A method for fixturing, scanning, and reorienting an additively manufactured part in preparation for subsequent machining

by

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NOMENCLATURE

AM	Additive Manufacturing
AMF	Additive Manufacturing File
CAD	Computer Aided Design
CNC	Computer Numerical Control
CMM	Coordinate Measuring Machine
DED	Direct Energy Deposition
DMLS	Direct Metal Laser Sintering
EBM	Electron Beam Melting
GUI	Graphic User Interface
LBM	Laser Beam Melting
RP	Rapid Prototyping
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
SM	Subtractive Manufacturing
STL	Stereolithography
VBA	Visual Basic for Applications

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ABSTRACT

This thesis presents a methodology for fixturing, scanning, and orienting additively manufactured (AM) metal parts prior to finishing operations using a process called CNC-RP (rapid prototyping), which is a subtractive rapid machining method that employs the concept of sacrificial supports. AM has enabled the manufacturing of complicated designs in a layer-based fashion but often produces parts with inadequate surface roughness and/or dimensional control. Subtractive manufacturing (SM) techniques typically fabricate parts with overall better surface roughness and feature accuracy but require fixtures and custom tooling for each part design. Combining the two technologies of additive and subtractive manufacturing to create metal parts would allow the design flexibility of additive while simultaneously enabling the accuracy and finish of subtractive. However, the process of locating components when two processes are involved can be challenging. Solutions to this challenge have been applied to the metal casting industry in the form of custom fixtures, but the fixtures made for these finishing operations are intended for high volumes of a single part; thus, these fixtures are too expensive to justify for the small batch sizes made through additive manufacturing.

Through non-contact scanning, a set of algorithms built into a localization software program identifies the location and orientation of a part secured within the fixture and outputs this identification in the form of a position vector. These algorithms also yield the angular rotations required to align the part's current position vector to the ideal computer aided design (CAD) model position vector in preparation for CNC-RP. Another program was developed to determine the finite rotations of the A- and B-axis when part length is taken into consideration. These rotations were physically implemented with a fixture hardware element.

Process capability metrics were employed to validate this method. For both axes, parts could be produced within tolerance only *after* this method was employed (Cp and Cpk values greater than 1.0 are "acceptable"); however A-axis correction fell short with a Cpk value of 0.985, but tighter process control and/or more accurate equipment may resolve this issue. Thus, this thesis provides a feasible methodology to combine additive manufacturing and CNC-RP subtractive manufacturing.

CHAPTER 1: INTRODUCTION

Over the last decade, developments in rapid manufacturing technology have allowed the effective fabrication of fully functional, near net shape parts. Demand to manufacture metal parts using this technology has recently increased, but there are still large opportunities to improve feature accuracy and surface roughness. Subtractive manufacturing techniques, such as machining, have been used as finishing operations because they consistently fabricate parts with better surface roughness and overall feature accuracy. However, unlike AM, machining can require custom fixture and tooling solutions for each part design. This research focuses on a method to merge additive and subtractive rapid manufacturing technologies in order to perform finishing operations on metal near net shape parts. This chapter presents challenges associated with these technologies, followed by the motivation and objective of this research.

1.1 Background of Additive and Subtractive Manufacturing

Rapid manufacturing, or rapid prototyping (RP), defines many methods employed to create the scale model of a part or a multi-component assembly quickly using three-dimensional computer aided design (CAD) data. Rapid prototyping began its first stages of development in the late 1980s and its role has grown exponentially since then.

Additive manufacturing (AM), or 3D printing, is a widely employed RP technology aimed to construct parts or assemblies for small production runs in a layer-by-layer fashion and is used today for a wide variety of applications. Some of these AM methods include Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), and Electron Beam Melting (EBM). Additive manufacturing involves the sequential deposition and fusion of 2½-D layers of material to fabricate the final part geometry. The term “2½-D” refers to the geometries of layers varying in the X and Y directions, but a Z height is held constant (*Figure 1a*). These layers are digitally created from the original CAD model of the part and, upon successful transfer of this information to the machine’s software, these layers are physically created in the AM machine by fusing particles together. Interior features, such as holes, are built concurrently with exterior features. Support structures are also fabricated during this time for geometry that cannot support itself during the build process such as overhanging surfaces, downward facing horizontal surfaces, and thin features.

Subtractive manufacturing (SM) fabricates parts in the opposite manner to that of AM and manufactures geometric structures through the sequential removal of stock material (*Figure 1b*). Common SM processes include milling, turning, and drilling. SM requires tool path planning by a technician for each setup and may include software or hand generated NC code for computer controlled machines. Each setup typically requires a manual fixturing technique that locates, clamps, and secures the stock material during the machining process. During the SM process, the sides of the stock accessible to the cutting tool are machined according to the pre-determined tool path for that setup. Other manual setups and tool path planning are required to machine the other sides. For example, the part in *Figure 1b* would require at least one more setup oriented 180 degrees to machine the bottom of the sphere.

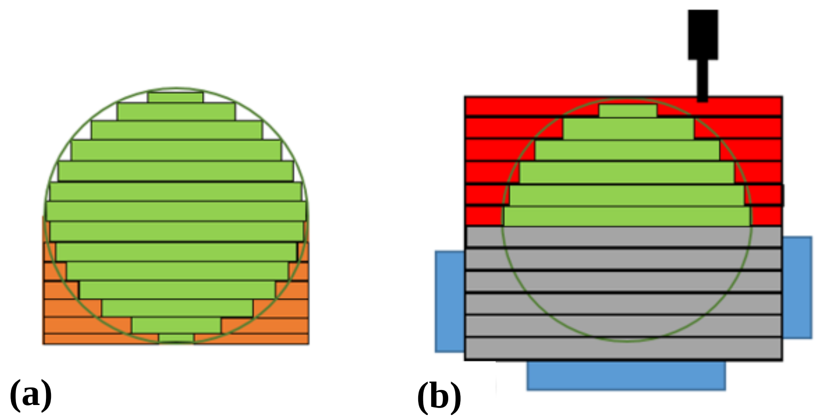


Figure 1*. Additive and subtractive manufacturing of a sphere; (a) Additive deposits 2 ½-D layers sequentially to create part (green) and support material (orange) versus (b) Subtractive manufacturing which removes 2 ½-D layers (red) to create part (green) from stock material (grey) secured by fixture elements (blue)*

This research focuses specifically on the manufacturing of metal parts. The primary factors of metal AM processes are the raw material as well as the energy source utilized for part creation. The powder bed technology systems are the most widely used class of metal AM machines. The energy sources come in the form of a laser or electron beam that is used to fuse material powder together to form the desired shape. This category of AM is different than other additive manufacturing methods, such as binder jetting, sheet lamination, and direct energy deposition (DED) (that uses focused thermal energy in the form of a laser or electron beam and wire feed techniques to fuse material), which are outside the scope of this thesis.

The two main powder bed methods are Direct Metal Laser Sintering (DMLS) and Electron Beam Melting (EBM). Today, the DMLS process is no longer limited to sintering; it has expanded to full fusion but has retained the older acronym. Both methods are able to manufacture fully functional metal prototypes and even production parts, increasing design efficiency for highly technical applications. This metal 3D printing technology can provide features of high density ideal for applications such as custom medical and dental parts, complex oil and gas components, aerospace components, production parts/tools, and applications requiring high temperature (*Figure 2*).

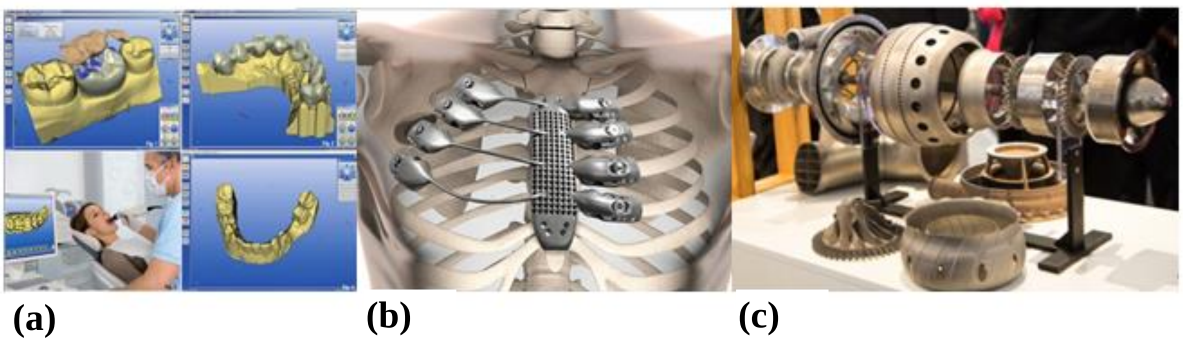


Figure 2. *AM application examples; (a) Custom dental parts [1], (b) Custom medical parts [2] and (c) Turbine engines for aerospace applications [3]*

The DMLS build process (*Figure 3)* begins by generating STL (stereolithography) files from 3D geometric (CAD) part models. This file is digitally sliced into layers and loaded into

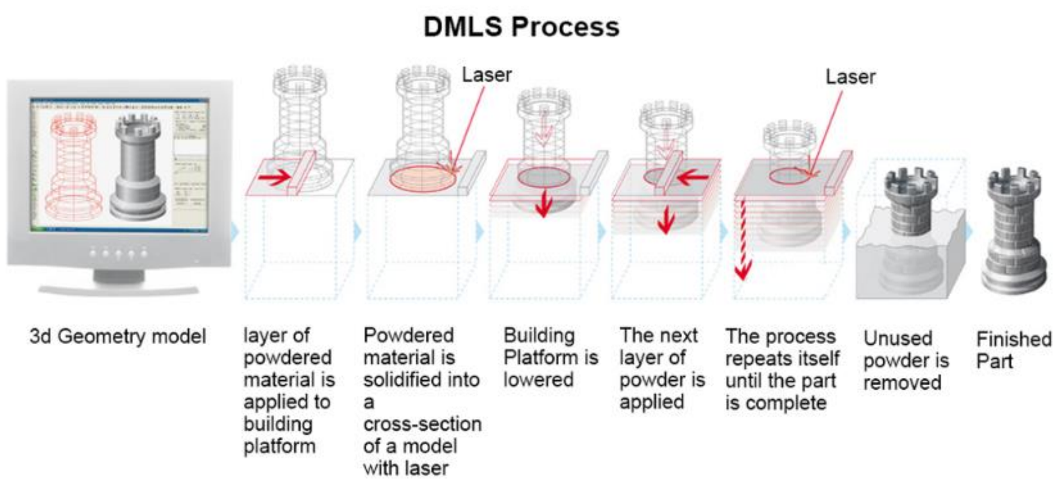


Figure 3. *DMLS process [4]*

the machine's software. Inside the machine's chamber (*Figure 4*), a leveling roller (or blade) is used to move new powder from the material dispensing platform over the build platform in a uniform layer. A fiber laser beam then activates, bounces off the scanning mirror and selectively scans/fuses thin layers of loose powder on the build platform below. This layer is a 2½ dimensional cross-section of the part's sliced STL model and this solidified layer approximates the true part geometry. After each scan, the build platform is lowered downward in the part-build chamber while more material is raised from the powder cartridge and recoated evenly on the previous layer so that a proceeding powder layer can be placed and fused onto the previous layer. This cycle is repeated until the part or assembly is finished. The completed part is then retrieved from the part-build chamber, unused powder is removed and the part is detached from the baseplate after a stress-relieving heat treatment. Support structures are also removed at this time and any subsequent finishing operations are applied.

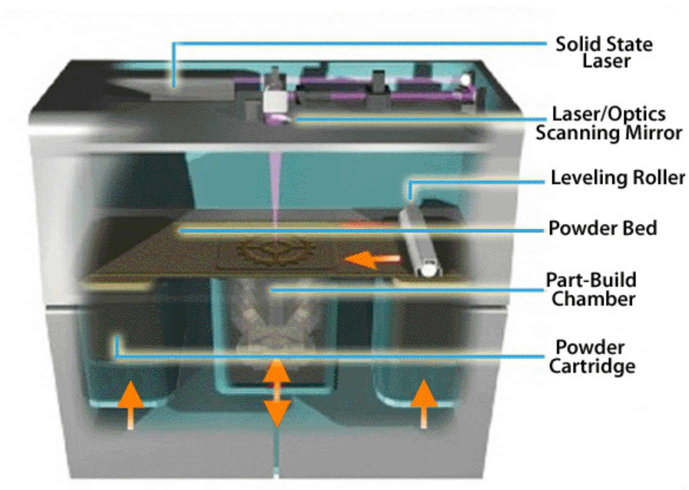


Figure 4. *DMLS machine [5]*

EBM parts are fabricated in a similar fashion but, instead of a laser, EBM uses an electron beam with up to about 3kW of maximum power, which raises the powder to over 3,000 degrees Fahrenheit. The electron beam requires operation to be in a vacuum (*Figure 5*). While DMLS usually makes parts with higher resolution, EBM generally makes parts faster than DMLS and is known for its application using titanium, which is a material with a work-hardening tendency.

The lead time for receiving a traditionally manufactured part can take weeks, creating a large bottleneck in a production process. DMLS typically produce parts in a matter of hours or days and EBM can be even faster. With such a reduction in the production time of functional metal prototypes, design cycles are accelerated and time to market is shortened.

While these manufacturing methods seem promising, high performance demands of these additively manufactured parts and related price have made it difficult for industry to qualify parts. At this time, concern seems to focus on the quality of the material [7]. Much more research is necessary to qualify and expand the process as an industry standard using a variety of new materials. However, this can be difficult as the modern process employed in DMLS and EBM manufacturing is quite complex. The complexities arise in the process variables and fine tuning to produce higher quality part resolution and enhanced material properties.

Challenges related to material quality include the labor intensive metallic support structure removal and associated post-processing (subtractive manufacturing) of the part as surface roughness and dimensional accuracy characteristics can be an issue for certain applications so post-machining or other processing is required to obtain the desired characteristics. Many believe that metal AM parts can one day be made readily usable when we have a deep physical understanding of the process, but others in the industry would argue that there will always be at least some post-processing. This need for the finishing process through subtractive manufacturing is an underappreciated part of AM and perhaps AM metal processes may not ever deliver perfected parts straight from the 3D printer [8].

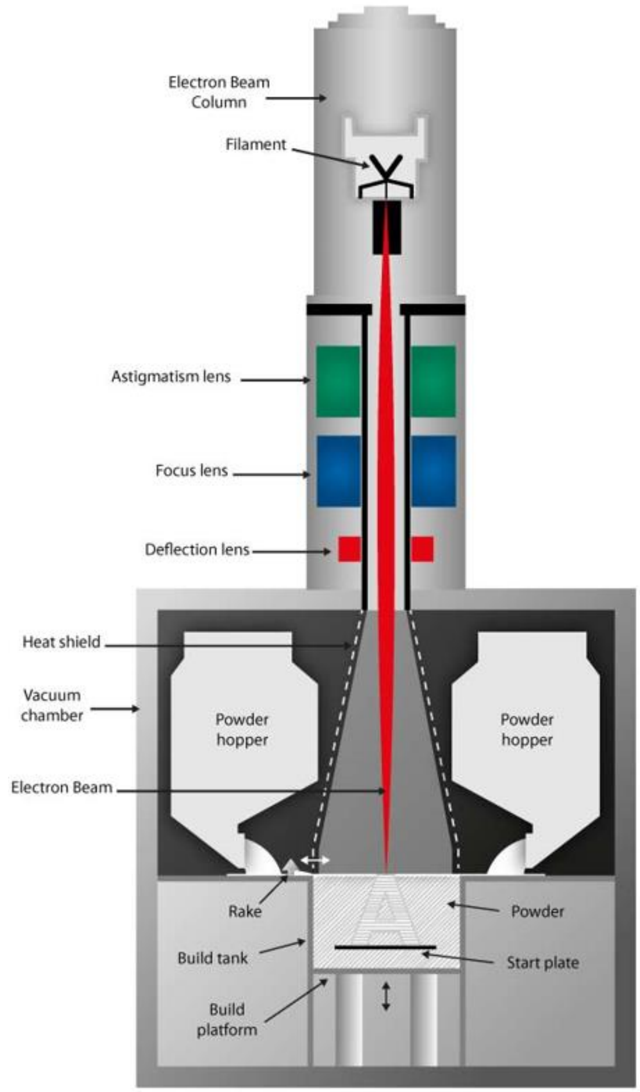


Figure 5. *EBM machine [6]*

That being said, neither additive nor subtractive manufacturing can always be suitable as the only fabrication method for all applications. There are advantages to both additive and subtractive manufacturing, and different factors comparing these two methods are presented as follows:

Complexity

The part complexity capability under a limited time frame can be considered the biggest difference between the two processes. AM methods generally exceed SM methods with regards to this factor. The reason lies in the layer-by-layer fashion in which AM parts are manufactured. Every 2½-D layer can be very detailed since interior features, such as holes, are built concurrently with exterior features with no obstacle. Additionally, since the assembly instructions are derived directly from the CAD file, limited to no technician support is needed and a great portion of the process is automated.

However, the SM process requires material removal from a larger piece of material. Hollow features may not be possible without combining more than one piece of material and the amount of part detail can be limited, especially considering the machine and tooling availability. SM should not be discredited, however, as an imprecise process. Provided sufficient time is given, a CNC machine and a skilled machinist can fabricate very complex and accurate parts.

Part Quantity

For a single prototype or a small batch, AM is generally the smarter choice based on its characteristically short lead times and often quick turnaround from CAD model to completed part. For larger production runs, SM is commonly considered the more cost-effective decision based on investment in pre-process engineering. SM involves a large amount of setup in preparation for even a single part. For example, programming a CNC machine's tooling path can be expensive in terms of time and skill. But investment in setup and program development time is more financially logical in this case since that tool path should be the same (or with minimal changes) for tens or hundreds of parts.

Material

SM methods, such as milling or turning, are standard choices for manufacturing a wide variety of metals but current research has opened the door for metal AM processes, such as DMLS and EBM, to use alloys so prototypes can be made out of the same material as production components. These processes offer a range of metals including cobalt-chrome, tool steel, stainless steel, bronze alloys, and titanium; each with its own inherent characteristics, advantages, and applications.

In terms of the mechanical properties of the final product, AM parts can vary greatly depending on the parameters of the individual process, build orientation, and post-fabrication surface finishing and treatments. Different part geometries require special design considerations such as supports and heat sinks that ensure built parts preserve geometric accuracy [9]. In terms of the general quality of heavily studied materials, the mechanical properties of the materials produced from AM tend to be on the higher end of the traditional mechanical properties spectrum, even when compared to their conventionally cast counterparts [10].

The mechanical properties of SM parts are even more highly reliable and consistent as the process involves removing material from original stock and heat deformation is not a big concern if proper lubrication is applied. In general with machining, the quality of the materials going into the process are nearly identical when completed; AM is not as reliable or dependable.

Cost

Some of the main cost drivers between AM and SM are capital investment, pre-process engineering, labor and material utilization. In general, the capital cost of AM is much higher; the cost of a professional 3D metal printer can range between $250,000 and $1,000,000; while the cost of a quite capable CNC machine can cost between $50,000 and $100,000. However, the pre-process engineering time and associated cost for CNC machining must also be considered. The pre-processing for AM can include some skilled technical decisions and setup, but far less than generating NC code and setup and fixture planning for CNC machining. This pre-processing overlaps into the labor cost, which also includes the cost during the build process. For AM, there are some technical decisions to be made, but once fabrication has begun, little to no supervision is generally required. For SM, however, the build process can require multiple setups and refixturing, depending on the part design, so a technician must be present throughout the process. The final cost consideration is the material utilization between the two processes. For subtractive manufacturing, all removed material from original stock direct waste in the form of chips. The magnitude of waste varies on a case-to-case basis, but in a worse case, the amount of discarded material via subtractive manufacturing in the aerospace industry can commonly approach 90 percent [11]. For powder-based AM, most of the unused powder can be generally recycled for multiple build cycles, but there is material waste in the form of the support structures that are cut off and discarded after build.

Tolerance

Dimensional capability of both AM and SM methods is contingent on the process used, parameter settings, and the tooling resources. For powder bed AM processes, the dimensional accuracy and surface finish of parts are dependent on parameters such as the resolution of the energy source, geometry of the desired part, and material [12]. For example, the material processing of AM and the nature of thermal expansion affect dimensional variability. The temperature of the metal powder is raised above its solidus temperature to fuse the particles, and when they cool and solidify the part tends to shrink. Dimensional errors fluctuate with various geometric shapes causing different percentages of shrinkage throughout the part (thin features are particularly vulnerable to this distortion) [13]. Because of this, extra stock material is added to compensate for any unexpected shrinkage. Extensive research for some materials has mitigated this distortion and has improved relative dimensional accuracy.

CNC machining can reasonably maintain most tolerance callouts within realistic limits, depending on how much time and money is available. A 2014 study on precision of mechanical parts with regards to current manufacturing performance for highly technical parts provided a comparison of machining to metal AM [14]. In this work, the manufacturing specifications for conventional machining (milling and turning), both for ultra-precision machining and standard machining of parts in the range of 100-400mm, were determined (*Table 1)* and these results were compared to EBM and Laser Beam Melting (LBM), which are both additive manufacturing processes. As expected, subtractive manufacturing was considered better in terms of minimizing distortion and promoting better surface finish and dimensional accuracy.

Table 1. *Performance of conventional machining and AM in respect to key specifications for parts found in high tech sector [14]*

Specification type		Ultra-precision*	Standard 100-400mm	EBM***	LBM***
Surface flatness	[μm]	5	10-50	n/a	n/a
Roughness (Ra)	[μm]	0.05	0.8-3.2	20-30	5-15
Geometric tolerance (profile)	[μm]	±2.5	±20-80	±300	±100
Minimal wall thickness	[μm]	400	400-600	600	200
Small features /channels**	[μm]	190	1000	200	400
Permeation (leakage)	[mbar/l*s]	1×10^{-9}	1×10^{-9}	600	600
Contamination (0.5 μm/5 μm)	particles/m^2	3520/20	3520/29	Unknown	Unknown

* State of the Art
** Smaller features can be obtained through EDM or laser cutting
*** Highly dependent on part design, material, machine type and manufacturing process paramaters

1.2 Finishing AM Parts Using CNC Machining

The most common finishing strategy for AM parts is subtractive manufacturing with a Computer Numerical Control (CNC) machine. CNC machines are milling devices that use coded commands that communicate to an internal computer to automate the machining of parts accurately and rapidly. Similar to casting, metal AM parts can be manufactured with an extra material envelope (i.e. material allowance) to compensate for any dimensional variability, ensure favorable internal stresses, and provide an opportunity to achieve desired surface finish with stock removal through CNC machining.

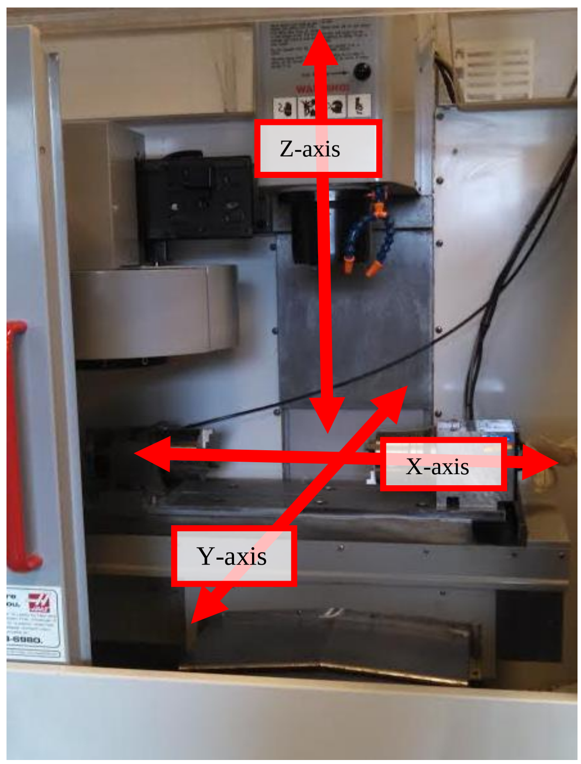


Figure 6: *Three-axis Haas mill*

The most common CNC milling machine is a three-axis mill, which can move laterally in the x, y and z axes (*Figure 6*). A four-axis machine adds a fourth degree of motion through rotation about the X-axis; also known as the A-axis. A five axis machine adds a fifth degree of motion through a rotation about the Y-axis; also known as the B-axis.

There is current research intended to explore the best ways to complete this post-processing CNC machining step. Computer Numerical Control-Rapid Prototyping (CNC-RP) is a proposed SM process and an automated rapid machining technique that merges CNC machining with the AM technologies concept of layered manufacturing; however, this approach subtracts material layer-by-layer rather than adding it [15]. CNC-RP is a method that fixes cylindrical stock between two opposing chucks in a four-axis CNC machine. To fabricate the part, the stock is oriented and machined about one axis of rotation until all surfaces are machined to within tolerance (*Figure 7*). These rotations would be challenging if traditional fixturing techniques are used as they employ vises, clamps, and/or v-blocks to hold the part during the machining process and numerous manual setups would be required, making this task labor intensive. To overcome this difficult rotation step, CNC-RP utilizes an automated fixturing concept in the form of sacrificial supports that have been employed in RP technologies (*Figure 8*) [17]. The supports are included in the CAD model along with all other features before any machining occurs and then removed after part completion. The supports are designed parallel to the part's axis of rotation; thus, to machine the supports, raw material should be in excess along the axis of rotation. This thesis concerns a method to combine the SM method of CNC-RP with the AM powder bed processes like DMLS and EBM. Combining two process can make locating a part difficult, however. Thus, to merge these two processes, a fixture is required. Fixtures are devices designed to hold, locate, and support parts during manufacturing operations. Fixtures are used to reference and align the cutting tool to the part, but they do not guide the tool. Fixture devices

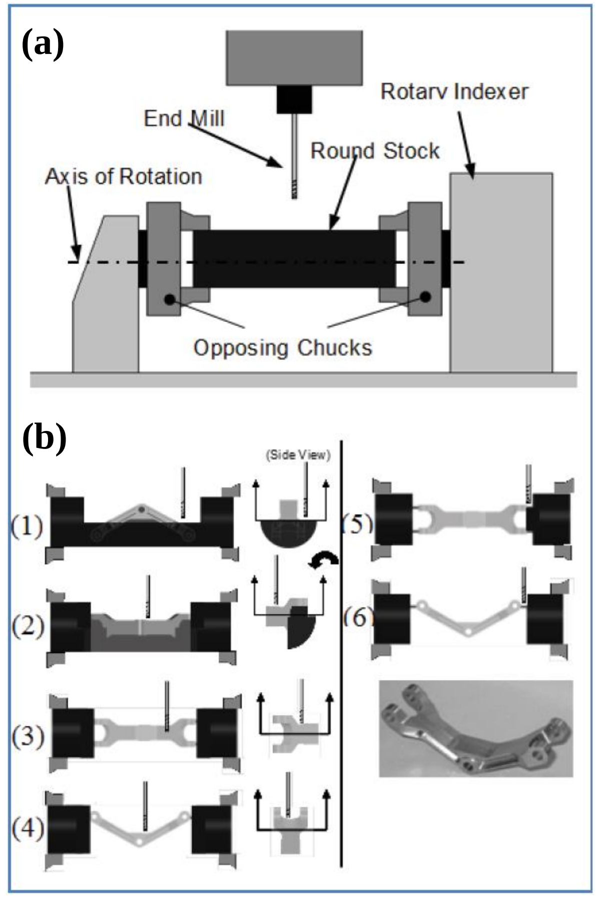


Figure 7. *CNC-RP process; (a) Setup (b) Example with steps and final product [16]*

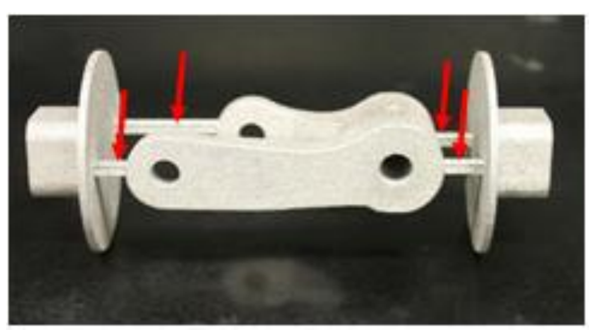


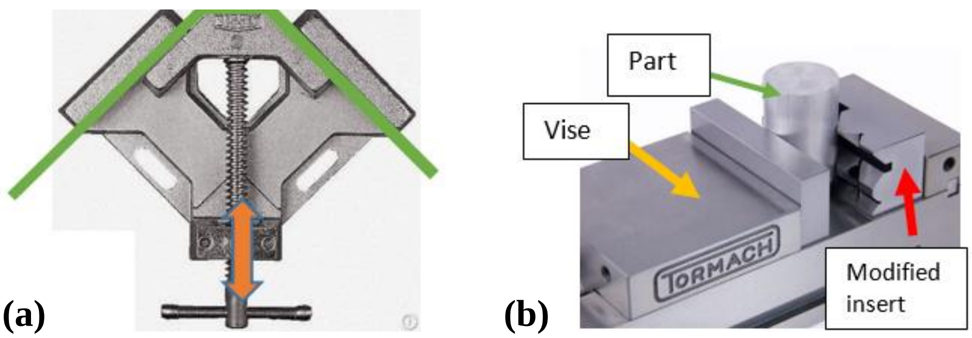
Figure 8. *Sacrificial supports along axis of rotation (highlighted by red arrows)*

can include various clamps, chucks, vises, and metal plates containing dowel and/or tapped locating holes or key slots (*Figure 9*).

Fixtures can be categorized by their construction (*Figure 10*) or with respect to the process or machine tool used in the machining process (*Figure 11).*

(a) **(b)** **(c)**

Figure 9. *Examples of fixtures; (a) Three-jaw chuck used as a workholding tool for drilling operation [18], (b) Chick vise for CNC machining [19] and (c) Section of aluminum plate with t-slot nuts [20]*



(a) **(b)**

Figure 10. *Fixture examples categorized by construction; (a) Angle-plate fixture with adjusting screw; part (green) contained by fixture [21] (b) Vise-jaw fixture with modification insert for a specific part [22]*

Furthermore, a fixture has to be designed such that it requires a minimum level of maintenance during its lifetime, withstands the forces generated by the machining process, and allows accessibility to the part.

To enable accurate machining, the part must be held in a setup that guarantees a definite position in space in relation to its

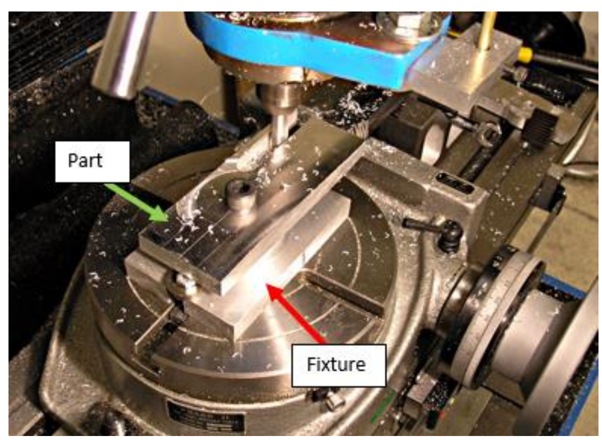


Figure 11. *Milling fixture with part clamped down during milling operation [23]*

datum points and/or surfaces. However, a part in space can move freely and this motion can be defined by twelve directional movements, or "degrees of freedom" (*Figure 12*). The axial degrees of freedom allow linear movement in both directions along the three main axes: x, y, and z, while the radial degrees of freedom allow rotational movement, in both the clockwise and counterclockwise directions, around the same three axes. Parts deviate from their expected position for multiple reasons such as:

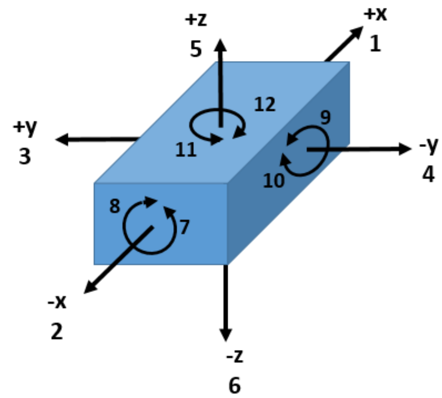


Figure 12. *Twelve degrees of freedom*

- *Fabrication:* There is always some variation in fabrication and there can be multiple causes for each variation (For example, AM parts can vary due to the sequential heating for fusion and cooling for solidification over multiple layers.).
- *Fixture-caused deviations:* Depending on the complexity of the fixture, there can be numerous sources of deviation error. For example, the force from screws and clamps move the part from nominal.

If a part's position is not accurately determined, the part will be machined incorrectly. Additionally, fixtures are often able to reorient a part if necessary, as does the fixture in this thesis. This can be done by determining part location and orientation and then adjusting the fixture as necessary, often with the use of a gantry style or articulated CMM (*Figure 13*). The inner features and complicated geometries associated with AM, however, can make metrology challenging in preparation for CNC machining. One of the more

Figure 13. *Coordinate metrology using Faro Arm*

apparent obstacles is that parts consist of minimal, if any, simpler geometric elements (examples: cylinders, circles, planes). Further, thin walls and flexible features can add to the level of difficulty. In this case, validation for AM parts might require the use of non-contact scanning systems. One common method is the use of laser scanning, which can also be integrated into an articulated CMM (Faro Arm).

Since the challenges of post-processing AM parts are similar to that of the machining needed for metal castings, there are existing efforts that are analogous to this research. Fixtures for castings are often customized for each design (*Figure 14*). Since this kind of production is high volume generally, costly one-of-a-kind fixtures can be justified.

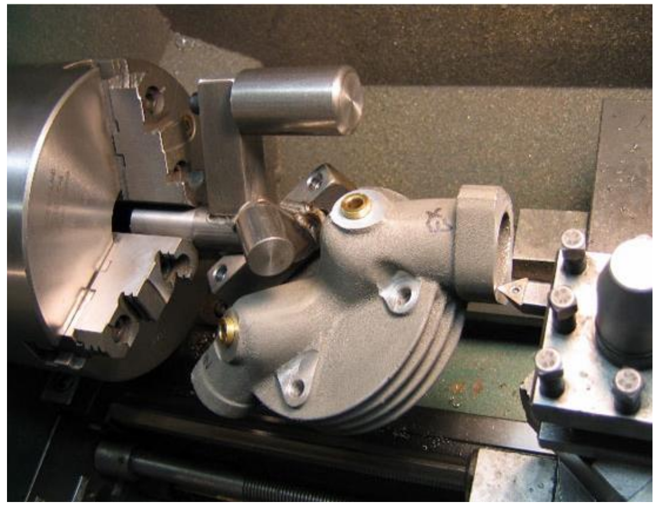


Figure 14. *Customized fixture to post-process metal casting [24]*

1.3 Motivation

Combining the two technologies of AM and SM would allow the flexibility of additive with the accuracy and surface finish of subtractive. This means that we can manufacture products with previously unachievable geometry and introduce high precision features in hybrid operations. The process of locating components when we have two processes, however, can be challenging. This can be made possible with a flexible fixture that can accommodate parts of any size, material, and shape in the transfer between the AM processes to the SM process. With that in mind, similar to the repositioning techniques utilized in the metal casting industry, this fixture must also allow technicians to measure and reorient the part as necessary for that subsequent machining. However, the fixtures made for finishing operations after casting are intended for multiple parts and batches. There does not exist a flexible fixture that allows one to laser scan and reorient an AM part suitable for these rapid manufacturing technologies.

1.4 Objective

The objective of this thesis is to create a method for fixturing, scanning, and reorienting an AM part for subsequent machining.

<u>Sub objectives</u>

In order to achieve the overall objective, two major sub objectives are proposed: (1) the creation of an algorithm that determines the motions needed to rotate the part into a correct orientation and (2) developing a hardware fixture element with the flexibility and stability required to orient and finish machine the component. Below are research tasks defined to support each sub objective:

Tasks to support sub objective 1:

- Create an Excel VBA program that inherits the AM process planning software output and accepts user input relative to part parameters (e.g. overall length) and then outputs the two rotations needed to resolve orientation issues
- Apply the rotations to the original scan to update/refine the relationship between the physical AM model and the AM part file

Tasks to support sub objective 2:

- Design a fixture that holds and reorients AM parts of different geometries and lengths for the CNC-RP machining process
- Perform experiments on AM parts to validate the fixture

1.5 Thesis Layout

The remainder of this thesis is presented as follows: *Chapter 2* presents an overview of existing work in additive manufacturing, hybrid processes, and different types of fixtures and their capabilities. *Chapter 3* provides the general solution methodology, the technical details and development of the resultant fixture and associated orientation-correcting algorithms, while *Chapter 4* presents the implementation and test results. Lastly, *Chapter 5* presents conclusions and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

Additive manufacturing is a common term used to generalize methods to manufacture parts in a layer-by-layer fashion. In 2010, the American Society for Testing and Materials (ASTM) established classification of these additive manufacturing processes into seven categories: binder jetting, directed energy deposition (DED), material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization [25]. Metal-based AM processes include binder jetting, directed energy deposition and powder bed fusion; of these, metal-based powder bed fusion is the scope of this thesis.

Overall, additive manufacturing is a rapidly growing manufacturing method. 2011 revenue in the primary additive manufacturing market, which includes all AM global products and services, increased an estimated 29 percent to $1.7 billion. Based on rising sales, technological and material advances, new applications, and the expiration of key patents, revenue trends are predicted to continually increase and exceed $6.5 billion by 2019. Powder bed fusion and binder jetting are the most common processes used by leading vendors, and 70 percent of these vendors use metal more than any other material [26]. The main industries supporting this market include automotive, medical, and aerospace at 19, 15, and 12 percent, respectively [27].

To further develop this technology, there has been a considerable amount of research efforts in the recent advancement and application of additive manufacturing materials. Researchers have studied metals such as titanium alloys, copper, and nickel-based superalloys that have been used for fabrication in AM processes [28-30].

While these materials have improved, most lack the repeatability required due to dimensional variability and surface roughness that can cause, for example, thermal stress [31-33] and shrinkage [34-35]. Factors that can ultimately control surface quality and dimensional accuracy are powder characteristics (particle shape, size, distribution, component ratio, etc.) and processing parameters (such as laser power, scan speed, and powder layer thickness) [36]. Further, microstructural and mechanical properties vary between different AM processes [37]. Extensive research to determine optimal parameters for each alloy needs to be performed in order to qualify that alloy as an industry standard. However, AM processes still do not have the capabilities to achieve the surface roughness accuracy for certain applications. Several groups, such as groups from NASA [38], support the post-machining of AM parts for overall surface roughness (especially for critical surfaces) as well as for material allowance removal and support structure removal.

This thesis focuses on post-machining via CNC-RP, which uses a three-axis CNC machine and a fourth axis indexer that is utilized to rotate the part to different orientations [17]. For each orientation, the process machines all visible surfaces layer-by-layer. The idea is that, upon completion of all orientations, all features have been machined to within tolerance.

In order to execute post-machining in general, a machining fixture is necessary. The design of a proper fixture can be complex, depending on processes, tolerances, geometry, dimensions, and manufacturing resources. Pachbhai and Raut (2014) performed an extensive review on the design of fixtures [39]. There are some generic fixture guidelines and principles [40-41]; however, each part and manufacturing process has its own unique fixturing requirements. The fixture design process includes phases such as fixture configuration design and then verification [40, 42]. Fixture design verification is traditionally the stage at which the fixture performance is analyzed [40, 42, 43]. Fixture design verification can consist of tolerance sensitivity, accessibility and stability and/or deformation analyses. The fixture performance is, of course, determined by the resulting end product quality. However, increases in the availability and integration of computer software tools allow the designer to verify the design during the fixture layout synthesis. The optimization of the fixture configuration design has attracted much research attention. If the fixture layout can be designed such that the part orientation in the fixture is error-proof, the part deformation is minimized [45-47]. Recent developments on machining fixture layout design, analysis, and optimization are also presented by Vasundara and Padmanaban (2014) [48].

Traditional, dedicated fixtures were introduced as a solution for batch product manufacturing and to counter machine idling time [49]. These fixtures may be effective if the industry produces only a few types of components with a high production rate for a long time period because, once these fixtures have been designed, it can be difficult and expensive to remove or change locating features of the fixture [50]. An et al. (1999) proposed an automated dedicated fixture configuration design that can be applied to predefined component types in mass production [51]. The main issues of dedicated fixtures are that these approaches require a great deal of technical skill and lack the flexibility to easily and consistently control parts of arbitrary shape.

The cost and lead time for design and fabrication are also higher for such fixtures, thus more adaptive and flexible fixture designs were required. A flexible fixture accommodates parts of different material, shapes and sizes and requires less time and effort. Flexible fixture designs can generally be classified into the following categories: modular fixtures, flexible pallet systems, sensor-based, phase-change, chuck-based, pin-type array fixtures and automatically reconfigurable fixtures [52]. Zheng and Qian (2008) introduced a systematic study of 3D modular fixtures that particularly caters to arbitrary shapes. Their modular fixturing method could adjust automatically for a part according to an algorithm [53]. Zhang et al. (2009) developed a modular system to weld sheet metal components for the automotive industry using adjustable locating pins and clamps [54]. Sela et al. (1997) developed fixturing systems for thin-walled flexible objects such as turbine blades consisting of suction clamps and pneumatic plungers [55]. Zhenyu and Darius (2007) presented a design with multipoint contact with the part using spring loaded plungers that are conformable to odd shaped parts [56]. Aoyama and Kakinuma (2005) developed a fixture for thin-walled parts that can support parts securely and with less deformation using a multi-pin supporter system with a low melting alloy as the working fluid to assist the part [57]. Yu et al. (2012) introduced a reconfigurable fixturing robot for sheet metal assembly consisting of parallel manipulators to change the locating point over a required space [58]. Yeung and Mills (2004) presented a reconfigurable gripper for use in automotive body assembly [59]. Arzanpour et al. (2006) developed a fixturing system to fulfill the objective of grasping a number of sheet metal parts using suction cup technology [60]. Leonardo et al. (2013) designed a locomotion and docking system for machining complex shaped sheet metal components using parallel manipulators and swing motion [61].

Based on the nature of CNC-RP, the flexible fixture for this thesis must be adaptable to the four-axis CNC machine and must be able to rotate with the chuck. Thus, any fixture that is going to present accessibility issues upon these rotations does not work as a viable option. Much of the existing research offers solutions that work for their specific application, but are considered too overbuilt or threaten accessibility issues for the rapid prototyping goals of the current work. Monkman (2001) proposed a solution combining electro adhesion and electro rheological fluids that can be used as force inducing media for irregular shaped components [62]. The approach might be suitable for the rotations needed for CNC-RP; however, it lacks the ability to adjust the part to align to the CNC machine's axis of rotation. Several researchers have focused on developing hybrid processes to combine additive and subtractive manufacturing, such as the LAMP process [63-64], Ultrasonic Consolidation [65-66], and 3D deposition-milling [67-68], but the majority of these are applicable only to direct energy deposition processes and not to powder bed fusion methods. The AIMS process supports integrating any AM method with CNC-RP [69], but this method also does not provide a way to resolve any orientation issues.

The post-machining of metal castings is analogous to this element of research for this thesis. However, setting up castings for machining is not only time consuming, sometimes requiring more time than machining itself, but errors in setup can result in scrapping expensive parts [70]. Varadarajan and Culpepper (2007) presented a moving groove fixture based on flexure bearings and piezo-actuators that had precision positioning and fixturing capabilities. The piezo-actuators and flexure bearings allow the fixture's alignment features to correct a part's position and orientation. (*Figure 15*) [71]. Culpepper et al. (2005) presented an eccentric ball-shaft fixture with the capability to compensate for fixture element tolerance, bearing run out and actuation errors [72]. These proposed methods provide repeatable alignment to promote accurate position and orientation, but do not have the rotational flexibility required for the CNC-RP process. Ryll et al. (2008) presented an intelligent fixturing system to promote rapid reconfiguration and part-to-fixture positioning. The system was capable of altering the clamping forces and positions with a repositioning algorithm to mitigate manufacturing errors derived from the fixture. The proposal was illustrated in a two-dimensional example with a rectangular part (*Figure 16*) and based on a 2-1 system (rather than the standard 3-2-1 system for three-dimensional fixture control) [73].

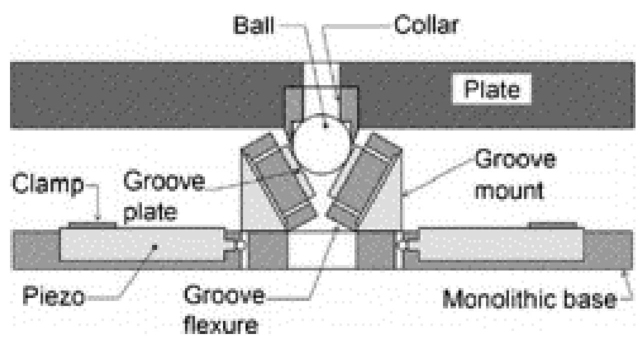


Figure 15. *Cross-section of ball-groove joint [71]*

The system would have limited ability for proper part alignment for AM components as the square ends may be unreliable referencing surfaces due to varying levels of surface finish on parts.

This section provided an overview of additive manufacturing and fixturing; however, current literature does not present a solution to merge additive manufacturing with subtractive manufacturing as described in this thesis. The following section describes a proposed methodology to provide a viable solution.

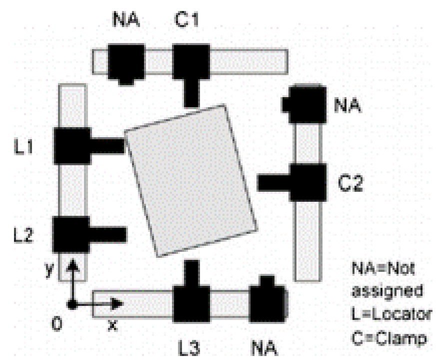


Figure 16. *Fixturing of a prismatic part [73]*

CHAPTER 3: METHODOLOGY

This thesis proposes a solution for the flexible and semi-automated fixturing of AM powder bed metal parts for rapid machining. The following sections provide details on the proposed method, starting with a basic overview of the hybrid process and the hardware design that enables this method and its assembly. Next, the causes of part location and orientation error and presented, along with a discussion of how those issues are resolved using the hardware and the software, respectively.

3.1 Overview of Hybrid Process

A general overview of the steps that collectively represent the process flow of a larger hybrid project to combine the advantageous attribute of powder bed AM and CNC-RP are given in *Figure 17*. *Figure 17a* represents the original CAD model that is analyzed by the CNC-RP software and placed at a position and orientation suitable for machining. The software then automatically adds sacrificial supports and ends to the original CAD model (*Figure 17b*). Using this information, the part is physically printed via the AM powder bed process (*Figure 17c*). Ideally, this part is ready for a post-machining operation; however, due to inaccuracies in the printing process, the final part position and orientation in the CNC machine is slightly inaccurate. To resolve this, the printed part is transferred to a fixture that is used to determine part location and to reorient the printed part before CNC machining (*Figure 17d*). This is accomplished using a Faro Arm to take scans of the part and fixture at different orientations and these scans are merged then into a 3D model (*Figure 17e*). At this point, the model is compared to the original CAD model in a separate software that provides output in the form of rotational angles for the two rotary axes and translational distances in the three linear axes that would be needed to manipulate the scanned model to the CAD model's correct position (*Figure 17f*). The position of the CAD model is then updated with the new information (*Figure 17g*). The printed part is then machined via CNC-RP (*Figure 17h*), and the sacrificial supports are removed during the finishing stages (*Figure 17i*). The work of this thesis only pertains to the steps presented in *Figures 1d-1g*. The following sections explain both the material and information process flow with regards to the proposed method to support these steps of the process.

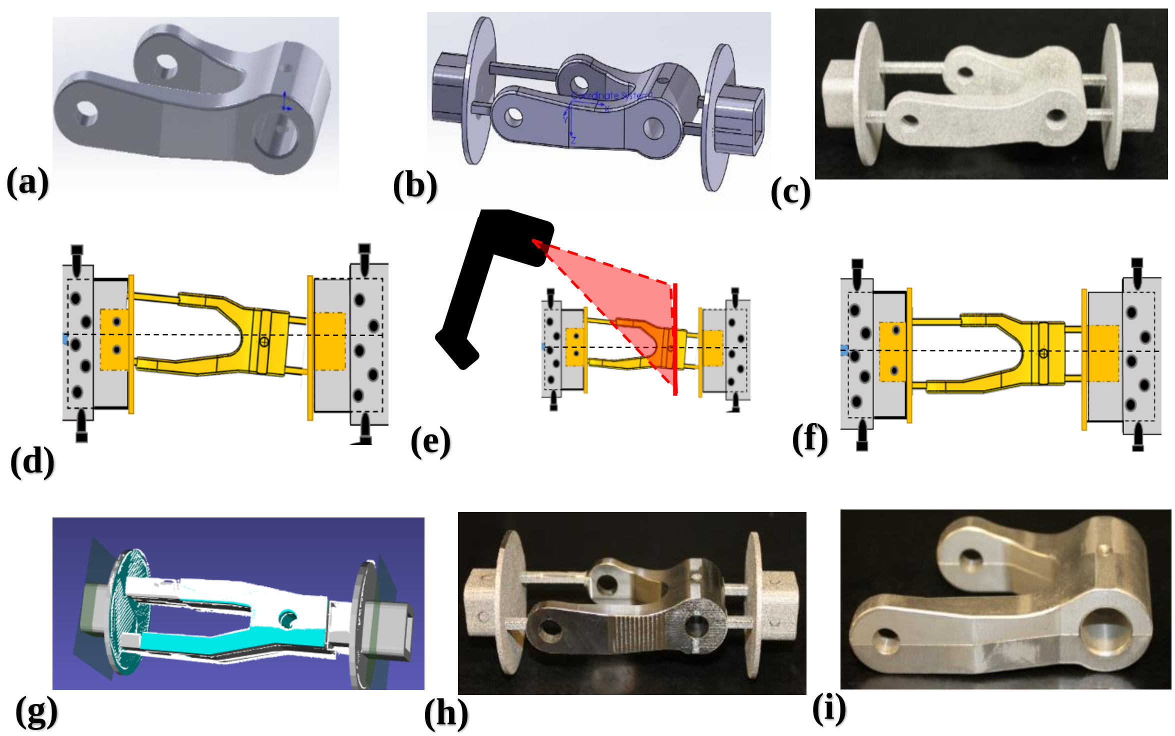


Figure 17. *Overview of current SM and AM hybrid process; (a) The original part CAD model (b) The CNC-RP software adds the sacrificial supports and ends automatically to the CAD model that is used to fabricate (c) the additively manufactured part. Inaccuracies during printing require the location and reorientation of the part for subtractive manufacturing so (d) a fixture is used to hold the part and (e) the part is located within the fixture with a scanning device. (f) The scanning information determines the manipulation moves to reorient the part and (g) the CAD model is updated to represent new physical position of the AM part. (h) The part is then machined to attain desired dimensions and (i) presents the finished machine part once the sacrificial supports and ends are removed.*

3.2 Hardware Design

The key to this method is the designed hardware. *Figure 18* displays the schematic of the fixture assembly, including the mated AM part. *Figure 19* presents the physical fixture assembly setup. An offline manual rotary assembly was built with two opposing chucks to mirror the assembly of the CNC machine. Both headstock and tailstock chucks of this fixture mate coaxially with a hollow outer cup made of high strength steel. Inside each of these outer cups, there is a smaller cup, the ball joint mounted cup and inner cup for the headstock and

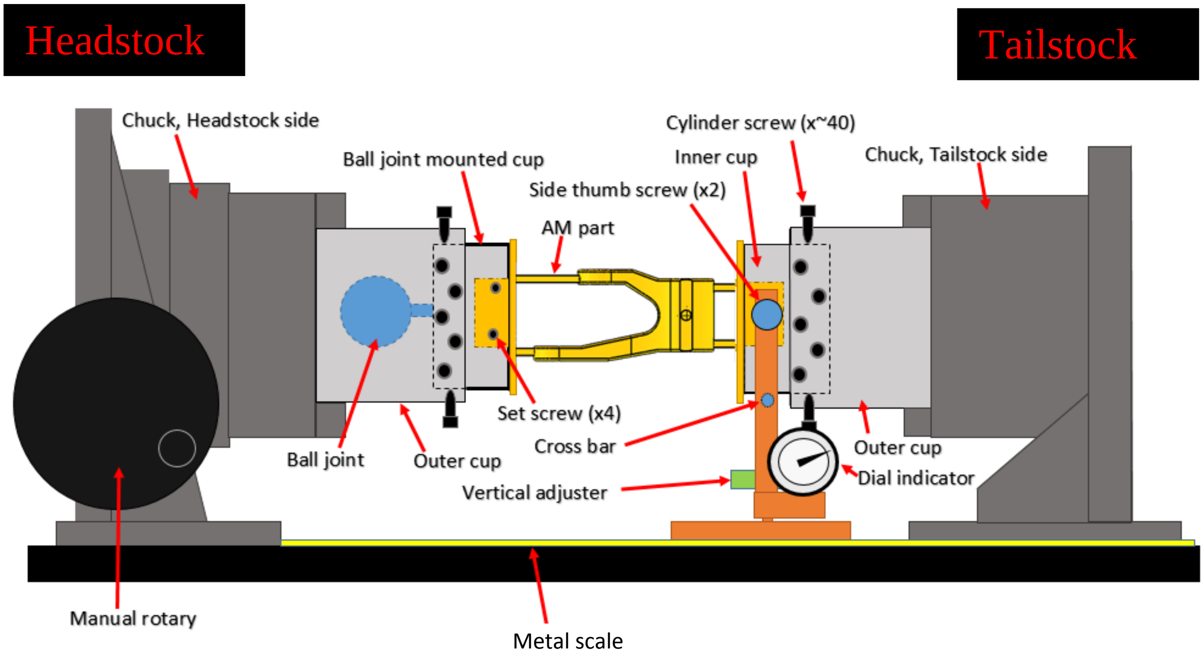


Figure 18. *Schematic of fixture assembly*

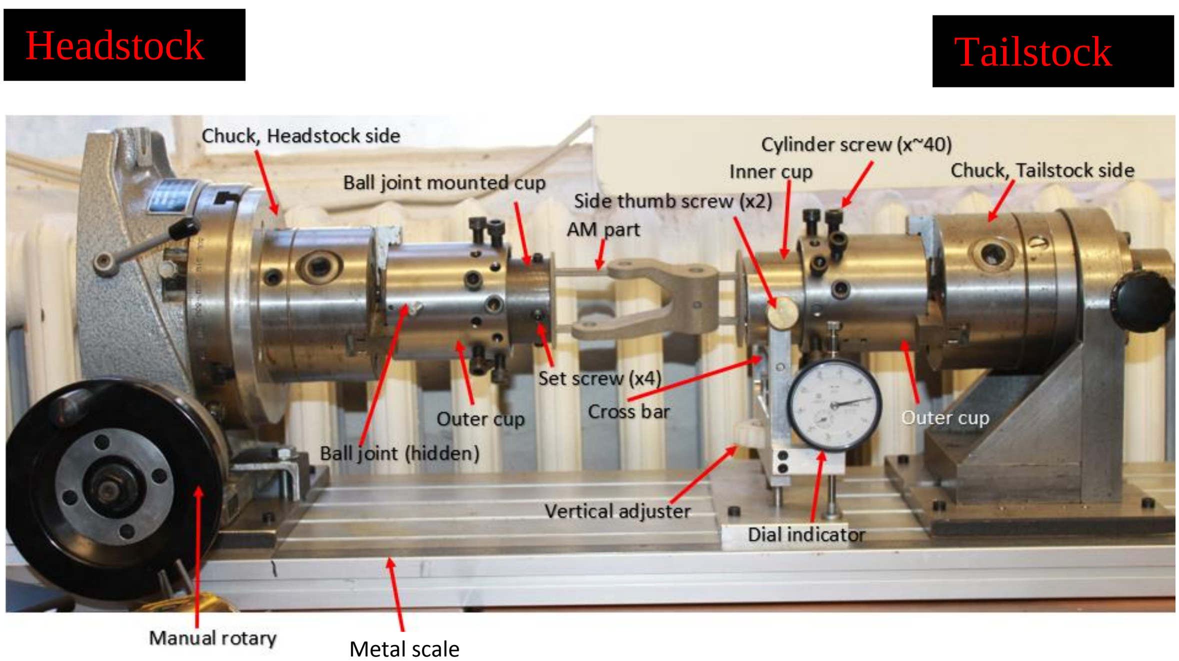


Figure 19. *Physical setup of fixture assembly*

tailstock side, respectively. These smaller cups are secured within the outer cups by cylinder screws (set screws) that are arranged in a cylindrical array and tightened to restrict the movement of the smaller cups. Each end of the AM part[1] fits and is secured in a part collet feature of these smaller cups. On the headstock side, the other side of the ball joint mounted cup is attached to a ball joint that serves as a multi-axis positioner that can move the part and other inner cup due to hardware linkages, unless the smaller cups are externally restrained by the cylinder screws. The headstock's manual rotary controls the magnitude and direction of an A-axis rotation (rotation of a point, vector, or general entity about the X-axis) (*Figure 20*). Through this rotation, the part transitions from its original position vector to a new position vector.

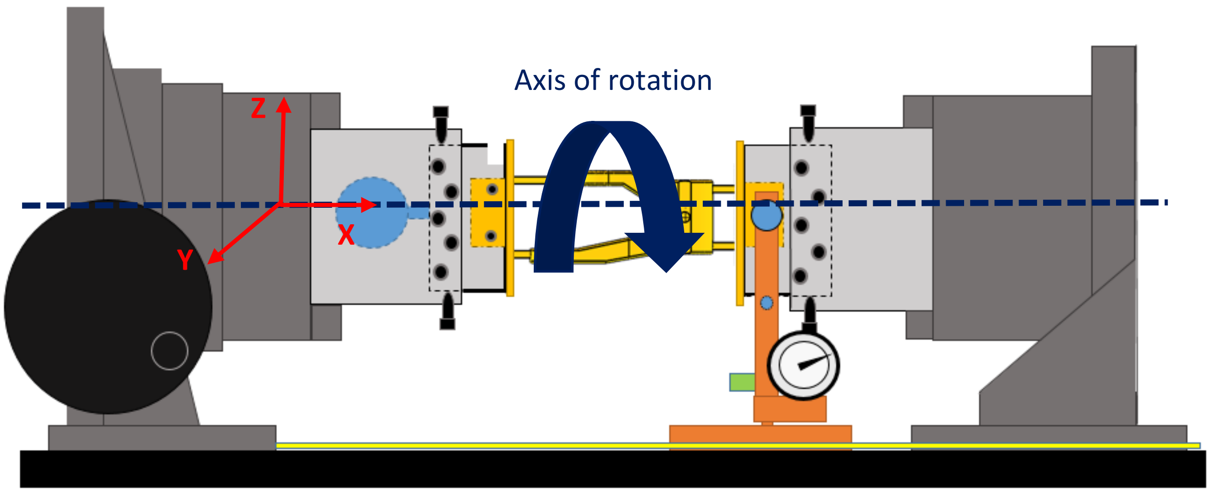


Figure 20. *A-axis rotation illustration on schematic*

The tailstock side does not include a ball joint. It does, however, incorporate a vertical adjuster assembly that serves as the lifting control for a cross bar that lifts or lowers the inner cup during a B-axis rotation (rotation of a point, vector, or general entity about the Y-axis) (*Figure 21*). This rotation requires the cylinder screws to be loosened so the assembly (from the ball joint to the inner cup) can change orientation. This rotation originates on the center of the ball joint. Horizontal movement of the inner cup is controlled by metal rods that are manipulated by side thumb screws on either side. Through this rotation, the part transitions from its original position vector to a new position vector. More detail on this rotation is discussed in section 3.3.

[1] While not within the scope of this thesis, the printed AM parts have been designed with a standard square end that is used for every part fabricated for this hybrid process. The ends are square shaped because they can easily be additively manufactured with 45 degree up-facing sides.

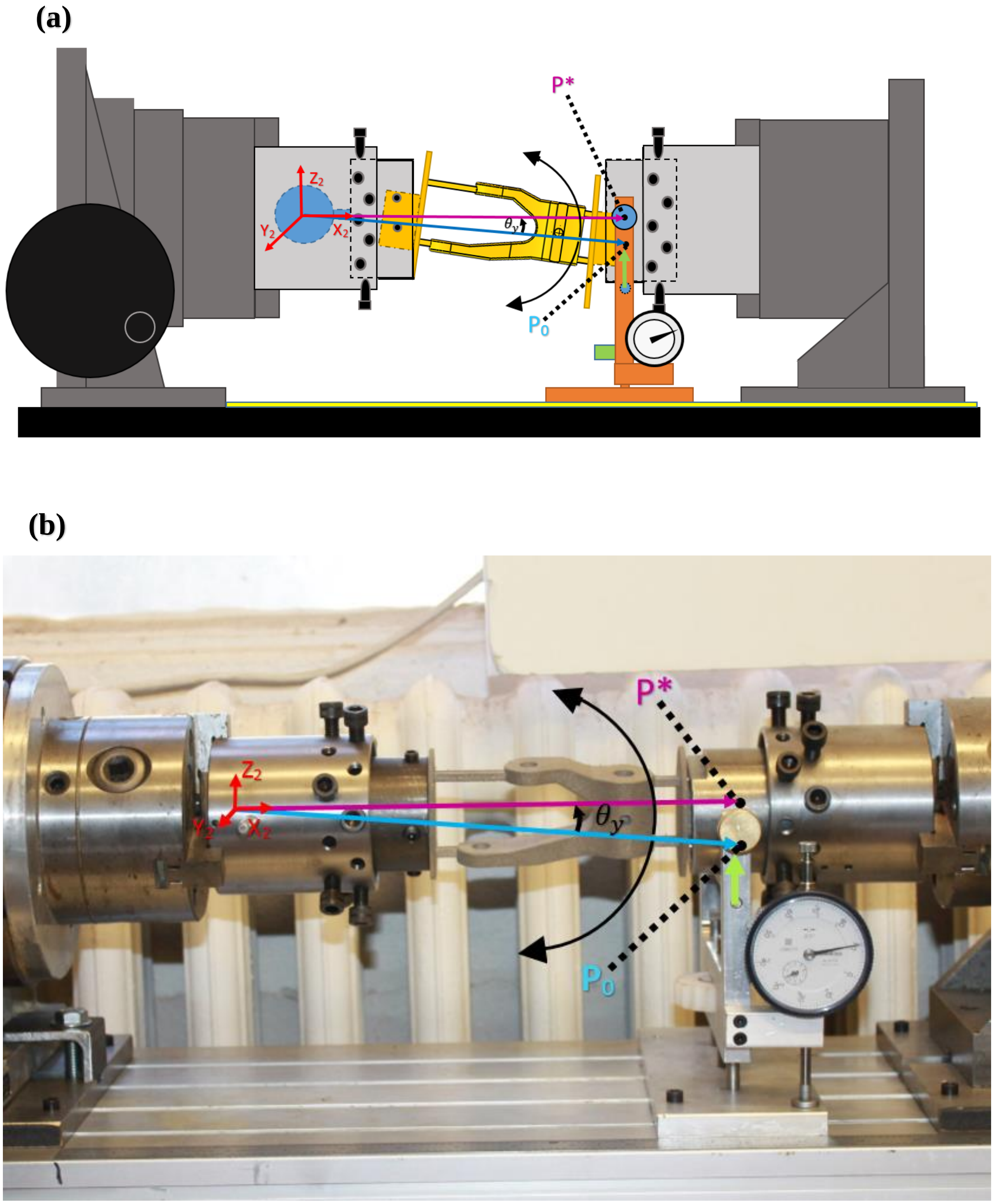


Figure 21. *B-axis rotation illustrations; (a) Schematic (b) Physical setup: P_0 represents the original position vector of the printed AM part that originates on the center of the ball joint. The cross bar either lifts or lowers the inner cup (that contains the part) a finite distance (green arrow) so that the part is now at a new position vector P*; with respect to these illustrations, the inner cup is lifted.*

3.3 Hardware Assembly

Headstock

This section focuses on the assembly of the fixture that mates with the headstock side of the offline manual rotary assembly (*Figure 22*). At the heart of this side of the fixture is a ball joint that is mounted into the backside of the ball joint mounted cup (*Figure* 23a) through a hole in the outer cup (*Figure 23b*). This outer cup has a built-in socket for the ball joint. A steel lid is placed over the ball joint on the outer cup to limit x-movement in the fixture assembly (*Figure 23c*). This subassembly is then secured in the three-jaw chuck with a chuck key (*Figure 23d*). The AM part is mated with the square part collet feature of the ball joint mounted cup (*Figure 23e*) and secured by four set screws within the ball joint mounted cup (*Figure 23f*).

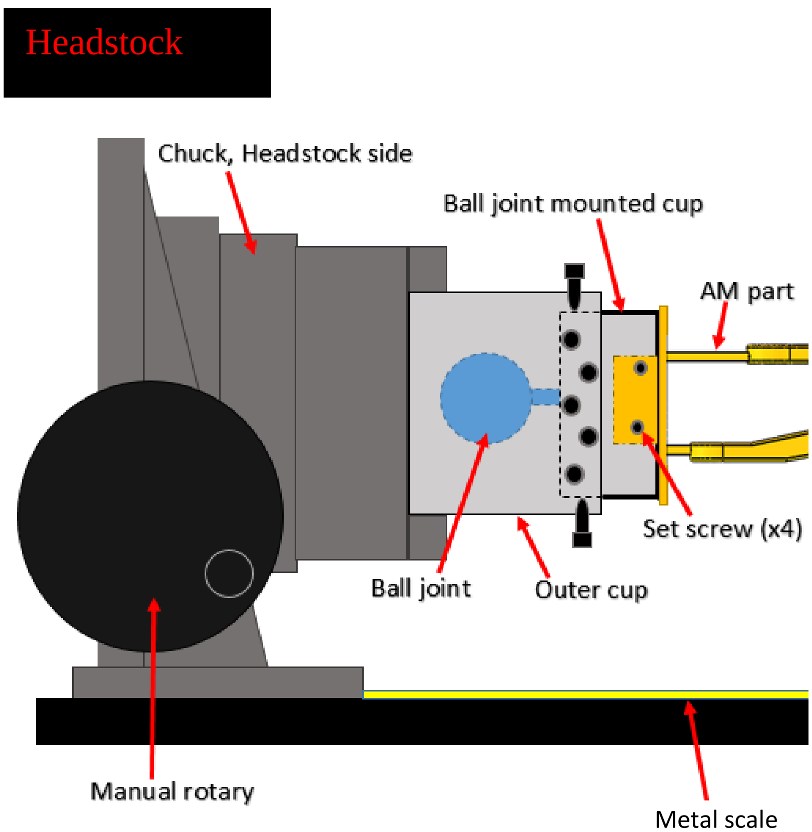


Figure 22. *Headstock schematic*

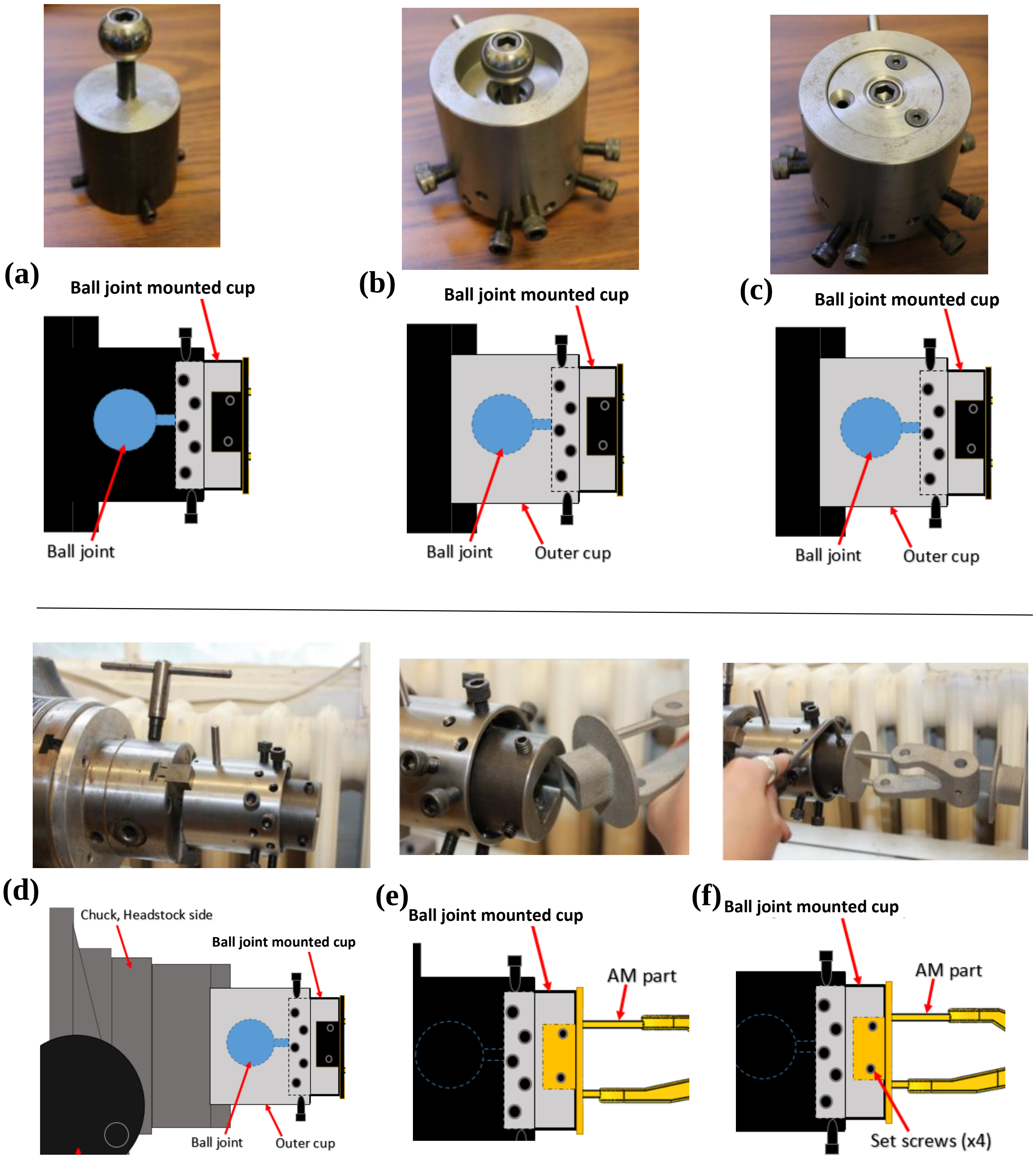


Figure 23. *Assembly overview for headstock side; (a) the ball joint is connected to the ball joint mounted cup by a threaded cylinder, but before the two are connected, (b) the outer cup is placed over the top of the ball mounted cup so that the hole in the outer cup overlaps the hole of the ball mounted cup. Then, (c) a lid is placed on top of the ball joint and secured with screws. (d) This assembly is placed in the chuck so that the outer cup is coaxial with the chuck. It is then tightened with a chuck key. (e) The AM part end mates with the ball joint mounted cup and (f) the set screws are tightened.*

<u>Tailstock</u>

The tail stock side (*Figure* 24) also includes the outer cup that is mounted coaxially into the chuck and secured with a chuck key (*Figure 25a*). The inner cup has a part collet feature that mates with the other square end of the AM part (*Figure 25b*). This inner cup is secured within the outer cup by the cylinder screws and placed above the cross bar (*Figure 25c*). The inner cup is secured in between metal rods that are manipulated by side thumb screws of the vertical adjuster assembly to restrict horizontal movement (*Figure 25d*).

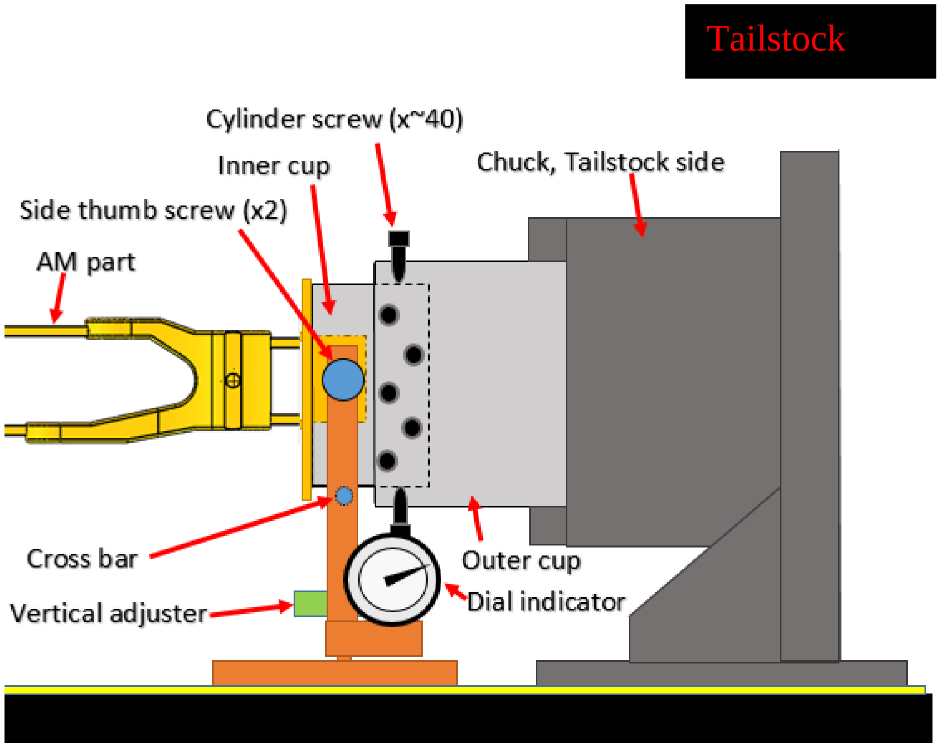


Figure 24. *Tailstock schematic*

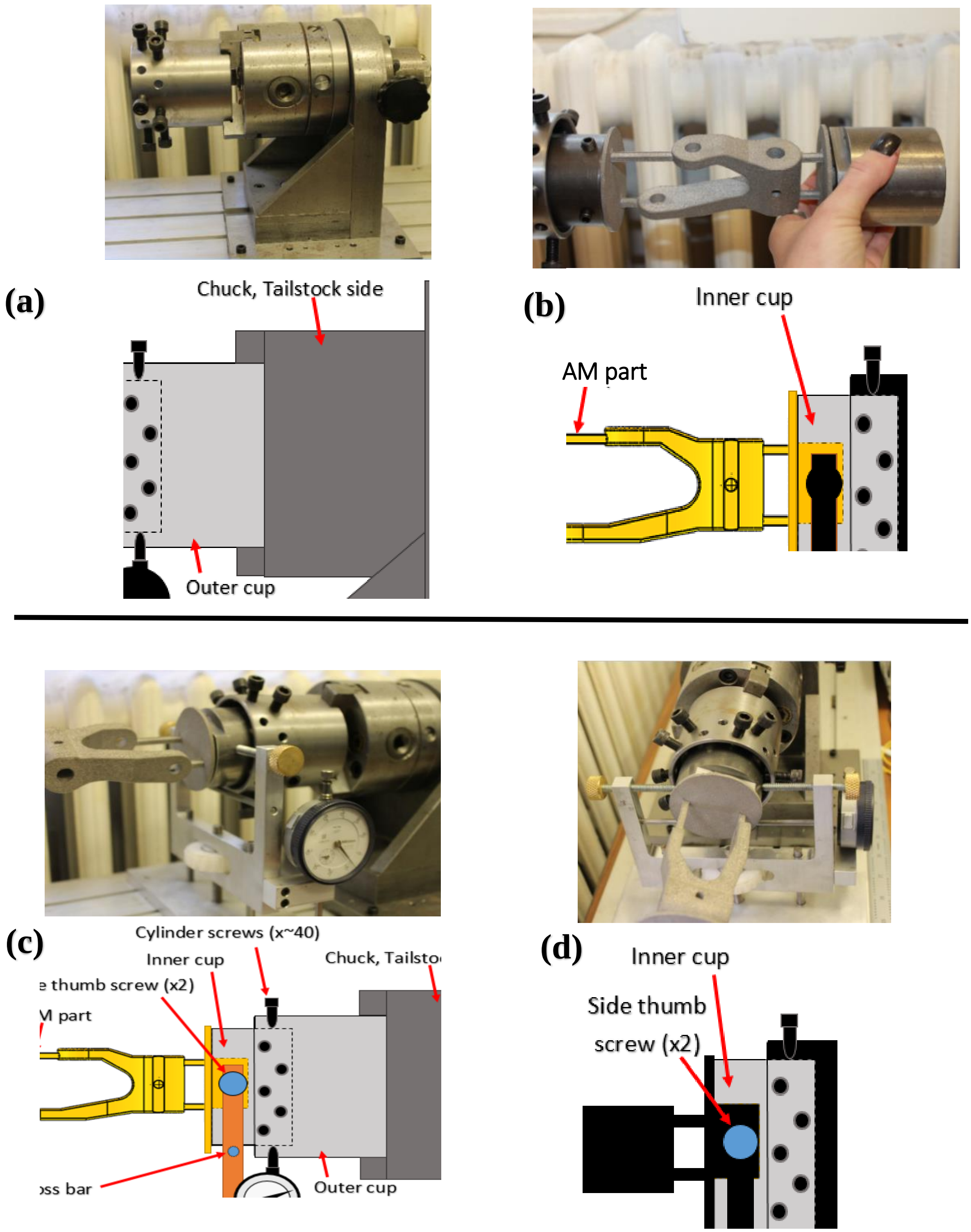


Figure 25. *Assembly overview for tailstock side; (a) The outer cup that is mounted coaxially into the chuck. (b) The inner cup has a part collet feature as well that mates with the other square end of the AM part. (c) The inner cup is secured within the outer cup by the cylinder screws and placed above the cross bar. (d) The inner cup is placed in between the metals rods that are manipulated by side thumb screws of the vertical adjuster assembly.*

3.4 Part Location and Orientation Deviation

Due to inaccuracies in printing, the actual printed part sits at a position and orientation in the CNC machine that is slightly different from the ideal CAD model. Thus, combining the AM and SM processes can make locating a part difficult. Thus, there is the potential for considerable discrepancy between the ideal CNC-RP setup and the realistic results (*Figure 26*): This discrepancy can be caused by four main factors: (1) surface roughness of the AM part,

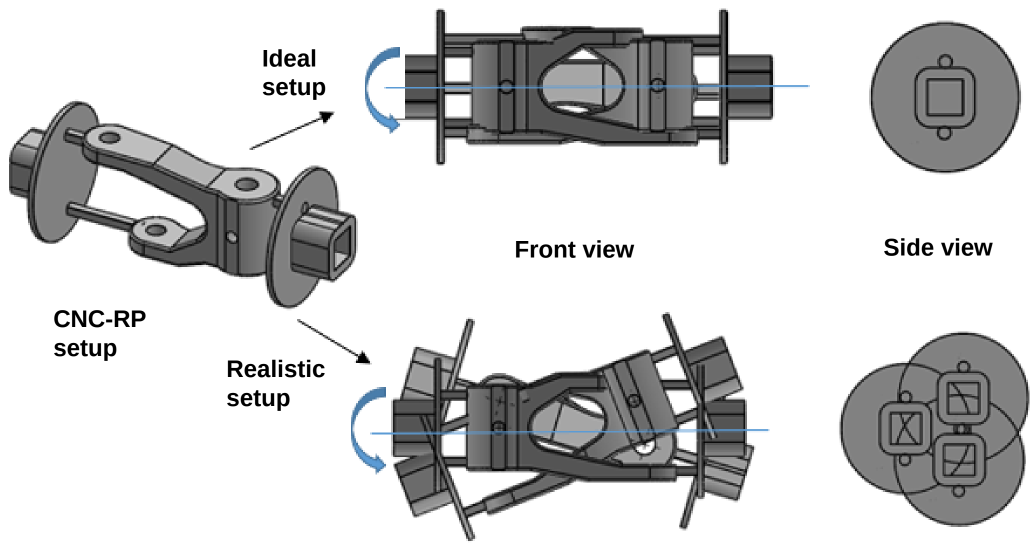


Figure 26. *Discrepancy between ideal and realistic AM part setup in fixture*

(2) geometric accuracy of the part collet features, (3) coaxial misalignment of the smaller cups within the outer cups and (4) geometric inaccuracy of the AM part's ends. The proceeding subsections give a quick overview of these factors and their impact on the successul integration of a subtractive finishing phase.

<u>Surface Roughness</u>

For the desired CNC-RP setup, both the centers of the square ends are coaxial to the axis of rotation in the machine. However, as a result of the inherent surface roughness derived from the metal additive processes (*Figure* 27), the axes can deviate from the desired orientation.

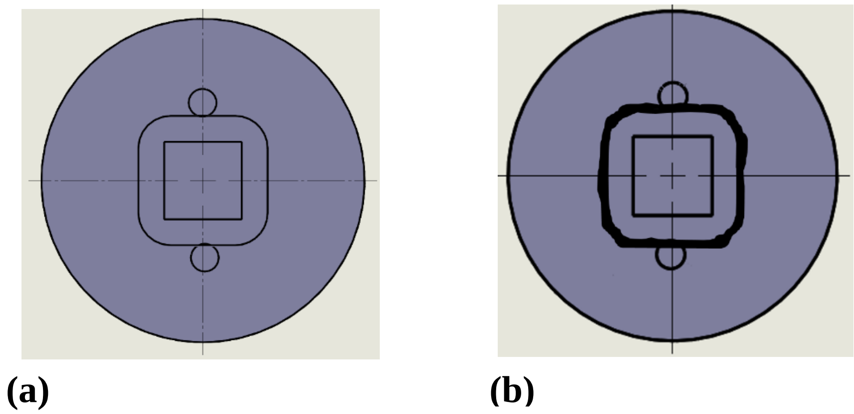


Figure 27. *Surface roughness on square ends that cause part orientation issues; (a) Ideal surface finish (b) Realistic surface finish*

Part mating with fixture cups

For both the inner and ball joint mounted cups, there is at least some extra space along the inner walls to allow easy insertion of the ends of the AM part. Since AM parts have some accuracy error, the ends are not the same size and do not have the same surface roughness from part to part, so this extra space and related part alignment vary in magnitude from part to part as well (*Figure 28*). Additionally, the force from set screws on the ball joint mounted cup can cause the part to deviate from nominal.

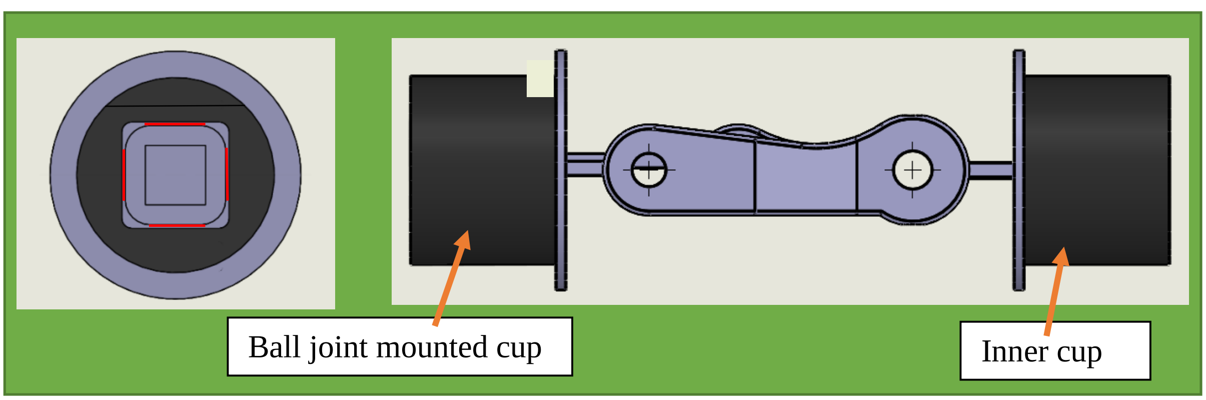


Figure 28. *Cup mating allowance*

Coaxial alignment of cups

In the case of an ideal setup for the fixture, both the centers of the outer cups are coaxial to the axes of the smaller cups within (*Figure 29b*). However, due to the inherent variation that derives from the manual tightening of the cylinder screws, the ideal coaxial orientation may not be attained (*Figure 29c*).

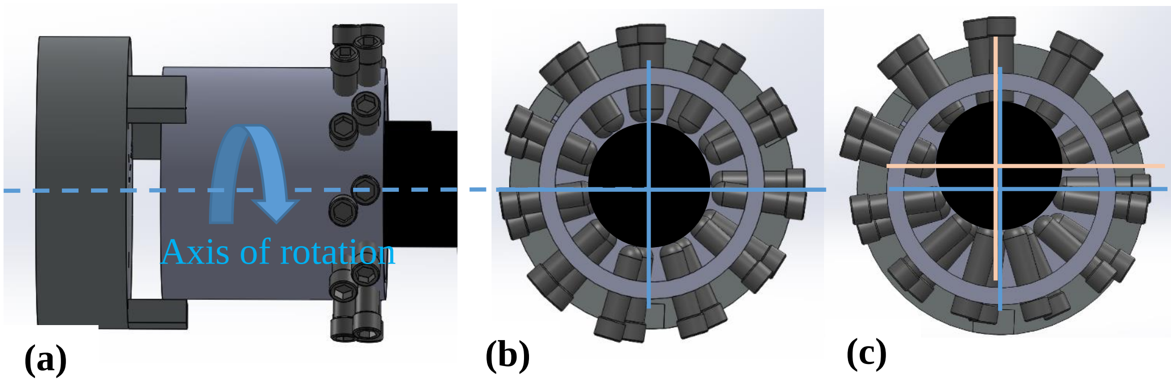


Figure 29. *Coaxial relationship of fixture cups; (a) With respect to the CNC machine's axis of rotation, (b) the outer cups ideally coaxially align with their respective smaller cups but (c) the axes of the outer cup and smaller cup realistically do not align.*

Inconsistent shrinkage throughout part

Based on the processing nature of most metal AM processes, shrinkage occurs because of the rapid heating and solidification of each layer. Both the global and local shrinkage variation through the cross sections of the part generate internal residual stresses. If the induced residual stress is excessive, the part will warp. Warping can lead to part distortion and bad junctions between supports and components (*Figure 30*) that can critically affect the part geometry.

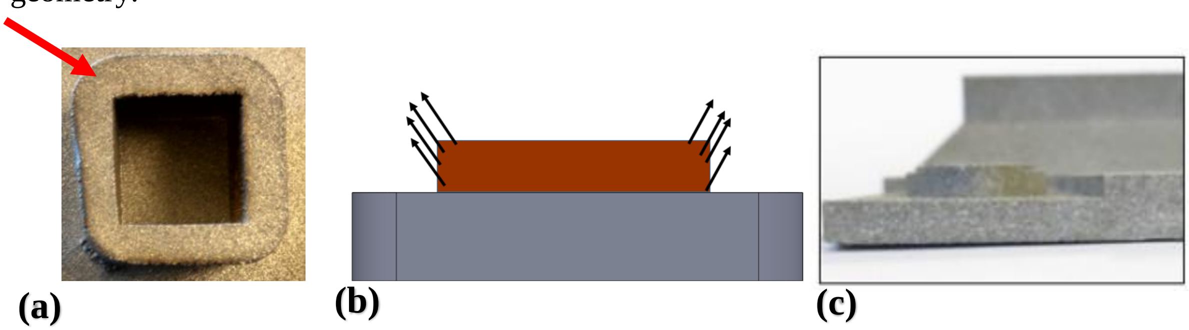


Figure 30. *Effect of non-uniform shrinkage on build part; (a) Non-uniform shrinkage can cause variability such as unevenly sized corners (larger rounded corner highlighted by the red arrow). (b) Shrinkage generates stress; and this stress may try to break through the edges of the build part and induce warping. (c) Part distortion due to warping [74]*

This shrinkage will not cause deformation if it is uniform throughout the part. However, uniform shrinkage is unlikely because of the many material and process variables that that interact with each other, such as molecular and fiber orientations, part cooling, and feature geometry. Research performed on a certain metal alloy helps in understanding the material properties and characteristics to control any thermal stress. While a precise estimate of shrinkage during AM cannot be determined, by considering potential factors such as material grade, build orientation, and cross section of the geometry, a reasonable approximation of part and feature shrinkage can be delivered. This information can be used to determine the extra material allowance required.

3.5 Part Location and Orientation Correction

Even though there are location and orientation deviations, these obstacles can be overcome by determining the position vector of the part and reorienting the part to align the part's new position vector with the CNC machine's axis of rotation. The initial position vector is created by scanning the part and fixture at different orientations and merging these scans into one three-dimensional representation of the system using a software called DASH that has been newly created for the purpose of this hybrid process. With these scans and the part file, the software can compute how much the part deviates linearly and rotationally from the CNC machine's axis of rotation, which also correspond to the necessary transformations in all five dimensions (x, y, z, a, and b). Linear translation deviations (x, y, and z) can be numerically compensated for in the CNC code before machining, so there is no need to physically adjust for them during this fixture stage, but the rotational deviations (a and b) need to be fixed in order for proper machining to occur. We can correct these issues by physically executing two correctional rotations on the fixture created for this thesis.

Describing the architecture of fixture assembly with respect to important dimensions helps define these rotations (*Figure 31*):

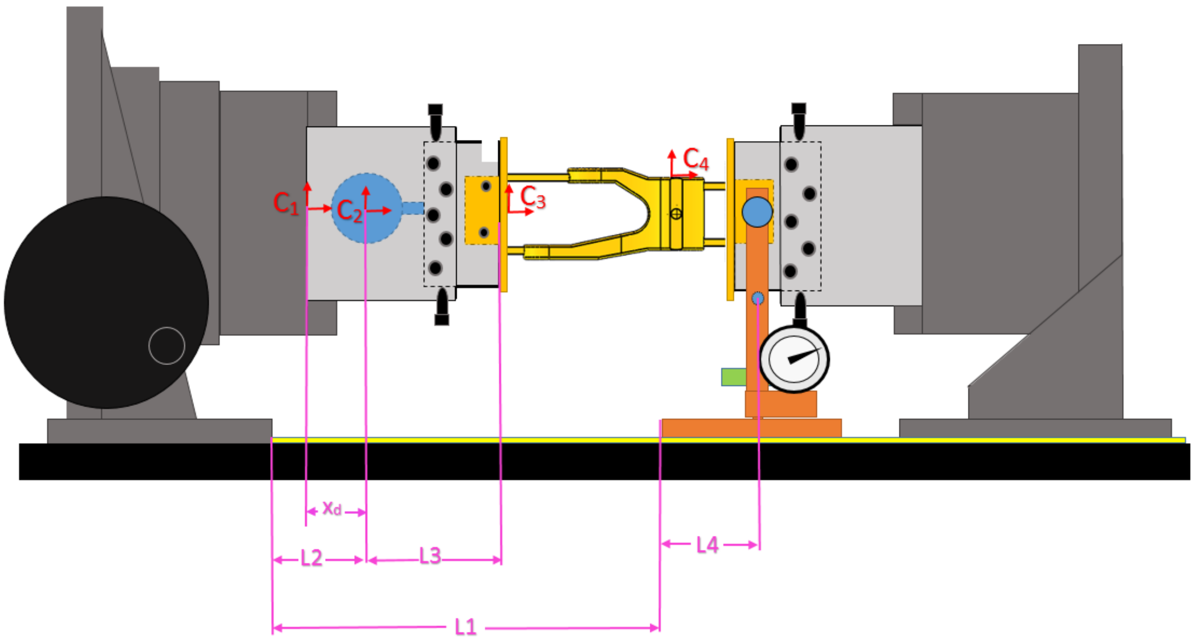


Figure 31. *Fixture assembly schematic with important dimensions*

L1= horizontal distance between the start of the metal scale and the corner of the vertical adjuster assembly) (*Figure 32*)
L2= horizontal distance between the center of the ball joint and the beginning of the metal scale
L3= horizontal distance between the center of the ball joint and the inner face of the ball joint mounted cup
L4= horizontal distance between the corner of the vertical adjuster assembly and the center of the cross bar
C_1= CNC work coordinate system for hybrid project
C_2= Fixture work coordinate system, based on the ball joint center
C_3= Work coordinate system, originates on inner face of AM part disk end
C_4= Part work coordinate system with respect to Mastercam software (this location is arbitrary and changes by part design)
x_d= horizontal distance from face center of headstock chuck to center of ball joint

L1 is determined by a metal scale built into the fixture's hardware (units are in inches and scale resolution is 1/64 inch) (*Figure* 32) and used for the B-axis rotation, which is discussed further in section 3.6. L2, L3, L4 and x_d are assumed to be fixed and known based on pre-determined measurements for this thesis:

L2= 73.95mm
L3= 91.00mm
L4= 38.05mm
x_d= 19.96mm

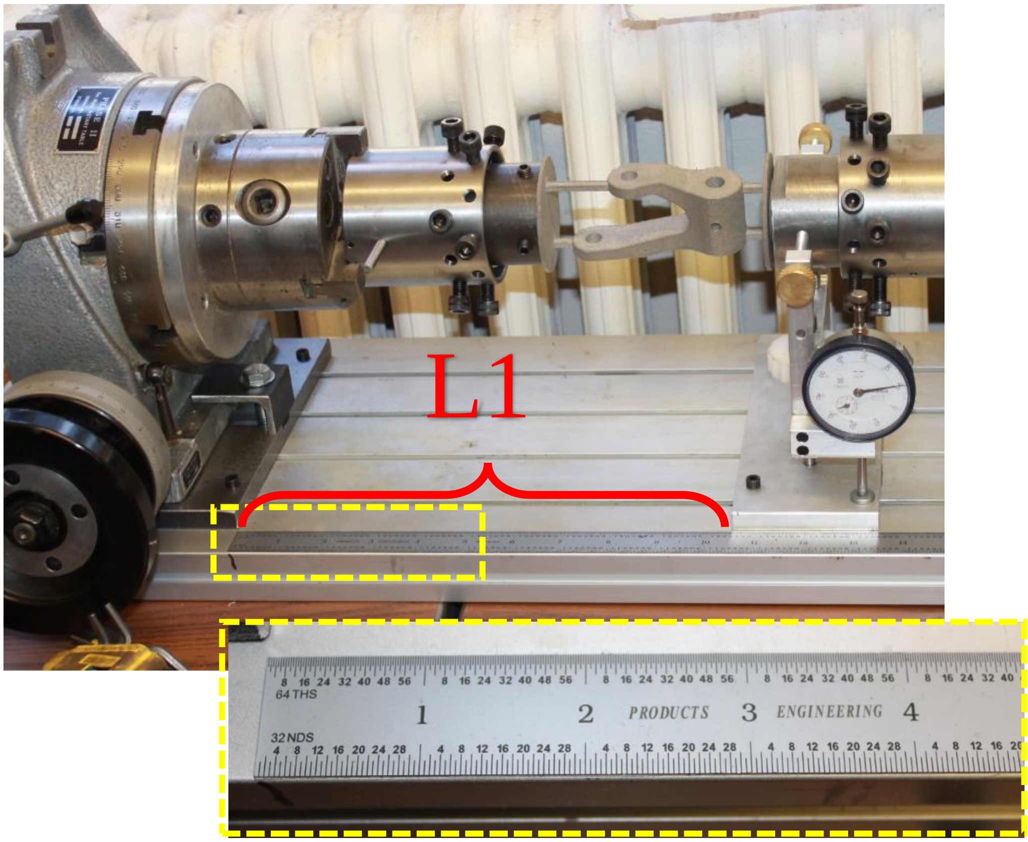


Figure 32. *Distance L1 illustration; Metal scale used to determine distance from corner of manual rotary to corner of vertical adjuster assembly (scale resolution: 1/64 inch)*

Currently, the CNC-RP coordinate system (C_1) serves as the software default coordinate system. Thus, the position vector created with the scans are made with respect to this coordinate system. However, in order for the rotations to occur with the ball joint as the origin, this information needs to be transferred from the CNC-RP coordinate system to the fixture coordinate system (C_2). The next subsection presents the transformation matrices derived in order to do this.

<u>Transformation models</u>

Figure 33 displays the CNC-RP coordinate system (C_1) and the fixture coordinate system (C_2) within the fixture assembly. C_1 originates on the center of the inner headstock chuck face. The chuck and the outer cup should be coaxial, which means that the only

transform that should be calculated to transition from C_1 to C_2 is a linear translation along the positive X-axis (x_d).

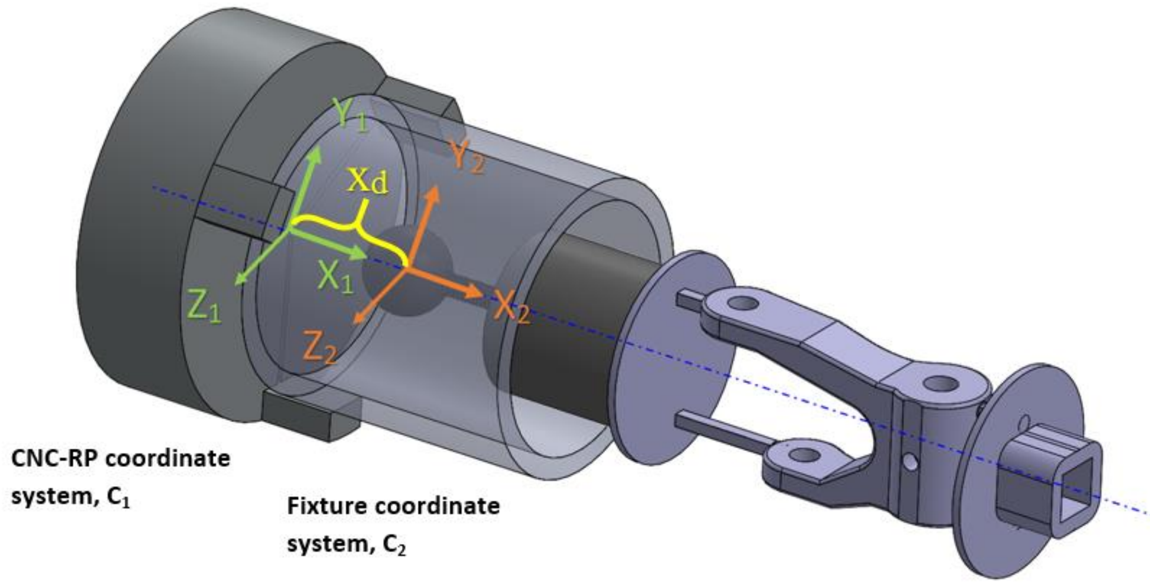


Figure 33. *CNC-RP and fixture coordinate systems*

For this example, since the value of x_d is 19.96mm, the translation transformation matrix to move to the fixture coordinate system (x_2, y_2, z_2) from the CNC-RP coordinate system (x_1, y_1, z_1) is given as:

$$[x_2 \quad y_2 \quad z_2 \quad 1]^T = \begin{bmatrix} 1 & 0 & 0 & 19.96 \\ 0 & 1 & 0 & y_d \\ 0 & 0 & 1 & z_d \\ 0 & 0 & 0 & 1 \end{bmatrix} * \begin{bmatrix} x_1 \\ y_1 \\ z_1 \\ 1 \end{bmatrix} \quad \textbf{(3.1)}$$

And can be simplified to:

$$x_2 = x_1 + 19.96 \quad \textbf{(3.2)}$$

$$y_2 = y_1 + y_d \quad \textbf{(3.3)}$$

$$z_2 = z_1 + z_d \quad \textbf{(3.4)}$$

Now, the required A-axis and B-axis rotations are with respect to the fixture coordinate system. Thus, the DASH software outputs the required rotations using the ball joint as its origin. A B-axis rotation (or rotation of a point, vector, or general entity about the Y-axis) (*Figure* 34) can be computed:

B-axis rotation: P*= [Ry] P_0 **(3.5)**

Where P*= new position vector

P_0 = original position vector

[Ry]= rotation matrix between vectors about the Y-axis

Or, in matrix form, the B-axis rotation is computed:

$$[x^* \quad y^* \quad z^*] = \begin{bmatrix} \cos\theta_y & 0 & \sin\theta_y \\ 0 & 1 & 0 \\ -\sin\theta_y & 0 & \cos\theta_y \end{bmatrix} * \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix}$$

(3.6)

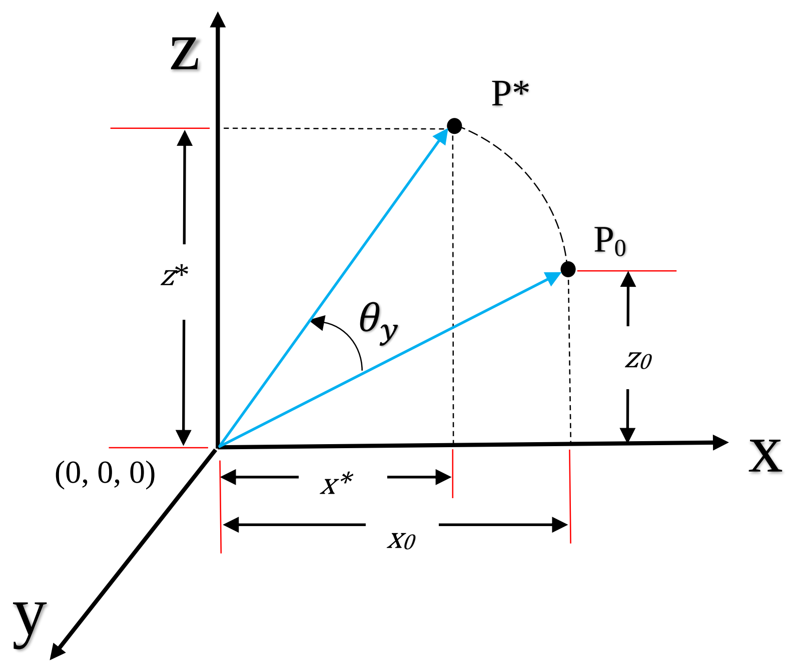


Figure 34. *Magnitude of a B-axis rotation is the rotational angle about the Y-axis*

Figure 35 represents the physical rotation that occurs upon determining the degree of this rotation (θ_y). The inner cup rests on a cross bar and the rotation occurs when this cross moves up or down. For this rotation, the cylinder screws are loosened and the inner cup is restrained on either side by metal rods that are manipulated by side thumb screws.

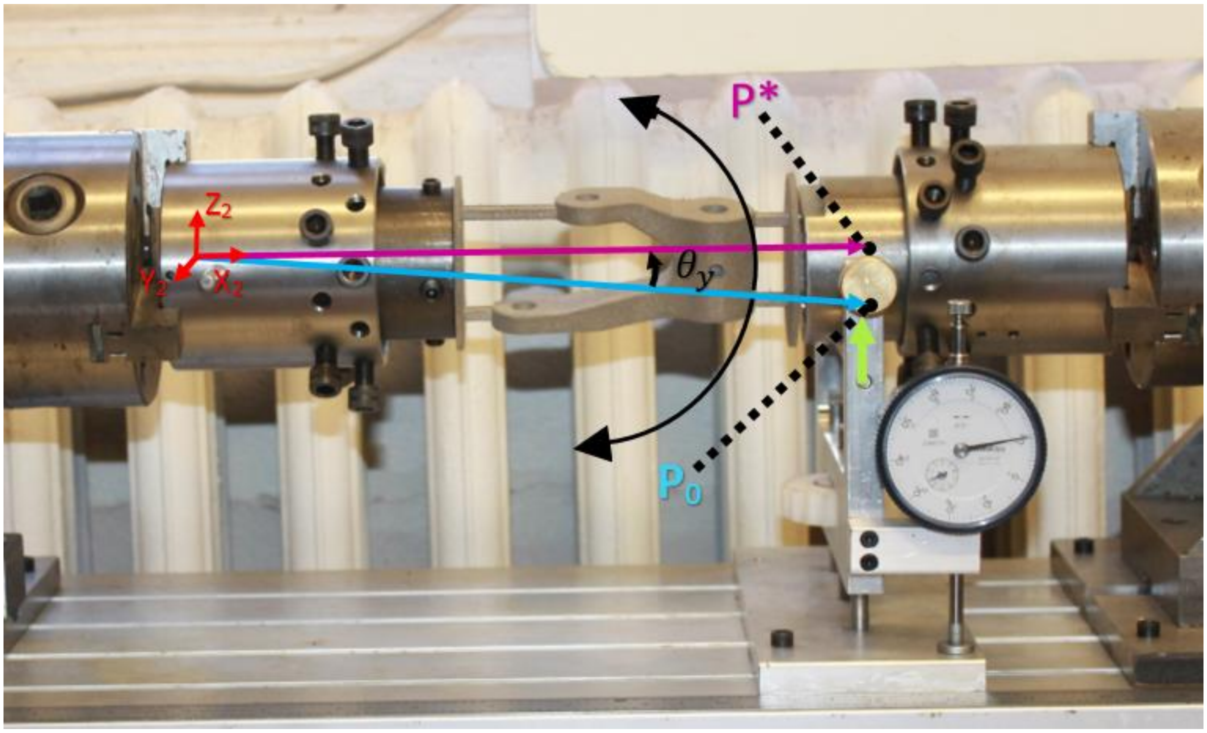


Figure 35. *B-axis rotation illustration on physical setup;* P_0 *represents the original position vector of the printed AM part that originates on the center of the ball joint. The cross bar either lifts or lowers the inner cup (that contains the part) a finite distance (green arrow) so that the part is now at a new position vector P*; with respect to this illustration, the inner cup is lifted.*

The cross bar is controlled by a vertical adjuster that is rotated manually (*Figure 36*). The dial indicator is the scaling tool used to control the specified magnitude of this rotation, which is computed using a VBA program that is discussed in section 3.6 (resolution of dial indicator: 0.001”).

Due to connectivity of the fixture assembly, the inner cup follows an arc path centered on the ball joint. Thus, as the cross bar moves either directly up or down, the inner cup slides on the cross bar to follow that arc (*Figure 37*).

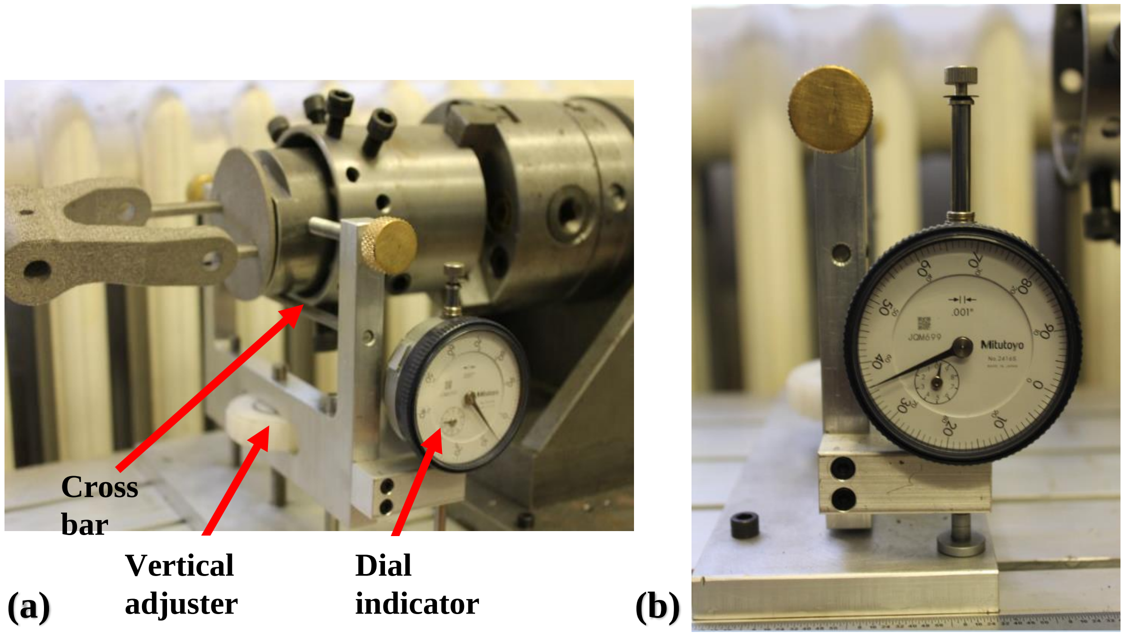


Figure 36. *Vertical adjuster assembly for B-axis rotation; (a) The cross bar is controlled by the vertical adjuster while the dial indicator is used as a measuring tool for this rotation. (b) Front view of dial indicator (resolution of dial indicator: 0.001")*

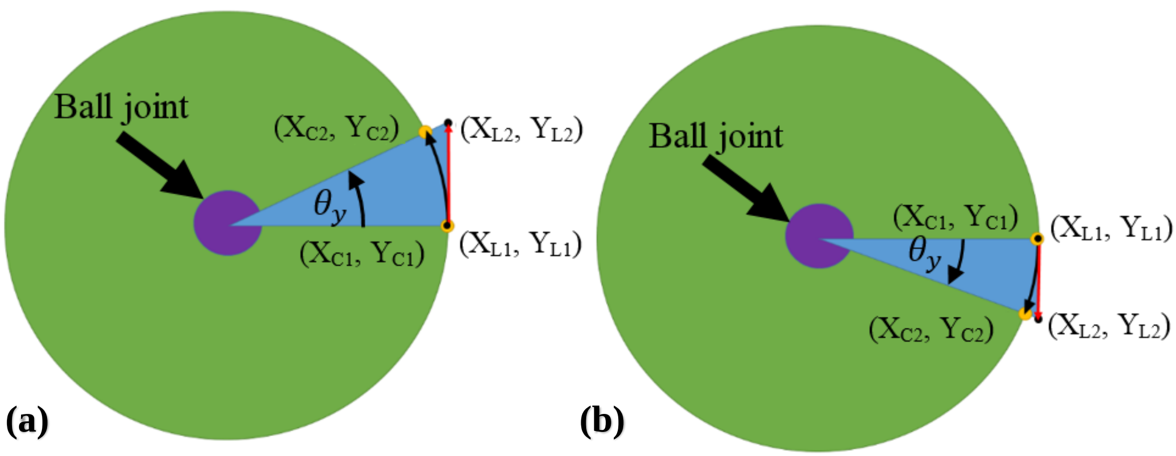


Figure 37. *Cross bar vs. inner cup path for B-axis rotation; The point on the cross bar that contacts the inner cup (X_{L1}, Y_{L1}) moves along a linear path (red) to final position (X_{L2}, Y_{L2}). Concurrently, the point on the inner cup that contacts the cross bar (X_{C1}, Y_{C1}) moves along an arced path (black) to final position (X_{C2}, Y_{C2}). (a) Illustration of upward movement of the cross bar (b) Illustration of downward movement of the cross bar*

The initial position (X_{C1}, Y_{C1}) reflects the initial coordinate of the point on the inner cup that contacts the cross bar; this point moves along an arced path during the required rotation to a final position (X_{C2}, Y_{C2}). Similarly, (X_{L1}, Y_{L1}) is the initial coordinate of the point on the cross bar that contacts the inner cup; this point transitions to a final position (X_{C2}, Y_{C2}), but this path of motion is linear.

Upon successful completion of the B-axis rotation, the A-axis rotation (or rotation of a point, vector, or general entity about the X-axis) (*Figure 38*) should be employed. Its computation is similar to that of the B-axis rotation:

A-axis rotation: $P^* = [Rx]\, P_0$ **(3.7)**

Where P^*= new position vector

P_0 = original position vector

[Rx]= point rotation matrix between vectors about the X-axis

Or, in matrix form, the A-axis rotation is computed:

$$[x^* \quad y^* \quad z^*] = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{bmatrix} * \begin{bmatrix} x_0 \\ y_0 \\ z_0 \end{bmatrix} \quad \textbf{(3.8)}$$

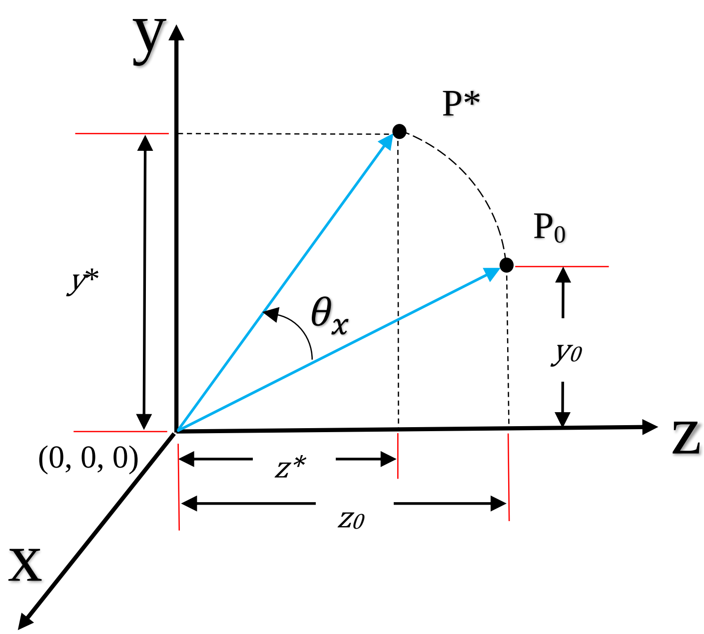


Figure 38. *Magnitude of an A-axis rotation is the rotational angle about the X-axis*

Figure 39 represents the physical rotation that occurs upon determining the degree of this rotation. The DASH software outputs the value θ_x, which is performed manually using the manual rotary. The scale on the handle of the rotary is used to control the specified magnitude of this rotation (manual rotary scale resolution: 1/60 degree), which is computed in an Excel VBA program that is also discussed in the following section.

3.6 Software

A Faro Arm is used to take scans of the part and fixture (including the chuck) at different orientations. The scanning information is in the form of discrete coordinate values (x, y, z) and stored as a point cloud. These scans are then merged together into one large scan through the localization (harvesting) software, DASH, to create a large 3D model of the setup, including the part and coordinate systems.

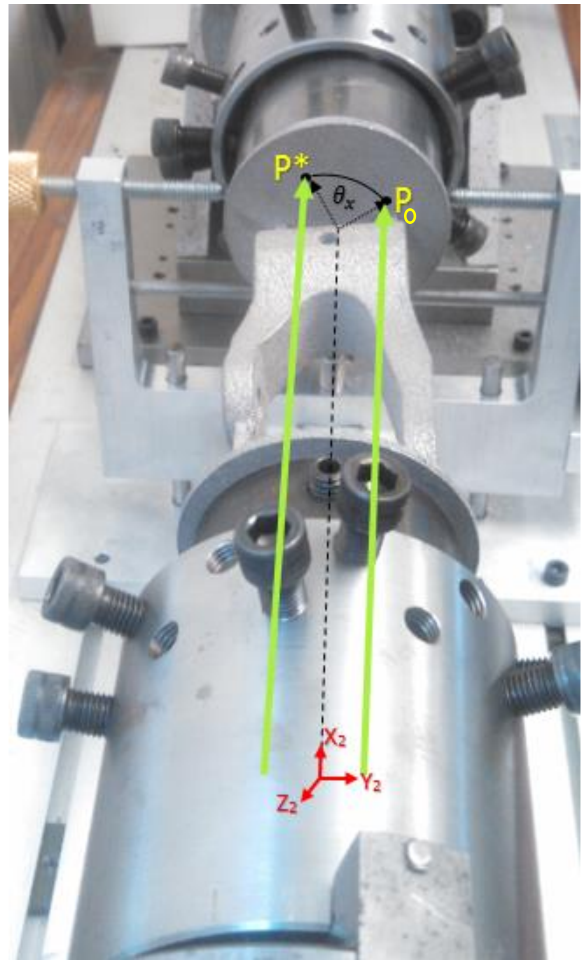


Figure 39. *A-axis rotation on physical setup; P_0 represents the original position vector of the printed AM part that originates from the center of the ball joint. The manual rotary is turned a finite distance either clockwise or counter clockwise so that the part is now at a new position vector P*.*

Most AM processes use an STL file format, which is a triangulated mesh of each independent feature to construct the desired part geometry, but this hybrid project uses an AMF (additive manufacturing file) format that includes more information such as color to indicate critical features and feature tolerances. This model is then input into the same file as the scanned model with respect to the fixture coordinate system (C_2). At this point, a localization algorithm through the DASH software computes the transformation matrices physically required to move the AMF model to a “best fit” position within the scanned model using the discrete coordinate values of each model and outputs the final dimensional deviations as discrete values (x, y, z, a, b) (*Figure 40*). The x, y, and z-axis deviations can be compensated for later in the CNC computer for the machining operation. However, deviations in the A-axis and B-axis effect orientation and, ultimately, part accuracy, so these deviations need to be physically corrected by reorienting the part back to nominal (or at least to within tolerance) via the fixture as discussed previously.

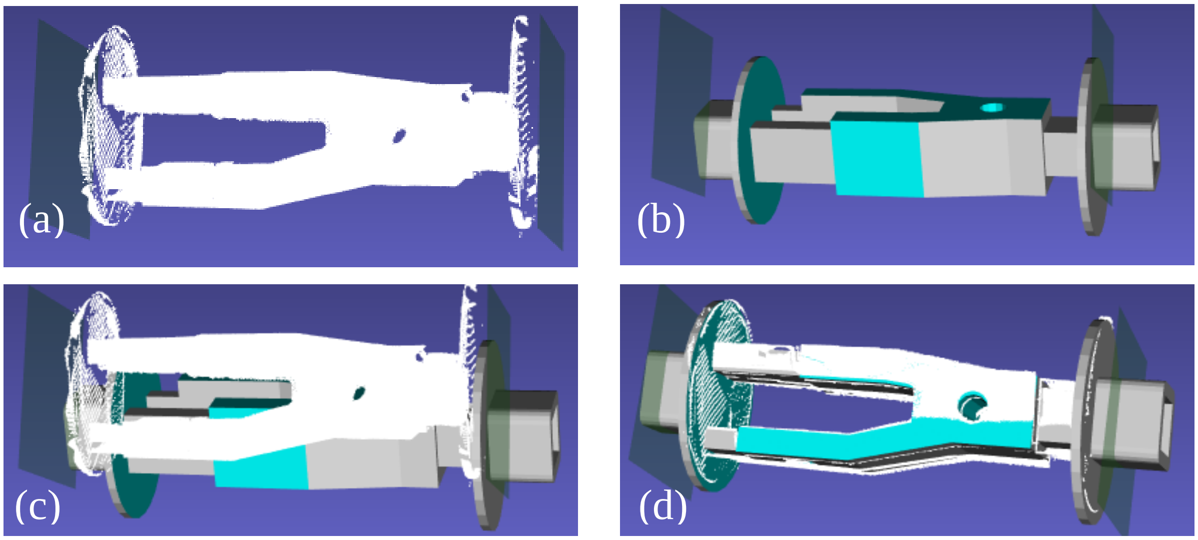


Figure 40. *Matching the AMF file with the scanned model; (a) Scanned model (point cloud) (b) AMF model (c)Input both models in the DASH software then (d) align the two models in the software using a localization algorithm, which also outputs the A-axis and B-axis deviations required by fixture assembly.*

The DASH software outputs the discrete values, but a separate interface is required to define the finite magnitude and direction with which to rotate the vertical adjuster and manual rotary. The intermediate graphic user interface (GUI) for this thesis was created in Excel VBA (Visual Basic for Applications) (*Figure 41*).

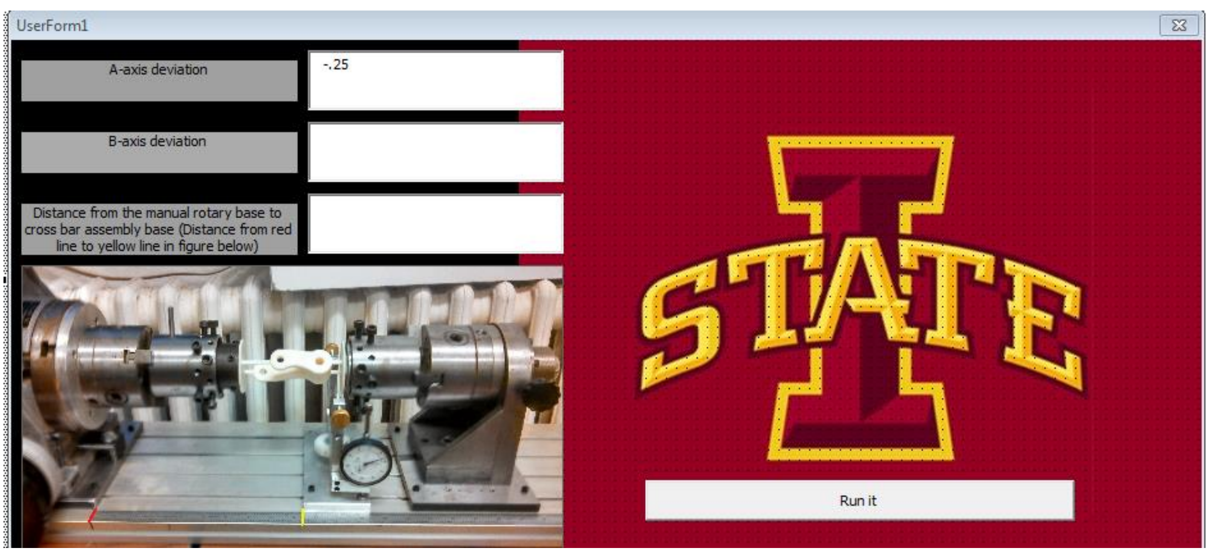


Figure 41. *Excel VBA GUI*

This user interface requests the A-axis and B-axis outputs from the DASH software, as well as the L1 distance that is ultimately linked to the length of the printed part (the length of the part is an important parameter that determines the finite distance the cross bar is raised or lowered). The output from this GUI then outputs the rotational direction (clockwise or counterclockwise) and magnitude (in degrees and dashes on the manual rotary and dial indicator for the A-axis rotation and B-axis rotation, respectively). Refer to Appendix A for Excel VBA hard code.

3.7 Other Fixture Application Requirements

This fixture fulfills other requirements for a successful system in the hybrid application that includes: (1) rigidity to withstand forces of machining and (2) a seamless transition between processes. The following section provides further detail.

Rigidity to withstand forces of machining

The stages of CNC-RP (along with the associated machining parameters, tooling, and material removal rate) can be divided into: (1) ‘hogging’, which uses a larger cutting tool for a roughing operation to reduce stock to a rough form of the part, (2) ‘roughing’, in which features are island milled to reduce the part to near-net dimensions and (3) ‘finishing’, where features are machined with a smaller cutting tool to achieve desired dimensions. While all three stages have proved successful for CNC-RP, the near-net additive processes within a hybrid process only require integration with the finishing CNC-RP stage. Thus, machining forces are low and, since the fixture is mostly built out of high strength steel, the fixturing elements are significantly stronger than the sacrificial supports; so if there is any deflection, it is highly unlikely this deflection occurs in the fixture.

Additionally, it has been assumed that, since the supports in the CNC-RP system have a much smaller cross section than the part itself, deflection of the part is the result of the deflection of the small sacrificial. During the machining process, two general types of deflection can occur: bending and torsion. Total deflection is quite small and torsion (angle of twist) makes up about 80% of the total deflection [12] (*Figure 42*). Thus, it is assumed that the sacrificial supports can twist but the part is rigid.

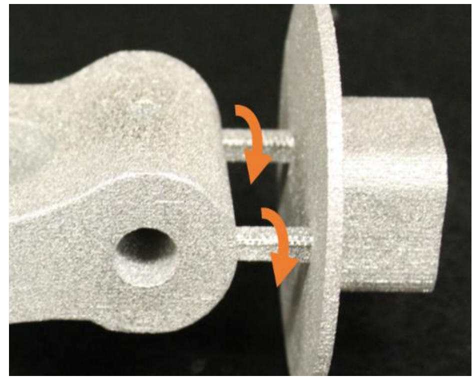


Figure 42. *Sacrificial support deflection due to torsion*

Seamless transition between processes

An important attribute of a hybrid process is establishment of a fixed coordinate system to seamlessly transition between additive and subtractive operations. *Figure 43* models the physical system and relationship between the different systems used including the CNC-RP coordinate system, C_1 (x_1, y_1, z_1), the fixture coordinate system, C_2 (x_2, y_2, z_2), and the CNC machine tool coordinate system, C_0 (x_0, y_0, z_0). The work coordinate system, C_3 (x_3, y_3, z_3), is created with respect to the inner face of the AM part disk and the part coordinate system, C_4 (x_4, y_4, z_4), is arbitrary and changes by part design.

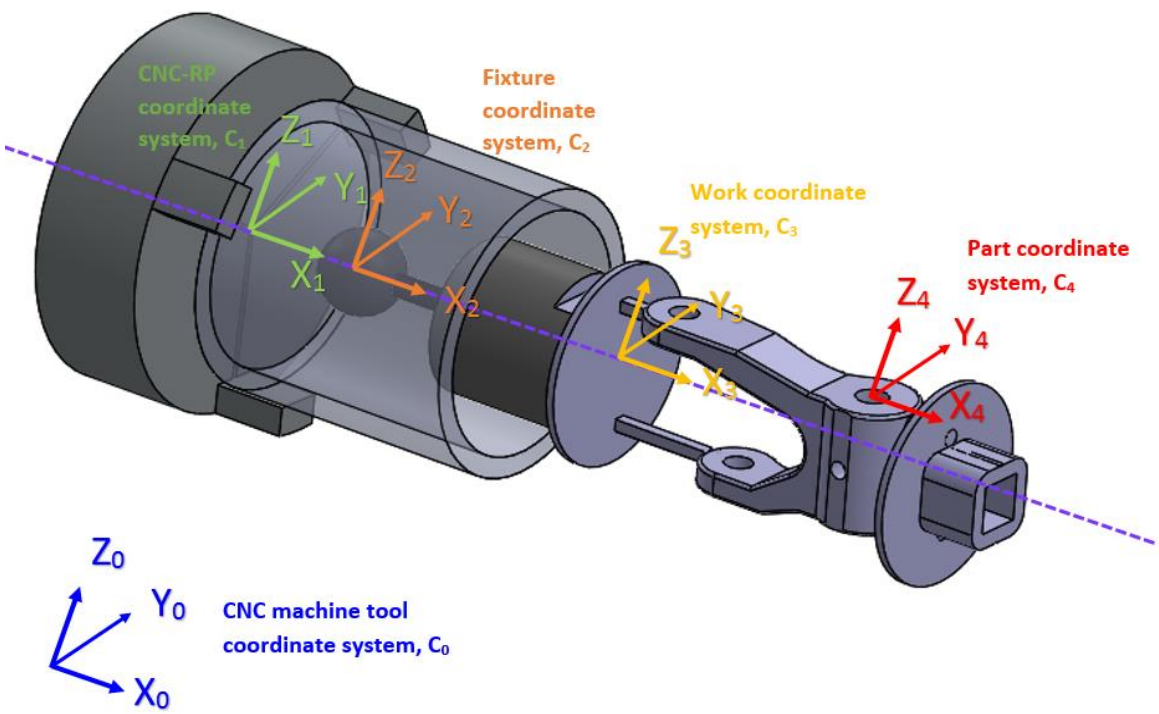


Figure 43. *Hybrid process coordinate systems*

The locations of part features are linked to the part coordinate system, C_4. The part coordinate system relates to the CNC machine tool coordinate system, C_0 (x_0,y_0,z_0), through a series of linkage transformations: CNC machine tool coordinate system→CNC-RP coordinate system→Fixture coordinate system→Work coordinate system→Part coordinate system→ part features. To relate C_3 to C_0, flat surfaces are incorporated in the fixture design. A flat on the ball joint mounted cup is used to establish 0º for the rotational axis A; and the inner face of the part end disk is used to establish x_3=0 (*Figure 44*).

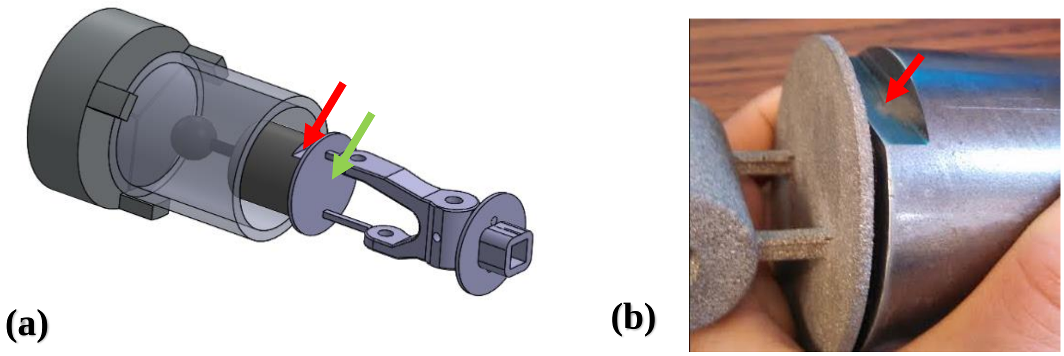


Figure 44. *Flat surfaces employed to align part with machine axis; (a) The red arrow highlights the flat in the ball joint mounted cup (horizontal flat parallel to the X, Y plane) and the green arrow highlights the disk face (for x_3=0) while (b) presents a close up of the same flat (highlighted by red arrow).*

In addition, a device has been designed to transfer the fixture and AM part assembly from the offline manual rotary system to the CNC machine. This device is designed to maintain the feature relationships of the fixture and AM part (*Figure 45*) and to adjust to different part lengths.

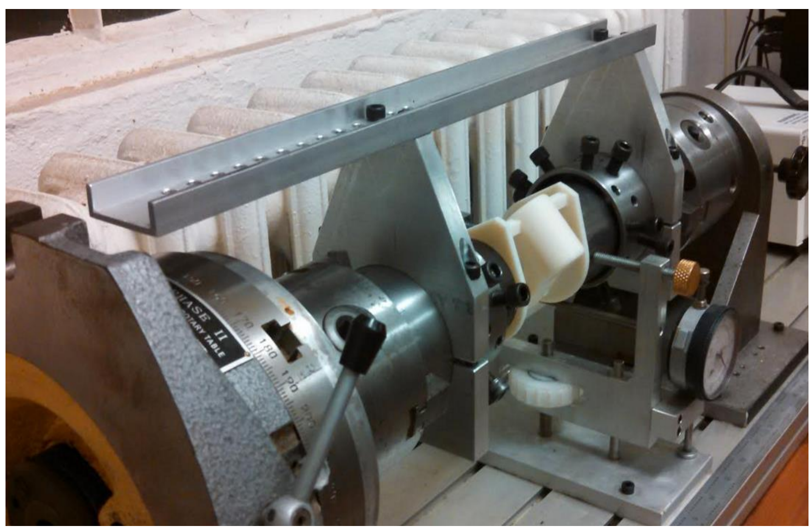


Figure 45. *Hardware carrying device*

3.8 Potential Sources of Error

Ideally, the implementation of this method proves zero deviation after the rotations are made, but there are sources of error (both systematic and random) that contribute to this deviation and must be considered. These sources of error can be categorized under measurement error and adjustment error:

$$\boldsymbol{Deviation = \varepsilon_{measurement} + \varepsilon_{adjustment}} \quad \textbf{(3.9)}$$

Where $\boldsymbol{\varepsilon_{measurement}}$ is the error associated with defining deviation and $\boldsymbol{\varepsilon_{adjustment}}$ is the error associated with resolving deviation. Causes of measurement error include but are not limited to:

- Varying output values derived from the software algorithm based on the number of surface points collected, for example
- Gear mesh on the indexer including compliance based on how tight the mesh is and gear misalignment, for example
- Thread size of the vertical adjuster, which has a fine pitch, but there still exists some inherent error
- Coaxiality of the chuck jaws, which effects initial positioning registration of the part and both rotations (B-axis rotations are more affected by this than the A-axis rotations)
- Inaccuracies of the dial indicator
- Parallax effect for accurate readings on the manual rotary, metal scale and the dial indicator
- Scanning inaccuracies, which also includes inaccuracies caused by the scanning algorithm, the manual movement of Faro Arm (distance, angle, etc.), and the approximation of a part’s surface with facets and a finite number of data points

Causes of adjustment error include but are not limited to:

- Gear mesh on indexer including compliance based on the number of teeth per gear and gear backlash, for example
- Thread size of the vertical adjuster, which has a fine pitch, but there still exists some inherent error
- Inherent error with manual adjustment
- Parallax effect for accurate readings on the manual rotary, metal scale and the dial indicator

The exact magnitude of each error that contributes to the overall deviation can be difficult to quantify, but attempts at quantifying some of these errors include coaxiality inaccuracies of the chuck jaws and scanning inaccuracies.

To estimate the coaxiality of the sets of chuck jaws (*Figure 46*), a Zeiss DuraMax CMM was used to measure the axes of both sets of chuck jaws using gage blocks to derive a coaxiality measurement for multiple trials (*Figure 47*).

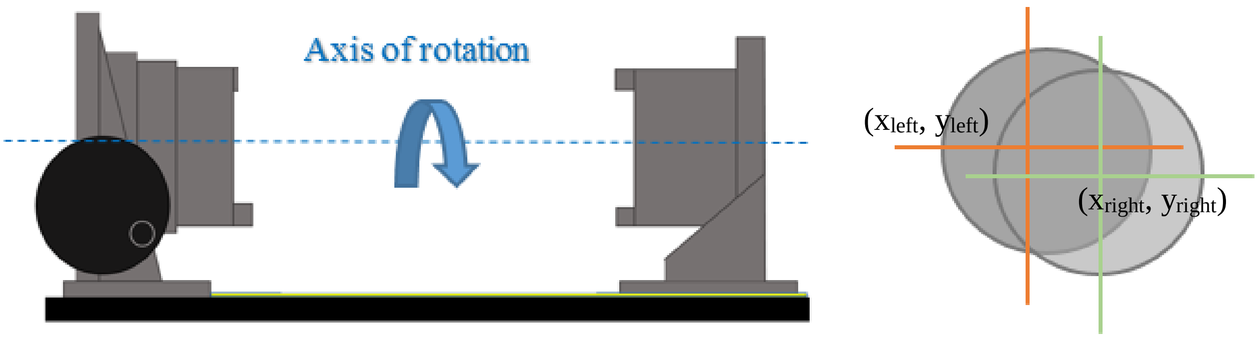


Figure 46. *Coaxiality error of chuck jaws*

To estimate scanning accuracy, multiple measurements of the same angle on an aluminum part were taken. To do this, two faces of the aluminum part (*Figure* 48) were scanned multiple times with the Faro Arm. Then, two planes were extracted from this scanning data using scanning software Geomagic Design X.

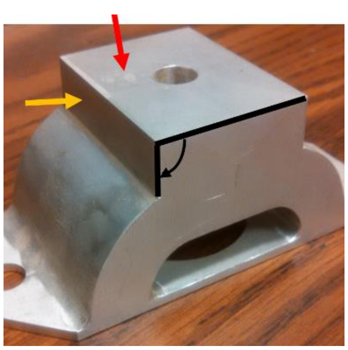


Figure 48. *Angular measurement used to estimate scanning error*

Figure 47. *CMM and gage blocks used to measure coaxiality of chuck jaws*

CHAPTER 4: IMPLEMENTATION, TESTING AND RESULTS

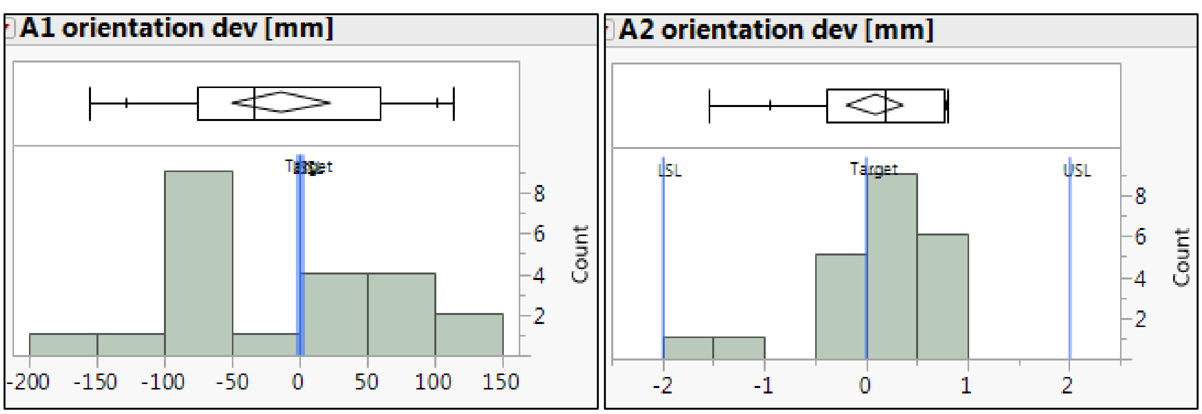
To validate this method, the above described DASH software and associated algorithms that determine the position vectors were implemented and tested on an Intel Core™ i7-2630QM CPU 2.0 GHz PC running Windows 7 with 8.0 GB of RAM. The program accepts the data from the scanning file and associated part AMF file as input to solve the transformational equations. The output from this solution takes the form of rotational angles for the two rotary axes and translational distances in the three linear axes to correct location and orientation deviations. The algorithms to determine the appropriate rotations for the fixture hardware used for this thesis were created using an Excel VBA user interface and tested on an AMD A6-6310 APU with AMD Radeon R4 Graphics 1.8 GHz PC running Windows 8 with 8.0 GB of RAM. This program accepts the A and B rotary axes output from the DASH software as well as the L1 distance and solves the equations to provide output in the form of rotational angles for the two rotary axes to correct orientation deviations.

Twenty-two different scanning trials were used to validate the fixture. To do this, the fixture assembly was initially scanned and, using the Dash software and Excel GUI, rotational angles were determined for both the A-axis and B-axis. Based on the output, orientation corrections were employed as explained in *Chapter 3*. Then, without removing the part from the fixture, the rotational deviations were determined a second time for both the A-axis and the B-axis with the same process.

The following results include data obtained as output from the DASH software both before and after the A- and B-axis deviation corrections as well as the L1 value for each trial. A1 and B1 are respectively used to define the A-axis and B-axis deviations before correction (these values are considered random since there was no controlled method used to initially place the part within the fixture); while A2 and B2 are respectively used to define the A-axis and B-axis deviations after correction. Additionally, the angular deviations were converted from units of degrees to units of millimeters to numerically express the maximum orientation deviation of part features from nominal based on the angular deviation in order to determine if these parts are within the 2mm material allowance. The results for the A-axis deviations are expressed in *Table 2* and *Figure 49*, while the results for the B-axis deviations are expressed in *Table 3* and *Figure 50*.

Table 2. *Results for A-axis rotation*

Trial	L1 [inches]	A1 deviation [degrees]	A1 orientation dev [mm]	A2 deviation [degrees]	A2 orientation dev [mm]
1	10.094	27.3	113.80	0.1	0.38
2	10.125	-14.3	-56.40	0.1	0.39
3	10.063	5.9	22.70	0	0.00
4	10.125	21	84.94	-0.4	-1.54
5	10.094	-17.4	-69.10	0.2	0.77
6	10.313	-20.6	-84.97	0.2	0.79
7	10.125	4	15.47	-0.1	-0.39
8	10.094	-16.8	-66.57	-0.1	-0.38
9	10.281	-34.6	-155.38	0.2	0.79
10	10.391	-14.6	-59.40	0.1	0.40
11	10.406	10.7	43.16	0.2	0.80
12	10.313	9.9	39.45	-0.1	-0.39
13	10.125	-20.2	-81.41	0.1	0.39
14	10.094	22.2	89.98	-0.1	-0.38
15	10.266	25.5	107.25	0.2	0.78
16	10.297	-33.2	-147.66	-0.3	-1.18
17	10.172	-3	-11.66	0.2	0.78
18	10.141	18.9	75.90	0	0.00
19	10.125	13.6	53.53	-0.1	-0.39
20	10.125	-14.3	-56.40	0	0.00
21	10.094	-20.1	-80.69	0	0.00
22	10.313	-18.3	-74.76	0.1	0.39

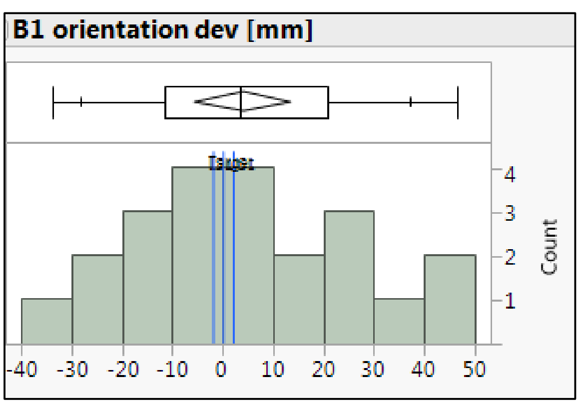


(a) **(b)**

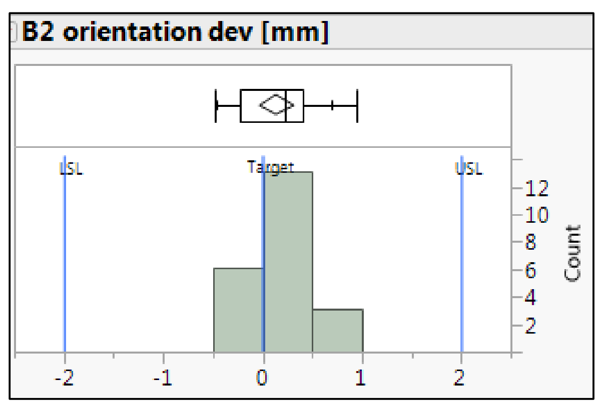
Figure 49*. Distributions of orientation deviations for A-axis; (a) Distribution before fixture correction (b) Distribution after fixture correction*

Table 3. *Results for B-axis rotation*

Trial	L1 [inches]	B1 deviation [degrees]	B1 orientation dev [mm]	B2 deviation [degrees]	B2 orientation dev [mm]
1	10.094	-1.0	-3.85	0.1	0.38
2	10.125	3.6	13.92	0.1	0.23
3	10.063	2.5	9.59	0.1	0.22
4	10.125	-6.9	-26.78	0.2	0.45
5	10.094	7.4	28.64	0.1	0.23
6	10.313	-8.5	-33.78	-0.2	-0.47
7	10.125	-7.5	-29.13	0.1	0.23
8	10.094	-3.1	-11.94	0	0.00
9	10.281	2.6	10.23	0.1	0.23
10	10.391	0.2	0.80	0	0.00
11	10.406	-2.2	-8.77	-0.2	-0.48
12	10.313	11.7	46.81	0.3	0.71
13	10.125	-1.5	-5.79	-0.2	-0.45
14	10.094	10.4	40.47	0	0.00
15	10.266	-4.5	-17.70	0.2	0.47
16	10.297	1.6	6.30	0.4	0.94
17	10.172	-3.0	-11.66	-0.1	-0.23
18	10.141	2.5	9.68	-0.1	-0.23
19	10.125	7.8	30.31	0.1	0.23
20	10.125	5.3	20.53	0.3	0.68
21	10.094	5.6	21.62	-0.1	-0.23
22	10.313	-0.5	-1.97	0.1	0.24



(a)



(b)

Figure 50. *Distributions of orientation deviations for B-axis; (a) Distribution before fixture correction (b) Distribution after fixture correction*

Both the A2 and B2 results yielded maximum orientation deviations of less than 2mm, which are within tolerance. Using JMP statistical software, Cp and Cpk values were determined to quantify and compare process capability before and after correction. For this analysis, Cp and Cpk values of at least 1.0 are considered acceptable and infer the process is capable of producing parts within the desired tolerance. Results (*Table 4*) convey that the amount of variation decreased and the ability to more accurately attain nominal increased for both the A- and B-axis after correction, thus promoting this method's ability to produce parts within tolerance. There is slight concern with the correction of the A-axis as the Cpk value fell just short of 1.0, but perhaps with increased control or a more accurate indexer, this value will increase.

Table 4. *Process capability*

	Cp	Cpk
A1	0.008	-0.047
A2	1.031	0.984
B1	0.03	-0.03
B2	1.721	1.598

To quantify the error associated with the coaxiality of chuck jaws (measurement error), a Zeiss DuraMax CMM utilizing the CALYPSO 2015 software was used to measure the axes of both sets of chuck jaws using gage blocks to derive a coaxiality measurement for 15 trials. Results of this analysis are presented in *Table 5*. The average distance between the chuck jaw coaxes was 0.025 inches with a standard deviation of 0.005 inches. For the context of this thesis, this error is considered fairly significant.

Table 5. *Coaxiality* of chuck jaws

Trial	Coaxiality [inches]
1	0.020
2	0.025
3	0.030
4	0.019
5	0.024
6	0.031
7	0.028
8	0.015
9	0.025
10	0.030
11	0.027
12	0.026
13	0.018
14	0.022
15	0.030

To estimate scanning accuracy, 20 measurements of the same angle on an aluminum part were taken. To do this, two faces of the aluminum part were scanned multiple times with a Faro Arm laser scanner. Then, two planes were extracted from this scanning data and the angle between them was determined using scanning software Geomagic Design X. According to the results (*Table* 6), the average angle measurement of these trials was 90.180 degrees with a standard deviation of 0.414 degrees. For the purpose of this thesis, this standard deviation is considered significant and a main contributor to the overall deviation.

Table 6. *Angular measurements taken to determine scanning inaccuracies*

Trial	Angle [degrees]
1	89.43
2	90.08
3	89.93
4	90.17
5	90.06
6	90.18
7	90.15
8	90.05
9	90.42
10	89.96
11	90.28
12	90.43
13	90.47
14	90.96
15	89.86
16	89.64
17	90.26
18	91.28
19	90.11
20	89.86

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

This thesis presented a method to combine additive and subtractive manufacturing techniques to create functional metal parts. Thus, the objective of this work was to create a method for fixturing, scanning, and reorienting an additively manufactured (AM) part for subsequent machining. A method was developed to determine the transformations required to orient and position AM parts for their rapid manufacturing using CNC-RP. These transformations were physically implemented through the design and validation of a hardware fixture element with the flexibility to support a wide array of parts and the rigidity required to withstand the forces exerted during the machining operation to follow. Process capability metrics were derived through the implementation of this method, which provided validation for a feasible solution to orient the AM part that enables precise machining of features such as flats and holes. This thesis also supports the ability to use a manual rotary and vertical adjuster assembly to orient and position an AM part in preparation for subtractive manufacturing on a four-axis CNC machine.

5.2 Future Work

The fixture hardware is perhaps overbuilt, but provides a feasible solution that meets the intended requirements of the research. However, there are several opportunities for improvement. Updating the hardware would help reduced the orientation deviation distributions. For example, a more accurate indexer would improve the A-axis rotations; the automation of these rotations could be used to obtain better accuracy and precision in positioning through the elimination of manual error. In addition, scanning accuracy can be more controlled with an automated scanning device that operates within the work envelope. Additionally, the strategies of this method can also be adapted to other metal-AM methods and different repositioning software. Positioning errors of the AM part can be determined prior to machining by analyzing the resulting orientation of the part with toolpath simulation software. Future work could focus on adding transformation matrix capability to the software to enable the use of other coordinate systems. Empirical models that estimate resulting orientation deviations can be developed using inaccuracies related to varying materials, build volume and build orientation. Finally, future research could focus on streamlining both the hybrid process steps associated with this thesis, those before and after the AM printing process.

REFERENCES

[1] 3D-printed dentistry image. Retrieved December 22, 2015 from http://3dmatic.com.au/wp-content/uploads/2015/09/Dental-3D-printing-500x393.jpg

[2] Custom 3D-printed metal sternum ribs image. Retrieved December 22, 2015 from http://www.methalab.net/health/cancer-patient-receives-3d-printed-sternum-ribs-in-first-of-its-kind-surgery/

[3] 3D-printed jet engine image. Retrieved December 22, 2015 from http://217.218.67.233/photo20150319/1669effa-f70a-405c-85ec-917618d3c0dd.jpg

[4] DMLS process image. Retrieved December 22, 2015 from http://www.rapidcut.com/dmls_detail.html

[5] Metal printing machine image. Retrieved December 22, 2015 from http://www.lasersintering.com/images/services/sls_machine.gif

[6] Frank, Matthew C. IE 545 *Rapid Prototyping and Manufacturing.* 2015. PowerPoint.

[7] Robinson, Lynne and Justin Scott. "Layers of Complexity: Making the promises possible for additive manufacturing of metals." *JOM* 16 (2014): 2194-2207. The Minerals, Metals & Materials Society.

[8] Zelinski, Peter, ed. "Is Direct-Metal Manufacturing Ready for Production?" *Modern Machine Shop* 1 Oct. 2009. *Gardner Business Media, Inc*. 21 Nov. 2014.

[9] Harris, Ian D. "Development and Implementation of Metals Additive Manufacturing." 2011. 24 Jan. 2016.

[10] ASTM International. (2013). A564/A564M-13 Standard Specification for Hot-Rolled and Cold-Finished Age-Hardening Stainless Steel Bars and Shapes. West Conshohocken, PA, USA.

[11] Cotteleer, Mark. "3D opportunity for production: Additive manufacturing makes its (business) case." *Deloitte University Press* 15, 28 July 2014.

[12] Pal, Deepankar; Chong Teng; and Brent Strucker. "Simulation of Powder-Based Additive Manufacturing Processes." *Additive Manufacturing.* Sept. 2015, 199-251.

[13] Ning, Y., Y.S. Wong, J.Y.H. Fuh, and H.T. Loh. "An Approach to Minimize Build Errors in Direct Metal Laser Sintering." *IEEE Transactions on Automation Science and Engineering* 3.1 (2006). 17 Jan. 2016.

[14] Goudsmit, Frans-Willem, Gerrit Oosterhuis, Erwin Sluiter and Ton Peijnenburg. "Typical Requirements for Precision Mechanical Parts and Opportunities for Additive Manufacturing." *ASPE 2014 Spring Topical Meeting.* Proceedings of Dimensional Accuracy and Surface Finish in Additive Manufacturing, University of California-Berkeley. The American Society for Precision Engineering (ASPE).

[15] Frank, Matthew C., Richard A. Wysk, and Sanjay B. Joshi. "Determining Setup Orientations From the Visibility of Slice Geometry for Rapid Computer Numerically Controlled Machining." *Industrial and Manufacturing Systems Engineering Publications* 5 (2006).

[16] Frank, M. C., R.A. Wysk, and S. Joshi. "Rapid Planning for CNC Milling- A New Approach for Rapid Prototyping." *Journal of Manufacturing Systems* 23.3 (2004): 242-255.

[17] Boonsuk, W. and M.C. Frank. "Automated fixture design for a rapid machining process." *Rapid Prototyping Journal* 15.2 (2009): 111-125.

[18] Three-jaw chuck image. Retrieved January 14, 2016 from http://www.deansphotographica.com/machining/projects/minichuck/14.jpg

[19] Chick vise image. Retrieved January 14, 2016 from http://www.cnczone.com/forums/tormach-personal-cnc-mill/183658-tormach.html

[20] Metal plate section and t-slot nut image. Retrieved March 31, 2016 from https://thingiverse-production-new.s3.amazonaws.com/renders/84/a3/12/e9/59/M4_T_SLOT_01_preview_featured.jpg

[21] Angle plate clamp image. Retrieved January 15, 2016 from http://2.bp.blogspot.com/-DBvpXtKydMw/UoU-LhaB9OI/AAAAAAAAIi4/zPAeUySSTRY/s200/An-Angle-Plate-clamp.jpg

[22] Workholding vise with multi V jaw image. Retrieved January 15, 2015 from http://www.tormach.com//uploads/images/Gallery/products/workholding/Vises_and_Jaws/31907-Multi-V-Jaw-Upright_lrg.jpg

[23] Milling fixture image. Retrieved January 15, 2015 from http://www.cnccookbook.com/CCRotabToys.html

[24] Custom bike fixture image. Retrieved January 15, 2015 from http://flashbackfab.com/excelsior-project-paul-brodie/excelsior-engine-production/

[25] ASTM Designation: F2792-12a. "Standard Terminology for Additive Manufacturing Technologies."

[26] Wohlers, Terry. "*Wohlers Report 2012*: Additive Manufacturing and 3D Printing State of the Industry." Wohlers Associates, Inc., 2012.

[27] Ford, Sharon. "Additive Manufacturing Technology: Potential Implications for U.S. Manufacturing Competitiveness." *Journal of International Commerce and Economics* (2014).

[28] Edwards, P., A. O'Conner, and M. Ramulu. "Electron beam additive manufacturing of titanium components: properties and performance." *J. Manuf. Sci. Eng.* 135.6 (2013).

[29] Lodes Matthias A., Ralf Guschlbauer, and Carolin Korner. "Process development for the manufacturing of 99.94% pure copper via selective electron beam melting." *Material Letters* 143 (2015): 298-301.

[30] Murr, L.E., E. Martinez, X.M. Pan, S.M. Gaytan, J.A. Castro, C.A. Terrazas, F. Medina, R.B. Wicker, and D.H. Abbott. "Microstructures of Rene 142 nickel-based superalloy fabricated by electron beam melting." *Acta Materialia* 61.11 (2013): 4289-4296.

[31] Paul, Ratnadeep, Sam Anand, and Frank Gerner. "Effect of thermal deformation on part errors in metal powder based additive manufacturing processes." *J. Manuf. Sci. Eng* 136.3 (2014).

[32] Zaeh, M.F., G. Branner, and T.A. Krol. "A three dimensional FE model for the investigation of transient physical effects of selective laser sintering." *4th International Conference on Advanced Research in Virtual and Rapid Prototyping* (2010).

[33] Klingbeil, N.W., J.L. Beuth, R.K. Chin, and C.H. Amon. "Residual Stress-Induced warping in direct metal solid freeform fabrication." *Int. J. Mech. Sci.* 44.1 (2002): 57-77.

[34] Paul, R., and S. Anand. "Material Shrinkage Modeling and Form Error Prediction in Additive Manufacturing Processes." Proceedings of the 41st NAMRC 2013, Madison, WI.

[35] Wang, R., L. Wang, L. Zhao and Z. Liu. "Influence of Process Parameters on Part Shrinkage in SLS." *Int. J. Adv. Manuf. Technol.* 33.5-6 (2007): 498–504.

[36] Gu, Dongdong and Yifu Shen. "Effects of processing parameters on consolidation and microstructure of W-Cu components by DMLS." *Journal of Alloys and Compounds* 473.1-2 (2009): 107-115.

[37] Gu, D., C. Hong, and G. Meng. "Densification, microstructure, and wear property of in situ titanium nitride-reinforced titanium silicide matrix composites prepared by a novel selective laser melting process." *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science* 43.2 (2012): 697-708.

[38] Hissam, Andy, Darron Rice, Kevin Baker, and David Whitten. "Additive Manufacturing Design Considerations for Liquid Engine Components." *Liquid Propulsion Subcommittee and Advanced Materials Panel Additive Manufacturing for Propulsion Applications Technical Interchange Meeting.* Sept 2014. NASA: Marshall Space Flight Center.

[39] Pachbhai, Shailesh S. and Laukik P. Raut. "A Review on Design of Fixtures." *International Journal of Engineering Research and General Science* 2.2 (2014): 126-146.

[40] Nee, A.Y.C., K. Whybrew, and A. Senthil Kumar. "Advanced fixture design for FMS." (1995). London: Springer.

[41] Trappey, J.C. and C.R. Liu. "A literature survey of fixture design automation." *International Journal of Advanced Manufacturing Technology* 5.3 (1990): 240–255.

[42] Rong, Y., S.H. Huang, and Z. Hou. "Advanced computer-aided fixture design." (2005). Amsterdam: Elsevier.

[43] Leopold, J. and L. Hong. "Clamping modelling: state-of-the-art and future trends." *Industrial Robot: an International Journal* 36.3 (2009): 249–254.

[44] Li, Q. *Virtual reality for fixture design and assembly*. Diss, University of Nottingham, 2008.

[45] Chaipradabgiat, T., J. Jin, and J. Shi. "Optimal fixture locator adjustment strategies for multistation assembly processes locator adjustment." *IIE Transactions* 41.9 (2009): 843–852.

[46] Tian, Z., X. Lai, and Z. Lin. "Robust fixture layout design for multi-station sheet metal assembly processes using a genetic algorithm." *International Journal of Production Research* 47.21 (2009): 6159–6176.

[47] Vishnupriyan, S., M.C. Majumder, and K.P. Ramachandran. "Optimal fixture parameters considering locator errors." *International Journal of Production Research* 49.21 (2011): 6343–6361.

[48] Vasundara, M. and K.P. Padmanaban. "Recent developments on machining fixture layout design, analysis, and optimization using finite element method and evolutionary techniques." *International Journal of Advanced Manufacturing Technology* 70 (2014): 79-96. *Springer-Verlag 2013.*

[49] Consalter, L. A. and L. Boehs. "An approach to fixture systems management in machining processes." *Journal of the Brazilian Society of Mechanical Sciences and Engineering* 26.2 (2004): 145-152.

[50] Dakhole, M. Y., Prof. P.G. Mehar and Prof. V.N. Mujbaile. "Design and analysis of dedicated fixture with chain conveyer arrangement for multistage special purpose machine." *International Journal of Engineering Research and Applications* 2.5 (2012): 181-192.

[51] An, Z., S. Huang, Y. Rong and S. Jayaram. "Development of Automated Dedicated Fixture Design Systems with Predefined Fixture Component Types: Basic Design." International Journal of Flexible Automation and Integrated Manufacturing 7.3-4 (1999): 321-341.

[52] Bakker, Otto Jan, Thomas Papastathis Svetan Ratchev, and Atanas A. Popov. "Recent research on flexible fixtures for manufacturing processes." *Recent Patents on Mechanical Engineering* 6.2 (2013): 107-121.

[53] Zheng, Y. and W. H. Qian. "A 3-D modular fixture with enhanced localization accuracy and immobilization capability." *International Journal of Machine Tools and Manufacture* 48 (2008): 677-687.

[54] Zhang, J., J. Yang and B. Li. "Development of a reconfigurable welding fixture system for automotive body." *ASME/IFToMM International Conference on Reconfigurable Mechanisms and Robots* (2009): 736-742.

[55] Sela, M. N., O. Gaudry, E. Dombre and B. Benhabib. "A reconfigurable modular fixturing system for thin walled flexible objects." *The International Journal of Advanced Manufacturing Technology* 13.9 (1997): 611- 617.

[56] Zhenyu, K. and C. Darius. "Fixture workspace synthesis for reconfigurable assembly using procrustes based pair wise configuration optimization." *Journal of Manufacturing Systems* 25.1 (2006).

[57] Aoyama, T. and Y. Kakinuma. "Development of fixture devices for thin and compliant work pieces." *CIRP Annals - Manufacturing Technology* 54.1 (2005): 325-328.

[58] Yu, H., B. Li and Y. Wang. "Conceptual design and workspace analysis of reconfigurable fixturing robots for sheet metal." *Assembly Automation* 32.3 (2012): 293-299.

[59] Yeung, B.H.B. and J.K. Mills (2004). "Design of a Six DOF Reconfigurable Gripper for Flexible Fixtureless Assembly." *IEEE Transactions on Systems, Man and Cybernetics, Part C (Applications and Reviews)* 34.2: 226-235.

[60] Arzanpour, S., J. Fung, J.K. Mills, W.L. Cleghorn. “Flexible fixture design with applications to assembly of sheet metal automotive body parts.” *Assembly Automation* 26.2 (2006): 143–153.

[61] Leonardo, L.D., D. Zlatanov, M. Zoppi and R. Molfino. “Design of locomotion and docking system of the swarmitfix mobile fixture agent.” *International Conference on Designing and Manufacturing* (2013): 1416-1425.

[62] Monkman, Gareth. “Work piece retention during machine processing.” *Assembly Automation* 21.1 (2001): 61-66.

[63] Liou, Frank, Kevin Slattery, Mary Kinsella, Joseph Newkirk, Hsin-Nan Chou, Robert Landers. “Applications of a hybrid manufacturing process for fabrication of metallic structures.” *Rapid Prototyping Journal* 13.4 (2007): 236-244.

[64] Zhang, J. and F. Liou. “Adaptive slicing for a multi-axis laser aided manufacturing.” *Journal of Mechanical Design* 126.2 (2004): 254-261.

[65] Janki Ram, G.D., Y. Yang and B.E. Stucker. “Effects of process parameters on bond formation during ultrasonic consolidation of Aluminum alloy 3003.” *Journal of Manufacturing Systems* 25.3 (2006): 221-238.

[66] Schick, D.E., R.M. Hahnlen, R. Dehoff, P. Collins, S.S. Babu, M.J. Dapino, and J.C. Lippold. “Microstructural characterization of bonding interfaces in Aluminum 3003 blocks fabricated by ultrasonic additive manufacturing.” *Welding Journal* 89 (2010): 105-116.

[67] Choi, D.S., S.H. Lee, B.S. Shin, K.H. Whang, Y.A. Song, S.H. Park, and H.S. Jee. “Development of a direct metal freeform fabrication technique using CO_2 laser welding and milling technology.” *Journal of Materials Processing Technology* 113.1-3 (2001): 273-249.

[68] Karunakaran, K.P., S. Suryakumar, V. Pushpa, and S. Akula, S. “Low cost integration of additive and subtractive processes for hybrid layered manufacturing.” *Robotics and Computer-Integrated Manufacturing* 26.5 (2010): 490-499.

[69] Manogharan, Guhaprasanna. *Hybrid Manufacturing: Analysis of Integrating Additive and Subtractive Methods*. Diss. North Carolina State University, 2014. Ann Arbor: ProQuest LLC, 2014.

[70] Peters, Frank. “Post-machining for castings.” Personal interview. 1 Mar. 2016.

[71] Varadarajan, K.M. and M.L. Culpepper. “A dual-purpose positioner-fixture for precision six-axis positioning and precision fixturing, Part I. Modeling and design.” *Precision Engineering* 31.3 (2007): 276–286.

[72] Culpepper, M.L., K.M. Varadarajan and C. DiBiasio. “Design of integrated eccentric mechanisms and exact constraint fixtures for micron-level repeatability and accuracy.” *Precision Engineering* 29.1 (2005): 65–80.

[73] Ryll, M., T.N. Papastathis, and S. Ratchev. “Towards an intelligent fixturing system with rapid reconfiguration and part positioning.” *Journal of Materials Processing Technology* 201.1-3 (2008): 198–203.

[74] Warping metal image. Retrieved February 24, 2016 from http://www.sf2m.asso.fr/CommissionsThematiques/DocComThematiques/EPMA_Additive_Manufacturing.pdf

APPENDIX A

Excel VBA Code

```
Private Sub CommandButton1_Click()
Range("A2").Value = UserForm1.TextBox1.Value
Range("B2").Value = UserForm1.TextBox2.Value
Range("C2").Value = UserForm1.TextBox3.Value

If UserForm1.TextBox1.Value = "" Then
MsgBox "Please enter a value", vbExclamation, "Rotation A"
UserForm1.TextBox1.SetFocus
Exit Sub
End If
If UserForm1.TextBox2.Value = "" Then
MsgBox "Please enter a value for B displacement", vbExclamation, "Rotation B"
UserForm1.TextBox2.SetFocus
Exit Sub
End If
If UserForm1.TextBox3.Value = "" Then
MsgBox "Please enter a value for length", vbExclamation, "Distance"
UserForm1.TextBox3.SetFocus
Exit Sub
End If

Dim ArotationDisplacement As Variant
Dim BrotationDisplacement As Variant
Dim LengthInput As Variant
Dim Pi As Double
Dim Tangent1 As Double
Dim BDashRotation As Double
Dim ADashRotation As Double
```

```
Dim Sigfig1 As Double
Dim Sigfig2 As Double
Dim Sigfig3 As Double
Dim Sigfig4 As Double
Dim Final1 As Double
Dim Final2 As Double
Dim Final3 As Double
Dim Final4 As Double
Dim DialIndVal As Double
Dim LHimm As Double


Pi = 4 * Atn(1) 'Defines pi value


Range("A1").Value = "A input"
Range("B1").Value = "B input"
Range("C1").Value = "Length of part"
Range("A4").Value = "Required Rotation of A in Degrees"
Range("B4").Value = "Required Rotation of B in Degrees"


ArotationDisplacement = Range("A2").Value
BrotationDisplacement = Range("B2").Value
LengthInput = Range("C2").Value

'To make A Rotation:
'On manual rotary for our setup, 1 dash=1/60th of a degree
ADashRotation = Range("A2").Value * (60) 'Gives number of dashes required for rotation
```

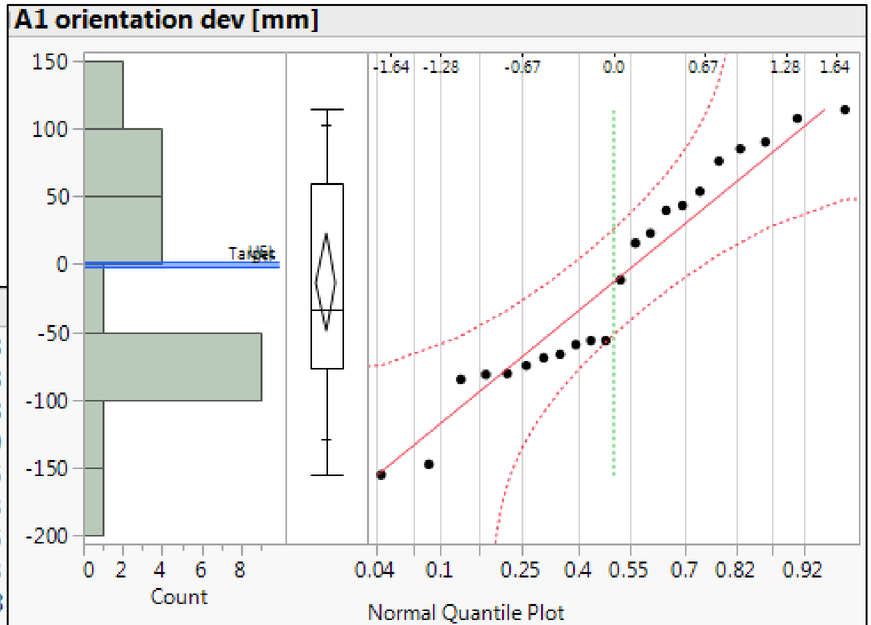
```
'To make B Rotation:
Range("B5").Formula = (Abs(BrotationDisplacement)) * Pi / 180 'Gives required rotation in radians, which is Excel's default, to do trig

Tangent1 = Tan(Range("B5").Value) 'Gives the tangent of angle
Range("G15").Value = Tangent1
Range("F16").Formula = ((LengthInput * 2.54) + 38.05 - 73.95) * Tangent1 'Gives liftheight value used in mm
LHimm = Range("F16").Value
Range("F17").Formula = LHimm * 0.03937008 ' Gives liftheight in inches, which are the units for dial indicator
DialIndVal = Range("F17").Value

'If value is positive, then rotate vertical adjuster CW respective degrees
'On dial indicator, 1 dash= .001"
Range("F18").Formula = DialIndVal / 0.001 'Gives number of dashes
BDashRotation = Range("F18").Value

'Minimizes significant figures to 1
Sigfig1 = Round(BDashRotation, 1)
Sigfig2 = Round(DialIndVal, 3)
Sigfig3 = Round(ADashRotation, 1)
Sigfig4 = Round(ArotationDisplacement, 2)

'Defines the direction to adjust the vertical adjuster and manual rotary
If BrotationDisplacement > 0 Then
DirectionB = "CW"
ElseIf BrotationDisplacement < 0 Then
DirectionB = "CCW"
End If
```

```
If ArotationDisplacement > 0 Then
DirectionA = "CW"
ElseIf ArotationDisplacement < 0 Then
DirectionA = "CCW"
End If

If DirectionB = "CW" Then
CrossBarMovement = "Down"
ElseIf DirectionB = "CCW" Then
CrossBarMovement = "Up"
End If

'Takes absolute value of all rotations
Final1 = Abs(Sigfig1)
Final2 = Abs(Sigfig2)
Final3 = Abs(Sigfig3)
Final4 = Abs(Sigfig4)


MsgBox ("You need to turn the vertical adjuster " & DirectionB & " so that " & Final1 & "
dashes register on the dial indicator and the cross bar moves " & Final2 & " inches " &
CrossBarMovement)
MsgBox ("Then, turn the manual rotary " & Final3 & " dashes, or " & Final4 & " degrees " &
DirectionA)


End Sub
```

APPENDIX B

Statistical Analysis

A1 deviation analysis (A-axis deviation before correction)



Quantiles

100.0%	maximum	113.8
99.5%		113.8
97.5%		113.8
90.0%		102.069
75.0%	quartile	59.1225
50.0%	median	-34.03
25.0%	quartile	-76.2425
10.0%		-128.853
2.5%		-155.38
0.5%		-155.38
0.0%	minimum	-155.38

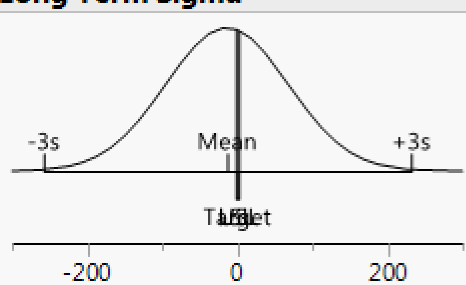
Summary Statistics

Mean	-13.55545
Std Dev	81.546984
Std Err Mean	17.385875
Upper 95% Mean	22.600453
Lower 95% Mean	-49.71136
N	22

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	-2	Below LSL	54.5455
Spec Target	0	Above USL	45.4545
Upper Spec Limit	2	Total Outside	100.0000

Long Term Sigma

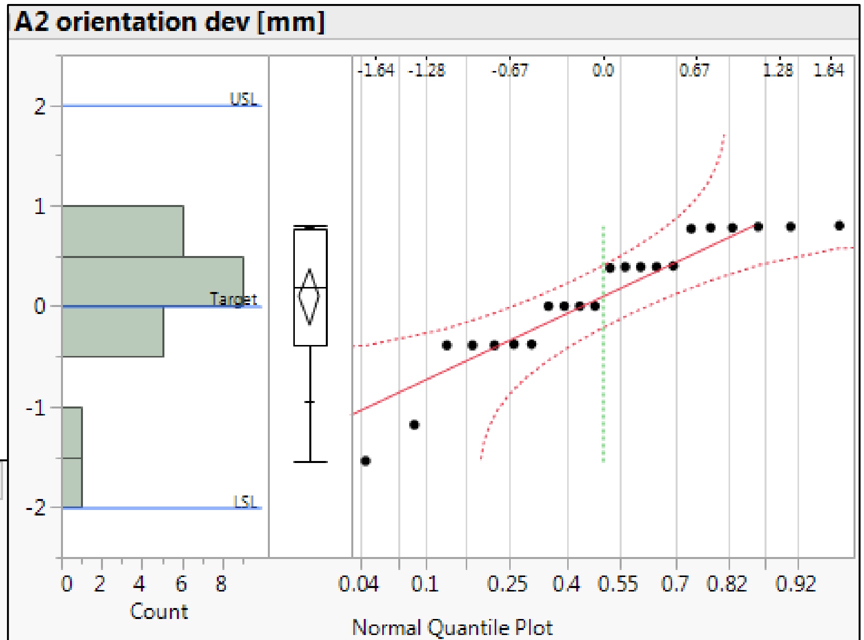


Sigma = 81.547

Capability	Index	Lower CI	Upper CI
CP	0.008	0.006	0.011
CPK	-0.047	-0.187	0.093
CPM	0.008	0.006	0.011
CPL	-0.047	-0.187	0.093
CPU	0.064	-0.078	0.203

Portion	Percent	PPM	Sigma Quality
Below LSL	55.6343	556342.71	1.358
Above USL	42.4359	424358.97	1.691
Total Outside	98.0702	980701.68	-0.568

A2 deviation analysis (A-axis deviation after correction)



Quantiles

100.0%	maximum	0.8
99.5%		0.8
97.5%		0.8
90.0%		0.79
75.0%	quartile	0.7725
50.0%	median	0.19
25.0%	quartile	-0.3825
10.0%		-0.943
2.5%		-1.54
0.5%		-1.54
0.0%	minimum	-1.54

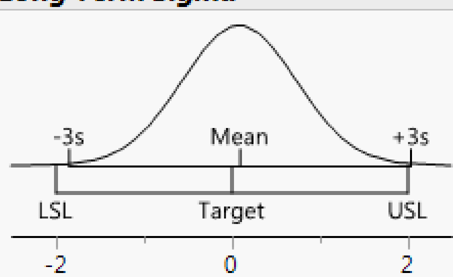
Summary Statistics

Mean	0.0913636
Std Dev	0.6467523
Std Err Mean	0.1378881
Upper 95% Mean	0.3781175
Lower 95% Mean	-0.19539
N	22

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	-2	Below LSL	0.0000
Spec Target	0	Above USL	0.0000
Upper Spec Limit	2	Total Outside	0.0000

Long Term Sigma



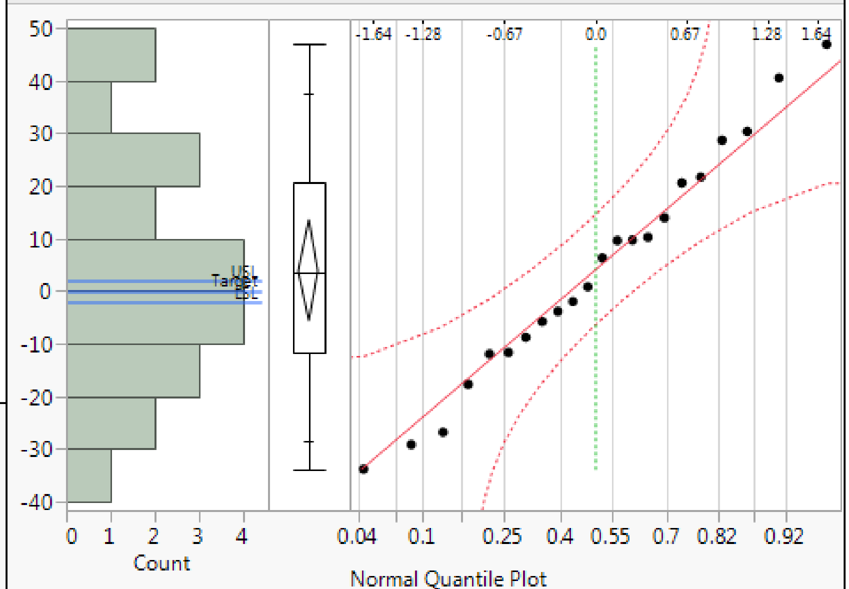
Sigma = 0.64675

Capability	Index	Lower CI	Upper CI
CP	1.031	0.721	1.340
CPK	0.984	0.655	1.312
CPM	1.021	0.738	1.350
CPL	1.078	0.723	1.428
CPU	0.984	0.655	1.308

Portion	Percent	PPM	Sigma Quality
Below LSL	0.0611	611.1186	4.734
Above USL	0.1583	1583.1770	4.451
Total Outside	0.2194	2194.2955	4.349

B1 Deviation Analysis (B-axis deviation before correction)

B1 orientation dev [mm]



Quantiles

100.0%	maximum	46.81
99.5%		46.81
97.5%		46.81
90.0%		37.422
75.0%	quartile	20.8025
50.0%	median	3.55
25.0%	quartile	-11.73
10.0%		-28.425
2.5%		-33.78
0.5%		-33.78
0.0%	minimum	-33.78

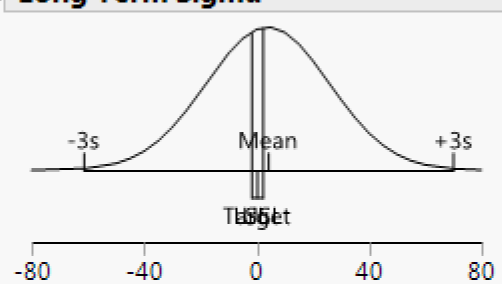
Summary Statistics

Mean	3.9786364
Std Dev	21.888006
Std Err Mean	4.6665386
Upper 95% Mean	13.683235
Lower 95% Mean	-5.725962
N	22

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	-2	Below LSL	40.9091
Spec Target	0	Above USL	50.0000
Upper Spec Limit	2	Total Outside	90.9091

Long Term Sigma



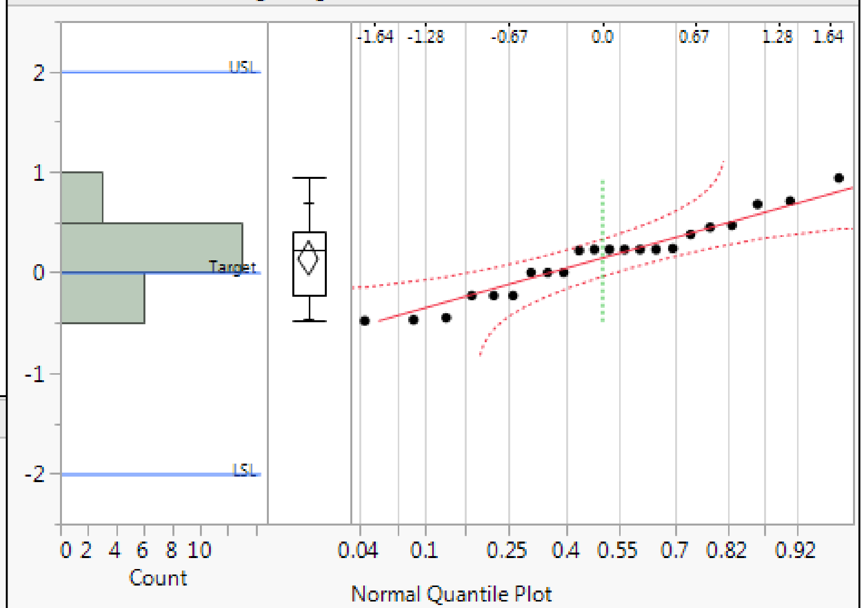
Sigma = 21.888

Capability	Index	Lower CI	Upper CI
CP	0.030	0.021	0.040
CPK	-0.030	-0.170	0.109
CPM	0.030	0.022	0.040
CPL	0.091	-0.052	0.232
CPU	-0.030	-0.169	0.110

Portion	Percent	PPM	Sigma Quality
Below LSL	39.2370	392370.23	1.773
Above USL	53.6015	536014.61	1.410
Total Outside	92.8385	928384.84	0.036

B2 deviation analysis (B-axis deviation after correction)

B2 orientation dev [mm]



Quantiles

100.0%	maximum	0.94
99.5%		0.94
97.5%		0.94
90.0%		0.701
75.0%	quartile	0.3975
50.0%	median	0.23
25.0%	quartile	-0.23
10.0%		-0.464
2.5%		-0.48
0.5%		-0.48
0.0%	minimum	-0.48

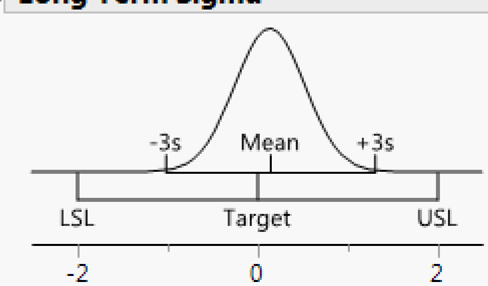
Summary Statistics

Mean	0.1431818
Std Dev	0.3872908
Std Err Mean	0.0825707
Upper 95% Mean	0.3148969
Lower 95% Mean	-0.028533
N	22

Capability Analysis

Specification	Value	Portion	% Actual
Lower Spec Limit	-2	Below LSL	0.0000
Spec Target	0	Above USL	0.0000
Upper Spec Limit	2	Total Outside	0.0000

Long Term Sigma



Sigma = 0.38729

Capability	Index	Lower CI	Upper CI
CP	1.721	1.205	2.237
CPK	1.598	1.095	2.101
CPM	1.615	1.168	2.127
CPL	1.845	1.272	2.414
CPU	1.598	1.097	2.096

Portion	Percent	PPM	Sigma Quality
Below LSL	0.0000	0.0157	7.034
Above USL	0.0001	0.8159	6.294
Total Outside	0.0001	0.8316	6.291