



## **Rapid manufacturing of Critical Industrial Parts: A Method based on Reverse Engineering, Rapid prototyping, and Coordinate Metrology.**

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# **Rapid Manufacturing of Critical Industrial Parts: A Method based on Reverse Engineering, Rapid Prototyping, and Coordinate Metrology**

## **Abstract**

This paper presents a method of rapidly manufacturing industrial parts that are critical to the production. In order to assist the Advanced Manufacturing industry, a senior project team at the University of Texas Rio Grande Valley (UTRGV) applied Rapid Manufacturing (RM) to manufacture or fabricate critical machine parts used to maintain production machines. Failures of parts and tools in industrial settings cost money and hurt output. Usually, the problem arises when the tooling being used is one of a kind and repair or replacements come with long lead-times. Other problems are encountered when original part or tool engineering drawing is not available and costly redesign is needed. The RM process implemented through the senior design project successfully provide a method to address these issues. This method demonstrates the successful integration of 3D Scanning, Reverse Engineering, Additive Manufacturing (3D printing), and Subtractive Manufacturing (Computer Numerical Control) to address this critical problem in industries. A quality analysis is also carried out by the team using Coordinate Measuring Machine (CMM). Also, discussed in detail in the paper are the pedagogical aspects of senior design project that includes the industry accepted CMM training and the subsequent internship in the industry.

## **Introduction**

The College of Engineering and Computer Science (CECS) at UTRGV promotes cutting-edge research with international impact as a path to a better life, built on compassion, community, and technology, and foresee every performed activity as a promoter for economic prosperity and commitment to the global community. With an extensive selection of undergraduate programs in the engineering field, the Department of Manufacturing and Industrial Engineering provides a setting for technology development and applied research in the Engineering Technology (ENGT) program. According to the program description, engineering technology education emphasizes primarily on the applied aspects of science and product improvement, industrial practices, and engineering operational functions. A capstone two-semester senior project course is a part of the engineering technology curriculum. This course provides the students an opportunity to address and experience the critical problems faced in the day-to-day life of an engineer in an advanced manufacturing industry. One such problem is to find a quick replacement for the damaged critical part that limits the operation of the bottle-neck machine in the production flow line.

The Industrial sector has many machines. From the manufacturing companies to the logistics companies, machines are everywhere and these companies bottom line depends on them. When a

critical part in one of the machines is damaged or broken, a problem arises. But problems tend to beget more problems.

In a manufacturing setting, this simple problem may be solved by replacing the critical part with a good part taken from the company's inventory. Another way to simplify the solution is having the dimensional documentation and engineering characteristics in company asset records. With the documentation, a prototype can be quickly made and machining of a new part could be underway quickly. Simple, right? Well, what if the company has neither?

New companies pack lightly. New upstarts and young companies and organizations try to have little to no inventory. The reason is that methods like lean manufacturing calls for low to no inventory in order to identify and thus correct problems in a production line. Inventory causes a "cushion" that does not let executives and managers preemptively feel problems in production and assembly lines. Also, new companies have low inventory and limited records kept out of necessity. Limited funds force companies to down size and stay downsized until profits rise and reinvestments are afforded.

Companies also lack engineering drawings and specifications for critical parts and components of machines. Sometimes, due to one-of-a-kind or proprietary reasons, no documentation is provided to the buyer, in this case the manufacturing company, for their records.

## **Background**

There exists a real problem for industries to quickly find the alternative for the broken or malfunctioning part of a complex machine or equipment to mitigate the crisis in manufacturing and production. The goal of this senior design project is to quickly develop an accurate digital representation and specification of a critical part, so that the replacement part can be produced without time delay. The method envisioned was to give an engineering drawing where there was none. According to one of the articles that was researched, "There are some reasons this is necessary: Some parts exist for which no manufacturing documentation exists. In some cases, it is necessary only to extract 2D profile data from the models in order to complete the part using these profiles using a surface/solid CAD/CAM system." The author went on to say, "The use of Reverse Engineering (RE) methodology in the R&D study of casting parts for automotive industry allowed optimizing a casting part and to manufacture the respective rapid tool for sand casting..."(Sokovic & Kopac, 2005).

Reverse engineering has been a preferred method to produce data from a physical existing part. For this reason, in this project, RE was used in the proposed methodology. According to an article that was researched, "The purpose of reverse engineering is to manufacture another object based on a physic and existing object for which 3D CAD is not available" (Paulic et al, 2000).

## **The Problem**

Sometimes critical geometric parts with no engineering documentation are compromised due to failure, misuse, or lack of proper maintenance. Reordering or machining are expensive and time consuming process.

## **Intended solution**

With this specific problem, the senior design project addresses the need of the manufacturing industry by creating a methodology to recreate a corrected prototype of a part from a damaged, unusable part. This solution would circumvent the need for background engineering documentation or dimensions and specifications. The senior design project has created a solution by having the failed critical part scanned using optical technologies, digitized and corrected using reverse engineering (RE) technologies; recreated a corrected prototype using additive manufacturing (AM) technologies and measured critical profiles and angles for quality analysis using metrology technologies. All of these processes are carried out at the Mechatronics and Metrology labs at the UTRGV, Brownville, Texas campus.

## **Methodology**

### **Reverse Engineering (RE)**

Reverse Engineering extracts information from a part, Rapid Prototyping (RP) produces a prototype, in this case a 3D printer. This is a common practice in lean manufacturing companies that are most competitive today, and use technologies, such as, Computer Aided Manufacturing (CAM), Computer Aided Design (CAD), and Computer Aided engineering (CAE). The methodology for RE used in this project was the one that includes digital point cloud acquisition by means of a 3D optical scanner (OS). The RE technique produced a 3D model of the critical part chosen for the study.

### **Additive Manufacturing (AM)**

Additive Manufacturing includes technologies like 3D printing, Laser Stereo Lithography and others. They usually consist of plotting thin layers taken from CAD Model data and joining together with powder, liquid or sheet material to produce ceramic, metal, plastic, or composite parts.

### **Dimensional Metrology**

Metrology is the science of calibration and physical measurement used to quantify 3D space as physical size or dimension of an object. Measured space are expressed as a value relative to a theoretical value. Theoretical values are set by a CAD file or the operator. Values are usually based on the 3D cartesian system (XYZ).

## Overview of procedure

Many different technologies can be used to solve the problem at hand. In this project, the group that is made up of RE, AM, and Metrology are used (Fig. 1). RE will be carried out by a 3D Artec Spider Optical Scanner and Inventor 2018 by Autodesk. AM will be carried out by a Dimension 1200 es 3D Printer. The metrology will be carried out by the Hexagon Global S Coordinate Measuring Machine (CMM).



(Figure 1: Rapid Manufacturing Process Sequence)

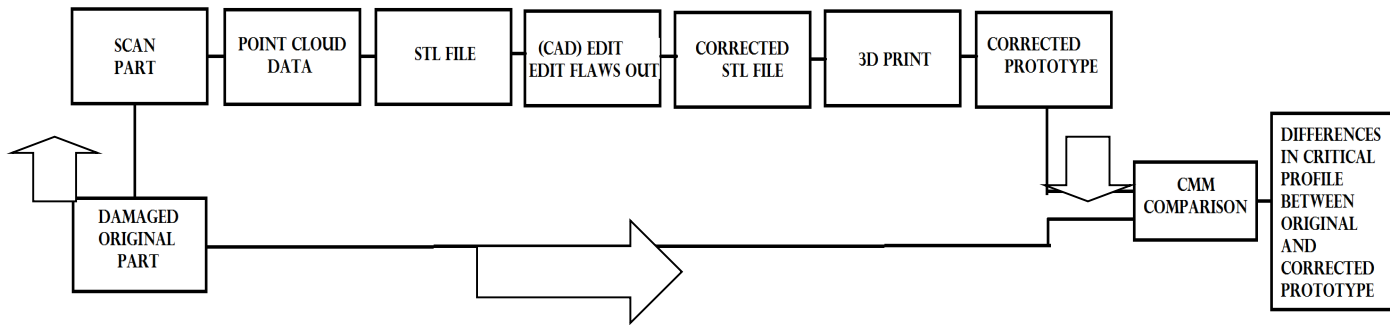
## Operator training

Due to high value and sophistication of instrumentation used in the project like the CMM, a special training was given to students in the operation of CMM. Training was given by the faculty (Certified Hexagon Global CMM trainers) at the Metrology lab at the UTRGV Brownsville campus. The training was done prior to the start of the project.

## Procedure

The procedure was done by scanning the damaged, deformed part with the 3D optical scanner, digitizing its surfaces as a point cloud and exporting it as an STL file, import STL and edit out imperfections from solid on CAD software, 3D print a corrected prototype and acquire engineering drawings, export as a STL file and import into 3D printer. Finally, print the edited part and compare critical profiles and angles within the part to original part (Fig.2).

1. Scan original damaged part with Artec spider 3D scanner.
2. Acquire point cloud data.
3. Export point cloud as STL.
4. Import STL. on to Inventor 2018 Autodesk.
5. Create virtual 3D solid model and edit out flaws.
6. Acquire Engineering documentation and dimensions.
7. Export corrected 3D solid model as STL.
8. Import STL. On Dimensions 1200 es 3D Printer.
9. Print corrected prototype.
10. Measure profiles of original part and corrected prototype using Hexagon Global CMM.
11. Compare results side by side.



(Figure 2: Process flow)

## Limitations

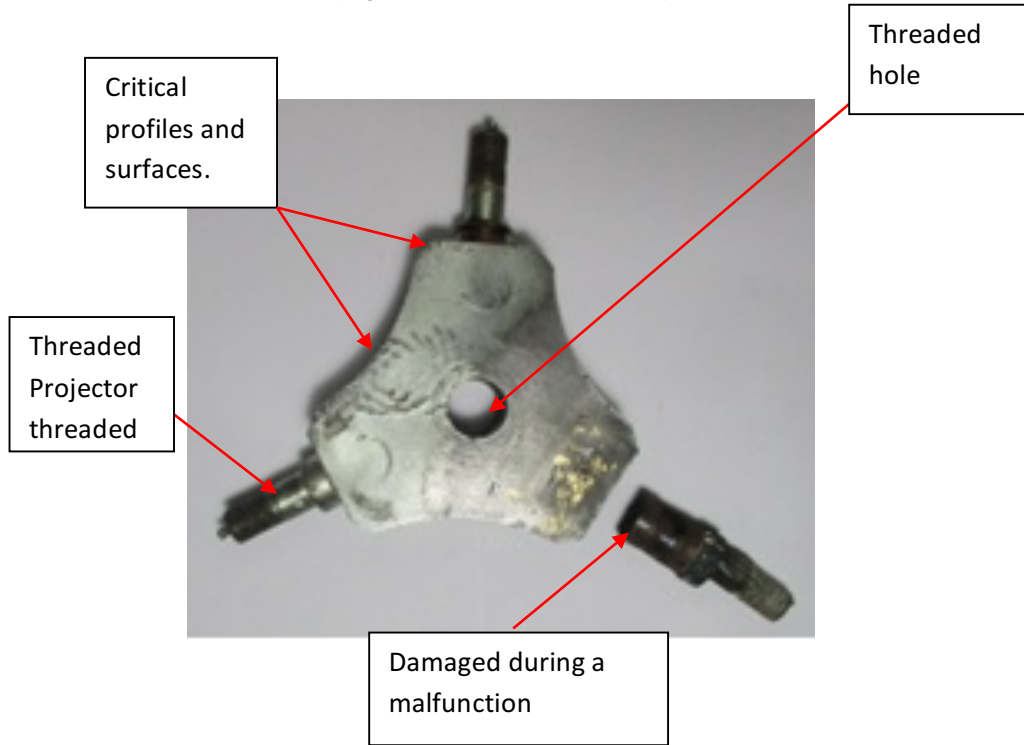
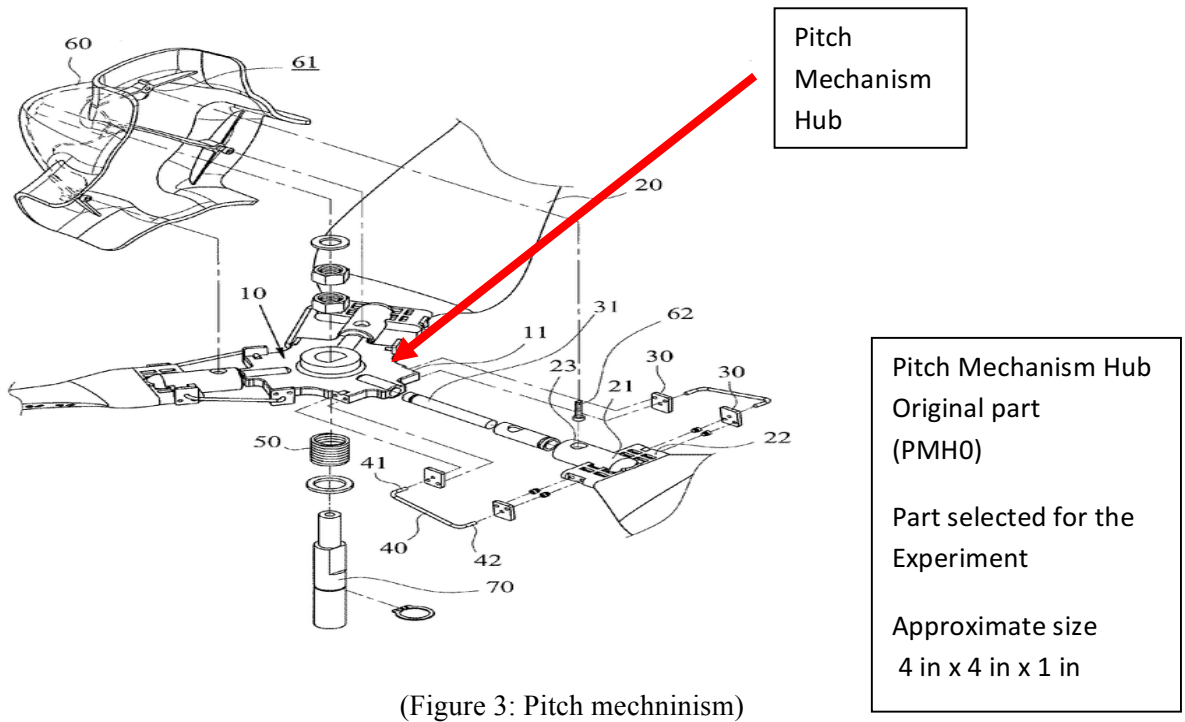
The following limitations were considered in the process:

The field of vision of the artec spider scanner is between 90 mm x 70 mm and 1180 mm x 140mm. The Dimensions ES 1200 3D build space is 245 mm x 254 mm x 305 mm. The CMM measuring space is 500 mm X 500 mm X 700 mm.

The artec spider scanner provides meshing of multiple scans and avoids limitations of part size. The CMM exceeds the build space of the 3D printer so it will be ignored as a limitation. Thus, the critical part that was selected for this Rapid Manufacturing procedure needs to be smaller than the building space of the 3D printer.

## Part selection

A part within the above discussed dimensional limitations was selected for the experimentation. The part selected needed to also have critical geometries and surfaces. A part was selected from the Machine Shop (M2) at the UTRGV Brownsville campus. Part of the Wind Energy Lab, three wind mill generators are out of commission and housed at M2. The part selected was a pitch mechanism hub (PMH) from one of the wind generators (Fig 3). Identification of the generator make and model were difficult due to wear. The part was selected because it was within dimensional limitations, has critical geometries and was damaged. The part also did not have any background engineering documentation. These are the criteria of the damaged part this procedure is trying to address. The part was identified as PMH0 for the purposes of this procedure (Fig. 4). The corrected prototype was identified as PMH1 for the rest of this procedure.



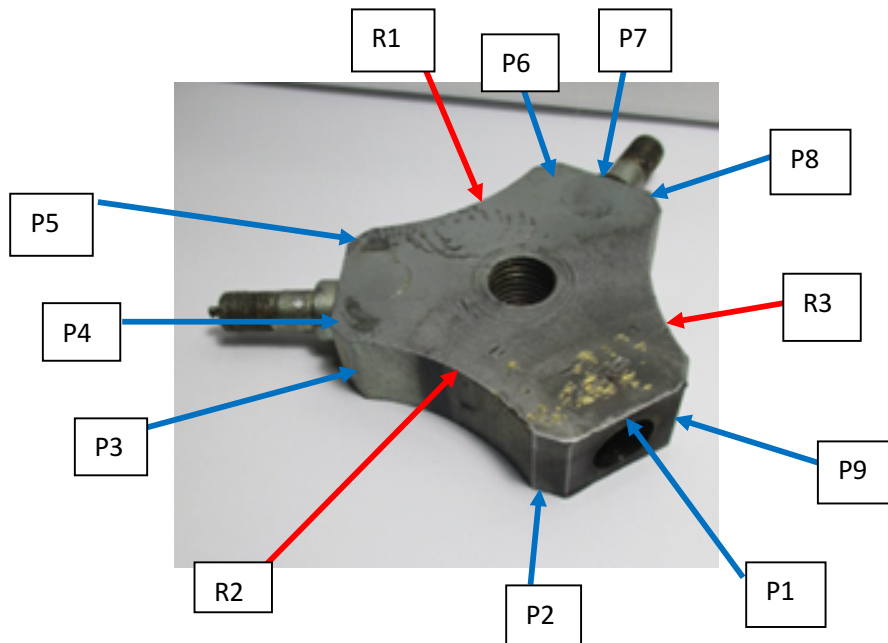
(Figure 4: PMH0 Selected)

## Defining part

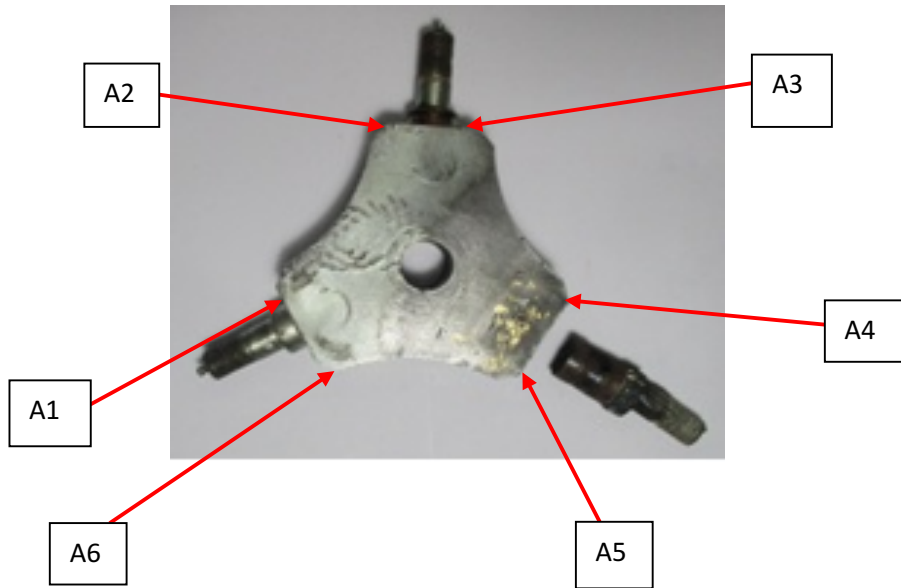
Defining the angles and profile of the part was necessary to carry out a metrological comparison. The comparisons were carried out for the profiles around PMH0 and PMH1. The part had a profile of planes and curvatures.

The experiment was focused on the available reverse engineering capabilities to recreate the damaged part. The profile was the major aspect of the procedure. The measurement of the profile was carried out by the CMM and the measurement of projected shafts were done by conventional metrology equipment.

The critical part profile consisted of 3 arcs and 9 planes. The arcs were identified as R1, R2, and R3. Planes were identified as P1...P9, to measure the angles between the planes. The angles provided the values to analyze the profile and integrity of the scan. The profile was oriented about the Z plane. Curvatures had a radius and a center datum. These were referred as arcs and the radius measured in Inches (Fig. 5).

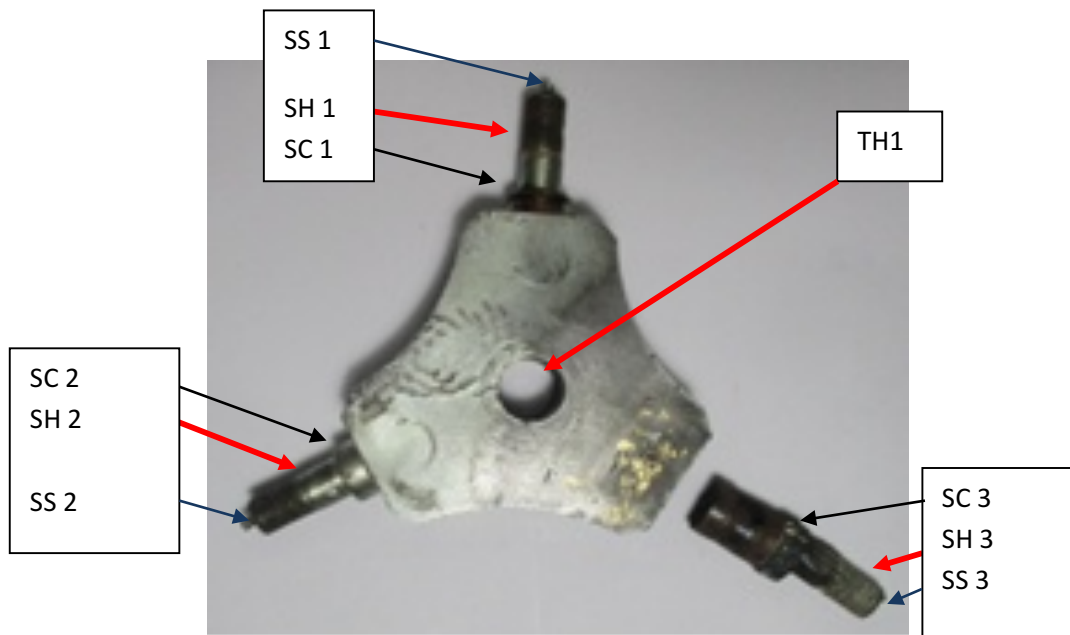






(Figure 5: Feature Definition 1 )

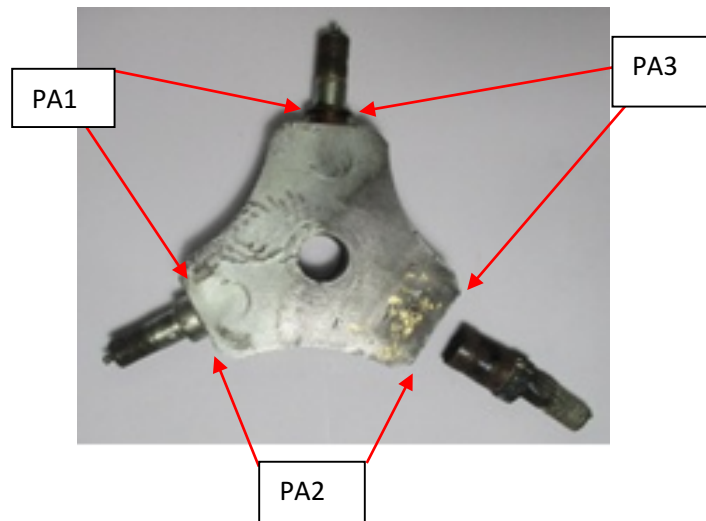
The shafts and hole were measured using the conventional metrological instruments. The part had three projecting shafts (one is very badly damaged and broken off), which were threaded. The shafts had three different diameters and a center threaded hole (TH1). The three projecting shafts were threaded and had a collar at the base of the shaft. Along these two diameters a third one resided at the tip of the shaft. A spacer node of cylindrical material was located at the end of the shaft. The projecting shaft was measured for distance and diameter. The collar also measured for distance and diameter. The hole was measured for diameter. The projecting shafts were identified as SH 1, SH 2, and SH 3. The collars were identified as SC 1, SC2, and SC3. The cylindrical materials at the tip of the part were identified as SS1, SS2, SS3. It is important to know that SS 3 was not dimensioned (Fig. 6).



(Figure 6: Feature Definition2)

### Additional Dimensioning

In addition to the above dimensional features, plate thickness was measured in inches. Furthermore, angles between P1, P4, and P7 were dimensioned and identified as PA 1, PA 2, and PA 3. The angles were dimensioned in degrees (Fig.7).

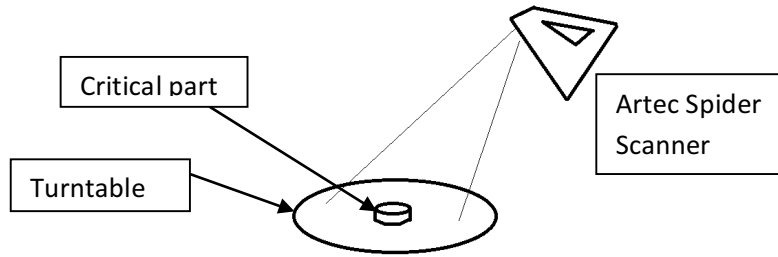


(Figure 7: Feature Definition 3)

### Scanning

Scanning of the critical part was carried out with the assistance of faculty at the Mechatronics lab at the UTRGV Engineering technology lab in Brownsville (Fig.8). The lab setting consisted of a HP laptop, handheld Artec Spider Scanner system, a turntable and the specimen. The scanning

3D point accuracy of the scanner was up to 0.05 mm and the resolution came out be up to 0.1 mm.

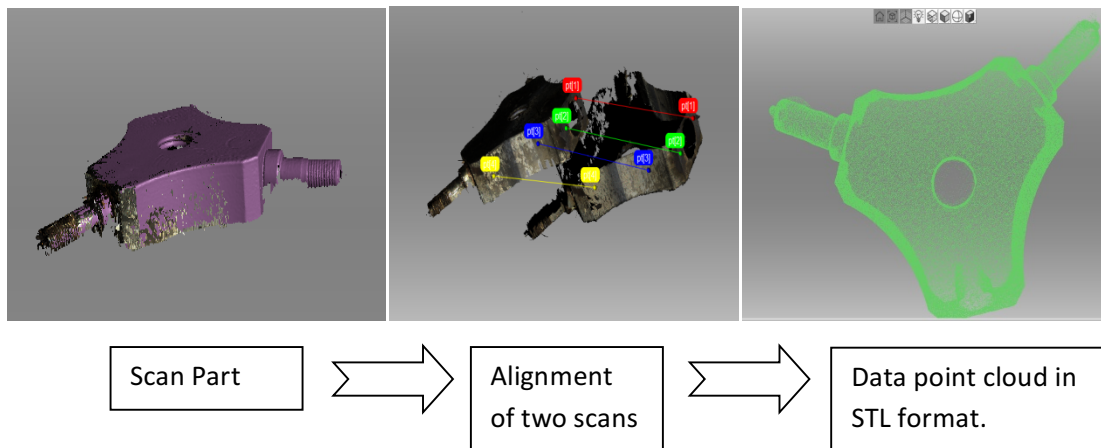


(Figure 8: Scan Setup)

Two full scans were used to mesh and make one virtual solid model on Artec Studio 12. No calibration was needed. The purpose was to collect a point data cloud. The process carried out to do the scanning went as follows (Fig. 9):

1. Scan part a. Scan side one b. Turn 180 degrees c. Scan side two
2. Run preprocessing a. Run global registration on side one b. Run global registration on side two
3. Cut off base a. Use cut off plane selected option in erase tools
4. Reduce noise a. Use remove outliers tool on scan one b. Use remove outliers tool on scan two
5. Align a. Make both scans visible in the Artec studio 12 workspace and align with auto align.
6. Post processing a. Apply global registration to aligned scans b. Apply sharp fusion
7. Simplify mesh with simplify mesh tool.

The Scanning produced a STL file that was exported onto a portable USB. Scanning took approximately 1 hr. to complete.



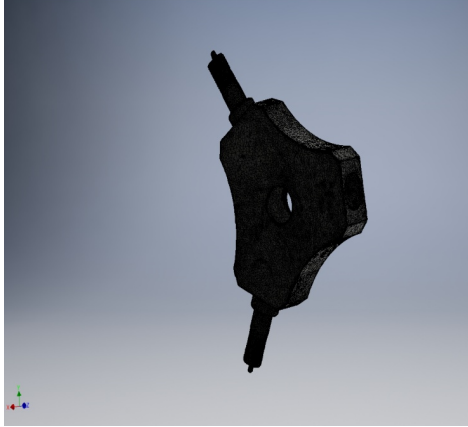
(Figure 9: Scanning Workflow)

## Reverse engineering

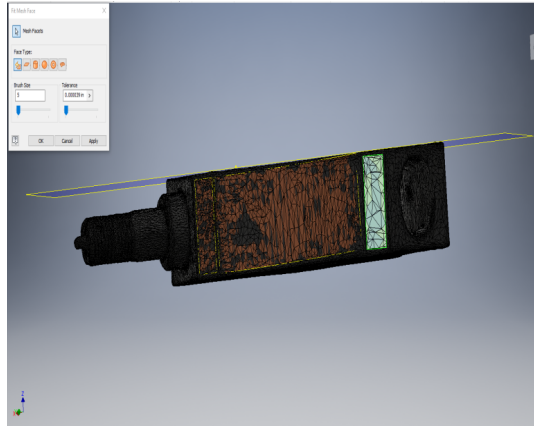
The digital reverse engineering of the part was carried out by very well-known CAD software called Autodesk Inventor. Autodesk inventor Professional 2018 was provided by the UTRGV and the College of Engineering and Computer science. The STL file exported from Artec Studio 12 was imported as Mesh.stl

The following steps were taken to complete the RE process (Fig. 10).

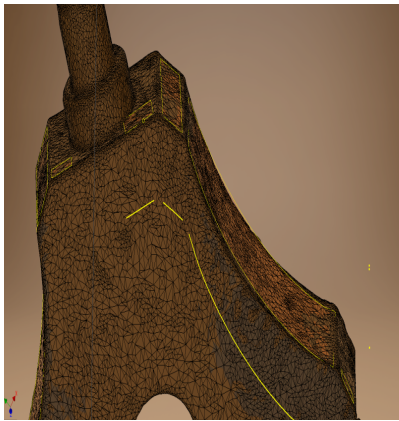
1. Autodesk Inventor Pro 2018 was opened
  - a. New part template was chosen
  - b. Inch was chosen as the units
2. Open Mesh file
  - a. Import Mesh file by going to the Large I icon and choosing IMPORT from the drop-down menu
  - b. Navigate to Mesh .stl file on USB
  - c. Click open
3. Orient
  - a. Right click on part and orient flat on X and Y plane
4. Select profile as planes and surfaces
  - a. Go to surfaces on tab
  - b. Click fit mesh face
  - c. Select profile curvatures and planes that make up the profile of the part
5. Set a new plane to sketch parallel to the X and Y plane.
6. Sketch on new plain and use Project Geometry.
  - a. Select the planes you previously set on surface of profile and click ok.
  - b. Selected surfaces will project on new sketch plain.
7. Selecting the profile sketch you can extrude the 3D solid part.
8. RE the hole and shafts
  - a. Use Project Geometry tool again
  - b. Click on the edges of the part to project the width of the shaft as well as the hole on to the sketch plane.
9. Size part to correct ratio
  - a. Open New environment
  - b. Go to manage tab
  - c. Click derive
  - d. Choose correct size ratio
  - e. For the scanned PMHO the ratio was .037 UM
10. Export file
  - a. Save part
  - b. Go to the Large I icon
  - c. Click export
  - d. Choose stl file and save on portable USB
11. Save file as Part.stl



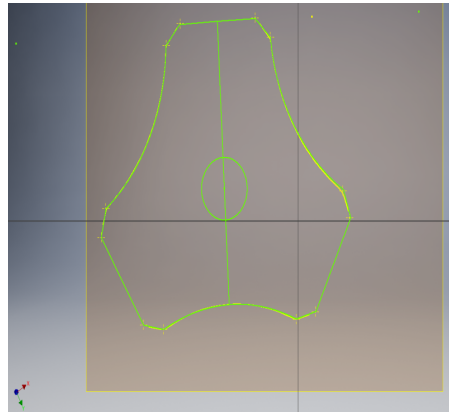
Import Mesh



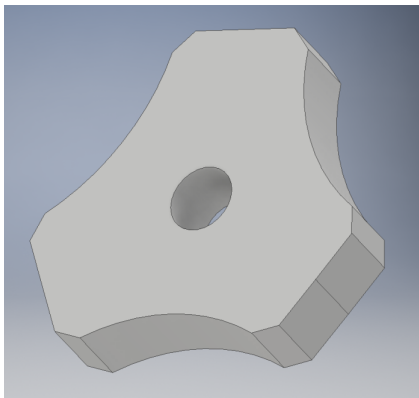
Place planes on surfaces of profile



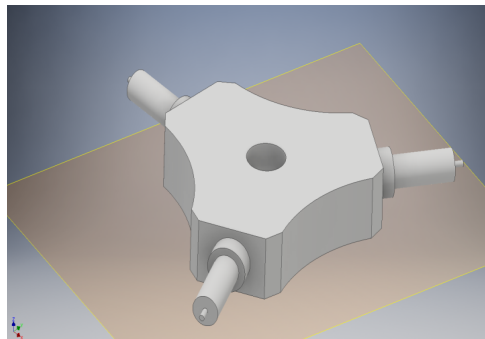
Place Sketch Plane to Project Profile on



Project entire profile



Extrude using projected lines on mesh surface as guides

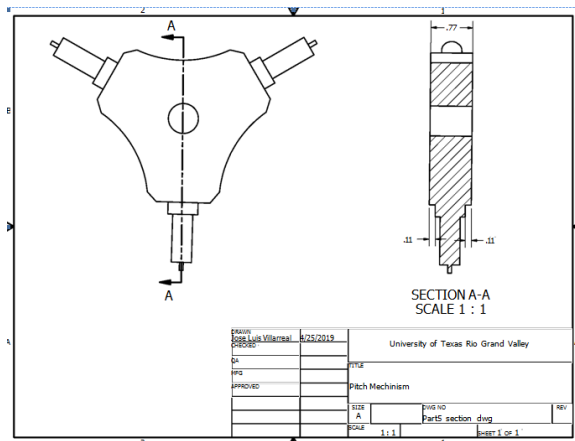


Finished 3D Model of PMH1

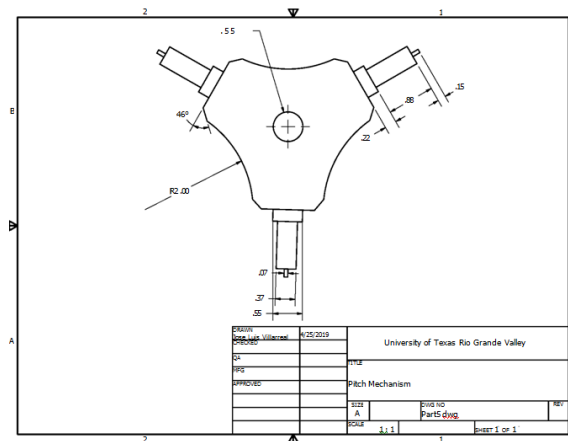
(Figure 10: Autodesk Inventor workflow)

## Autodesk Inventor CAD output

This process produced a 3D solid model of the critical part. The damaged area was edited and corrected. The CAD model gave a base on which an engineering drawing was created. The threads were not considered in the reconstruction process, as it was not a big problem to make the threads using conventional machining. Engineering inspection planning and production planning were carried out using the acquired engineering drawing. The following two drawings were produced using the RE PMH (Fig.11,12). Total time elapsed during the RE process was approximately 30 minutes.



(Figure 11: CAD Drawing1)



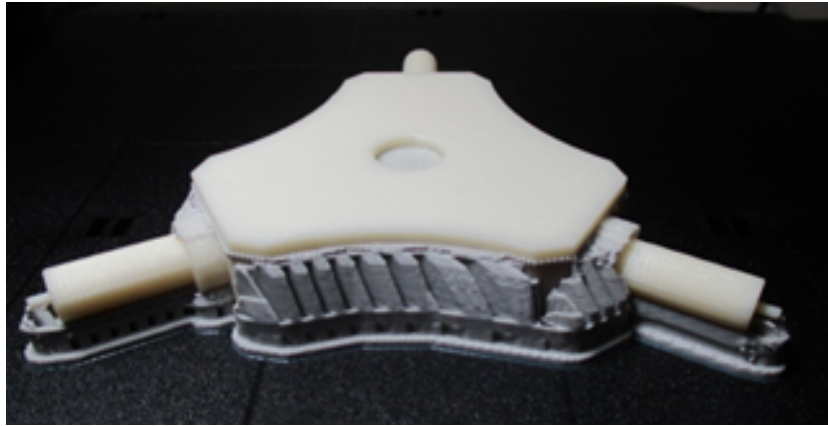
(Figure 12: CAD Drawing 2)

## Printing

3D Printing of PMH1 was carried out by the Dimension 1200es 3D printer (Fig.13). The chosen 3D printer (Stratasys Dimension 1200es) featured the largest build envelope of any Design Series performance 3D printer. The printer ran on Fused Deposition Modeling (FDM) Technology, it printed in nine colors of real ABSplus thermoplastic. This 3D printer allowed us to choose fine resolution or faster printing, with layer thicknesses of 0.254 mm (0.010 in.) or 0.33 mm (0.013 in.). The scanner had a high resolution of 0.1 mm and the resultant part was printed with the fine resolution of 0.254 mm layer thickness.

Printing took about 3 hrs. The file was opened on the Dimensions on boarding software. Some issues arose as the file was being imputed and simulated for printing. The scale ratio was 1:1 and had to be adjusted to 1: 1.0375. Minor increments had to be entered until right size was exhibited on the simulation workspace. This adjustment was necessitated because of the slight accuracy mismatch between the scanner and the printer. The scanner had a higher resolution than the finest layer thickness of the FDM printer. The second issue arose when the corrected prototype (PMH1) was printed. About  $\frac{3}{4}$  of the way up the prototype, a layer of support material was placed all across the section of the prototype (Fig. 14). The CAD file was revised and no flaw in

the CAD file was found. Upon further analysis, it had been found that the problem arose due to the glitch in the printer software.



(Figure 13: 3D Prototype PMH1)



(Figure 14: PMH1 Problems)

### **CMM comparison**

The CMM comparison was carried out in the Metrology lab under the supervision of the faculty advisors. Before the measurement, 0.5mm Ruby tip probe was calibrated. The Probe tip 4 x 40 was used in the measurement. The fixtures holding (PMH0) and (PMH1) were easily accessible and fixture fabrication was avoided. The PMH0 was fixed on three magnetic fixture pillars. The sizes of the pillars were 5 inches long and 1 inch in diameter. The pillars were screwed on to the CMM table and the metal (PMH0) was placed on top. The face on the X and Y plane was set flat on the three pillars. For the (PMH1) measurement, an existing fixture was placed on the CMM table and the (PMH1) was fixed to it. It followed the same orientation as (PMH0), with the X and Y plane of the part flat on the X and Y plane on the CMM. In order to fix the (PMH1) a threaded hole was placed on the part. A hole  $\frac{1}{4}$  inch deep was made with an ANSI #8 drill bit. Then an ANSI 10-30 thread tap finished off the walls of the small hole. The fixture threaded on to the (PMH1) and desired orientation was achieved.

The following steps were used:

1. Startup machine
2. Startup PC-DIMS
3. Place Part on table
4. Calibrate tip
  - a. Use tip 4X40
  - b. Set up A0B0 angle as master tip
5. Create alignment
6. Create measured features of all planes in profile of part
7. Create measured features of all arcs
8. Create dimension report of angles between planes and radius of arcs.
9. Print report

This process was applied to both (PMH0) and (PMH1).

The measurement for the projecting shafts and its diameters and lengths were carried out by the conventional metrology instruments. Values were recorded in inches and with a resolution of .01 inches.

## Results

The Following are the dimensions that were measured and recorded (Table 1, 2). The values are in Inches. The values recorded were according to profile definition and projecting shaft definition established in the Part Selection section of the paper.

Table 1: Features measured with CMM

Features measured with the CMM			
PMH0		PMH1	
Measurements in Inches			
R1	1.9669	R1	2.08
R2	1.9252	R2	2.03
R3	1.9608	R3	2.05
Measurements in Degrees			
A1	128.5309	A1	128.0335
A2	133.2379	A2	131.4512
A3	133.2276	A3	133.6369
A4	133.1166	A4	133.4654
A5	133.5003	A5	132.2224
A6	137.4629	A6	136.1956
PA1	55.5569	PA1	58.3883
PA2	59.8551	PA2	61.7722
PA3	66.5881	PA3	59.8395

Table 2: Features Measured with Conventional Metrological Instruments



Features measured			
PMH0		PMH1	
Measured in Inches			
Part Thickness	.78	Part Thickness	.77
L1 (length of projected Shaft 1)	1.31	L1	1.30
L2 (length of projected Shaft 2)	1.30	L2	1.31
L3 (length of projected Shaft 3)	Missing	L3	1.30
SS1	.11	SS1	.06
SH1	.39	SH1	.36
SC1	.57	SC1	.55
SS2	.10	SS2	.07
SH2	.38	SH2	.36
SC2	.55	SC2	.56
SS3	Missing	SS3	.06
SH3	Missing	SH3	.37
SC3	Missing	SC3	.56
TH	.54	TH	.55

## Discussion

Although some differences exceed a degree or tenths of an inch, the capabilities of Reverse engineering a corrected part from a damaged one was impressive. The similar values in the profile establish that replicating a critical part can come close to a tenth of an inch to the original part. Abilities to correct a critical aspect of a part that has been damaged are also exhibited here with the prototype being completely rehabilitated. The approximate time for someone to rehearse this procedure would be 5-6 hrs. This is a great groundwork for further exploration in Rapid manufacturing. The detailed procedures involved in the project were presented so that other institutions can further explore the efficacy of this methodology through applied research or senior design projects.

## Lessons Learned

The senior design students have proved their ability for continuous self-learning, by understanding how to address professional responsibilities. As a result of the different personalities coming together to work on a demanding assignment, friction between students was a problem, and should not cause any disturbance in team collaboration; by the end of the project, through counselling, cohesion became evident and the team performance showed improvement.

Students' commitment and self-confidence in their work, from the beginning of the project, was vital for the successful completion of the project. Stressful situations and technical difficulties tend to drop the students' interest in the project, but true commitment and enthusiasm to participate in an innovative, groundbreaking project kept the students on track; for this assignment, students remained aware of the challenges resulting from participating in a cutting-edge engineering project and the high level of commitment involved.

The project was constantly monitored by the faculty over the period of two semesters through weekly meetings with the students and providing them with the feedbacks on their progress. The students also maintained a diary of activities that monitors the accomplishments of various tasks and logistics. The project management was organized and monitored through the modern computer tools, such as Gantt charts and Excel project management system. The students had to provide periodic weekly written reports and make PowerPoint presentations of their project before the faculty and peers. These reports and presentations were valuable to students in gaining feedbacks and insight of the project. At the end of the project, the students learned the importance of organization, scheduling and made the best use of the meeting sessions to achieve specific goals according to the schedule. The project success was validated by the implementation of the rapid manufacturing methodology in producing critical parts for industries.

Communication between the students and faculty advisors was vital to create and promote a learning-friendly environment, determine project definition and identify benchmarks to ensure outcomes. Weekly team meetings are recommended to confirm completed benchmarks and analyze results.

Faculty must foresee challenges and have a possible solution in advance, to avoid delays affecting the project outcomes. It is vital for the faculty advisors to formulate multidisciplinary teams with critical thinking skills since the beginning of the project, linking different learning backgrounds to achieve improvement in the overall team performance.

### **Conclusions and Future Work**

Engineering solutions influence society at every foreseen and unforeseen level. Therefore, engineering education strategies must be developed to prepare undergraduate students for the ever-changing global environment. The senior design project experience will prepare the students to face the challenging tasks in the real-world industries. With the use of new technologies, the proposed rapid manufacturing techniques can lead to the development of practical solution to the complex problems faced by the modern industries.

Evaluation and analysis of student learning outcomes through capstone projects describe the qualitative values of the student understanding on the impact of engineering in a social and global setting. Self-learning and continuous education are expected, yet, a multidisciplinary engineering design team can effectively provide a wider range of viable solutions, improving expected outcomes. The integration of industry specific problems through capstone engineering projects are vital for the collective improvement of undergraduate engineering education.

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