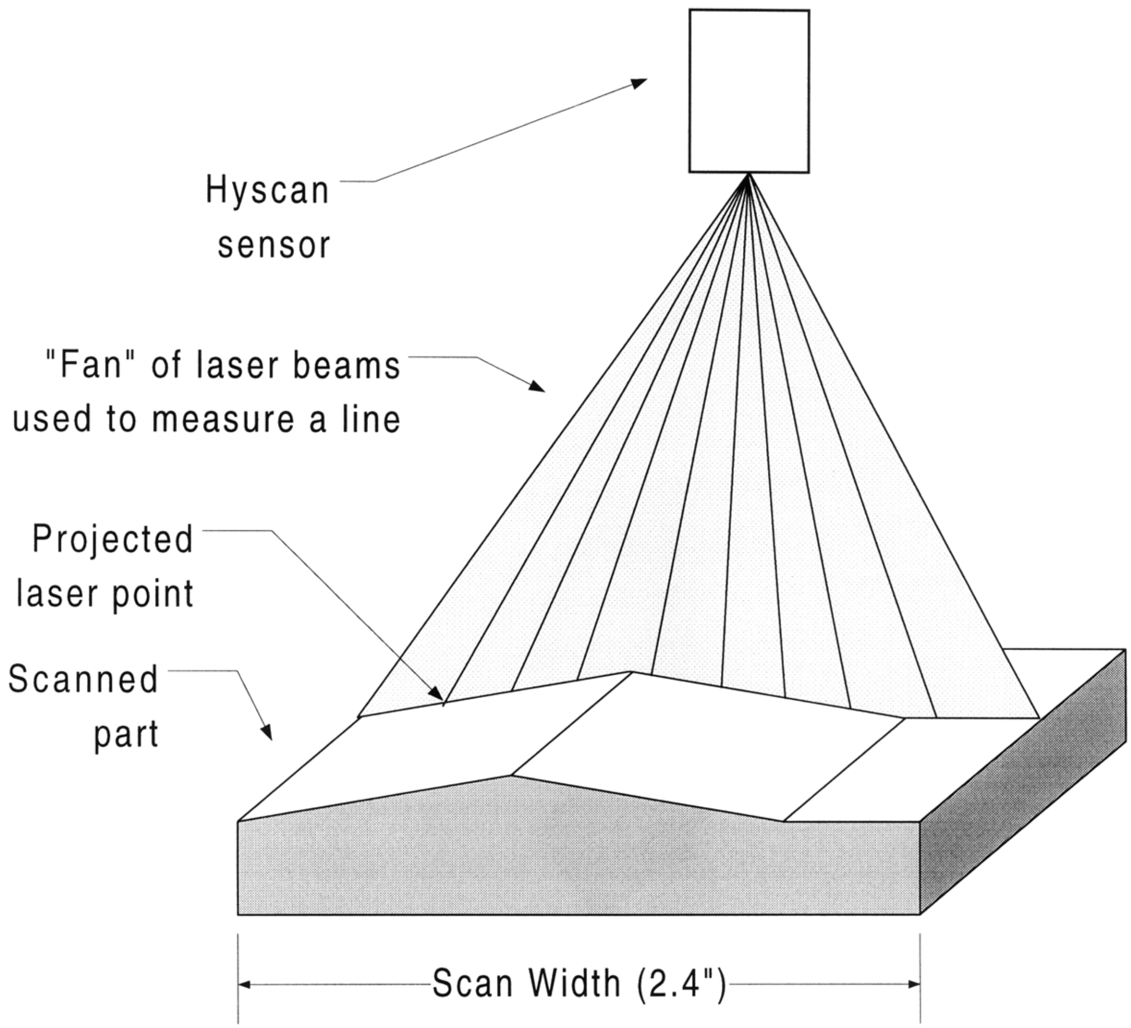


Figure 5–15: Hyscan sensor scanning a part

The sensor alone can have a 3σ accuracy of 0.001". The DOF for this sensor is equal to the width of the scan line. Currently these values are nominally 2.4 inches but can changed. The sensor, computer, and installation cost around $100,000.

5.7 Structured Light

The structured light method is another refinement in point triangulation that increases the scanning rate. Instead of projecting a point, a plane of light is projected and imaged to result in scanning a line of the part at a time. This is shown in Figure 5–16

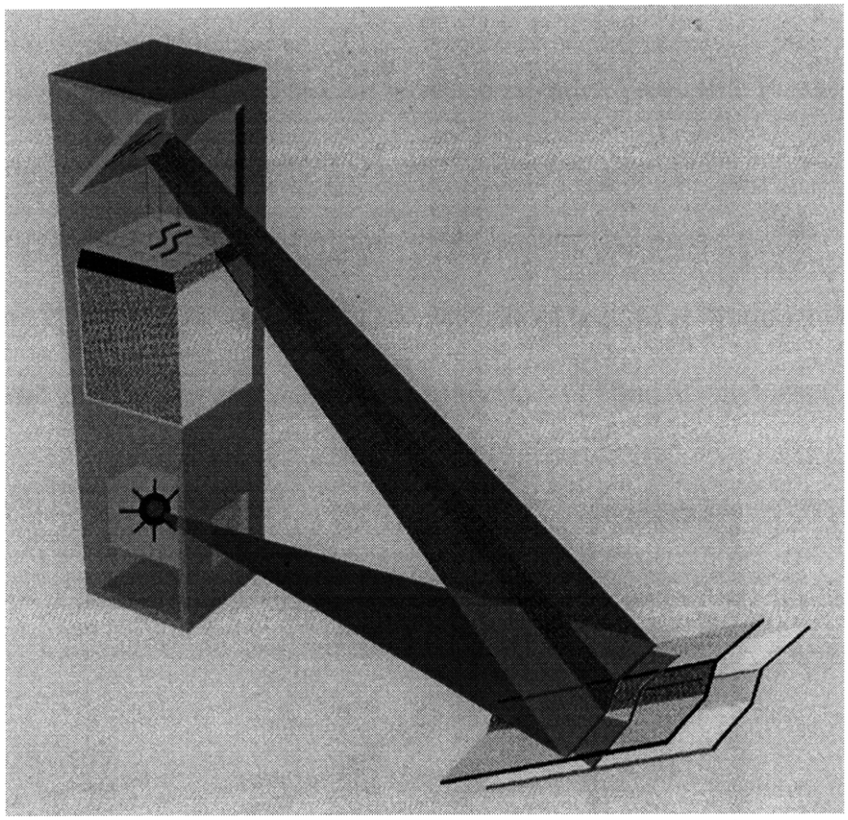


Figure 5–16: A plane of light is project to measure a line on the part (Perceptron TriCam)

5.7.1 Example: Perceptron OCF

The Perceptron Optical Checking Fixture (OCF) uses the structured light method of triangulation, as shown in Figure 5–16, to measure parts. This TriCam sensor emits a plane of light and collects 500 points of data from that line in less than a second. The line can either be 2.4" or 4.4" inches wide, which is the field of view. The DOF is around 2.2 times the FOV. The sensor is then moved by a CMM–type frame, to scan the rest of the part. The sensor, without the translation frame, has an accuracy of 0.002" when there is a 2.4" field of view. The accuracy is decreased to 0.004" with a 4.4" field of view. However, when attached to the CMM–type frame, the accuracy of a 2.4" FOV system is reduced to 0.014" due to the inaccuracies of the frame. The sensor and frame cost

$350,000–400,000. The sensor currently is not designed to be attached to a third–party CMM.

This sensor still uses the basics of triangulation, as illustrated in Figure 5–13. This sensor is simply an improvement on basic point triangulation and is illustrated in Figure 5–17. Please note, graphically, how to sensor field of view (which is the DOF by this thesis' convention) is limited by the size of the CCD array in the diagram. In actuality the sensors DOF and FOV are limited by the *xy* size of the CCD array.

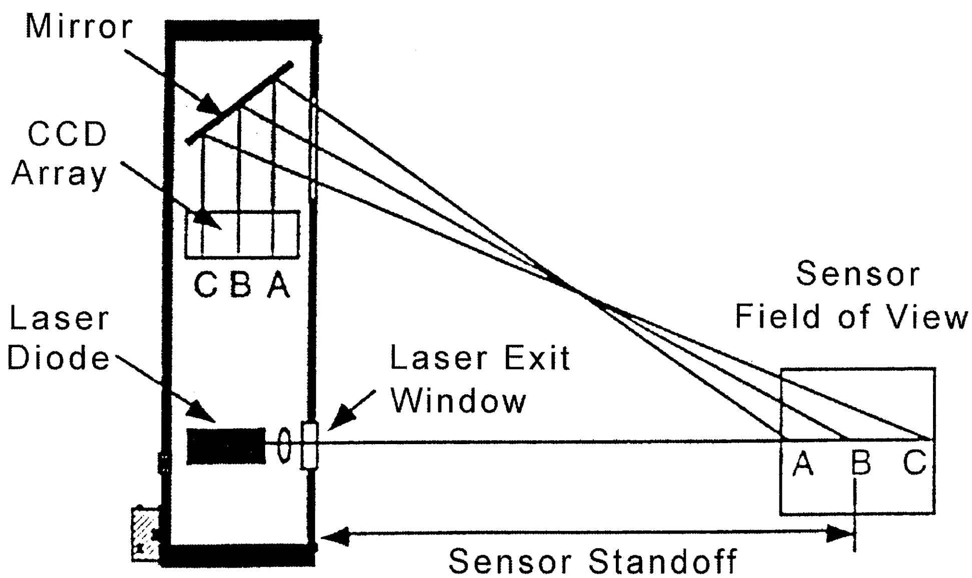


Figure 5–17: A schematic of triangulation, as used with the Perceptron TriCam

Though the Perceptron OCF and Hymarc Hyscan use different methods of measuring a line of points, their use is essentially the same. The main difference is Perceptron claims no part preparation is necessary, unless the part has a mirror surface. Their sensor claims to be able to compensate for the specular qualities of sheet metal.

5.7.2 Example: IAS 4DI

Industrial Automation Systems or IAS offers the 4D Imager (4DI) which projects a grid of laser light and measures a full 2D frame in $\frac{1}{30}$ second. The 4DI projects 100 laser planes across the 2D field of view. In turn, each plane results in 500 points of data. Then by using three cameras and stereo vision (similar to stereo photogrammetry discussed in Section 5.9) and triangulation, a 3D image is captured and created in less than three seconds. A major advantage of this system is the full frame measuring capability without the use of any moving parts. The 4DI measuring a propeller is shown in Figure 5–18. The planes of laser light can be seen on the surface of the propeller.

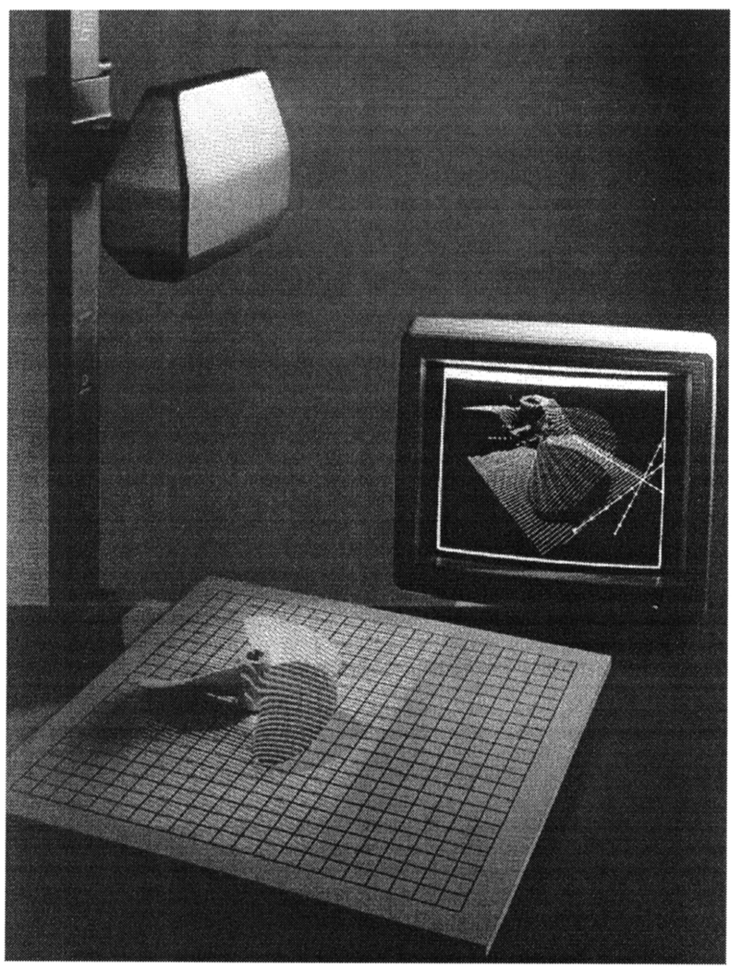


Figure 5–18: IAS 4DI measuring a propeller

However, due to the geometries of the sensor and triangulation, increasing the field of view decreases the accuracy, depth of field, standoff, and range; all undesirable effects. The DOF is half the FOV and accuracy is 1/1000 the FOV. Thus for 0.003" accuracy, there is a mere 1.5" DOV, which is about half of the standard Hymarc DOV. In this configuration, the FOV would be only be 3" x 500 points. The 500 points could be spread about an arbitrary length. The only drawback is the point spacing would be increased for longer parts. The imaging speed of this system is comparable to the Hymarc and Perceptron systems and but will still require a CMM to measure a large part.

By using a CMM, the 4DI could be moved to take *n* images of the object. This way, the field of view is decreased by a factor of *n* and the accuracy, depth of field, standoff, and range are increased by a factor of *n*. When comparing with the Hymarc and Perceptron system, the 4DI can give as accurate results, in probably less time since it scans a 2D patch instead of a line. The main disadvantage of this system is its small DOV. This results in the same problems when comparing large DOV sensors and small DOV sensors: programming the CMM becomes very difficult and there is a loss of flexibility.

However, for parts that do not require as much accuracy, this system may be ideal since it will be able to image the whole part at once, without the use of an expensive CMM. The systems sells for approximately $50,000.

5.8 Projection Moiré Interferometry

Projection moiré interferometry is a triangulation method of shape measurement but often is incorrectly considered to be in a different category since the technique seem different yet, in actuality, still relies on triangulation. There are many methods of moiré metrology. Only one common method is presented here but Kafri and Glantt (1990) and Patorski (1993) detail many other moiré methods.

5.8.1 Operating Principles

The moiré effect is "a fringe pattern formed by the superposition of two grid structures of similar period" (Kafri & Glatt, 1990, p. ix). The resultant interference fringe pattern is at a lower spatial frequency than that of the two grid structures. This is illustrated in Figure 5–19. Two grids of lines are superimposed and the resultant pattern is series of light and dark patterns tilted slightly to the right of vertical. In practice, the two grid would have a finer pitch (therefore higher frequency) to yield a more distinct low frequency pattern.

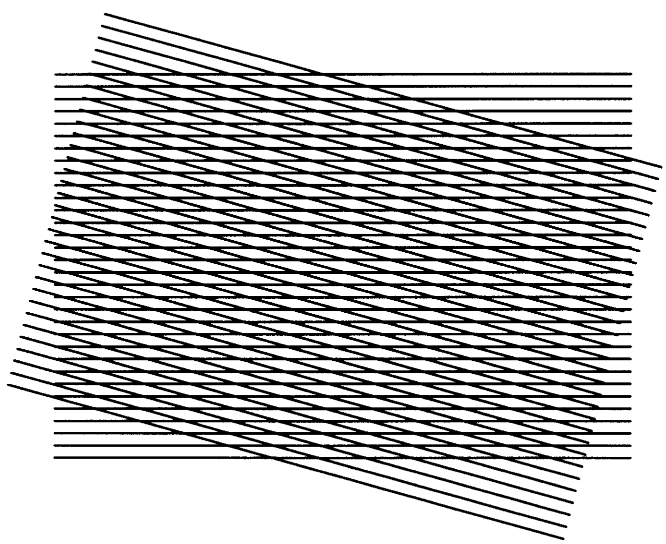


Figure 5–19: Moiré effect

Classically, interferometry is the method of measuring distances by using interference fringes. These fringes or patterns occur when two beams of light travel different optical paths and are made to interfere. Interferometry is described briefly in Section 5.12.1 and in much more detail in Hariharan (1992).

A schematic for projection moiré interferometry is shown in Figure 5–20. The two optical axes of the source and detector are separated by the angles α and β. A light source, or signal, is projected through a projection grating onto the object. This beam illuminates a 2D patch of the object. As the beam interacts with the surface and is reflected back to a detector, the surface geometry changes the optical path length and therefore, the phase of the signal. The beam returns and passes through the detection grating that is matched in pitch to the projection grating. The return beam can be imagined as a distorted grid. When that grid is compared to the detection grating, a moiré pattern is formed. This interference pattern contains information about the contour of the surface. Physically, the pattern shows lines of equal height. The change in height (Δz) between lines is directly related to the pitch (d) of the grating and inversely to the tangent of the two angles of separation. This relation can be expressed as

$$\Delta z = \frac{p}{\tan\alpha + \tan\beta}.$$

where one of the angles is often zero so the tangent of the angle is zero as well.

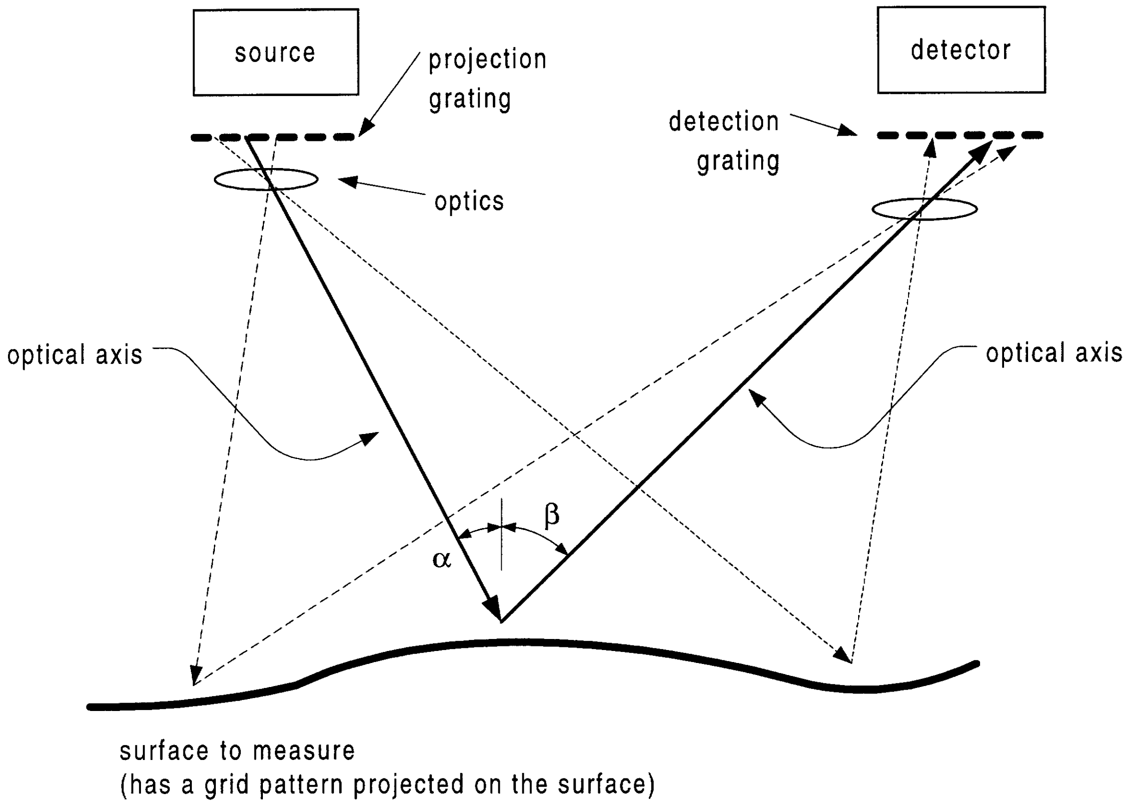


Figure 5–20: Schematic of projection moiré interferometry

The system is good for measuring the relative range changes in the part. There can be range ambiguities if there are sudden changes in range or range discontinuities. It often is helpful to have a priori knowledge about the object before data analysis. Therefore, this system is best used for measuring smooth surfaces with gradual height changes.

A common use of moiré interferometry is to measure strains in a part at an instance. In this case, the shape changes are small and only the relative shape change is of critical importance. Another use for this method is to gage lenses and optical equipment.

One solution to avoid range ambiguity is to take several measurements with different gratings or projection angles and then compile the results. This way, one can have absolute range measurements and measure across discontinuities (Gordon, 1994). There are also software methods to unwrap the phase and minimize range ambiguity.

A moiré system would be used with a CMM to measure 2D patches of a part. As with traditional triangulation systems, FOV, DOF, resolution, accuracy, and data spacing are all related. As FOV and DOF increase, the resolution, accuracy, and data spacing decrease. Also, as the FOV increases, the scan time for a part decreases since it takes less images of the part. Again, since the method is a optical system, the surface finish is important. Specular surfaces, such as sheet metal, probably have to be prepared with some type of coating, as is the case with many other optical methods.

5.8.2 Example

The Electro–Optical Information Systems (EIOS) Mini–Moiré system is a sensor that is based on a variation of the projection moiré method. Instead of having a physical detection grating, a video camera images the target and processes the signal in software. This can also be done through a spatially modulated photodetector (Patorski, 1993). The sensor is attached to a CMM to image the part. The sensor moves around the part and images a patch of the part in less than 0.5 seconds.

The accuracy, A, is related to the FOV (F by F inches) by the equation $A = \frac{3F}{4000}$. Since F can range from one to twelve inches, accuracies under 0.001" are possible. The DOF is half of F.

The Mini–Moiré system is different from traditional moiré systems since it is much less expensive and is extremely portable. The basic system costs $60,000 with each additional sensor for less than $10,000. A powerful use of the Mini–Moiré system is when it is used with a portable CMM. This way, the part can be imaged easily and quickly, as compared to using mechanical contact probes. Though this effect can be achieved similarly with full frame, structured light, laser triangulation sensors, it is better suited to be used with the portable CMM. Since portable CMMs are hand controlled, the sensor must image the target quickly and the Mini–Moiré images faster than other methods. This setup is shown in Figure 5–21.

However, as the part gets large, the number of patches increases, and subsequently the scan time. For example, as the FOV increases from FxF to $2F$x$2F$, the scan time is decreased by four but the accuracy is only half as good. Another disadvantage, like the 4DI system, is that the DOF is smaller than the 2.4" (or potentially larger) DOF with the Hymarc system. However, both moiré and triangulation methods are comparable in performance and neither have significant advantages over the other.

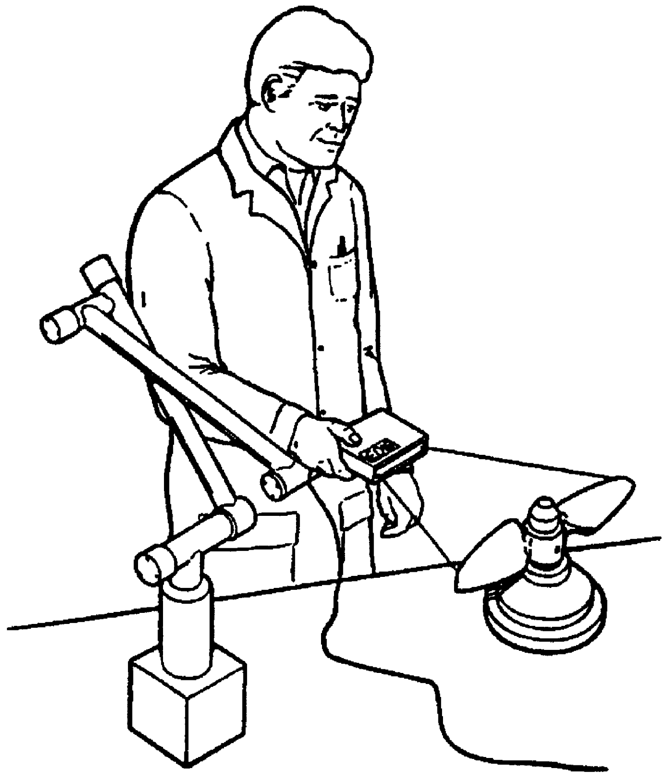


Figure 5–21: The EOIS Mini-Moiré sensor being used with a portable CMM

5.9 Photogrammetry

Photogrammetry is the science of reconstructing the size, shape, and location of objects from their images. This method is commonly used for aerial mapping with images from aircraft or satellites. Close range photogrammetry is used for industrial applications. These methods result in highly accurate measurements over large areas.

5.9.1 Operating Principles

Several images of the object are taken with cameras. These different images of the same object are used to reconstruct a 3D model of the object by triangulation. Film based photogrammetry can take several hours to process because of film developing and scanning. However, with the advent of high resolution video and digital cameras, video or digital photogrammetry can output results in minutes or even real time. The main advantage of this method is the surface qualities are not critical to the measurement as in traditional triangulation or moiré systems. Photogrammetry measures all points simultaneously so measurement time is low.

There are two types of photogrammetry, stereo and convergent. Stereo photogrammetry involves imaging the target with two parallel line-of-sights. This is how the human eye works and how some maps are made. This method is simple to execute but difficult to process. There needs to be a skilled operator or complex software to create an accurate 3D image.

On the other hand, convergent photogrammetry does not require a skilled operator and can easily be automated by computer. The main drawback is the object needs to have "targets" to locate where the data will be taken. This method is commonly used in industry. Placing the targets on the surface is usually the most time consuming step of this method. If lower accuracy is acceptable, one can use natural physical landmarks, such as edges and corners.

Optical sensors can increase grid spacing by changing the optics or scanning method. To get a denser grid spacing with photogrammetry, the targets have to be placed close and eventually, there is a physical space limitation.

Accuracy from these methods can approach 0.001". However, accuracy is dependent on range since this method is another triangulation method. Moreover, overall accuracy increases with more "targets," as does the setup time.

5.9.2 Digital Photogrammetry

Modern digital photogrammetry use digital CCD cameras to image the object. Two examples of convergent digital photogrammetry are explained in the following sections.

5.9.3 Example: Metronor Inc.

This digital photogrammetry system uses two cameras (one for certain applications) positioned so they have a line of sight to the object and should be separated by an included angle of 60–90 degrees. After a brief calibration period, if two cameras are used, imaging can begin. A picture of the Metronor system is shown in Figure 5–22.

There are several methods of imaging the object. One method is to use a "light pen" that an operator uses to manually locate points on the object, even recessed points or

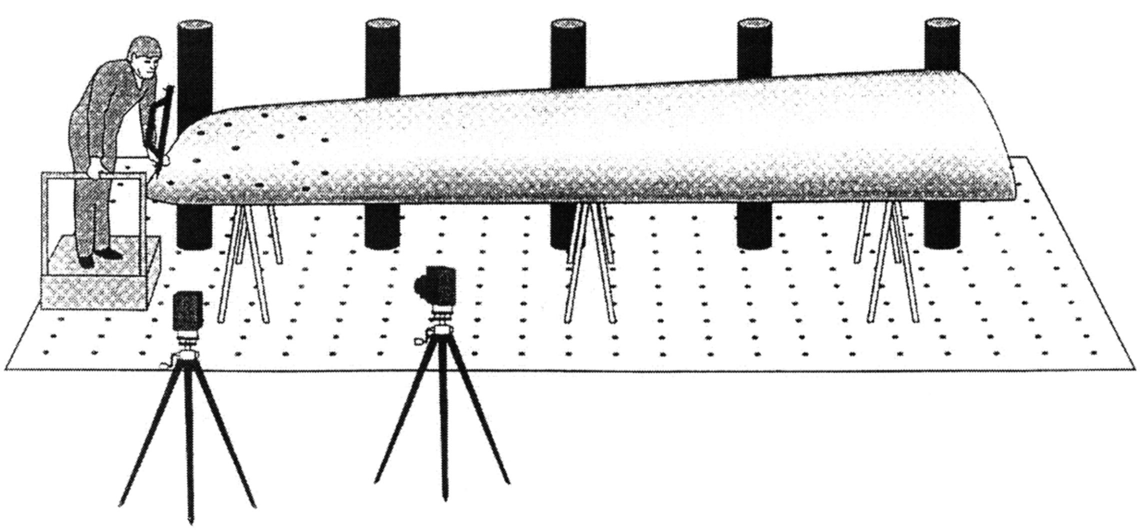


Figure 5–22: Metronor digital photogrammetry system in use

points not visible to the cameras. The operator touches the point with the "light pen," signals the camera, the data is taken, and the spatial coordinates are displayed. Another method is to attach LEDs to the target and use those to identify the data points. The

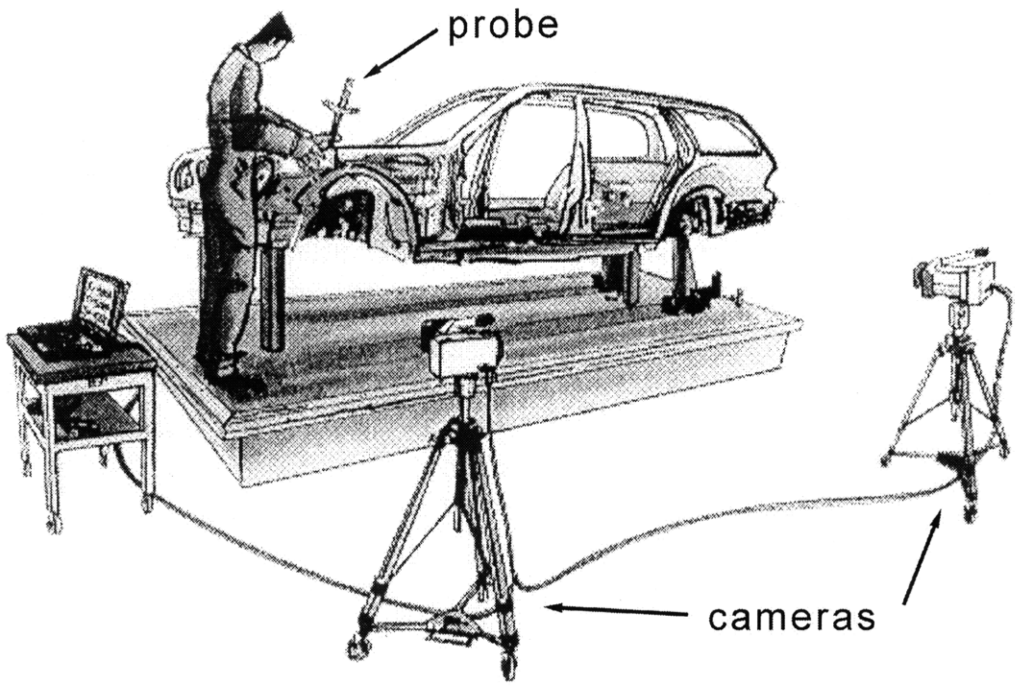


Figure 5–23: The GSI photogrammetry system used with a probe and two cameras

LEDs can be attached to the part by laying down a tape covered with LEDs. Both the light pen and LEDs are shown in Figure 5–22.

An experimental method is to project laser spots and the camera can measure hundreds of these points a second. Currently, Metronor is developing an Automated Laser Projection System that will allow the system to project grids of points and allow the operator measure with a dense grid array, a common need for measuring sheet metal parts. However, the project is still under development.

For a part with a plan area of six feet by six feet and cameras fifteen feet away (line-of-sight distance), Metronor claims an accuracy around 0.003".

The basic Metronor system costs around $300,000. The experimental Automated Laser Projection System (ALPS) is estimated to be an additional $100,000. If the ALPS system is developed, the Metronor system would be comparable in performance to the laser triangulation systems, yet not require and expensive and bulky CMM.

Perhaps the greatest disadvantage is the lack of automation in the measurement. An operator must place and move the target on the part. This makes dense surface mapping difficult, but still possible.

5.9.4 Example: GSI

The GSI system is similar to the Metronor system except they strongly suggest using retroreflectors as "targets" and use higher resolution cameras. If targets are placed on the part, GSI claims 0.001" accuracy at 50 feet. One camera will take 6–12 photos from different locations and the result, after seconds of processing time, are available. This system costs around $125,000. Real time measurements using multiple cameras are available at lower accuracy. Figure 5–23 shows the GSI system being used with a probe. The probe is basically the light pen used with the Metronor system.

5.9.5 Film-based Photogrammetry

Film–based photogrammetry is almost identical to video or digital photogrammetry except conventional film is used. These methods can take hours to complete since the film must be developed and the image digitized. Because of the delay, film–based photogrammetry is becoming antiquated. However, since film has much higher resolution and current digital images, accuracies currently can be five times better.

5.10 Theodolites

Theodolites are precision instruments for measuring angles. A theodolite consists of a head and a tripod. Figure 5–24 shows a theodolite head and Figure 5–25 the theodolite head and tripod. The head unit has a telescope and scales that are capable of measuring the horizontal and vertical angles of where the telescope is aligned, usually a target. These two angles are used to determine the line of sight vector in a spherical coordinate system. This is illustrated in Figure 5–26 where θ is the horizontal angle (azimuth), ϕ the vertical angle (elevation). Theodolites are used in surveying as well as industrial applications. When two or more theodolite heads are sighted on the same target, the position of the target can be triangulated.

Figure 5–24: Theodolite head

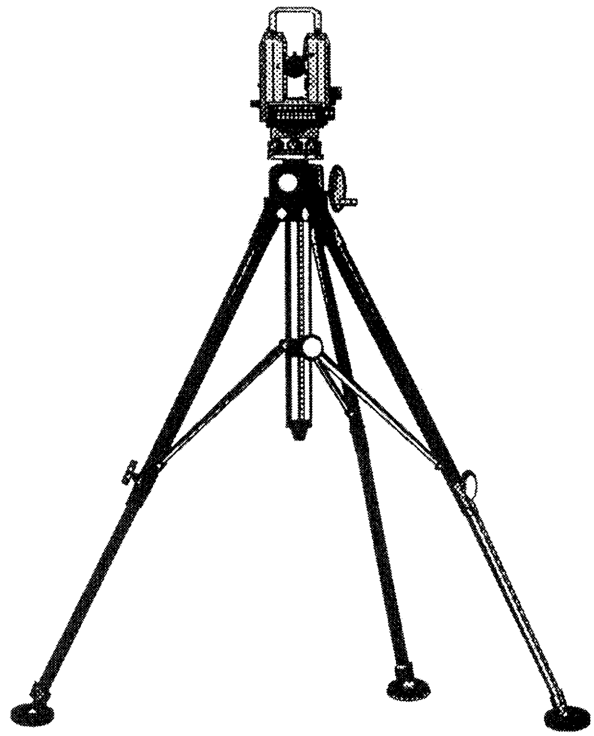


Figure 5–25: Theodolite head and tripod

The most common way of sighting on a target is to put a "target," as described previously, on the part. This is a contact method of measurement. This method can also be a non–contact method of measurement. A laser diode is attached to the telescope, as coaxially as possible but there will be a slight parallax error. This is similar to the laser sights on rifles. The laser hits the target and the two theodolites sight on the laser "dot." With this method, two trained operators can sight in on a target every few seconds.

The next level of sophistication is an industrial station. This machine is a theodolite with a distance sensor. That way, all three spherical coordinates are given to locate the target. The industrial station is similar to a laser tracker as described in Section 5.12. The accuracy is relatively low, around 0.020", but industrial stations are designed to be used outdoors easily.

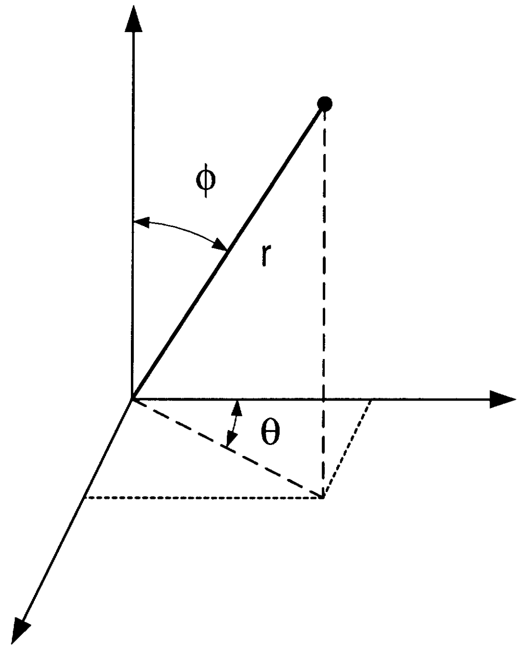


Figure 5–26: Spherical coordinate system

5.11 Summary of Triangulation Methods

Despite the advantages of the systems, their underlying technology is still triangulation. Even with their refinements to achieve incredible scanning speeds, the fundamental problems of triangulation are unresolved. Since triangulation relies on geometry and similar triangles, the inherent error or uncertainty maybe magnified as a triangle scales in size. Therefore, the accuracy is still a function of the range. Moreover, since the laser must interact with the surface of the target, specular surfaces still cause problems for the sensor and laser. The depth of view is limited as well. They also are limited by the size of the CMM, if one is used.

5.12 Laser Tracker

A laser tracker is a measurement tool that uses a servo–controlled laser interferometer (a precision distance measurement tool) to follow and measure the position of a retroreflective target. Since the retroreflector much contact the part, this is a contact method of measurement but the operating principle is a non–contact method. A picture of a laser tracker can be found in Figure 5–27 and a schematic of the main components in Figure 5–28.

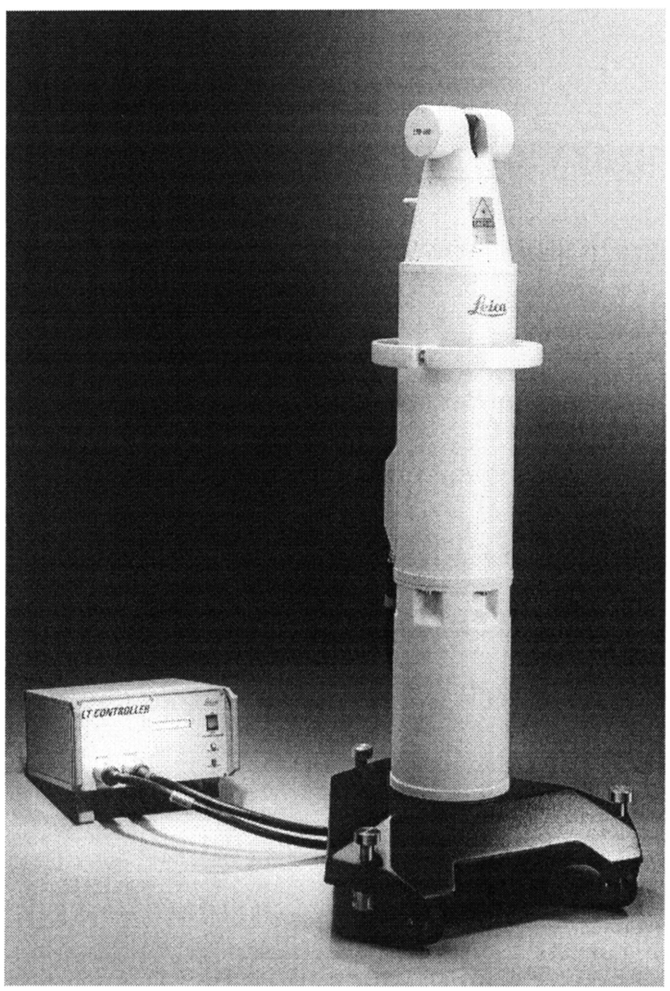


Figure 5–27: Leica laser tracker

5.12.1 Operating Principles

The basic feature of the laser tracker is the interferometer; an instrument common in high precision measurements. Greenwood (1993) explains:

> The basic operating principle is that light reflected back upon itself can generate

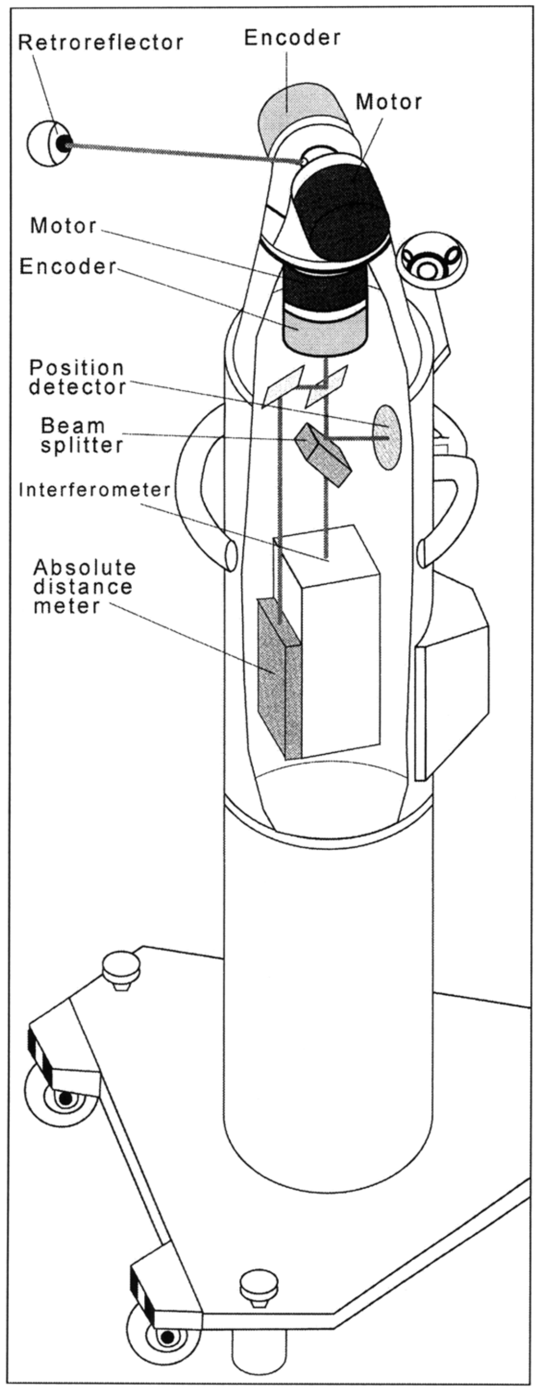


Figure 5–28: Schematic of the main components of a laser tracker (Leica LT 500)

> a fluctuating interference intensity pattern proportional to changes in distance which can be counted electronically. Each count corresponds to a fractional wavelength change in position. The result is a range measurement system so linear, repeatable, and accurate that it has become the standard in many industries.

The laser leaves the tracker, reflects off the target, and returns to the tracker. The tracker does this several hundreds of times a second, taking a measurement each time. The measurement is taken in a spherical coordinate system (two angles and a range) and converted to a Cartesian coordinate system. The spherical coordinate system is illustrated in Figure 5–26. This laser is redirected with a gimbaled mirror and a control system is used to follow the target to always maintain a return signal. The target can be placed on the object and manually moved across the part. The laser will continually to follow and measure the position of the target (Greenwood, 1993).

The accuracy of the system is extremely high, even at ranges over 100 feet. The system accuracy of some systems can be 0.001" every 17 feet of range or even better. The accuracy improves almost linearly when the range is decreased. The system accuracy is a combination of three factors, the range accuracy and the two angular coordinates. The range accuracy is almost an order of magnitude better than the angular accuracies. The high accuracy of the system comes from the resolution of the interferometer. The interferometer is actually a relative measurement device since it only compares the path difference of two laser beams. The target starts at a known reference point located on the laser tracker. As the target is moved, the interferometer counts to determine the path length change. As a check, there is often a lower resolution absolute distance meter to give an reference measurement.

This fixture is effective for measurement and machining. It provides support everywhere. However, the main disadvantage is that it is part specific and not flexible.

7.8.2 Profiled-Edge Fixture and Dimensional Check Tool

The profiled–edge fixture and dimensional check tool uses a series of blades to support the part within a frame. A diagram of the tool is shown in Figure 7–2. These blades have a profiled–edge to conform to a certain cross section of the part. A series of these blades can approximate a continuous surface. This type of fixture is used by the Boeing Commercial Airplane Group, Wichita Division (Walczyk & Longtin, 1997).

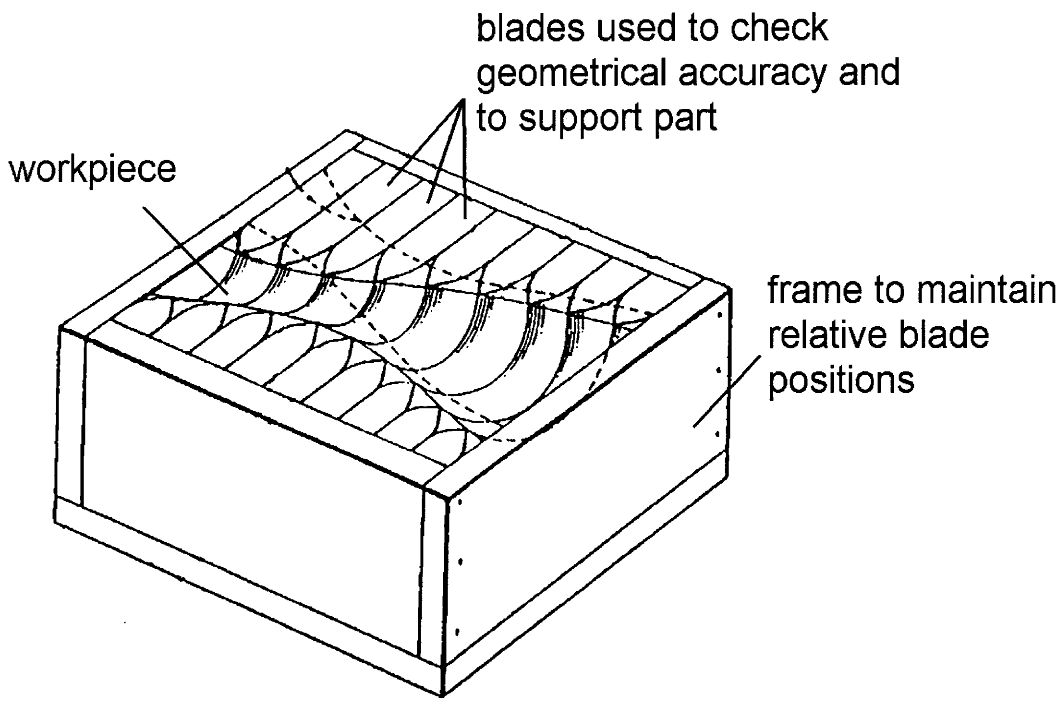


Figure 7–2: Profiled–edge fixture and dimensional check tool

This tool can also be used to check dimensions. Each part uses a specific set of blades to create its own dedicated fixture. If the part conforms to the tool, the part will be area of planning. The heuristic method of planning is being implemented by using artificial intelligence and expert systems. These systems attempt to mimic the human decision process (Pham & de Sam Lazaro, 1990). Non-heuristic methods include kinematic analysis and finite element analysis (FEA). One problem with the FEA approach is the need to know exact information such as forces and locations (Bausch 1990), which is often difficult to determine.

7.8 Sheet Metal Fixturing Systems

This section will briefly describe different methods of fixturing sheet metal parts that are used in industry. Many of these are able to support large sheet metal parts for contact and non–contact measurement, as well as machining.

Despite the research in this area, many measurement companies suggest just laying the part on the table. Their reasoning is that the part will not deflect enough to matter, and if it does, hand forces can force the part to fit the assembly. This may be true but there should be a higher standard or more precise method for precision assembly.

7.8.1 "Dedicated" Holding Fixture

This is the type of fixture described in Section 2.6 and is the "conventional" method of fixturing sheet metal. The formed part is placed over a holding fixture that conforms to the shape a perfect part. This forces the part to a specific shape. The part is held down either by vacuum pressure or dead weight (sandbags). A picture this fixture is found on Figure 2-10. This fixture is used at the Northrop–Grumman Corp, Vought facility (Walczyk & Longtin, 1997).

are used to reference and constrain the part (Asada & Fields, 1985). A detailed review of sheet metal fixturing is given by Cai, Hu, & Yuan (1996).

7.6.2 Drilling and Routing

Currently to drill and route sheet metal parts, there are dedicated dies and operators to hand machine these features. This method is not in line with the FMS ideologies. Research has been completed to determine the best support points around a drilled hole. The three to four support points are a characteristic distance away from the hole and the "boundary" of the "neighborhood" of the hole. The part can not "snap through" or yield locally either through the machining forces or the reaction forces and moments at the support points (Youcef–Toumi, Liu, & Asada, 1988). There is also work done about practical issues such as how to actually drill into sheet metal accurately (Fields, Youcef–Toumi, & Asada, 1989).

7.6.3 Practical Issues in Support

In actual practice, the locations of the supports are determined by an expert machinist based on experience and rules. Then the supports are manually adjusted. In the FMS, this process should be automated and made flexible.

For sheet metal, work has been done to implement a N-2-1 method of support (Rearick et al., 1993), (Soman, 1996), (Cai et al., 1996). Some have been integrated into FEA and solid modeling programs.

7.7 Automated Fixturing

Fixturing is done in two phases: planning and execution. As mentioned in Section 7.6.3, both of these phases are done manually. There has been little practical work done in the major types of fixtures are mainly for prismatic parts. There are also flexible fixtures dedicated for sheet metal (Asada & Fields, 1985) which rely on modular elements.

Adaptable fixturing is the general term used for fixtures that have surface contact instead of point contact with the workpiece. This naturally results in discrete conformable surfaces or ultimately a phase changing type fixture to provide continuous support for the part. By using surface contact, the fixture can provide the same clamping force over a larger area. This results in lower stresses in the part that yields less part damage. Moreover, the surface can support forces and moments, as opposed to only forces with point supports. This may result in fewer supports locations than with only using point contacts (Buitrago & Youcef–Toumi, 1988).

7.6 Sheet Metal Fixturing Issues

7.6.1 Support

Until now, most of the discussion has been related towards fixturing methods for prismatic parts, which have high rigidity. With rigid parts, only six degrees of freedom need to be constrained to locate the part. However, for less rigid parts like sheet metal, more degrees of freedom may need to be constrained to prevent movement and deflection during machining loads. The part may also be already deformed before machining loads due to gravity loads so even more supports may be needed.

A common method of fixturing sheet metal parts is to support them on a “bed of nails” (Asada & Fields, 1985). The part is originally located by two reference marks on the part. For example, there commonly is a hole and slot on the part. The hole and slot

7.4 Flexible and Conventional Fixtures

The increased desire to move towards a flexible manufacturing system (FMS) results in systems able to responds faster to the consumer. With frequent part changeovers, small lot sizes, and a variety of parts and production requirements, all the operations within the system should be flexible. This involves the material handling system, CNC machine tools, process monitoring systems, and also fixtures (Gandhi, Thompson, & Maas, 1986).

Flexible fixtures are adaptable to a wide range of parts. This is in contrast to conventional or dedicated fixtures that are part specific and are best for large lot sizes. Conventional fixtures are can be faster to setup and more accurate but the cost of design, manufacture, and storage of the fixtures are prohibitive. Moreover, dedicated fixtures are inflexible to design changes (Youcef–Toumi, Bausch, & Blacker, 1988). Therefore, there is a strong desire to create flexible fixtures that preferably are automated as well.

7.5 Flexible Fixturing Methods and Definitions

Five major types of flexible fixtures have been developed: matrix fixturing, programmable clamps, fluidized–bed vise, flexible programmable vises, and modular fixturing kits (Buitrago & Youcef–Toumi, 1988). Matrix fixturing is based on the reconfigurable pins of a RTFF–type tool. This method conforms to the part shape. Programmable clamps and programmable vises are for turbine blades and prismatic parts respectively. These devices close to conform to a specific part. A fluidized–bed is a bed of beads fluidized by air at high pressure. The phase change from liquid to solid fixtures the part. Lastly, modular fixturing consists of a set of different pieces that can be adjusted and arranged in many configuration and hold a wide variety of parts. These five

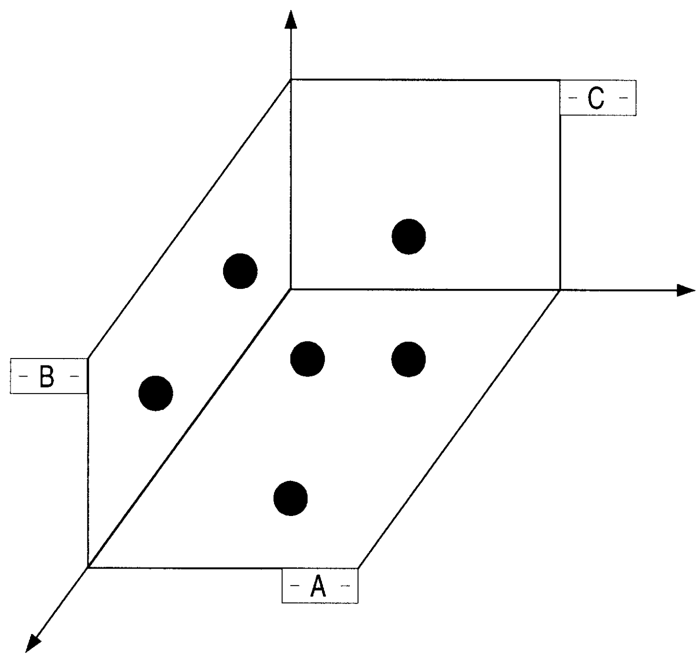


Figure 7–1: 3-2-1 locating principle

In practice, the points are often point contacts. After locating the part, it also must be held in place. This is normally accomplished with clamps

One issue of concern is overconstraint. Since clamping is usually a surface to surface interaction, there will be more than three points trying to define one plane. If the points are not coplanar, there will be deformation in the part. This distortion is a problem since when the part is unclamped, the part will change shape (Drake, 1984).

To determine the locating points, normally the points are located to minimize part deformation and stresses due to the external forces. These forces include gravity, a body force, and machining forces, normally point forces (Soman, 1996). This problem is a critical issue in fixture design that has yet to be mastered.

7.2 Importance of Fixturing

Fixturing is critical to manufacturing since almost all operations require fixturing. Moreover, most manufacturing operations run open loop with respect to the fixture. After the part is fixtured, the machine assumes the fixture and part are stationary during the operations. Therefore, fixturing provides the physical link between the workpiece and the machine operations, or the material world and information world (Bausch, 1990).

7.3 Fixture Theory

Objects have six degrees of freedom: three translational and three rotational. To properly locate the part, the fixture must constrain all six. A common method is to use the 3-2-1 locating principle. This principle uses three orthogonal datum planes, A, B, C, on the part. Three points are on datum plane A which uniquely constrains the part to one plane. Now there are only two translational and one rotational degree of freedom. Then two points are on datum plane B which constrains one translational and one rotational degree of freedom. Finally, one point is on datum plane C which uniquely defines the orientation of the part (Rearick, Hu, & Wu, 1993).

Chapter 7

Sheet Metal Fixturing

7.1 Functions of Part Fixturing

A fixture is an assembly that usually accomplishes four functions: locating, clamping, guiding, and supporting of a workpiece. The locating function positions the part for clamping. The clamping function immobilizes the part form its own weight and cutting forces. The guiding function helps start the position of the tool path and the supporting function reacts against loads that may cause deformations due to loading. A fifth function, linking, is a result of the need for integrating the four previous functions (Liu, 1994).

Another view of a fixture is a device that must hold the part stationary during the operation, locate the part's position, and allow access for the operation to take place (Bausch, 1990). However, for sheet metal applications, as opposed to fixturing prismatic parts, the main functions are locating, clamping, and supporting while at the same time providing tool access to the part.

For an inexpensive and immediate solution, the portable CMM with a mechanical contact probe would be the best system. Portable CMMs are used throughout industry in applications similar to ours.

array so position in space is related to the position on the array. Though the grid spacing may be large, it is adequate for the RTFF project. Also, the method is flexible. The accuracy is also independent of the range, which is not the case for triangulation systems.

Another advantage of the Lincoln Lab method is the ability for the method to evolve and be used to measure larger parts. To measure parts larger than the CMM with the triangulation sensor, a larger CMM must be used.

The system requires the laser and camera to stay stationary and a fixed distance apart. Without having to purchase an expensive CMM, a simpler, less expensive stationary frame can be created. However, the system is still under development and much engineering work needs to be completed. One drawback is since it is an optical system, specular surfaces still may cause a problem, just as it does with the standard laser triangulation systems. The measurement system also requires precise linear motion to move some optics. An investigation of a proposed design can be found in Appendix A.

6.6 Recommended System

In the long run, the recommended system is the Lincoln Lab method. There are other techniques that can measure the part. Many of these techniques have elegant improvements on existing technologies. However, the Lincoln Lab solution is revolutionary because it uses a radically different method of solving the same problem. The result is a method that can measure large parts accurately yet, not rely on an expensive CMM to move the sensor around. However, it is still under development and the RTFF project is currently negotiating a potential contract with Lincoln Lab.

Therefore, there are many realistic options to measure RTFF parts. They each have their own characteristic advantages and disadvantages. Accuracies vary but are basically acceptable across the board. The major differences were in cost, measurement time, and in the issues mentioned in the Notes section of Table 6–3.

Eventually, the RTFF program decided to adopt the Lincoln Lab method. This method was chosen since it is fast, does not require part preparation, does not require a CMM, the associated programming, and the environmental constraints a CMM needs. However, this method is still in development and is uncertain. Preliminary results have been very positive. The next section will describe the Lincoln Lab method, the limitations, and performance issues.

6.5.2 Lincoln Lab Technique

This method is currently being developed at MIT Lincoln Laboratories under the direction of Dr. Lyle Shirley. The method is based on laser speckle wavelength decorrelation. Dr. Shirley's proprietary third generation method images the whole part at once and gives range information with accuracies independent of range. This benefit is not found with most sensors.

The current proposed system specifications are superior to commercial systems. The cross range accuracy or more correctly grid spacing is targeted to be 0.016" (which is determined by the CCD array used and size of image) and the range accuracy to be 0.002". The system should be able to image a 6x6 feet object and provide the data in less than ten minutes. The imaging time should be less than one minute. The cross range accuracy is not as accurate as other methods but for the RTFF project, cross range information is not as critical as the range information. The image is mapped to the CCD

Table 6–3: Comparison of the measuring methods for RTFF

Specifications \ Methods	CMM with mechanical contact probe	CMM with laser triangulation (Hymarc)	Portable CMM with mechanical contact probe (Romer)	Photogrammetry	Laser tracker	Lincoln Lab method
Imaging Area	limited by CMM but 6'x6' is possible	limited by CMM but 6'x6' is possible	8' diameter sphere, but can range from 5-12'	6'x6' or larger	6'x6' or larger	6'x6' or larger
Accuracy	0.001"	0.001" + CMM accuracy	0.002"	0.001"-0.003"	~0.001" at close range	0.016" in cross-range, 0.002" in range
Measurement Time	hours	> 20 minutes	5-20 minutes (estimate)	few minutes, but setup can take hours	5-20 minutes (estimate)	< 10 minutes (estimate)
Cost	>$500K	$100K + CMM = >$600K	<$100K	>$125K	~$200K	not available
Notes	must be programmed, vibrations & dirt cause problems, needs temperature control	might need to treat surface, part specific CMM programming, limited by CMM	manual, very portable, not repeatable, vibration during measurement reduce accuracy	can be very fast, but targets must be attached manually or surface manually probed	manual, very portable, not repeatable, vibration during measurement reduce accuracy	research project, expandable size, 1 minute data acquisition, might need to treat surface

maintenance. Lastly, the workers in the area can be a problem if lasers are used due to the health and safety issues.

Most of these problems occur because the RTFF project is attempting to perform a metrology room type measurement on the shop floor. The project wants the machine to be accurate, large–scale, robust and fast; currently these features are usually mutually exclusive.

While in the factory, the part will be located on a flexible fixturing setup to support the part. This will be described in detail in Chapter 7.

6.5 Summary of Potential Measurement System

6.5.1 Overview

The measurement system needs to be able to measure the RTFF parts with accuracies in the thousandths of an inch range. There is a strong emphasis on having automated measuring. This automatically eliminates a few options but a group of plausible options are shown in Table 6–3. These options are compared to our specifications with comments. That table summarizes much of the material in Chapter 5. Please use Table 6–3 as a guide. Many vendors tend to give optimistic information about their products, rather than what is achievable.

6.4 The Environment and Resulting Errors

The measurement device will be located away from forming tool but not in a metrology room. The device will be on the shop floor with vibrations, dirt, temperature changes, workers, and other disturbances characteristic of a factory. Thus, the measurement device must be able to operate in this type of environment. Each of these disturbances adds to the complexity of the measurement problem and possibly error.

Since the measuring device will be in a factory that does not have strict climate control, the temperature will vary widely. For example, factory temperatures can vary from 50–110° F. This 60 F° (28 C°) change will decrease dimensional accuracy. Aluminum has a coefficient of thermal expansion, α, of $1.3 \times 10^{-6} \frac{\text{in}}{\text{in} \cdot {}^{\circ}\text{F}}$. Therefore, a 60 F° temperature rise results in a 0.009” elongation per foot.

The vibrations transmitted to the measuring instrument from the factory environment are also a problem. These vibrations introduce error to the measuring system that further decreases the accuracy. An impractical solution is to stop all other activity in the factory to minimize the outside disturbances. A more desirable alternative is to mount vibration isolation pads under the measurement machine. If these passive methods are not enough, active damping can be used for more accuracy. Small amplitude random vibrations potentially could be averaged out. On the other hand, sudden shocks may cause less predictable and more difficult to correct errors.

The dirty environment is another issue. This environment can degrade the lifespan of delicate measurement devices. Debris can accumulate in the bearings and wear the components and decrease accuracy unless there is more frequent preventative

Since the part was stretchformed, it will be piecewise smooth and have gradual curves. The range accuracy is more important than the cross range accuracy, since the curvatures are gradual and an uncertainty in the cross range position normally results in a smaller range uncertainty. A range accuracy of 0.002" was chosen since that is the order of the forming accuracy.

The Nyquist sampling criterion states that to correctly capture a signal with frequency, f, one must sample at least at a frequency $2f$. For our parts, the pin spacing and size (1.125" square) determines the spatial frequency of the system. Thus the grid spacing should be at most $\frac{1.125}{2}$" square, or 0.5" square to be safe. With this spacing, the measurement system should be able to detect all features caused by the pin positions or the shape of the die. Taking more data could be useful, but for most measurement systems, there is a tradeoff between taking more data and measurement time.

There will be two holes drilled when the part is on the tool for part registration. Inserts can be added to help locate the holes. The two holes will be similar in function as "dog ears," shown in Figure 2–11, are in current practice. Part registration is used to orient the part in space with respect to some global coordinate frame.

Optical measurement systems might encounter problems since the sheet metal surface can be specular. Material can be applied to the sheet and easily washed off to create a matte surface for the optical instruments. However, the RTFF program would like to avoid those extra steps.

Another problem is the lack of rigidity of the part because of its large size and thinness. Therefore, the part must be strategically supported to prevent significant errors in measurement induced by gravity. Fixturing will be discussed further in Chapter 7.

7. Field deployable and factory hardened. Able to perform in a production shop environment with large temperature variations, high humidity, debris, etc. The prototype may not need to be as robust as a production item.
8. Ability to locate two reference points (holes on possibly holes with inserts) on the part for part registration.
9. Eye safe lasers or permissible for factory use.

Section 6.3 will explain specifications 1, 2, 3, 6, and 8. Section 6.4 will explain specifications 7 and 9. Specification 5 is indicated for maximum flexibility for the data processing. The imaging and analysis time specification of 10 minutes is to give a sense of "fast" measuring times. Since measurement will be used to close the shape control loop, the cycle time can not be "long" (several hours) as in current methods. Another detail is the grid spacing of the data. That requirement is implicitly stated since the data is used for gaging. Grid spacing was discussed in Section 4.4 and will be discussed in Section 6.3.

Section 4.3 discussed some of the challenges in measuring 3D parts. The RTFF project is going to determine how to treat the data. The measurement method will simply have to output data in a form that the software can recognize. That data must characterize the 3D surfaces and contours of the part. The requirement is directly related to the grid spacing and accuracy of the system.

6.3 "To Be Measured" Part Description

The measurement device will measure parts formed on the RTFF tool. The RTFF tool is being designed to stretch form a 4x6 feet piece of sheet metal. The maximum pull off angle should be no more than 45°. Therefore, if the part is bent parallel to the 4 foot side, the maximum height of the part will less than $\frac{3}{\sqrt{2}}$ or close to 2 feet. Thus, the measuring volume is close to 4x6x2 feet.

Table 6–1: Primary needs

Measure all RTFF parts
Faster than current methods
More accurate than current methods
Output to be compared with CAD data
Measure on the shop floor
Ready to use when we need it
Easy to use
Convenient
Cost effective
Expandable to measure larger parts in the future

Table 6–2: Secondary needs

No part coatings
No on–part probes
Measure on the tool
Automated
Can measure pin height

6.2 Measurement System Specifications

The measurement system the RTFF project is looking for should be able to measure RTFF parts and output data to be used for gaging. The system should have the specifications listed below.

1. Imaging area: 6x6 feet (2x2 m)
2. X & Y accuracy (cross range): ±0.005" (125 μm=125x10^{-6} m)
3. Z accuracy (range): ±0.002" (50 μm)
4. Image and analysis time: under 10 minutes
5. Data output format: ordered triplets of point locations
6. Ability to deal with surface qualities of shop aluminum sheets, potentially specular or clad material.

Chapter 6

RTFF Measurement Needs

6.1 Customer Needs

The goal of this measurement system is to help the RTFF to make good parts. Good parts are what the end user needs. To fulfill that need, RTFF project members have discussed the primary and secondary needs. Primary needs are defined as features we feel the system must have. Secondary needs are features that are desirable but not vital for the system. Moreover, these needs are described in the "language of the customer," not engineering specifications.

The primary needs are listed in Table 6–1 and the secondary needs are listed in Table 6–2.

matching landmarks on both sets of data. The information can also be used to extract geometric information.

For the project, the measurement system only needs to output x,y,z data, which is simple for the methods discussed. The RTFF project is providing their own data reduction, surfacing, and data manipulation software. There will be two registration holes on every formed piece of sheet metal. Those two holes will be the landmarks on the formed piece and CAD data. They are aligned and a least square fit will be used to tilt the part to the optimal orientation. After measurement, the shape can be used to adjust the die via the DTF described in Chapter 3.

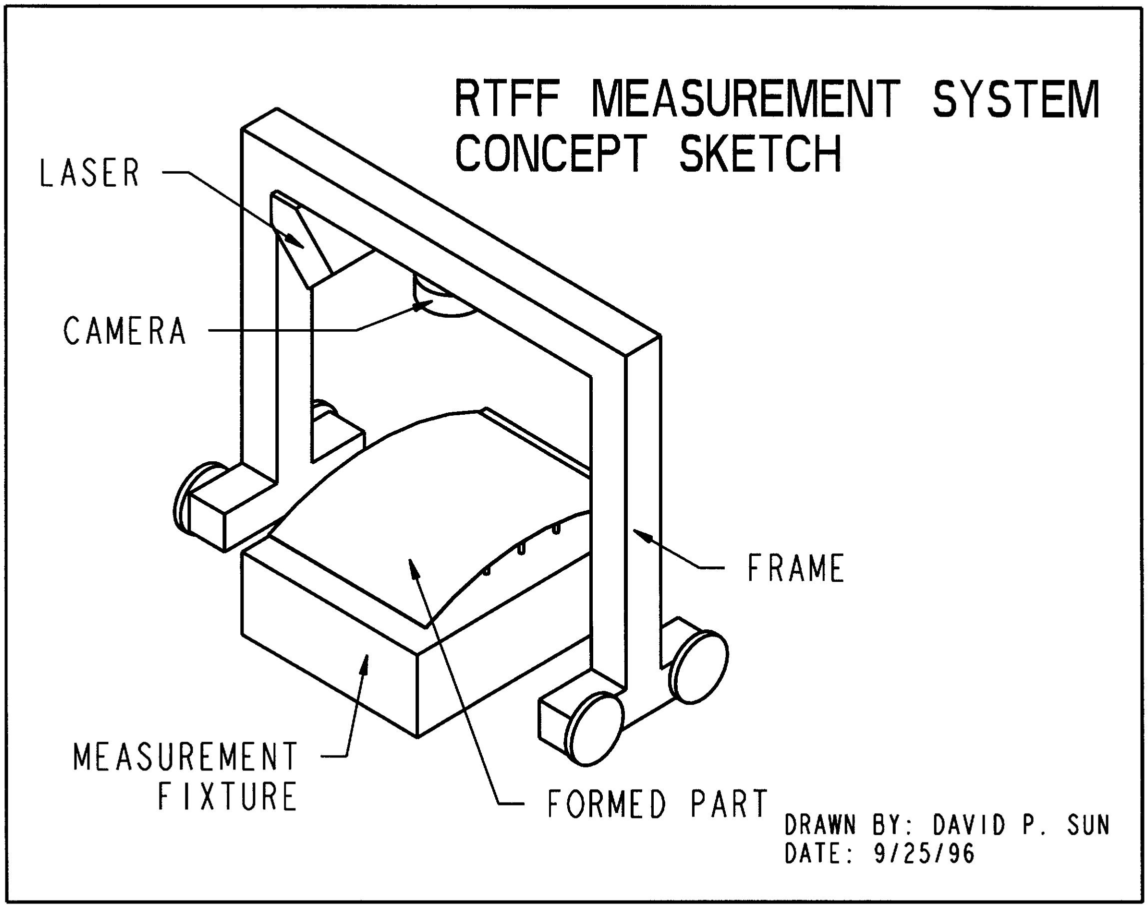


Figure 5–29: Lincoln Lab setup

5.15 Software Interface

The software technology available allows the operator compare the measured part data with a CAD file. Generally, the data from the sensor are coordinates in the form of ordered triplets, *x,y,z*, and sometimes also the normal vector to the surface, *i,j,k*. This data can then be processed in many ways.

The cloud of points can be averaged or processed. The resulting points can then be surface fitted with a curved surface or a type of mesh. The data can then be compared with CAD files or master parts to determine deviations. The data usually first needs to be registered with the data it is being compared with. This normally involves aligning or as critical as the range information. The cross range information is represented by the array for the CCD. Though the grid spacing may be large, the CCD is stationary so the position is known and repeatable.

In contrast, most other methods have accurate cross range information since it is based on the CMM's location and the range is the more uncertain value since it is determined by the measurement system and the part's location. The Lincoln Lab method has more range than cross range accuracy, as compared to most other types of measurement systems. The cross range accuracy can be increased by using a denser CCD array, at the cost of greater exposure and computation time.

This new method is still under development and seems to be promising. The system uses inexpensive components and can fit in two boxes that must be kept a fixed distance apart. One drawback is since it is an optical system, specular surfaces still may cause a problem. A suggested setup of the system is shown in Figure 5–29.

The pattern appears to boil, or decorrelate, as the laser frequency varies. This is the wavelength dependence of speckle. The frequency shift needed to decorrelate the pattern is related to the size and shape of the target object.

The result is a method that can image the whole target at once and give shape information that is independent of range (unlike triangulation). Moreover, this method can measure steep angles (unlike moiré interferometry) and the incident angle is not important. The lateral or cross range resolution is limited by the sensor used and the analysis is computationally intensive.

5.14.3 Two Point Image Speckle

This method is a refinement of the speckle pattern sampling method. A tunable laser is still used and the range is still related to the wavelength dependence of interference. However, now the lateral resolution is determined by conventional means (triangulation) and mapped to a CCD array. This will be explained in the next section.

5.14.4 Third Generation Device

This proprietary method is another refinement of the previous methods. There is no need for a reference or tunable laser as in speckle–pattern sampling. This method is also less computationally intensive yet still provides range information independent of range. The cross range resolution is dependent on range since it uses triangulation. The image is mapped to the CCD array so position in space is related to the position on the array. The data grid density is related to the density of the CCD used and size of the part. For example, if a 2x2m part were projected upon a 512x512 CCD array, the grid spacing would be $\frac{2000mm}{512}$ or close to 4mm. However, for the RTFF project, the cross range is not other settings but the nominal claimed accuracy is better than 0.050". Realistically, according to Perceptron, the accuracy is around 0.250–0.500".

5.14 Laser Speckle Wavelength Decorrelation

5.14.1 Operating Principles

This method is currently being developed at Lincoln Laboratories under the direction of Dr. Lyle Shirley (Hallerman & Shirley, 1996; Shirley & Hallerman, 1996). The method is similar to FM CW methods but instead of imaging points at a time, a full field strategy is used.

Laser speckle is a random interference pattern on a diffusing surface caused by laser illumination (Hariharan, 1992). Originally it was thought to be a nuisance, but it carries information. Essentially the speckled image is made to interfere with a reference image and the interference pattern can be used for metrology.

Currently there are three methods for measuring a part using laser speckle wavelength decorrelation methods. The first two methods are public but the third is still proprietary so only the results are given

5.14.2 Speckle Pattern Sampling (SPS)

The method was first developed to identify and range ballistic missiles. The shape and range had to be determined quickly and from long range. The entire target is illuminated with a frequency tunable laser and the detector records the interference (speckle pattern) between light reflected off of all points on the target at once, as well as light from a reference object. The frequency is scanned and a series of speckle patterns are collected. The range is determined by the wavelength dependence of speckle, not triangulation.

and aircraft, direct timing is adequate. However, for industrial gaging applications, phase shift methods, as described in the following sections, are used to provide more accuracy (Karlin, 1995).

5.13.3 Amplitude Modulation Continuous Wavelength (AW CW)

Operating Principles

The AM CW method uses an amplitude modulated laser beam to range the target. The phase difference between the transmitted and received signal and the physical characteristics of the laser beam give range information. The physical characteristics of the laser are precisely known but the phase difference is more uncertain. The phase detector's accuracy is limited by the accuracy of the sensor and the signal to noise ratio. This is best used for long distance measurements.

Another problem is range ambiguity since phase can only be discriminated to modulo 2π. This range ambiguity is half of the wavelength of the laser but can be improved by software and hardware methods. This problem is similar to the range ambiguity problems with moiré systems in Section 5.8 (Karlin, 1995).

Example

The Perceptron Lasar system (not to be confused with the Perceptron OCF) is based on the AM CW technique. It yields range and intensity values for each surface point illuminated by a laser spot. The sensor has an effective range of from 5 to 130 feet and wide field–of–view. The systems scans the field and data is acquired in five seconds. The accuracy is not as high as the other methods surveyed. It is dependent on range and station, the laser tracker is best used indoors, but not necessarily in a metrology room. Lastly, this method has the best accuracy and data collection rates comparable to laser point triangulation or scanning point triangulation.

5.12.3 Example

Leica has a laser tracker, Model LT 500, that is typical of many laser trackers. This particular system has a range of 114 feet (35 m) with a 2σ accuracy of 0.004" (0.1 mm) and resolution of 39 μinches (1 μm). Figure 5–27 and Figure 5–28 are pictures of this particular laser tracker. The tracker costs around $200,000.

5.13 Laser Radar

5.13.1 Operating Principles

Laser radar sensors are time of flight (TOF) sensors that determine range information by measuring the TOF of an energy beam from the sensor to a point on the target and back. Three-dimensional information can then be determined by scanning the part. The energy beam is usually a pulsed or modulated (AM or FM) signal and the TOF is determined either by direct timing of a pulsed signal or by the phase shift of a modulated signal (Slocum, 1992).

5.13.2 Pulse Laser Radar

Pulse laser radar is laser radar technique that relies on direct timing. The TOF is twice the time from the sensor to the target. With this time, the distance can be calculated since the velocity of light is a known and fixed value in industrial settings. The range resolution is limited by the timing accuracy. However, for large and distant objects such as buildings

The system is also portable. It normally consists of a tracker and a cart. The tracker is the size of a parking meter. Both units can be rolled around to different parts of the factory. Moreover, one operator can quickly measure specific points at long range. The working volume can be very large as well, so long as there is a line-of-sight path from the target to the laser tracker.

However, this system is extremely sensitive to vibrations. If the tracker moves, the measuring coordinate system moves as well. Vibrations on the part are detected too. Taking large amounts of data at each location does decrease effect of the vibrations since the average location can be computed. This method is also a contact method of measurement. The retroreflector size limits the type of feature detectable, just as with a mechanical contact probe.

Another disadvantage is the lack of automation in the measurement. An operator must place and move the target on the part. This makes dense surface mapping difficult, but still possible. This method is often compared to a portable CMM with a touch probe/ Both are intuitive to use and manually assisted methods of shape measurements.

5.12.2 Comparable Measurement Devices

Laser trackers seem very similar to laser point triangulation, theodolites, and industrial stations. However, laser trackers actually rely on different technology. To reiterate, laser trackers use interferemetry, not triangulation, to determine range like laser triangulation methods, theodolites, and industrial stations. Also, the laser tracker must have a retroreflector to return the signal. Most laser point triangulation methods rely on the part surface to reflect the signal. Also, theodolites, industrial stations, and laser trackers often perform similar tasks. They can measure targets from far away. Unlike the industrial

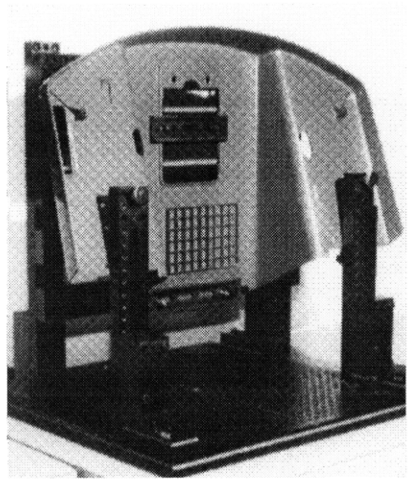


Figure 7–3: Modular fixturing device holding a sheet metal part (Flexx Systems Co.)

close to the correct dimensions. This can be said of any fixture with a programmed shape.

7.8.3 Modular Fixturing Kits

These tools form a large family of devices that have many different types of pieces that can be assembled and used to fixture a wide variety of parts. Usually these parts screw into a baseplate with a grid of threaded holes. These parts can include structural members, clamps, vacuum suction cups, and vee–blocks. Two examples can be seen in Figure 7–3 and Figure 7–4.

This manual process can be very effective since it can accommodate many different types of parts. However, the drawback is the planning stage. One must determine the location and type of parts to use to support the part. If not done correctly, the fixture and over or underconstrain the part and lead to errors. There was research on an automated method done by Asada & Fields (1985). However, the location of the supports still has to be determined manually.

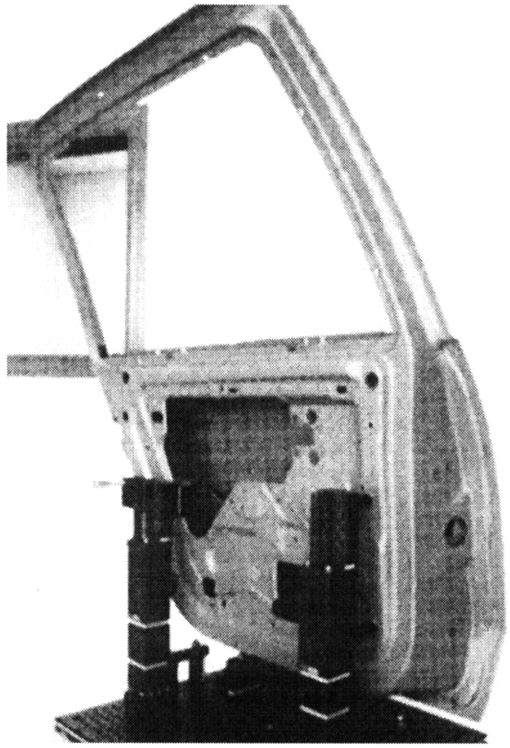


Figure 7–4: Modular fixturing device holding a sheet metal car door (Flexx Systems Co.)

7.8.4 "Pogo" type Devices

These types of devices have an array of "pogos" or pins found on the RTFF tool. These pogos are located on a base either at a fixed spacing or can be adjusted. Then, the pogos can change height and clamp the part with suction. The result is a "bed of pins" that can be programmed to a specific shape to support a specific part. These devices can also be used with CNC machining centers to perform machining operations. The two main companies providing pogo–type devices are CNA Manufacturing and M. Torres.

These devices are ideal for our purpose except that they cost too much. These machines range from $500,000 to over $1 million. Currently there are RTFF efforts to create a similar type of machine at a lower cost. Since the RTFF project is only looking for a measurement fixture, to start, the cost should be less since the pogos will have no longer have to take the machining loads.

The DEA Five U-nique is a manual version of the previous two devices that must be used in conjunction with a CMM. There are several columns with adjustable height. The user programs the heights and locations of these columns and the CMM moves to the first height and location. The user than moves the column under the CMM head, raises the column and mates the end with the CMM head to determine the programmed location. This process is manually repeated. Finally, the parts are clamped with mechanical clamps. This product is shown supporting a part in Figure 7–5. Figure 7–6

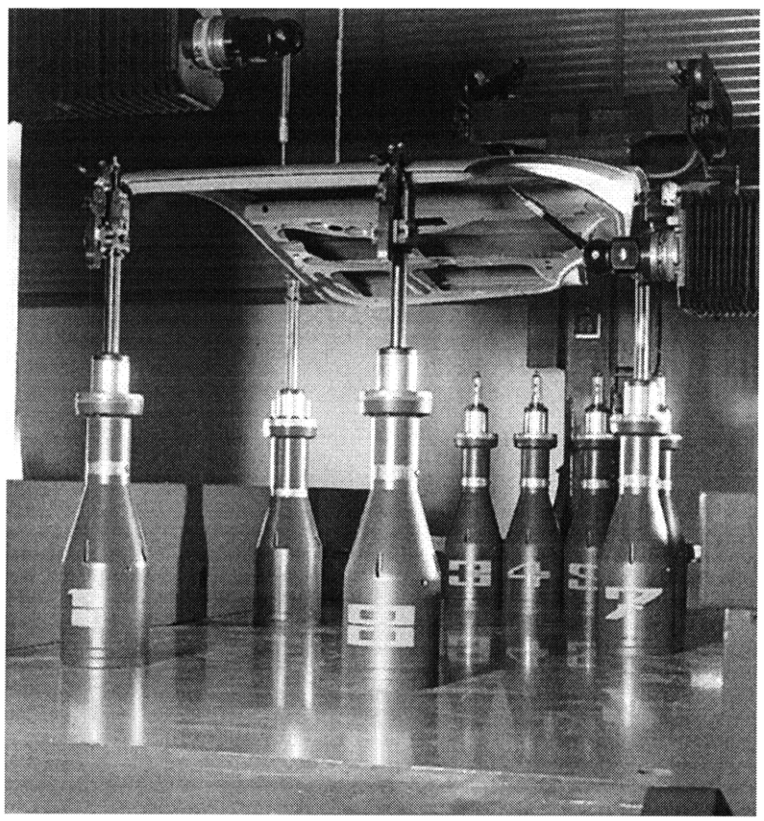


Figure 7–5: FIVE U-nique supporting a part

shows the FIVE U-nique supporting a part while being measured by a Typhoon CMM.

This is an interesting product that would work for our applications. However, the locations of the supports are still determined by an operator, usually based on experience, instead of deterministic methods.

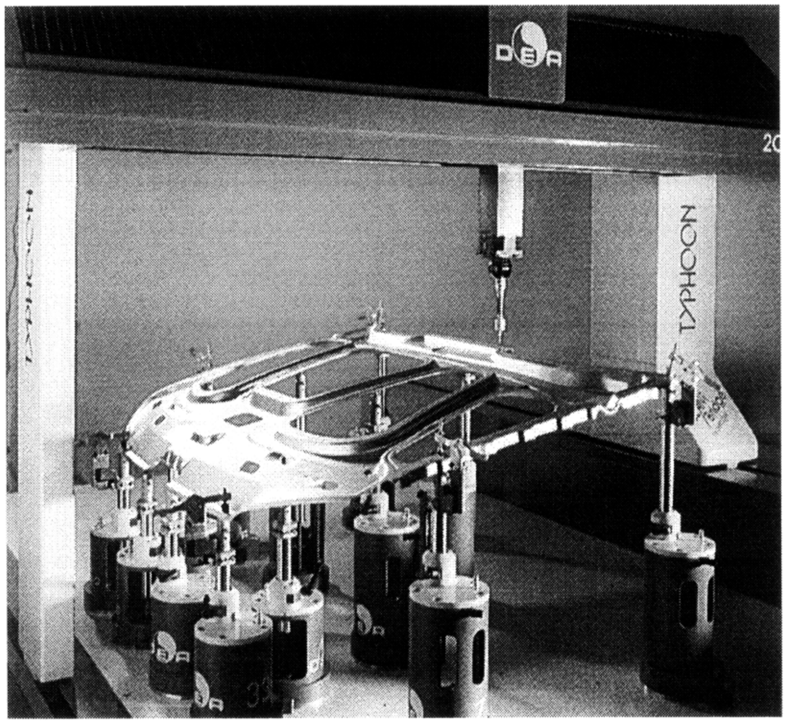


Figure 7–6: FIVE U-nique supporting a part while being measured by a Typoon CMM

Chapter 8

Sheet Metal Drilling and Trimming

8.1 Purpose of Drilling and Trimming

The purpose of sheet metal drilling is to create holes for assembly. Trimming is to cut the part out of the formed sheet metal. Large pieces of sheet metal are stretchedformed. However, the actual part might be a small fraction of the formed part. Therefore, trimming is needed to remove the excess metal.

8.2 Methods of Drilling and Trimming

This section will briefly discuss the different methods of drilling and trimming. Of particular interest will be the cutting forces, process residue, and the interference of the process with the fixture. The cutting forces affect how large the clamping and supporting forces need to be for the fixture. The amount of residue also affects how much sealing and cleaning is needed for the fixture. The interference is how much the process affects the support structure under the part. Much of this is based on discussions with and a presentation by Walczyk (personal communications, January 14, 1997).

Table 8–1 summarizes some characteristics of different drilling and trimming operations, as well as measurement relative to each other. The characteristics will be discussed in the following sections.

Table 8–1: Process vs. cutting force, residue, and interference

Process	Cutting Force	Residue	Interference
conventional drilling and trimming	high	medium	medium
abrasive water jet	low	high	high
laser machining	N/A	low	medium
non–contact measurement	N/A	N/A	N/A
contact measurement	low	N/A	N/A

8.2.1 Conventional Drilling and Trimming

Conventional drilling is the most common method of hole making for stretchformed sheet metal. The operator uses a twist drill bit with a hand drill to make the holes. The holes can also be created with a CNC machine. Conventional trimming is done by routing or milling. One problem is holding the part that is to be cut out since there are no edges to clamp too. Normally one uses a hand routing fixture, as shown in Figure 2–10. Dowel pins are used to help constrain the part without interfering with the trim path. The operator can use a hand router or a CNC machine to trim the part.

8.2.2 Abrasive Water Jet

Abrasive water jet (AWJ) uses high-pressured water forced though a small nozzle at high speeds. These speed can be 2.5 times the speed of sound. The abrasive (similar to sand) is entrained in the flow and removes material from the part through a grinding process. AWJ can be used with sheet metal part on a fixture in a production environment. Though the cutting forces a low, the residue is high. The residue is large amounts of water with abrasive. Therefore, the machine nozzle and workpiece are usually over a large pool of water. Also, the interference is high since the water jet continues to cut after the stream passes through the part. This distance can be minimized but the flow of water past the part can not be eliminated.

8.2.3 Laser Machining

Laser machining uses a laser to create a concentrated point of energy to melt and evaporate the material. Lasers can be used for drilling and trimming. This process is relatively expensive. The cutting forces are very low, even negligible and the residue is low. The interference is medium since the laser's strength and penetration can be controlled more carefully than with AWJ.

Chapter 9

System Integration

Chapter 2 discusses how different processes are currently being used to manufacture sheet metal parts. This section will investigate how the alternative processes might be used and executed in the future to create a more flexible factory.

Ideally, all the processes will be accomplished on the forming tool or in one cell. With the Lincoln Lab system, the forming tool can be used to support the part and the measurement system can measure the part in process. If the part is not acceptable, the part can be stretched again and remeasured. The reconfigurable tool can act as a check fixture, much like the HRF. The tool can be reconfigured to the ideal part shape and then the formed part can be compared with the ideal part shape. It also will support the part during measurement since it does not need to take any machining loads. Moreover, if the support needs to be adjusted, the tool is capable of doing so.

To drill and trim, current pogo technology is adequate but expensive. New versions or variations of these pogo tools are attractive for the RTFF project. The major benefit is that a pogo tool decouples the processes downstream of forming with measuring. However, if the part can be machined on the tool, an extra station would not be needed. Since the current tool does not provide support for machining loads, laser machining is attractive.

Chapter 10

Conclusions

The Reconfigurable Tooling for Flexible Fabrication project is developing new methods for manufacturing sheet metal. One important aspect of manufacturing is gaging so a measurement method is needed. There are many commercial methods that can measure the parts we need. However, there is also developing technology from MIT Lincoln Labs that promises improved performance without many of the drawbacks of the current commercial systems. From a review of the commercial systems available, researching and developing the Lincoln Lab method is the best solution for the RTFF project.

Large scale, rapid, 3D measurement conventionally is a balance between data density with speed and flexibility. With conventional touch probes and laser triangulation methods, a limiting factor is the need for a large CMM. Portable CMMs are attractive, but not automated or highly accurate. Laser trackers are more accurate but not automated as well. Moreover, these methods all have range resolution that is a function of size, another limiting factor in flexibility. The Lincoln Lab method does not have those constraints. It is a flexible system, ideal for quickly and automatically measuring mild curvature shapes, like RTFF parts. Moreover, the accuracy is independent of range.

In the future, it will be exciting to see the new Lincoln Lab method working and measuring parts. However, the device is still under development.

Appendix A

Stepper Design Problem

A.1 Role of the Stepper

A stepper is a mechanical linear translator. Conventional linear translators have a range of motion limited by the resolution of the actuator or sensor. The stepper moves a discrete number of "step" or desired locations.

A stepper is used in Dr. Lyle Shirley's laser speckle wavelength decorrelation measurement device at Lincoln Labs. It moves a critical optical component and the repeatability of motion is related to the overall accuracy of the measurement device. Therefore, the stepper is a critical component in the functioning of the measurement device.

A.2 Initial Problem Definition

Dr. Lyle Shirley asked Prof. Hardt and MIT to consider a design of the stepper. Dr. Shirley was looking for an "accurate, inexpensive linear translator that moves in a small number of repeatable stages, say a sequence of 15, 60, 240, and 480 microns (total translation)" (email to Prof. D. Hardt, November 26, 1997). He suggested using a "multi-stage solenoid having stops associated with progressively stiffer springs that give way in sequence as more current is passed through the solenoid" (email to Prof. D. Hardt, November 26, 1997). The device should fit in a child's closed hand, around 2x2x7 cm^3 in volume.

This device is supposed to replace a conventional linear translator. Since the stage only has to move discrete, repeatable steps, the price for the hardware and control system might be less expensive since there is less functionality. For example, a competitor is the Newport Linear Travel Mini-Stage model PM500-1L. It has a 25 mm (1 in) travel with 50 nm repeatability. The hardware is $10,000 and the control system is another $8,000. That device meets the requirements of moving the set sequence for 15, 60, 240, and 480 μm. However, Dr. Shirley would like to see if something less expensive is available.

A.3 Final Problem Definition

After some improvements on the optical part of the design, the requirements for the stepper have changed. The current specification were given on April 29, 1997 (L. Shirley, personal communication, April 29, 1997).

The goal now is to move two objects back and forth about a centerline. It is unclear that the displacement has to be symmetric about that centerline. One object has to move a series of steps on the order of microns ($\mu m=10^{-6}m$). The steps will be 0.5, 1, 2.5, and 5 μm with a repeatability of at least, if not better than, 0.1 μm (100 nm). The stepper will be upside down, in a sealed container, but in the manufacturing environment. Moreover, the stepper will have to move a "light" mass with low accelerations. The temperature can be controlled to ±0.1°C and the device should be smaller than 2x2x7 cm^3 in volume.

A.4 Specifications and Physics

This section will list the specifications and the physics limiting or the reasoning for these specifications. The listing can be found in Table A–1.

Table A–1: Stepper specifications

Specification	Value	Physics/Reasoning
Travel length (μm)	5	Limited by range of components
Step locations (μm)	0, 0.5, 1, 2.5, 5	Limited by control system and resolution
Repeatability	<0.1 μm (100 nm)	Limited by components
Control method	Computer controlled	Increases amount of electronics
Environmental control	Upside down, sealed box, in a factory	
Temperature control	±0.1°C	Given
Size	Around 2x2x7 cm^3	Limits size of actuator
Cost	< $18,000	Current cost for manual system
Settling time/step (s)	2	Dynamic response, damping, inertia, force, etc
Force (N)	N/A	Depends on setup

A difficult specification to meet is the size requirement. The size requirement is how large the stepper should be while in the container that contains the optics for the measurement system. The controller and computer connected to the stepper can be located elsewhere are not part of the size requirement. Though, not directly related to the performance of the system, the size constraint limits the use of certain commercial methods described in Section A.5.

Another issue is the force the actuator must produce. That depends on how the system is setup. If one were to assume the actuator needed to move a block of steel, with the volume specified, at the speeds and distances specified, the actuator would need to output 0.6 μN or 2.2 micro–ounces, a tiny amount for the actuators described in Section A.5. They can easily generate forces greater than 10 N, or even 100–200 N. However, if the actuator were to move a smaller mass but would have to overcome spring forces, friction, and other external forces, the force needed can easily approach the 10 N or greater range.

Lastly, the specifications never mention what is being moved and what are the specifications for tilt and angular errors. It was suggested that the object may be fiber optic cable or a mirror. Moreover, how the object is mounted is unspecified as well.

A.5 Commercial Methods

There are many different commercial actuation methods of creating linear motion in the micron ($\mu m=10^{-6}$ m) and nanometer ($nm=10^{-9}$ m) range. For larger ranged devices, leadscrews, ball screws, rack and pinions, or linear motors can be used. However, for movement in the micron range, other methods are used and will be described shortly. One can also use levers to increase the range or increase the resolution of the motion (Smith & Chetwynd, 1992). However, due to size constraints, levers will not be investigated.

The control systems for these methods have varying degrees of complexity. Some methods are open loop control and others are more complicated and have closed loop control. Generally closed loop control has better accuracy since the position is measured and fed back to the controller.

Lastly, these methods may also require some type of bearing to constrain the actuator's motion to a line. The simplest method is not to have one and assume the actuator's movement is linear. For 5 μm of travel, some sources recommend this method of attaching the moving part directly to the actuator. This method is acceptable but does not seem to be typical of precision assembly. Another method used in larger ranged devices is to use linear bearings or bearings and rails. These methods are commonly found in machine tools and can also be miniaturized for use in micron–level applications. Also, for smaller ranged devices, flexures can also be used and are described in Section A.5.1.

There first will be a subsection on flexures and afterwards, a listing of different technologies to create linear motion. There will be commercial examples given for methods that would be better for the Lincoln Lab application.

A.5.1 Flexures

Flexures are ideal for small displacements over a known axis. They are "elastic mechanisms of known stiffness" (Smith & Chetwynd, 1992, p. 95). A diagram of a simple one is shown in Figure A–1. When a force, F, is applied, the stage moves horizontally with no friction. However, there is a slight vertical motion of h. Usually, that slight displacement is negligible. These inexpensive devices are commonly used for these precision applications and more details can be found in Slocum (1992) and Smith & Chetwynd (1992).

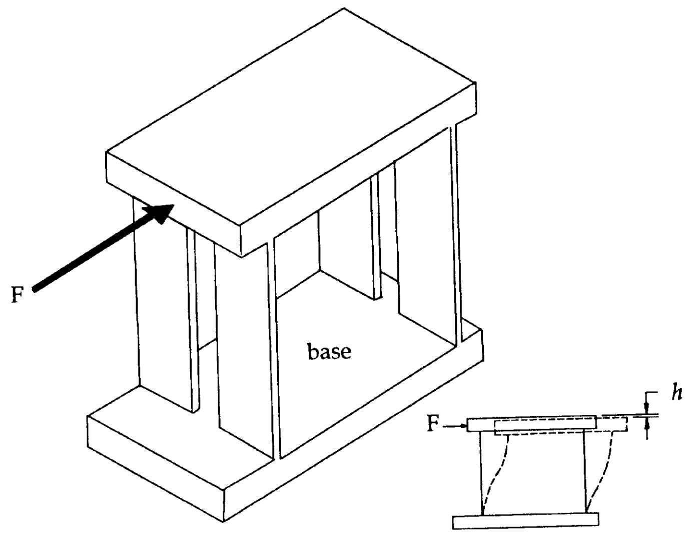


Figure A–1: A simple flexure (Smith & Chetwynd, 1992)

For this application, the actuator would move the flexure stage. A typical application setup is illustrated in Figure A–2. As the actuator pushes against the flexure, the flexure deforms elastically. As the actuator is drawn back, it does not pull on the

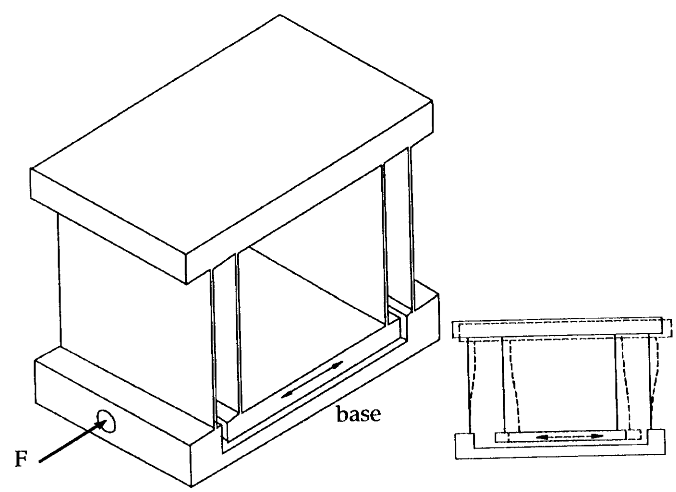


Figure A–2: A more complicated, higher performance flexure (Smith & Chetwynd, 1992) stage. Rather, the stage pushes back on the actuator with a restoring force from the stored elastic energy of the flexure. In this design, the vertical displacement is kept to a minimum. Stages are inexpensive and cost a few hundreds of dollars. There can be a sensor to measure the position of the flexure stage to increase accuracy. However, that raises the cost to several thousand dollars. In actuality, using a stage also requires extra work to carefully align and position all the parts. Therefore, to decrease the complexity, one can also purchase integrated stages and actuators.

A.5.2 Solenoids

A cylindrical solenoid, shown in Figure A–3, is essentially a coil of wire wound around a cylindrical spool (body). As current is passed though the wire, a magnetic field is created. The field in the spool is almost uniform and parallel to the axis and the field outside is very small (Sears, Zemansky, & Young, 1987). This field can be used to attract an iron component (plunger) and move it coaxially.

The force generated by the solenoid is a complex, non–linear relationship. The

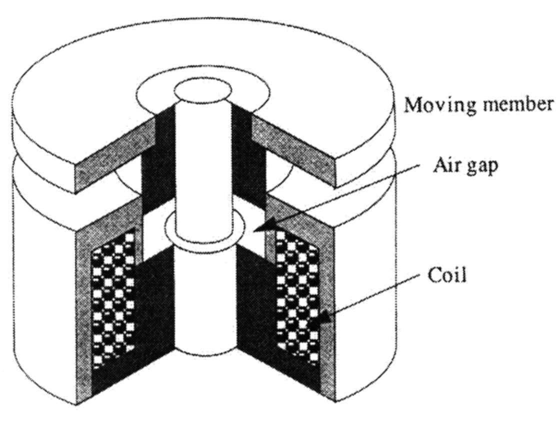


Figure A–3: A schematic of a solenoid (Slocum, 1992) force is approximately proportional to the number of turns of wire (N), the current (I), the plunger cross sectional area (A), the magnetic permeability of air (μ), and the inverse of the air gap (h) between the plunger and body. Slocum (1992) approximates this relationship as

$$F \propto \frac{N^2 I^2 A \mu}{2h^2}. \tag{A–1}$$

Yang (1985) continues with a more detailed analysis of the problem. In both analyses, the force is highly non–linear and therefore not as easy to control as a linear system. Thus "solenoids are most often used as inexpensive actuators for forcing components against fixed mechanical stops" (Slocum, 1992, p. 663). This way, there is no need for a complex control system. This is the basis of Dr. Shirley's proposed design for a new stepper.

Solenoids are commonly used for hydraulic and pneumatic switches or other short-stroke (around ½ inch), on/off type applications. The force generated can easily exceed ten pounds. The heating of the elements due to the current is also another issue to consider. Finger–sized solenoids can dissipate 100 Watts (or more) of power at low duty cycles. Also, since coil resistance increases with temperature, other parameters are effected. Ultimately, this adds complexity to controlling the force.

A.5.3 Voice Coil Actuators

Voice coil actuators are "limited motion devices that utilize a permanent magnet field and a coil winding to produce a force proportional to the current applied to the coil" (BEI Sensors & Systems Company [BEI], 1995, p. 2). There were originally were used in loudspeakers and one is shown in Figure A–4 and Figure A–5.

Figure A–4: Voice coil (BEI, 1995)

The actuator is governed by the Lorentz's eqation, $F = iL \times B$, where i is the current, L is the engagement length of the moving coil, and B is the magnetic field from

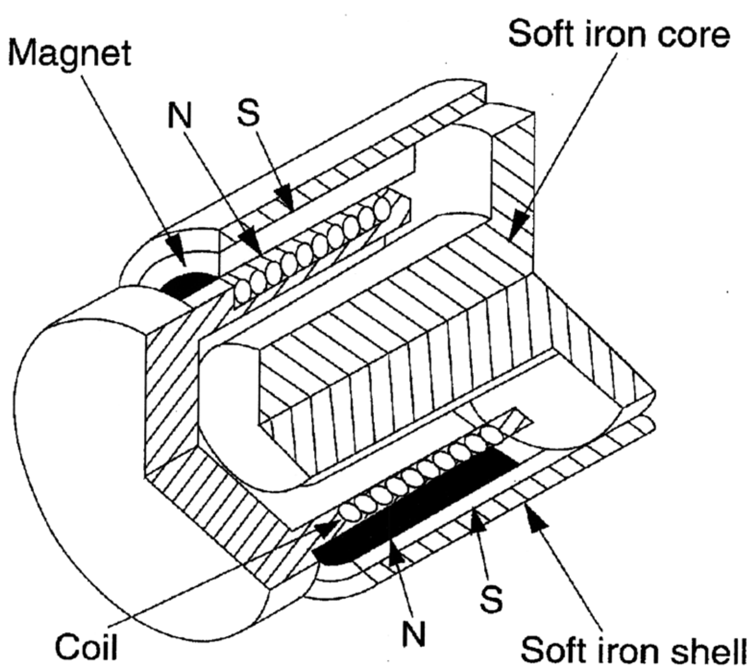


Figure A–5: The components of a voice coil (BEI, 1995) the permanent magnet. Thus, a change in current leads to a change in the force. This force can be used to move the coil and magnet relative to each other. This electromagnetic device allows for high force, high accelerations, and high frequency applications (BEI, 1995).

Voice coils are usually preferred over most actuators since they have the excellent performance. According to Slocum (1992), the positioning capability of a voice coil and appropriate bearings are only limited by the sensor and servocontroller. Nanometer resolutions over a range of millimeters are possible. However, voice coils, like solenoids and electric motors, can dissipate hundreds of watts of power. Unfortunately, commercial solutions must be custom assembled.

A.5.4 Piezoelectric Actuators

Piezoelectric actuators rely on the physical properties of piezoelectric material in the actuators. These materials change shape when an electric potential is applied. When many piezoelectric crystals are assembled and voltage is applied, there can be microns of motion. The applied voltage often exceeds 100 volts. The main advantage of piezoelectric actuators is the low power dissipation. As opposed to the hundreds of watts of power dissipated with similar performance electromagnetic actuators, piezoelectric actuators only dissipate milliwatts of power (Slocum, 1992). However, these actuators can be non–linear in performance and exhibit hysteresis and creep. Therefore, they normally operate under closed loop control. They can be arranged in many geometries but a tube form is ideal for large ranges of linear motion. This is shown in Figure A–6.

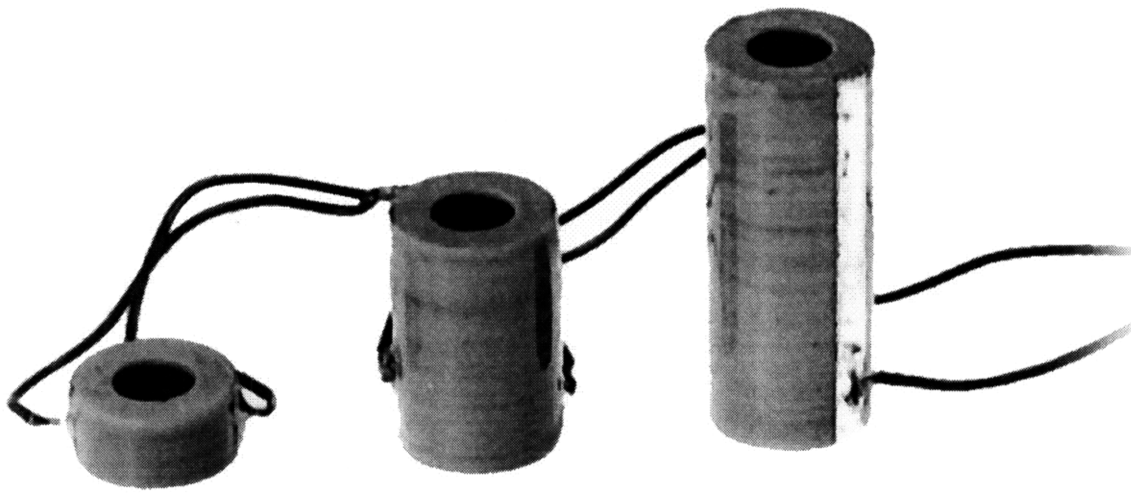


Figure A–6: Piezoelectric actuator in a tube geometry

Physik Instruments (PI) has an actuator (P–841.10) and controller (E–662.SR) for $5000 that would meet the requirements. A flexure bearing is not included and may not be needed. The piezoelectric actuator has a position sensor integrated onto the stack of piezoelectric crystals. The controller can be computer controlled with a standard computer interface. The system has a 15 μm range with a 15 nm repeatability. The object to be moved must be carefully mounted to the actuator. There is a tapped hole for assembly and normally a part is machined to hold the object to be moved and is screwed in the tapped hole. Queensgate also offers a similar system (DPT-C-S with CM controller) for $6500 but with better than 10 nm repeatability. That system is shown in Figure A–7.

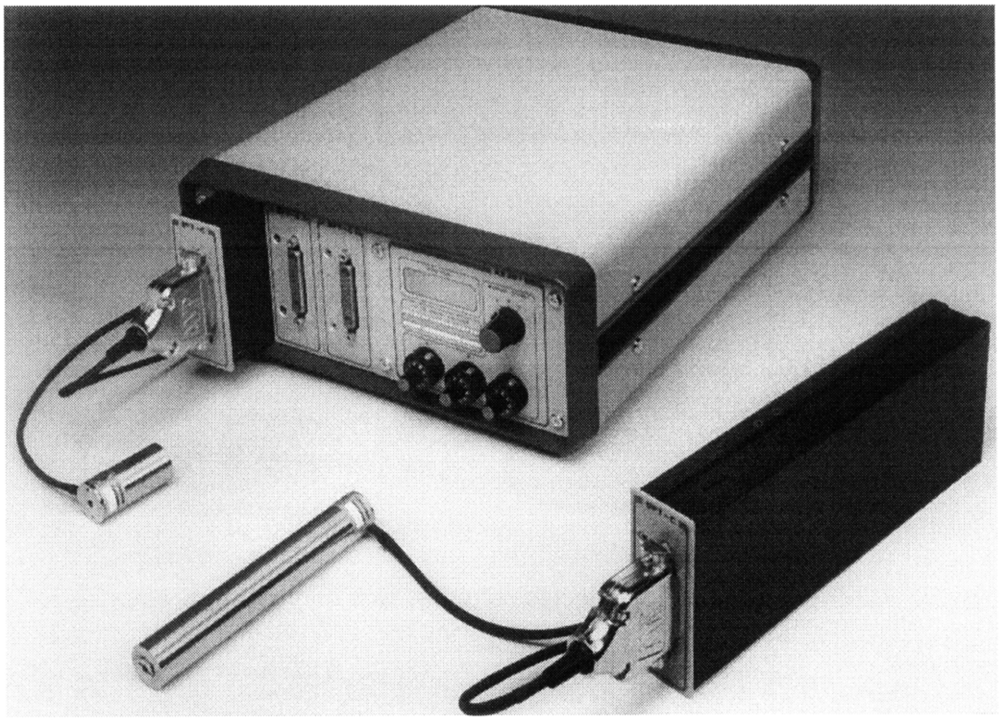


Figure A–7: Piezoelectric actuator and controller (Queensgate)

PI also has an integrated system including an actuator, flexure stage, and position sensors. This is an alternative solution if an actuator without a flexure is inadequate. If the part needs highly accurate positioning, has a mass larger than a simple fiber optic cable or small mirror, has offset loading, or other complications, a flexure stage may be needed.

The S-320 tilting mirror mount has three actuator for three–axis tilting. However, one can achieve linear motion when all three actuators are driven together. The system has a 10 μm range with a 60 nm repeatability. The surface of the stage is a flat surface for mounting. Mirrors and other objects are usually attached using glue or other adhesives. Another mirror tilting system, S-316.10, is almost the same. The main difference is the 12 μm range and the mounting hole in the center of the stage. Both systems cost around \$4500 and require \$6,000–9,000 of control and power equipment for a total of over \$10,000. Queensgate offers a one-axis system including the actuator, flexure stage, and sensors for \$10,000. It has a 15 μm range with and amazing 0.1 nm repeatability. The supporting control and power equipment will be another \$6,000 or more for a total of over \$16,000 for the complete system.

A.5.5 Electrostrictive Actuators

Electrostrictive actuators rely on electrostriction, an effect "superficially similar to the piezoelectric effect" (Smith & Chetwynd, 1992, p. 187). The underlying physics are different but in performance, they are similar to piezoelectric actuators in many ways. Their behavior is non–linear so these actuators have a limited range as to operate in the near–linear manner. However, they do have less hysteresis than piezoelectric devices so they may be able to be used without feedback control.

Newport has a system \$3,000 but it does not meet the requirements. It has an open loop control system and does not have true computer control. The actuator (ESA1330-OPT-01) and controller (ESA-CXA) allow for 30 μm range with a 2.1 μm repeatability and resolution of 40 nm. The actuator is designed to attach easily to a stage (461-X-M) with crossed–roller bearings. The system is not truly computer controlled since stepping the actuator is not an automated process. The computer commands the actuator by sending a voltage signal. However, the operator must read the appropriate voltage from a printed hysteresis chart supplied with each actuator. If extra accuracy or control is needed, a sensor can be added to close the control loop for an extra \$5,000, for a total of \$8,000.

A.5.6 Mechanical Micrometers

Micrometers are common mechanical devices used to generate linear motion. They miniaturized lead or ball or roller screws. Rotational motion is translated to linear motion be means of a screw. The screw moves a given distance with each rotation with potential errors resulting from thermal growth, inaccuracies in part geometry, and backlash. These mechanisms are most often found in measuring micrometers.

For greater accuracy, differential micrometers are used. These have counter–moving threads that limit range but increase accuracy. According to Smith and Chetwynd (1992), these devices can position to 0.1 μm manually and to 0.001 μm with feedback. Practically, differential micrometers can be commercially purchased and assembled with a stage, control system and sensors. Newport has a differential micrometer (DM–13) for $400 with a 200 μm range, 70 nm resolution, and up to 100 nm of backlash. Coupled with a stage, control system and sensors, this can meet all the specification, except perhaps the size constraint.

A.6 Concept Selection

From the previous section, there are several commercial methods that allow for performance in the range needed. However, depending on what is actually being moved, a stage may or may not be necessary. PI seems to have the best solutions according to the product description and Prof. A. Slocum of MIT (personal communication, June 19, 1997).

The PI piezoelectric actuator system without a stage costs around $5,000. If an integrated system were used, the cost would be around $10,000. Thus, these values indicate the approximate expense to purchase an "off the shelf," widely used solution to the problem of precision motion.

A.7 Stepper Design

A.7.1 Overview

Dr. Shirley's novel concept of devising an inexpensive new way of achieving precision motion is to have a "multi-stage solenoid having stops associated with progressively stiffer springs that give way in sequence as more current is passed through the solenoid" (Shirley, 1996). A figure of the initial sketch is shown in Figure A–8. A CAD drawing is shown in Figure A–9. It shows the overall geometry but is not to scale. The aspect ratio is not correct either. As more current is passed through the solenoid, the solenoid would create a larger magnetic field. This field results in more force. This force would move one stage of the multi–staged solenoid at a time to step through the 5 μm

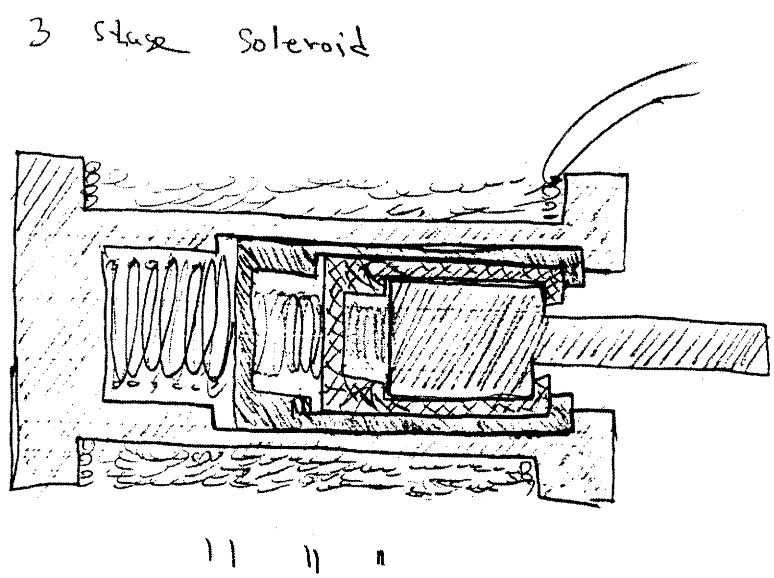


Figure A–8: Dr. Shirley's actuator concept sketch

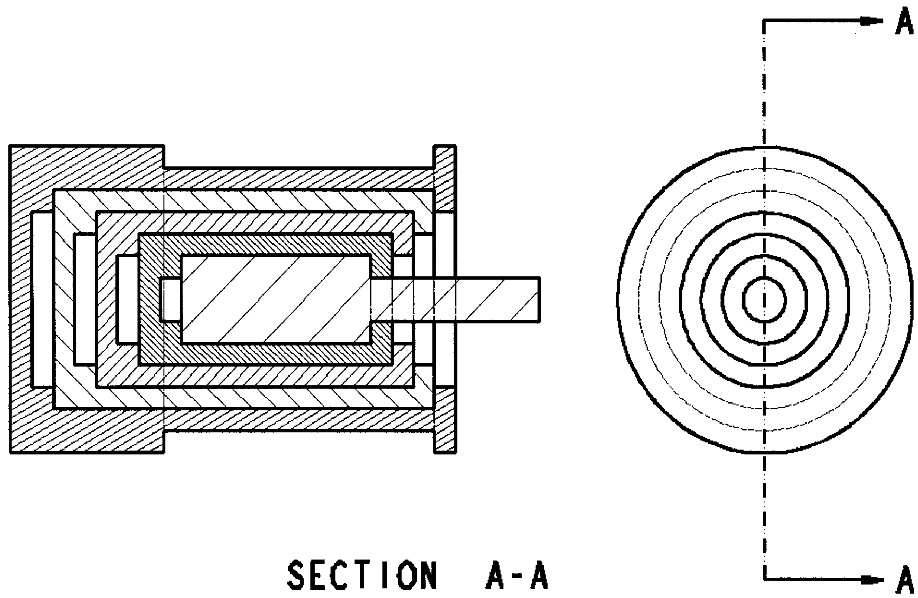


Figure A–9: Stepper geometry, not to scale

range. This actuator can then either push a flexure stage with the object attached or move the object directly, just as one would a piezoelectric actuator.

When the design was conceptualized, Dr. Shrirley envisioned inexpensive components, but more importantly, no closed loop feedback control. The elimination of the control system will greatly decrease the cost of most systems. The current could be step changed and at each step, the solenoid would have corresponding step changes in magnetic force. These changes would move the different stages of the solenoid against fixed stops to move then end of the actuator. This concept extends the ideal use of a solenoid to another, more complex situation. Also, this system would have a multi-stage solenoid, something not commercially available.

A.7.2 Mechanics of the Motion

A schematic of one portion of the stepper is shown in Figure A–10. In this state, the linear extension spring with spring constant, k, is preloaded with a force $F_{preload}$. That is, the spring is stretched out a small amount before attaching to the core, m_1, that moves. In that way, m_1 initially is being pulled back to the right with respect to the figure.

As a force, F_{12}, is applied, the stepper steps to another position shown in Figure A–11 when mass m_1 moves in contact with mass m_2. The force is generated by the solenoid and consists of three components,

$$F = F_{preload} + k\delta + F_{external} \ .$$

$F_{preload}$, the preload force on the core, before the force is applied. The term, $k\delta$, is the force needed to overcome the spring force to move the mass an amount δ and hit the hard stop. The external forces, $F_{external}$, are other forces. These can include gravity, stiction, friction, contact forces with m_2, and forces needed to accelerate the masses within the field.

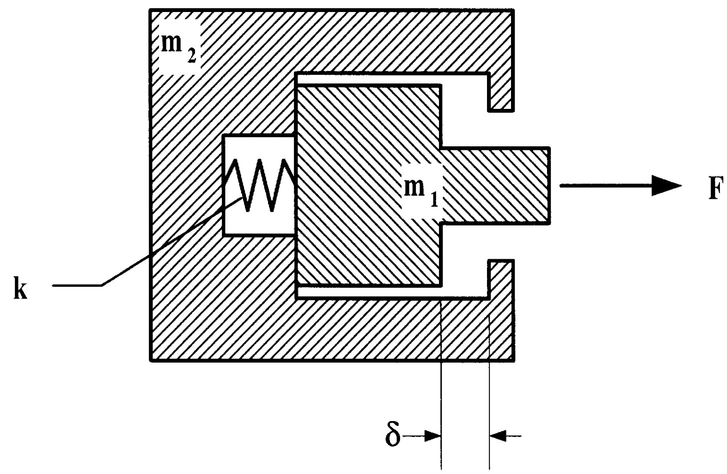


Figure A–10: Schematic of one section of the stepper, before stepping

Then, as the current is increased, the force increases to another level. That next level will be F_{23}. That force will then step masses m_1 and m_2 as an unit to the right until the combined mass contact mass m_3 (not shown in the figures). This continues for each step and decreasing the force retracts the masses.

A.8 Analysis

A.8.1 Overview

Though initially the stepper concept sounds promising, after more analysis, this design is not practical given the RTFF project's timeline. There is simply too much development work needed to create this actuator. The commercial solutions can be considered expensive (around $10,000) but offer much more flexibility. They can be positioned at various locations, not at fixed locations as with the stepper. They are established technology and known to work.

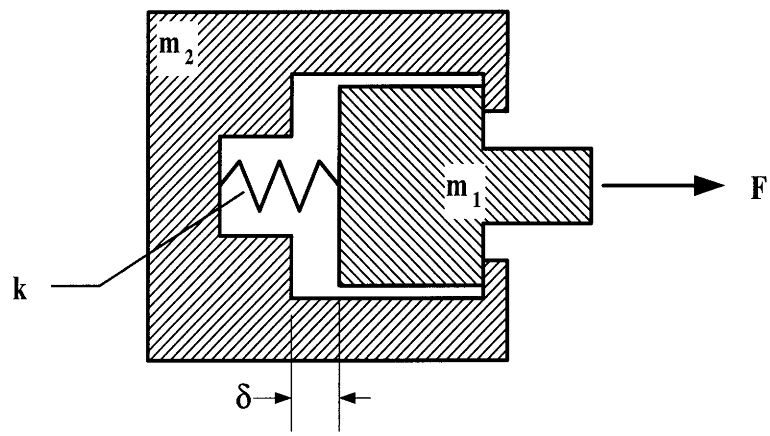


Figure A–11: Schematic of stepper, after stepping

However, the concept is plausible according to Prof. S. Leeb of MIT (personal communication, July 23, 1997) and he believes it can work. The main challenge, after the physics is confirmed, is to create such a small and precise actuator.

The rest of this section will look at different aspects of the design and discusses the issues that need to be resolved. This will detail areas where work is needed and reveal aspects of the design that may be impractical. For analysis, the stepper was viewed from the standpoint of the one stage of the multi–stage solenoid. That is the basic unit and is shown in Figure A–10 and Figure A–11.

A.8.2 Electromagnetic

The electromagnetic effects of solenoids have been studied and documented. However, solenoid design is still complicated. Controlling the force, even with a typical solenoid, is difficult since the behavior is non–linear and affected by many variables. Another issue is the relation between the force and current. According to Equation A–1, the force is proportional to the current squared. Therefore, for higher forces, the current requires geometrically increases. This can lead to coil heating and other thermal effects, which would require heat sinks or other cooling methods. If there were a temperature rise, it would also contribute to the thermal elongation of the components that would decrease accuracy. For example, steel has a coefficient of thermal expansion, α, of 17 $\frac{\mu m}{m/{\circ}C}$. Therefore, for a 10 cm structure, a one degree change in temperature results in 1.7 μm if thermal growth.

It is also uncertain that the magnetic field will penetrate though all the layers of nested solenoids. When it does, there also is the chance of the different components being attracted to each other with an induced magnetic charge. Since the components will be microns from each other, the attractive magnetic force between the two bodies will be extremely high due to the inverse square ($1/r^2$) nature of the force. Lastly, solenoids are generally have slow response times so the transient response and speed would have to be considered.

A.8.3 Dynamics, Mechanics, and Kinematics

From initial observations, each stage can be modeled as a standard spring–mass–damper system. The governing differential equation and initial conditions are

$$m\ddot{x} + b\dot{x} + kx = F(t)$$
$$x(0) = \dot{x}(0) = 0$$

where *m* is the mass of the objects to be moved, *b* the damping constant, *k* the spring constant, *F(t)* the force, and *x* the position taken along the axis of the cylinder. *F(t)* is the force generated by the solenoid. That force will be step changed when different stages are energized. However, when a stage is energized and moves to the hard stop, *F(t)* should be constant. Ideally, as the system is tuned, one should try to have it critically damped so there is no overshoot. That way the mass will slowly slide up to the stop. However, if there is overshoot, the system should function as well and will ensure a firm contact between the two surfaces.

Another issue is the actual geometry of the parts. In the figures, the parts have straight lines and radii. However, in actuality, the parts may have more complex geometries. Of particular interest is the interface between m_1 and m_2 in Figure A–11. As illustrated, the interface is a set two planes but the actual surface is not necessarily planar. The actual problem is to design a kinematic or deterministic interface so m_1 can repeatably mate with m_2. This interface also must be able to withstand the wear associated with the lifetime of the product. Finally, a perfect surface is useless if there is debris at the interface. The debris can come from the environment or the wear of the parts themselves. Ferrous debris particles will also be attracted to the magnetic components too. This debris can either cause systematic errors or random errors.

Tolerances

The tolerances for the radial dimensions were determined using standard ISO methods based on ANSI B4.2-1978, R1984. This standard describes how mating parts (generally termed "shafts" and "holes") should be toleranced with the metric system. The method is described in Green (1992). The first step is to determine what type of fit is needed, and then there are tables that calculate the necessary tolerance. For this application, there are two likely fits, the close running fit and the sliding fit. The close running fit is for "running on accurate machines and for accurate location at moderate speeds and journal pressures" (Green, 1992, p. 624). The sliding fit is "not intended to run freely, but to move and turn freely and locate accurately" (Green, 1992, p. 624).

As an example, the inner core is toleranced and described below. First, the aspect ratio of the inner cylindrical part had to be determined. Generally, there is a rule of thumb that says sliding parts should have their $L/D \geq 4$. That is, the length divided by diameter should be greater than four. A commercial piezoelectric translator has a core diameter of around 10mm. So, for our analysis, we will assume a nominal shaft diameter of 10mm with a length of 40mm. The nominal shaft diameter will be the maximum value so the analysis will use a "shaft basis." The results of the calculations are shown on Table A–2.

Table A–2: Tolerances for a hole and shaft

Type of Fit	Dimension	Value (mm)
Close Running Fit (F8/h7)	Shaft, minimum	9.985
	Shaft, maximum	10.000
	Hole, minimum	10.013
	Hole, maximum	10.035
	Separation, minimum	0.013
	Separation, maximum	0.050
Sliding Fit (G7/h6)	Shaft, minimum	9.991
	Shaft, maximum	10.000
	Hole, minimum	10.005
	Hole, maximum	10.020
	Separation, minimum	0.005
	Separation, maximum	0.029

Tilt Errors

After the parts are toleranced, the end of the inner core must be supported to prevent deflections and tilting. A flexure could provide the support and constrain the motion for the application. The other cores might need support as well. Each part must be supported and constrained since the resulting errors are large compared with the accuracy needed. The simplest type of error is shown in Figure A–12 and Figure A–13. Figure A–12 shows the part before tilting and Figure A–13, the part after the tilt error.

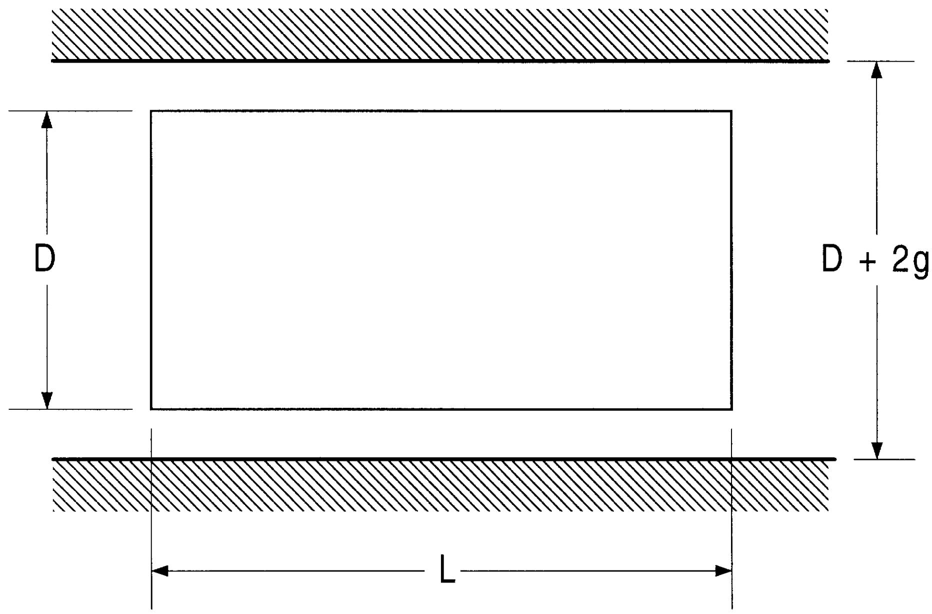


Figure A–12: Part before tilting

The errors in the horizontal and vertical directions are calculated by using the transformation

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix}$$

where $\begin{bmatrix} x \\ y \end{bmatrix}$ are the original coordinates and θ is the counterclockwise positive rotation angle. Figure A–12 and Figure A–13 show the notation used. Point 1 is

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} L \\ D/2 \end{bmatrix}$$

and Point 2 is

$$\begin{bmatrix} x' \\ y' \end{bmatrix} = \begin{bmatrix} L\cos\theta - \frac{D}{2}\sin\theta \\ L\sin\theta + \frac{D}{2}\cos\theta \end{bmatrix}.$$

Therefore, the error is the difference between the two as shown as

$$\begin{bmatrix}\Delta x\\ \Delta y\end{bmatrix}=\begin{bmatrix}x-x'\\ y'-y\end{bmatrix}=\begin{bmatrix}L(1-\cos\theta)+\frac{D}{2}\sin\theta\\ L\sin\theta+\frac{D}{2}(\cos\theta-1)\end{bmatrix}.$$

The maximum errors occurs when θ is the maximum. This value can be calculated similarly. The part is to allowed to rotate until the upper right corner contacts the other surface of the hole. This is shown in Figure A–14. The calculations start with the equation

$$\begin{bmatrix}x'\\ D+2g\end{bmatrix}=\begin{bmatrix}\cos\theta_{\max} & -\sin\theta_{\max}\\ \sin\theta_{\max} & \cos\theta_{\max}\end{bmatrix}\begin{bmatrix}L\\ D\end{bmatrix}$$

since the starting point in known and is rotated until the *y* component is at the far surface of the hole, *D+2g*. Therefore, θ_{max} can be calculated by solving

$$D+2g=L\sin\theta_{\max}D\cos\theta_{\max}.$$

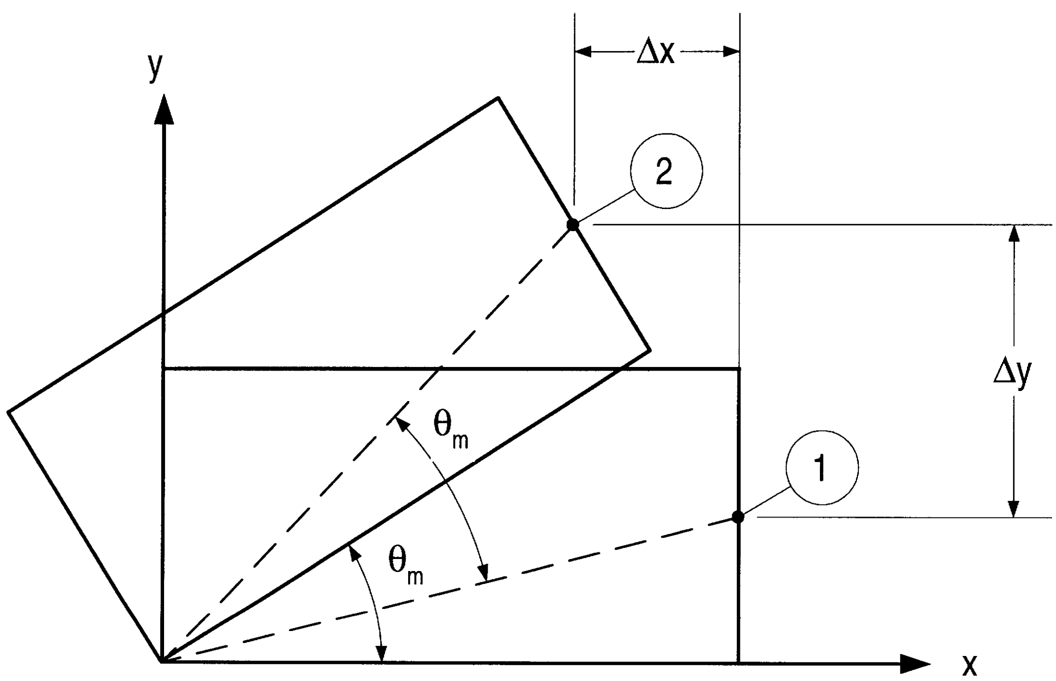


Figure A–13: Part with tilt error

Afterwards, θ_{max} can be used in the equation for $\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}$ to solve for the errors.

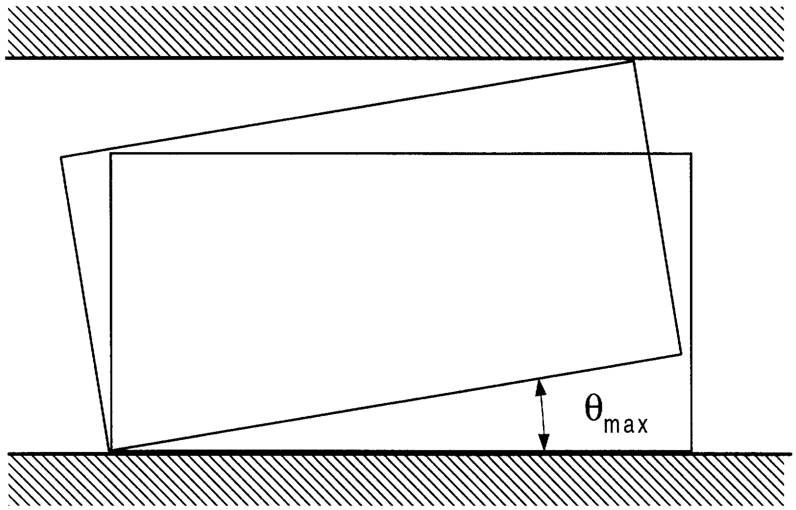


Figure A–14: Part at maximum tilt

Despite the tight tolerances on diameter with the different type of fits, when the core is tilted, the resulting axial deviations are much larger than the accuracy needed. The results of the calculations are shown in Table A–3 for both a close running and sliding fits. The result is an error of at least 29 μm. That error is almost six times the total travel of the stepper, which is too large. This analysis was done on one set of a series of cascaded solenoids. With more solenoids, the maximum error will be greater.

In addition to many design issues to resolve, manufacturing can also be a problem for the current design. The radial dimensions are not difficult to manufacture. However, accurate stops are. Since some stops have to be half a micron (0.5 μm) away from the mating piece, the tolerance and surface finish of the parts are critical. According to Kalpakjian (1995), the only manufacturing processes capable of tolerances on the micron range are honing, lapping, buffing, or polishing. Then, the surface finish should be better than one eight of the tolerance to prevent the surface finish dominating the tolerance (Green, 1992). In that case, superfinishing might be needed. These tight requirements all add to longer manufacturing time and more expensive manufacturing costs.

However, from the design, one cannot assemble the device. Therefore, each part must be made of at least two subparts. These two subparts must be carefully machined and assembled to keep the subassembly within tolerance. These subassemblies may even have to be measured, and their dimensions used to adjust the dimension of the other parts.

Table A–3: Errors associated with tilt

Value	**Close running fit**	**Sliding Fit**
L (mm)	40	40
D (mm)	9.985	9.991
g (mm) = max separation/2	0.025	0.0145
θ_{max} (degrees)	0.0716	0.0415
Δx (μm)	6.27	3.63
Δy (μm)	50	29

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Company Contact Information

Below is a list of companies or vendors that were contacted during research. The first line will be the company name. The next line, the first indented line per entry, will be a brief description of what the company does with regards to the work detailed in this thesis. Then, there will be several lines of their contact information. The usual order will be: postal address, phone number, and the corporate WWW homepage URL. If there is limited contact information, that denotes a contact that was suggested but not contacted during research.

3SPACE Inc.
    measurement services
    Indialantic, FL
    407–952–1575
    www.iu.net/3space/

BEI Sensors & Systems Company, Kimco Magnetics Division
    solenoids and voice coil actuators
    804–A Rancheros Drive
    San Marcos, CA 92069
    760–744-5671

Brown & Sharpe
    CMMs and fixtures
    Precision Park
    200 Frenchtown Rd
    North Kingstown, RI 02852–1700
    800–766–4673
    www.bwnshp.com

CNA Manufacturing Systems
pogo fixture
18103 NE 68th Street, #C–100
Redmond, WA 98052
800–331–8547
206–861–4065
www.cnaflextool.com

Electro–Optical Information Systems (EOIS)
moiré sensors
1221 Broadway, Suite 204
Santa Monica, CA 90404
310–451–8566
www.eois.com

Faro Technologies
portable CMMs
125 Technology Park
Lake Mary, FL 32746
800-736-0234
www.faro.com

Flexx Systems Co.
flexible modular fixturing systems
4760 North Chestnut
Colorado Springs, CO 80907
719–260–8409

Geodetic Services, Inc. (GSI)
photogrammetry equipment
1511 South Riverview Drive
Melbourne, FL 32901
407–724–6831
www.geodetic.com

Hymarc Ltd.
3D scanning laser digitizer
address??
38 Auriga Drive, Unit 5
Ottawa, Ontario, Canada K2E 8A5
613–727–1584
www.hymarc.com

IMETRIC International Inc. (Image Metrology Inspection and Control)
Switzerland

Intelligent Automation Systems, Inc. (IAS)
developers of automation equipment
149 Sidney Street
Cambridge, MA 02139
617–354–3830
www.ias.com

Leica, Inc.
laser tracker and theodolite systems and other measurement devices
3155 Medlock Bridge Road
Norcross, GA 30071
800–367–9453
www.leica.com

M. Torress
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Metronor Inc.
photogrammetry equipment
21652 Melrose Avenue
Southfield, MI 48075
1-888-US-METRO (876–3876)
www.metronor.com

MIT Lincoln Laboratories – Dr. Lyle Shirley
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244 Wood Street
Lexington, MA 02173-9108
781–981–0419
shirley@ll.mit.edu

Newport Corporation
electrostrictive and other types of actuators and stages
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Irvine, CA 92606
800–222-6440
www.newport.com

Perceptron, Inc.

laser measurement devices
23855 Research Drive
Farmington Hills, MI 48335
313–414–6100
www.perceptron.com

Physik Instruments (PI)

microposition products, piezo electric translations devices
Germany
www.physikinstrumente.com
Polytec PI, Inc. (exclusive distributor of PI and Polytec in the North America)
Suite 212
Auburn, MA 01501
508–832-3456
www.polytecpi.com

Queensgate Instruments Inc.

piezoelectric translations devices
Suite 600
90 Merrick Avenue
East Meadow, NY 11554
516–357–3900
www.queensgate.com

Sandia National Laboratories – Tim Cooley

high performance 3D range image acquisition research
Sandia National Laboratories, New Mexico
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Albuquerque, NM 87185-0780
505–844–2077
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Romer Inc.

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Carlsbad, CA 92008
800-218-7125
www.romer.com

RTFF Project

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Tarus Products Inc.

CMMs and manufacturing machines
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Sterling Heights, MI 48312
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