ABSTRACT

Title of Document: DESIGN OF AN AUTOMATED ASSEMBLY
LINE FOR MANUFACTURING VISUAL
TENSION INDICATING FASTENERS

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Threaded fasteners play a major role in mechanical assemblies to clamp components or flanges. While bolted joints have been in use for many centuries and are simple to design and use, they are not foolproof; it is often difficult to achieve the required clamping force accurately by applying the designer-prescribed tightening torque, determined assuming ideal conditions of the contacting surfaces. Therefore, a concept that can directly measure tension on bolted joints is necessary. In this work, the concept of visual tension indicating fasteners is introduced and explained. After testing the feasibility of the concept, an automated assembly line is designed and fabricated in order to produce these fasteners with a more reliable manufacturing process.

DESIGN OF AN AUTOMATED ASSEMBLY LINE FOR
VISUAL TENSION INDICATING FASTENERS

By

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Dedication

This thesis is dedicated to my grandmother, parents and my younger sister who have sacrificed their lives for me to be who I am today. They have given me the support I need throughout my life and specially during this project. This work could not be done without their support.

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This project would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

First and foremost, my utmost gratitude to Dr. Chandrasekhar Thamire whose sincerity and encouragement I will never forget. He has been my inspiration as I hurdle all the obstacles in the completion of this research work. He has always had kind concern and consideration regarding my academic career. His unselfish and unfailing support as my academic advisor has always been the driving force for this project. His patience and steadfast encouragement to complete this study has been amazing. I do not have enough words to express my gratitude and appreciation to him, so I simply say: "Thank you!"

My former lab mate, Aleksandr Gorbashev, has been my idol in this lab. He taught me how to think out of the box and defined a higher level of quality expectation for me. I will always appreciate his patience for teaching me machining and for being a great friend outside of work environment.

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I consider myself lucky knowing Karim Najjar and Shreyas Parameshwaran. Karim and his high quality expectations brought this project to a new level. Shreyas

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Chapter 1: Introduction

1.1 Fasteners in Industry

There are many industrial applications where bolted flange joints are used. They are extensively utilized in the chemical, petrochemical, and nuclear power industries. Although bolted flange joints, shown in Figure 1, are considered as simple components in the industry, they are far from being foolproof. In addition to being prone to leakage, they often require maintenance while in operation in which case the bolts are either retightened as is hot torqueing or untightened to be replaced. Shutting down a power plant in order to do the maintenance on bolted joints is costly. Such maintenance work exposes the operator to a potential risk because the bolt load alteration can produce a gasket load unbalance, which results in the local gasket contact stress to drop below some critical value, causing major leak and hence jeopardizing the life of the worker. Therefore there are both safety and cost issues involved with bolted joints in industry. There are many rules and guidelines such as ASME guideline for bolted joints in order to find the proper torque value, but there are still many issues with the discrepancy between the theoretical calculations and actual measurements. [1-3]

Figure 1. Bolted Joint: Pipe Joint

1.2 Types of Bolted Joint Designs

There are two main types of bolted joint designs. In one method the bolt is tightened to a calculated clamp load, usually by applying a measured torque load. The schematic of this type is shown in Figure 2. The limiting factor in this type of design will be the clamping force, meaning that, all of the components in the joint will be designed in a way that they will have higher strength than the clamping force [1]. This type of joint design provides properties such as:

- Greater preloads in bolted joints reduce the fatigue loading of the fastener.

- For cyclic loads, the fastener is not subjected to the full amplitude of the load; as a result, the fastener's fatigue life can be increased or extended indefinitely.

- As long as the external loads on a joint do not exceed the clamp load, the fastener is not subjected to any motion and will not come loose, obviating the need for locking mechanisms.
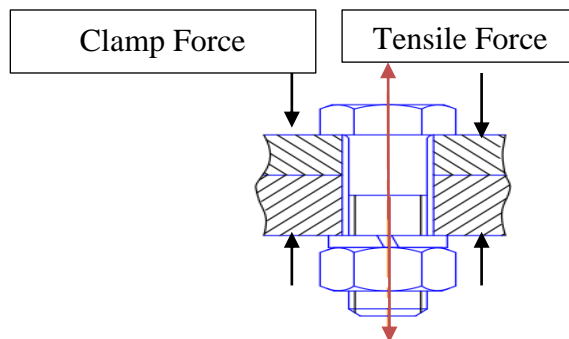

Figure 2. Bolted Joints with Known Required Clamping Force

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The other type of bolted joint does not have a designed clamp load but relies on the shear strength of the bolt shaft, as shown in Figure 3. This may include clevis linkages, joints that can move, and joints that rely on a locking mechanism.

The clamp load, also called preload, of a fastener is created when a torque is applied. The clamp load is generally a percentage of the fastener's proof strength. A fastener is manufactured to various standards that define, among other things, its strength and clamp load. In assemblies involving flanged joints, threaded fasteners are extensively used to exert the required sealing pressure at the joints, while offering the flexibility of loosening and tightening during maintenance or other needs. Such fasteners need to be preloaded each time to a pre-determined tension value for appropriate sealing [1].
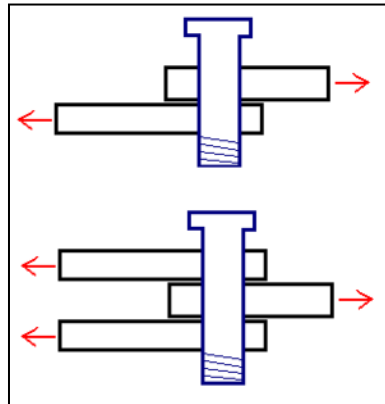
Figure 3. Bolted Joints with Known Shear Force

1.3 Bolts in a Joint

A bolt in a joint can serve one of the following purposes. It can either act as a pin to keep two or more joint members from slipping relative to each other or it can act as a heavy spring to clamp two or more pieces together. There are a lot of factors which affect the results we get when we tighten a bolted joint like friction, the hardness, finish and dimensions of all parts, and the creep of gaskets. Each of these

factors will vary from bolt to bolt and joint to joint because of manufacturing or usage tolerances. Instead of dealing with hard-and-fast numbers, we will be forced to estimate the amount of preload we might get while admitting that there is a possibility that we will get something else, and often a chance that we will not get any preload at all. Thus, we will be dealing with risk rather than with certainty.

1.4 Torque versus Clamping Force

Currently, in nearly all the industrial applications that require flanged joints, fastener-tightening torque values are determined by engineers using widely known correlations between fastener load and fastener tightening torque. There are torque charts available in order to apply the correct amount of torque to tighten a fastener in a joint which is based on its property class or grade.

One widely used correlation is the Maney's formula [1], which provides a simple relationship between the initial bolt tension, installation or the fastener-tightening torque, coefficients of friction at the fastener bearing surface and thread-contact surfaces, and geometries of the thread and bearing.

$$T = \frac{1}{2}F\left(\frac{P}{\pi} + 1.155\mu_s d_p + \mu_w D_v\right) \qquad \text{Eq. 1}$$

p in the above equation is the thread pitch and μ's are the frictional coefficients. It can be seen from the above equation that the torque value is proportional to the clamping force and also depends on the frictional characteristics and geometry of the mating parts. The above relationships assume uniform contact pressures and rigid-body approximation of the clamped component.

D_v in the above equation is called the equivalent diameter of friction torque on the nut-bearing surface and is given by:

$$D_v = \frac{2}{3} \frac{(d_w^3 - d_h^3)}{d_w^2 - d_h^2} \qquad \text{Eq. 2}$$

Another popular method to estimate the bolt-tightening torque is provided below. There are three friction components to be considered: the pitch friction component, the under-head friction component due to the sliding of the fastener head on the flange and the thread-friction component between the male and female thread. The basic torque distribution for a fastener is shown in Figure 4. The torque applied to a fastener is absorbed in three main areas. First, there is underhead friction, which may absorb 50% or more of the total torque. Thread friction absorbs as much as 40% of the applied torque. The final 10% of the applied torque develops the clamping force that holds the components together. Therefore if the friction force (on any component) is increased by 5%, it can reduce tension by half.

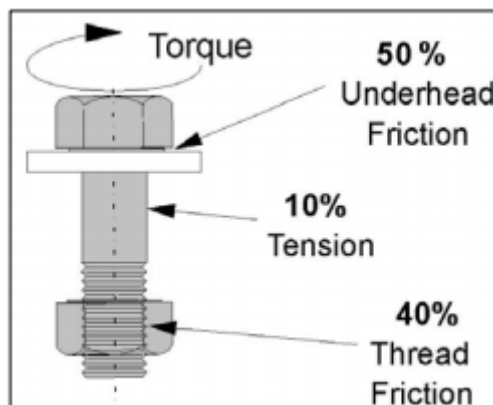
Figure 4. Friction Distribution in a Bolted Joint

The K, or nut factor, depends on anything that increases or decreases the friction within the threads of the nut. Although a nut factor of 0.2 is usually assumed for steel-bolted joints, the torque value applied can have error up to ±30%. The preload developed in the bolt is related to the value of torque as shown in the following equation.

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$$T = KFD \qquad \text{Eq. 3}$$

This equation assumes a linear relationship between torque verses angle of rotation. For most common fastener materials the engineering values of the two variables (D & F) are well-defined. The problem with this equation lies in the Nut Factor (K). This is a combination of three factors where each factor is a function of different variables as discussed below:

- K1, a geometric factor in the shape of the threads. Variation in the shape of the thread may cause friction to increase or decrease.

$$K_1 = K_1(p, D) = \frac{P}{2 \times D} \qquad \text{Eq. 4}$$

- K2, a thread friction related factor- the friction between the threads of the bolt and the threads of the nut.

$$K_2 = K_2(\mu_t, \alpha, D, r_t) = \frac{\mu_t r_t}{D \times \cos\alpha} \qquad \text{where } r_t \propto (D, p) \qquad \text{Eq. 5}$$

- K3, an under head friction related factor- the friction of the nut against the surface it rotates on.

$$K_3 = K_3(\mu_c, D, r_c) = \frac{\mu_c r_c}{D} \qquad \text{where } r_c \propto (D, D_{\text{Nut Head}}) \qquad \text{Eq. 6}$$

The friction coefficients μ_t and μ_c are key variables in the basic equation. While there are published tables for K, these will usually vary from publication to publication. These values are usually combined values. From these nut factors, there will be three different torque values defined. Torque necessary to overcome the pitch friction component (geometric factor) is given by:

$$T_1 = K_1 FD \qquad \text{Eq. 7}$$

Similarly, torque component required to overcome the friction force between the male and female threads is given by:

$$T_2 = K_2 FD$$

where α is half of the thread angle profile which is 30° for many threads. The torque component that is needed to overcome the turning fastener head or nut and the clamped joint surface is:

$$T_3 = K_3 FD$$

Then the total torque will be the summation of these three components of torque which is calculated (estimated) from the three different friction coefficients:

$$T = T_1 + T_2 + T_3$$

Determination of a safe preload level for a bolt has been the emphasis of many discussions and research programs. [9] The practice of applying high clamp loads in the range of the fastener yield stress is often used to prevent loosening of bolts under vibration conditions and helps prevent fatigue failure. However, this practice may degrade the reliability of the fastener when aggressive environmental conditions involving corrosion are encountered. There is a lot of work done on the failure analysis of a fastener in order to determine the service stresses because these stresses have a significant effect on the in-service behavior. Determining if a bolt was over tightened after the bolt fails is difficult, but would be a significant help in determining the circumstances leading to failure [1-5].

Therefore, having a system that can measure the elongation or clamping force of the bolt directly is necessary in industry. Unfortunately, strain gages or data acquisition systems that can measure strain (or elongation) are costly and in some

locations not practical to attach them to the bolt [2]. A technology or concept is needed to be developed in order to make sure a bolted joint is tightened properly. The flow chart shown in Figure 5 describes what the requirements are for this concept. In the following chapters of this work, the developed concept that can directly indicate the tension in fasteners is introduced. It is followed by the proof of concept tests. After testing the feasibility of the concept, the manufacturing process and the automated assembly line for these types of fasteners are discussed in detail.
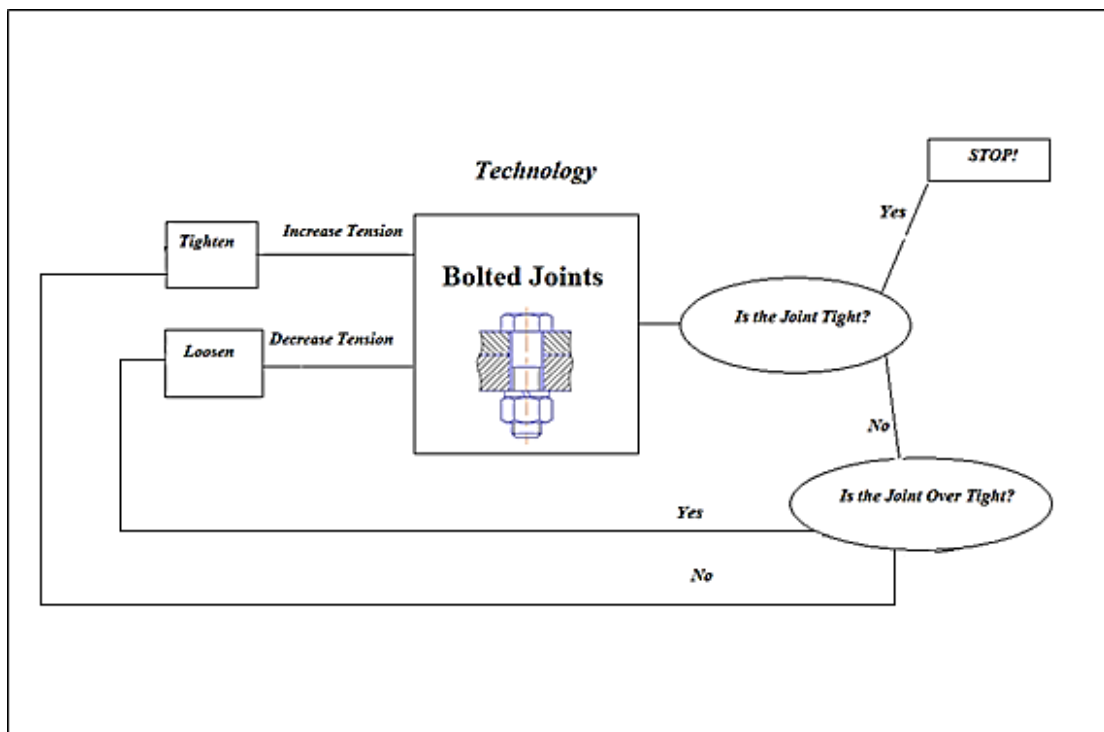
Figure 5. Flow Chart for Checking if a Bolted Joint is Tight or Not

Chapter 2: Concept of Visual Tension Indicating Fasteners

2.1 High Resolution Visual indicating fasteners

The dependency of bolted joints, more specifically required clamping force, on applied torque, discussed in the introduction of this work, is eliminated by using the concept of visual tension indicating fasteners. This concept, titled the "Visual indicating fastener", involves indication of tension visually instead of being derived from torque values. Figure 6 shows the following elements of a Visual indicating fastener:

- Pin and Silicone Washer

- Micro-Indicator

- Optical Element

- Window Assembly

Figure 6. Smart Bolt and Internal Components

Operation of these fasteners is based upon the response of the optical micro-indicator element to the stretch of the fastener under tensile loading, measured

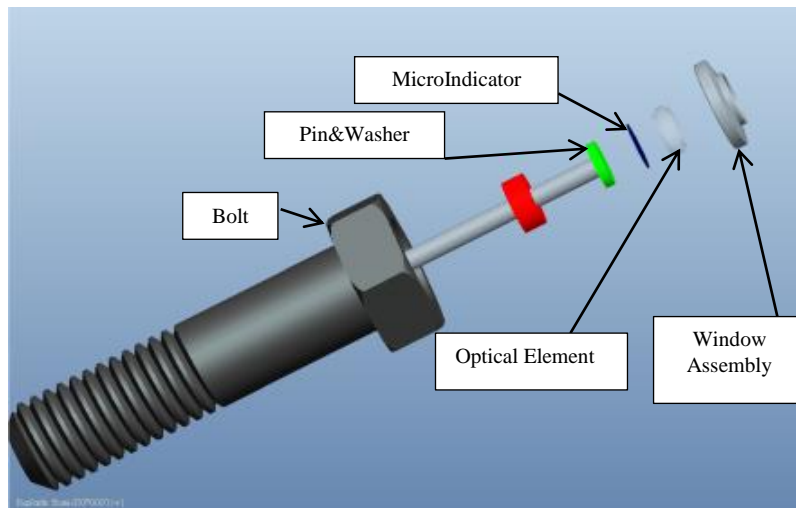relative to that of the pin secured within the fastener. As the fastener changes length under tensile loading, a reproducible visible color change is produced through the flow of the micro-indicator fluid into the cavity created by the stretch of the bolt. Figure 7 shows the cross section of a bolt and the relative motion of the internal components. The amount of the fluid flowing and hence the composite color of the fastener window change as the load applied is changed. The visual indicating fastener concept is based on the behavior of an optical microindicator element. The microindicator changes color on the head of the pin due to relative motion of pin with respect to the window ring on the head of the bolt.
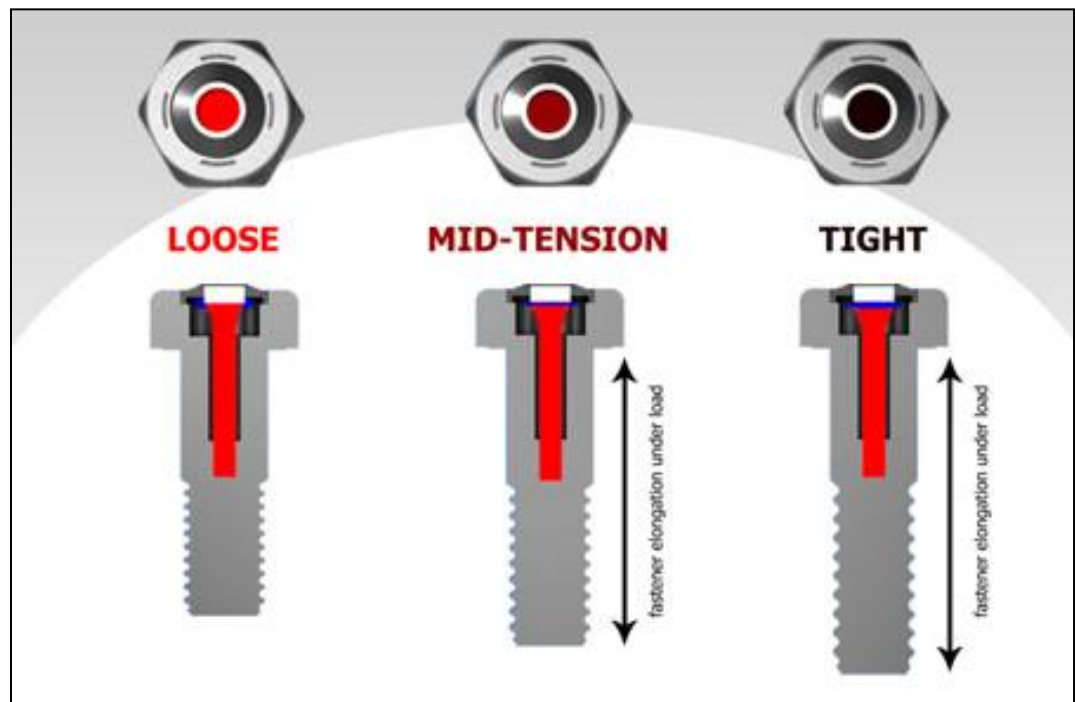
Figure 7. Cross Section of Visual indicating fasteners, Left: Loos, Middle: MidTension, Right: Full Tension[24]

The indicator portion of an unloaded bolt has the gage pin head pressing up against a transparent window. The window is free to move axially, however it is biased towards the pin head by a resilient ring (wave spring) as shown in Figure 8.
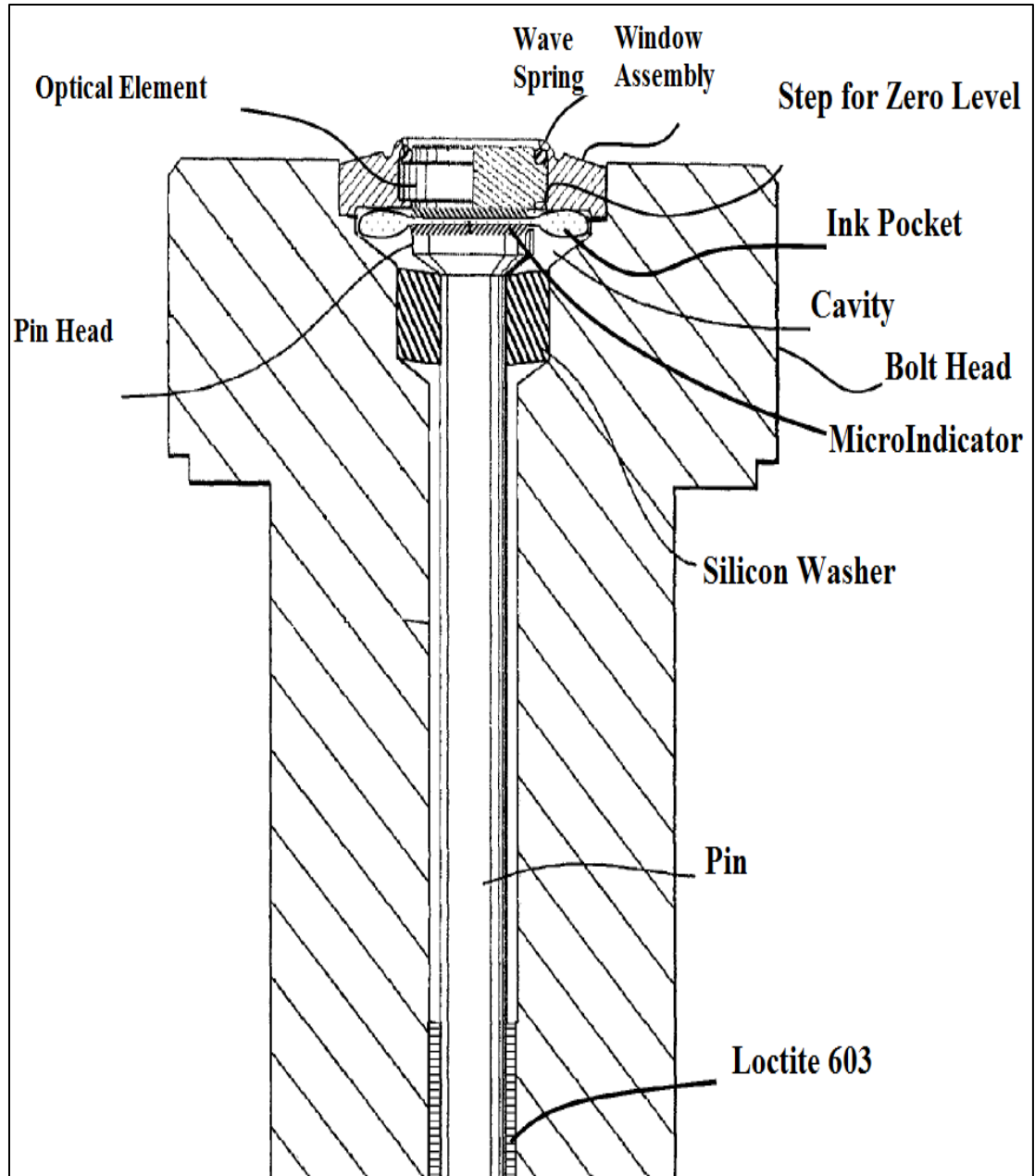
Figure 8. Cross Section of Visual Indicating Fasteners and Internal Components [25]

Between the window and pin head, a flexible transparent envelope (microindicator) contains a tiny drop of a proprietary light-absorbing fluid. The window pressing against the pin head squeezes the fluid from the gap. With no fluid in the gap, the color of the pin head (bright yellow) may be seen through the window. Tightening the bolt retracts the pin and the window follows along because it is urged

downward by the resilient ring. The result is no color change with initial tightening. Additional tightening makes the window hit a stop, thereby preventing further downward movement. Further tightening of the bolt lets the fluid enter the gap between pin head and window, triggering a dramatic color change from yellow to green. The entire color change takes place in the final 10 to 15% of the tightening sequence, boosting sensitivity and tension resolution.

HR (High Resolution) Visual indicating fasteners have been engineered to maximize indicator sensitivity and to position this maximum sensitivity response at the "fully-tightened" or high end of the tension range. The bright yellow indicator begins to turn color at 85-90% of design tension, is a grass green color at design tension (typically 90% of proof load) and turns to nearly black at over tension. The sensitive microindicator is capable of visually resolving a deflection of only 60 micro inches, which allows tensioning to an unprecedented precision, specified at 5% accuracy but often as precise as 2% of fastener minimum tensile strength. This represents the highest precision available in any self-contained commercial direct tension indicating fastener product. Customer's specialty bolts or commercially available bolts of diameters ranging from 7/16" (M10) to 1 ¼" (M32) can be usually converted into Visual indicating fasteners.

Microindicator between a window in the bolt head and the brightly colored pin head contains a tiny drop of fluid that absorbs light. Tightening the bolt strains the bolt linearly and moves the gage pin away from the window, so there is a thicker layer of fluid between it and the pin head. The fluid absorbs incident light of intensity, I_0, according to the Beer-Lambert Law of Absorption[26]:

$$\frac{I}{I_0} = e^{-kt}$$

which states that the amount of radiation, I, absorbed in a fluid layer is inversely exponential with the fluid layer thickness, t, and is therefore linear on a semi-log plot. The term, k, quantifies a fluid's absorption properties.

The tension-indicating mechanism has no moving parts in the usual sense, operating entirely by elastic deformation and fluid migration. As a result, the indication is completely reversible and may be operated innumerable times without wear or degradation. This feature also helps the bolts resist damage from the severe vibrations common in helicopters, automobiles, etc.

2.2 Proof of Concept Test

2.2.1   Test Setup

In order to evaluate the feasibility of the concept, to be able to display a clear color change when subjected to design load, five ½-13x4 ¼" UNC Grade5 Visual indicating fasteners were tested. The objective was to compare the readings from the strain gages with the fastener color response and catalogue for calibration and analysis. Every fastener, used in a joint, applies a compression load. As a result, the reaction force on the fastener is tension. Therefore, if a known tension value is applied to the Visual indicating fastener and the elongation on the bolt is measured by strain gage and correlated with the color change on the head of the bolt, the concept can be tested for feasibility and repeatability.

In order to verify that the stress applied to a specimen (bolt in this case), the stress and strain should be measureable and the tension applied should be controllable. There are different methods to put the fasteners under tension. However, having access to the shank of the fastener in order to attach the strain gages is the main limitation in available bolt tensioners in industry. A key factor in designing this test setup would not be only to ensure that the load is applied completely to the bolt and not to the members of the structure but also ensure the load is applied symmetrically about the axis of the bolt. As shown in Figure 9 and 10, different concepts were generated in order to design this setup. After evaluating each concept, 3D CAD representation shown in Figure 11 was selected as the final concept [11-12].
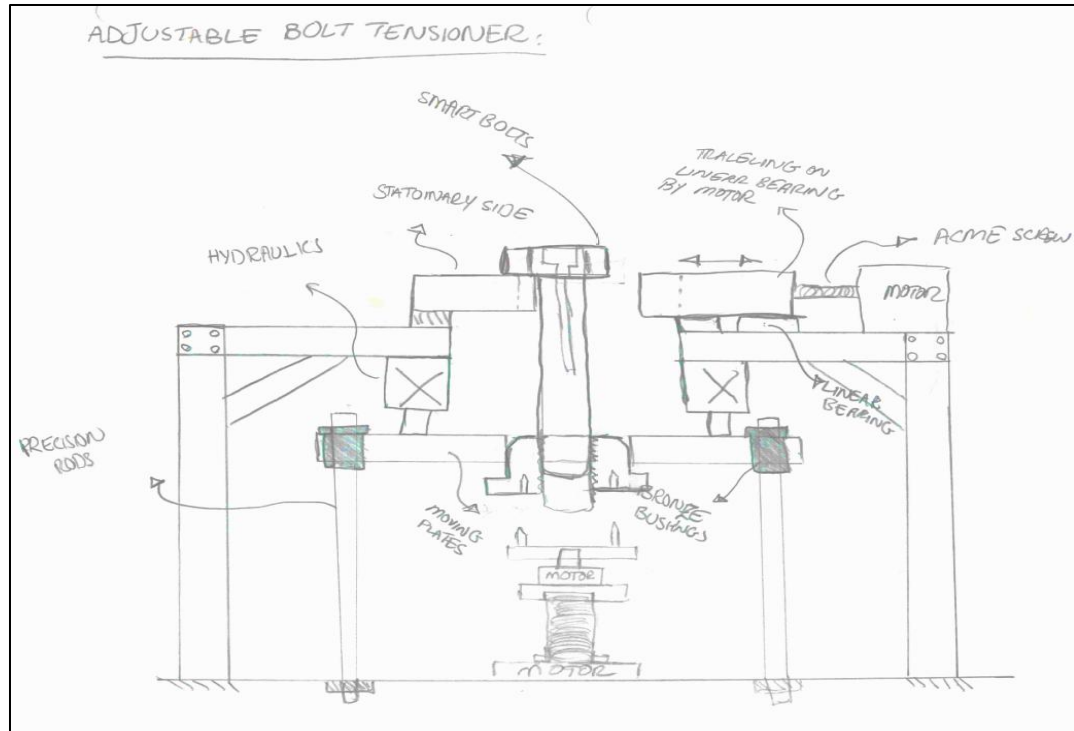
Figure 9. Sketch for Adjustable Bolt Tensioner

The concept shown in above figure has the capability of accepting different sizes of bolts in diameter due to the gripping mechanism introduced. The lead screw attached to the motor would open and close the vice around the shank of the bolt. The top horizontal beams are stationary and rigid and the hydraulic cylinders push the bottom plate downward, causing the bolt to go under tension. However, the center of the bolt would change its location from one bolt to the other and misalign the uniaxial load applied.
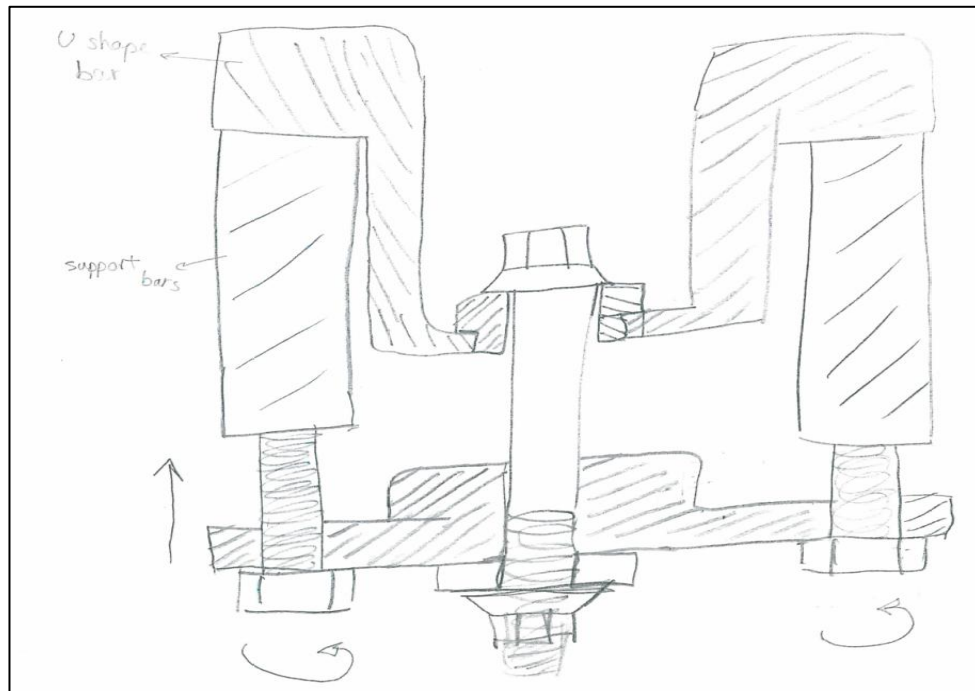
Figure 10. Sketch of Bolt Tensioner

The concept shown in the above figure is based on the concept of tightening two other bolts until the main specimen (central bolt) would go under tension. However, manufacturing the U shape part in the center and having no deflection on the piece is critical and challenging. After evaluating each concept, 3D CAD representation shown in Figure 11 was selected as the final concept [11-12].
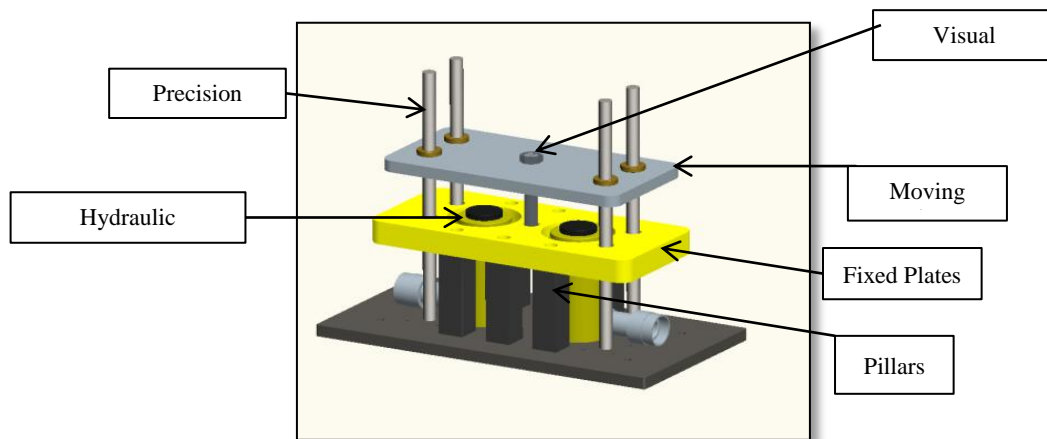
Figure 11. 3D CAD Representation of the Test System

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The concept involves mounting the bolt between a stationary and a movable plate. In order to do that, the bolt is put in the system and the nut is hand tightened. In practice, two threads are exposed for any bolt and nut joint. Then two hydraulic cylinders push the movable plate uniformly upward until the bolt starts going under tension. Pillars are used in order to keep the stationary plate fixed. The stationary plate is 1" steel plate which is heat treaded (SAE specifications, heating temperature of 1500F and oil quenched and tempered) around the nut area. The movable plate is ½" steel plate. Bronze bushings were press fitted into the movable plate to gain a transition fit between the bronze bushings and the steel precision rods.

It is again important to note that the pressure can be measured by the hydraulic cylinders gauges and the strain on the bolt can be measured by the strain gauges attached to the shank part of the bolt. The tension applied to bolt is completely controllable. The fixed plate has two threaded mounting holes for the hydraulic cylinders. This setup is capable of accepting different bolt heights. It can apply tension to bolts from 2" to 4 ¼" in length.

After designing the test setup, the physical prototype was fabricated as shown in Figure 12. By attaching the strain gauges on the shank of the bolt and applying different loads by the hydraulic plungers, changes in the bolt were observed.

Figure 12. Physical Test Device

2.2.2   *Experiment Procedure and Results*

There were five samples used in this experiment which were ½"-13x4 ¼" Grade 5 Visual indicating fasteners with the nominal yield strength of 120,000psi (proof strength of 92,000psi). Bolts were preloaded using a force of 7500lbs. To measure elongation of the bolt, the Wheatstone bridge concept was used. From the output voltage elongation of the bolt and the nominal bolt stress were calculated.

In order to make sure that there is a significant difference in the color of the bolt when different loads are applied, digital photographs of the bolt were taken during different stages of loading. Every color that can be seen by eyes has three components of Red, Green and Blue color in it. By knowing the RGB (red, green, blue) values of the images of the bolt, they were compared to each other and between trials by using the RGB Color Picker software. Figure 13 shows the pictures taken under no load in the loose condition (left; red indication), 50% of design load

(middle; dark red indication), and 100% of design load which is 7500lbs for this specific experiment (right; black indication).

Experiments were done for five different bolts and five times for each bolt. RGB values were recorder for loose, 50% design load, and 100% load design load settings. Table 1 shows the 95% confidence intervals for the three settings. As these values indicate, variance in the results is small. Individual as well as repeated tests nearly yield the same result, implying high repeatability of the performance of the fastener under the test conditions.

Table 1. 95% Confidence Intervals

	Red	Green	Blue
Loose	238.67~239.69	35.77~37.43	35.92~36.86
50% Load	100.99~102.07	6.96~8.1	49.97~51.97
100% Load	44.3~45.96	12.03~13.17	49.9~51.04

Results in Figure 14 show the mean of R value for each tension. As the results show, means for the three states are significantly different from each other, which is an indication that the color difference between applications will be notable.
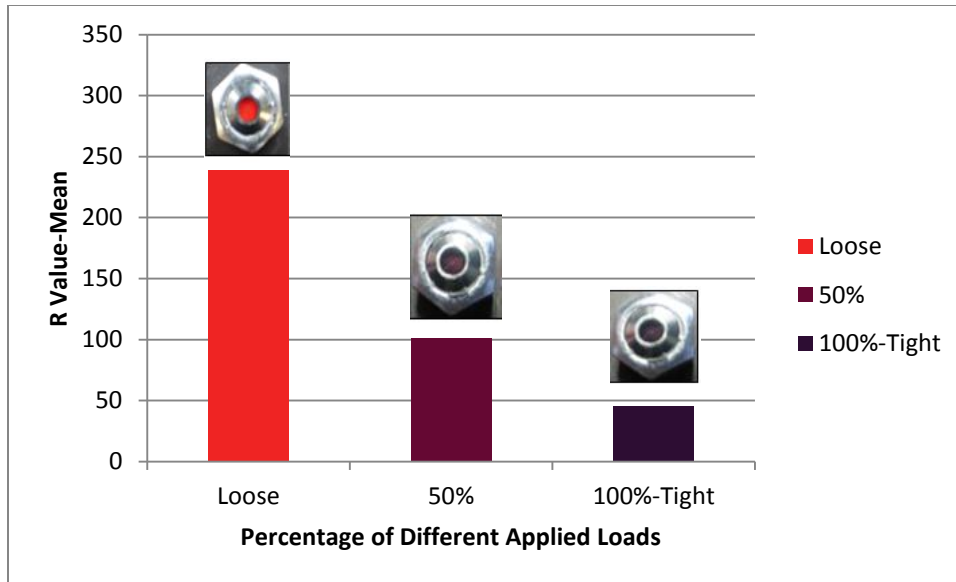
Figure 14 Response of Visual Indicating Fasteners to Changes in Applied Loading

Results from Tukey-Kramer multiple comparisons test indicate that all three values are significantly different from each other (p<0.0002). The resulting pair-wise confidence intervals for the differences in means are given in Table 2.

Table 2. 95% Confidence Intervals For Pair-Wise Differences in Means of Red Values

	95% Confidence Interval for Pair-wise Differences	Mean Value for Difference between Means
$\mu_{Loose} - \mu_{50\%}$	136.4 ~ 138.8	137.6
$\mu_{Loose} - \mu_{100\%}$	192.8 ~ 195.2	194
$\mu_{50\%} - \mu_{100\%}$	55.2 ~ 57.6	56.4

2.2.3   Color Chart

After evaluating the color changes for loose condition and 50% and 100% of design load settings, more experiments were conducted for 25%, 75%, and 125% (over tight) design loads for the selected bolt size. Based on the results, the following

color chart was developed. By comparing the color on the Visual indicating fastener with the color on the chart, one can determine if the fastener is tightened to the design load (or a proportion of it).
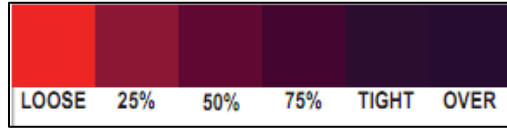
Figure 15. Color Indicator Chart for Visual indicating fasteners

Colors on the color chart, shown in Figure 15, were also tested for repeatability. As in the previous case, bolts were tested in the loose, 50% tightened, and 100% tightened condition. Load values and corresponding RGB numbers from the color chart were noted. Results from the color chart were compared to the measurements from photographs taken during previous set of experiments. Table 3, 4, and 5 shows the results from direct measurement of the color chart along with the confidence intervals for the means of RGB values from the photograph measurements, respectively.

Table 3. Loose Condition

	Red	Green	Blue
Color Chart	239.6	37	36.8
Confidence Interval	238.67~239.69	35.77~37.43	35.92~36.86

Table 4. 50% Design Load

	Red	Green	Blue
Color chart	101.4	7.8	51
Confidence Interval	100.99~102.07	6.96~8.1	49.97~51.97

Table 5. 100% Design Load

	Red	Green	Blue
Color Chart	45	12.4	50.4
Confidence Interval	44.3~45.96	12.03~13.17	49.9~51.04

In practice, if bolt loads needed are known, corresponding color values can be noted from the color charts and required bolt loads can be applied until the bolts meet the color requirement.

2.2.4 *Tension versus RGB*

After running multiple experiments on these bolts, the data points are plotted in order to create a mathematical model for the relation between tension and R component of the color value.   In different applications such as pressure vessels, boilers, wind turbines, the design tension (or required clamping force) rather than the torque value required to tighten the fastener. Therefore, the correlation between the R value and design tension is developed too, shown in Figure 16 and Equation 12.
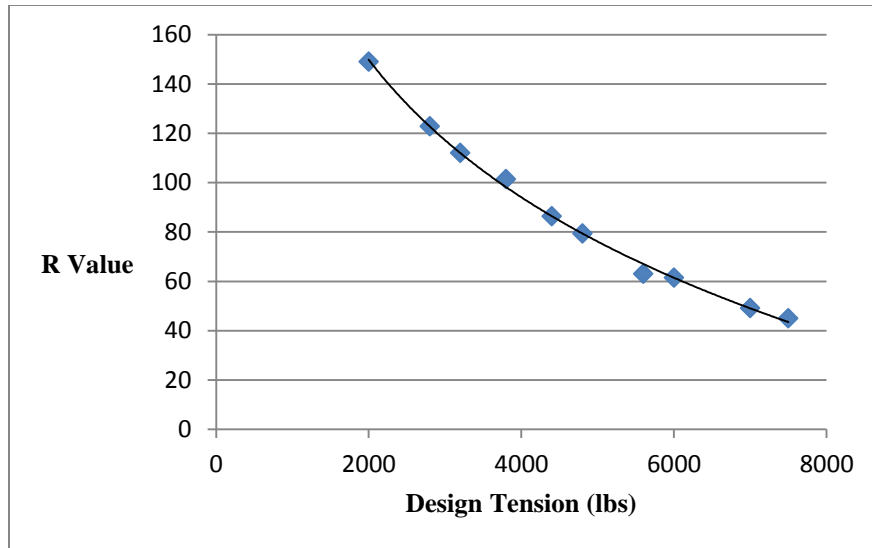
$$R = -80.42 \ln(T) + 761.06 \qquad \text{Eq12}$$

2.2.5   Torque Value

Currently torque values are extensively used in order to fasten joints. In order to replace fasteners in service for which torque values have been used previously, different corresponding clamping forces were applied to the bolt and corresponding R values of the bolt were detected. Figure 17 shows the relationship between the measured R values and applied torque.
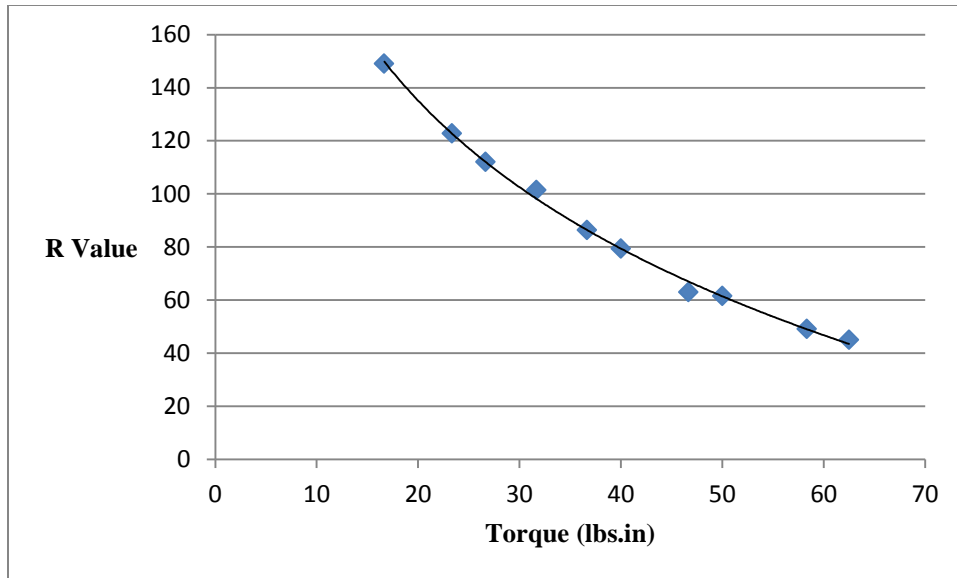
Figure 17. R Value vs. Torque

The correlation was developed based on the measurements. This relationship can be used when replacing existing fasteners of the same size considered in the study, which currently use bolt-tightening torque values for tightening. The correlation between the R values versus torque is shown in Equation 13.

$$R\_Value = 223.67e^{-0.002T}$$ Eq. **13**

For replacement purposes, color chart with different R values noted on it will be made available to assembly operators. R values for the specific application can be found from the corresponding torque values. Operators can then tighten the replacement Visual indicating fasteners until the "tight color" is achieved.

By having these correlations the color charts developed are more accurate and can be used in different applications. Operators can either tighten the replacement

Visual indicating fasteners until the tight color is achieved or for new applications the color chart defines the design tension.

2.3 Effect of Cavity in Visual indicating fasteners

In the previous sections, the feasibility of the concept is tested. Although there are many benefits using visual indicating fasteners in industry, there are also tradeoffs involved. One of the main disadvantages of using visual indicating fasteners is the machined cavity in the bolts. In order to realize the effect of this modification on these bolts, the following study is done.

2.3.1 Simulation Setup

Each visual indicating fastener needs a cavity for the internal components to go houses. The cross section of the cavity is shown in Figure 18. In order to understand this effect of this modification on strength reduction in the bolt finite element analyses is done by use of commercially available ProEngineer software and the results are compared with a bolt (same grade) without cavity. In this section of the paper, these studies and their results are discussed.
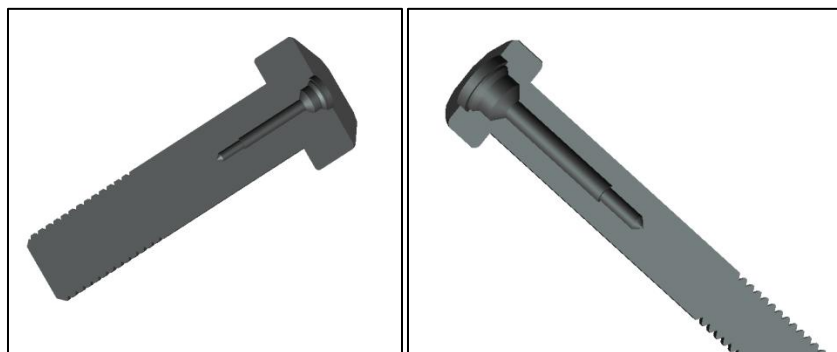

Figure 18. Left: Cross Section of Cavity in 1"-8 Bolt, Right: Cross Section of Cavity in 1/2"-13 Bolt

As mentioned in previous section, Visual indicating fasteners change color at *design tension (design load).* For each bolt in industry, there is either a grade or class specified which define a corresponding proof Strength (in pressure unit) for it. Design tension in Visual indicating fasteners is defined as the following equation.

$$Design\ Tension =$$

$$(safety\ factor) \times [Proof\ Strength\ \times Tensile\ Stress\ Area\ of\ the\ bolt]$$

<div align="right">Eq. 14</div>

The safety factor is usually a percentage from 60 to 90% of proof load. However, for the simulations done we are considering the 70% (which is the most common one for different applications). By defining the safety factor, it is assured that the smart bolt will not reach the plastic region during tightening process. There are four common fasteners used in industry that are studied in this paper. For each bolt, design tension is calculated using the Eq. 14 and shown in Table 6. These bolts are all grade 8 bolts with proof load of 120ksi.

<div align="center">Table 6. Design Tension for Different Bolt Sizes</div>

Bolt Size (inches)	Design Tension (lbs)
1/2-13x4	11900
5/8-11x4	18970
3/4-10x4	28070
1-8x4	81410

For each simulation, the bolt was modeled in ProEngineer. They are constrained from under the head of the bolt and the corresponding design tension is applied to the threads holding the nut as shown in Figure 19.
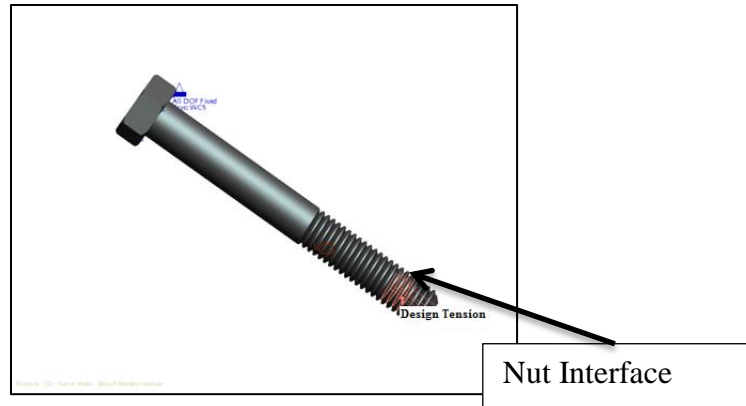
Figure 19. Simulation Configuration of the Finite Element Analysis on 1/2"-13 Bolt

2.3.2   *Finite Element Analysis Results*

As an example for ½-13 UNC bolt, design tension of 11900lbs is applied to the bolt. The results (stress concentration) for the bolt with the cavity and without the cavity are compared. In Figure 20, the von Mises stress is shown for two different bolt sizes of 1/2" and 1" diameter with and without the cavity.
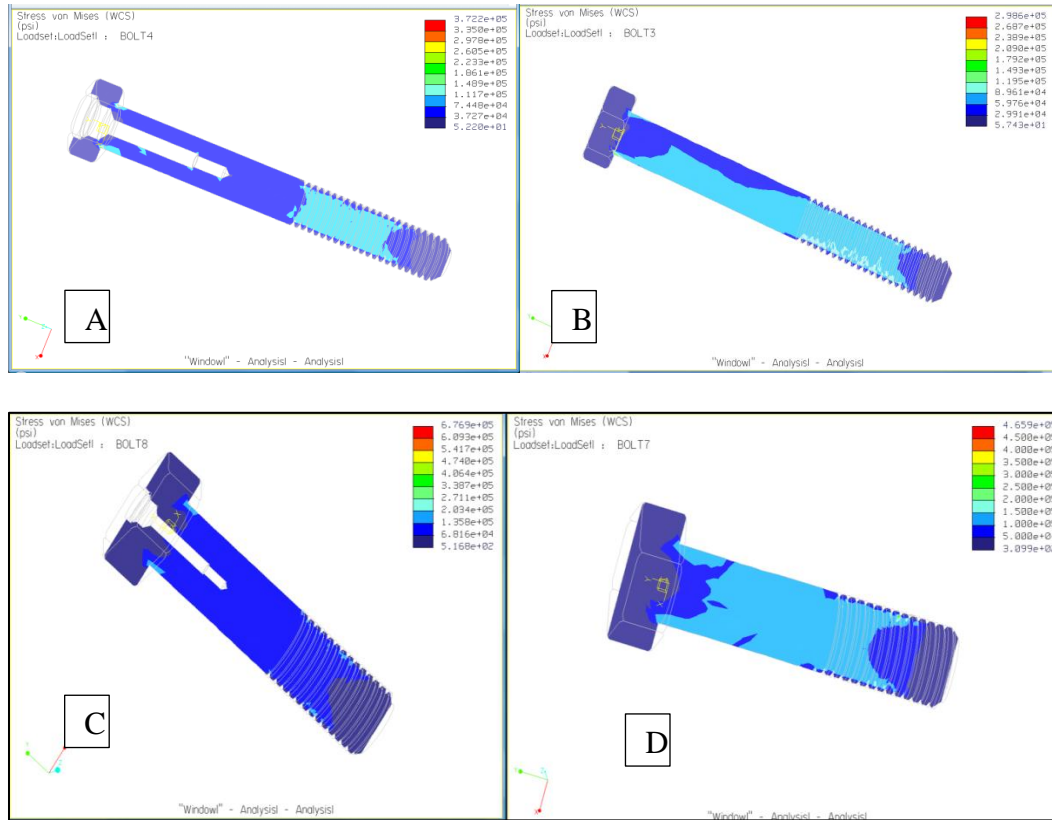
Figure 20. von Mises Stress Concentration on: (A) 1/2-13 Bolt with Cavity, (B) 1/2-13 Bolt without Cavity, (C)1-8 Bolt with Cavity, (D)1-8 Bolt without Cavity

There are three locations in the fasteners where failures could be expected to occur: (1) under the head of the bolt at the radius; (2) the first thread in the nut, and (3) the hole shank where the pin is bonded. The maximum von Mises stress (psi) is observed at three different locations on each bolt. Each of these results is plotted in order to understand the effect of this modification on the location of stress concentration. Figure 18, 19, and 20 show how the stress changes at different locations of the bolt due to this modification.

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Figure 21. Comparison of maximum von Mises stress around the head area of different sizes of bolts with and without cavity
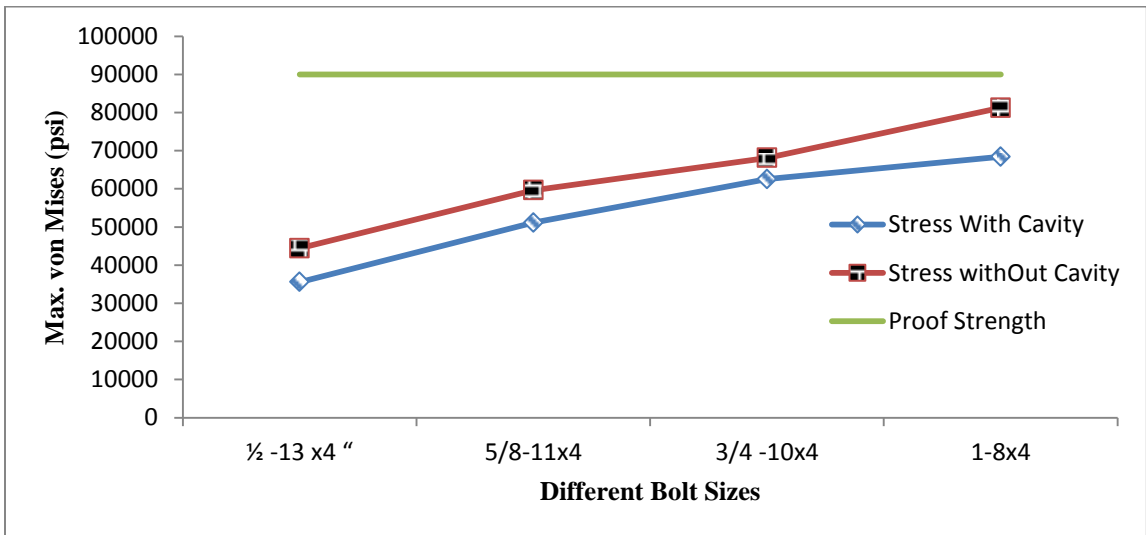
Figure 22. Comparison of maximum von Mises stress around the shank area of different sizes of bolts with and without cavity
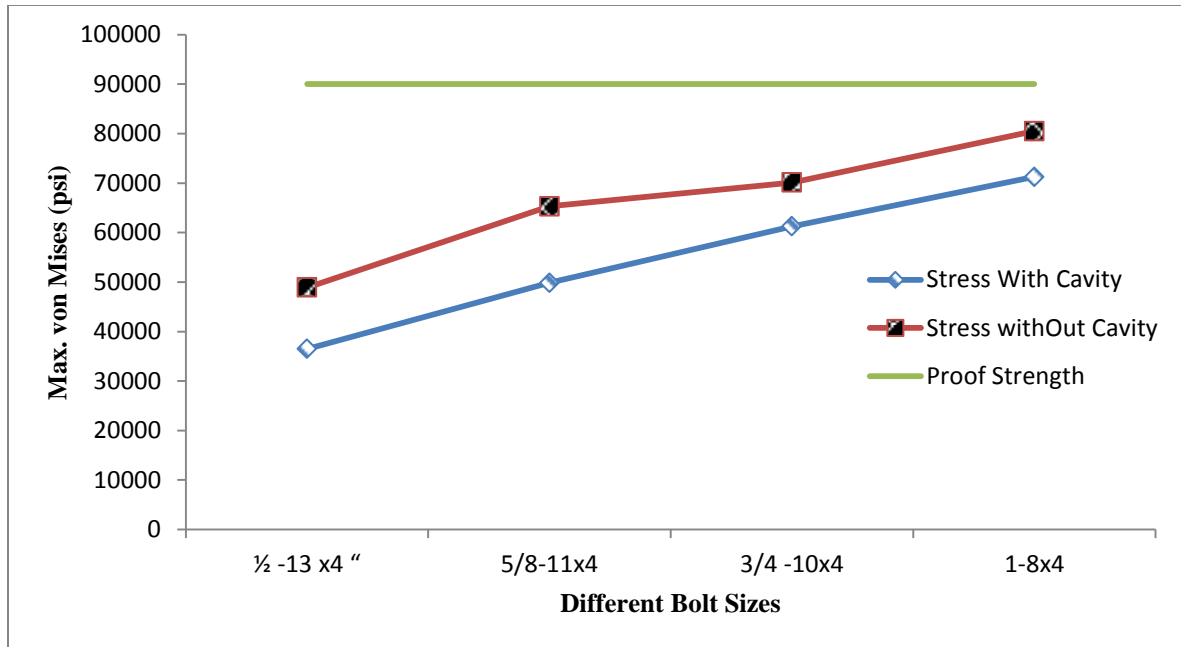
Figure 23. Comparison of maximum von Mises stress around the thread area of different sizes of bolts with and without cavity

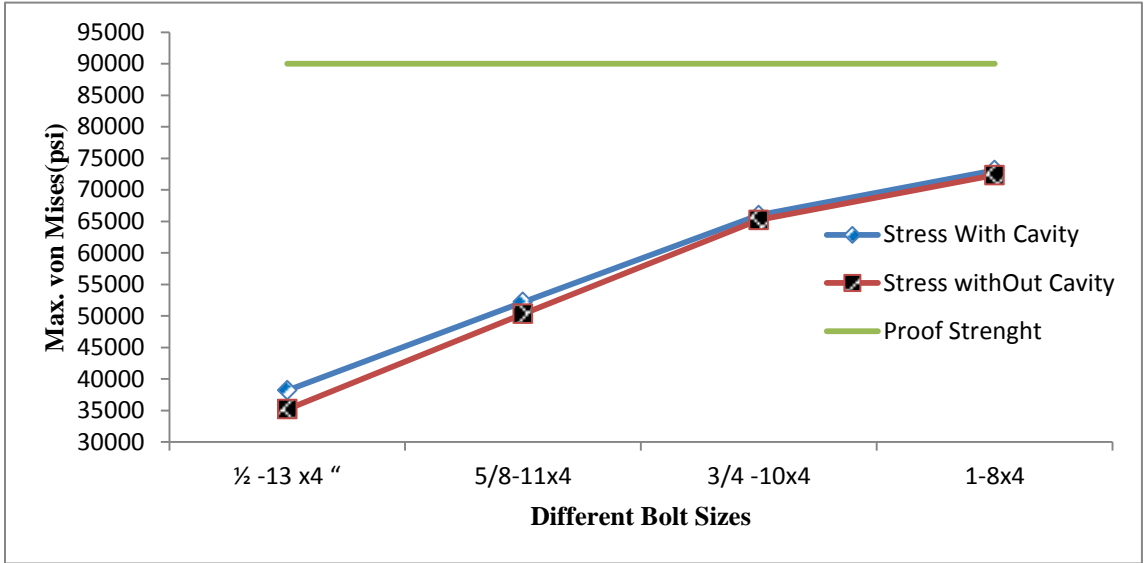As shown in above graphs, the stress under the head of the bolt increases due to this modification. However, there is an advantage regarding stress distribution around the shank and thread portions of the bolt. The stress increase around the head of the bolt is mainly due to the material removal. Since the cavity shape is the same for different sizes of bolts, as the diameter of the bolt increases this effect decreases. Figure 21 shows the results for von Mises stress below the head of the bolt. By knowing these values, the conclusion can be made and said if the modification (cavity effect) on the bolts affects the strength of the fasteners or not. The percentage difference between the von Mises stresses for the bolt with and without cavity versus the bolt diameter can show how increasing the diameter of the bolt changes the stress concentration around the cavity.
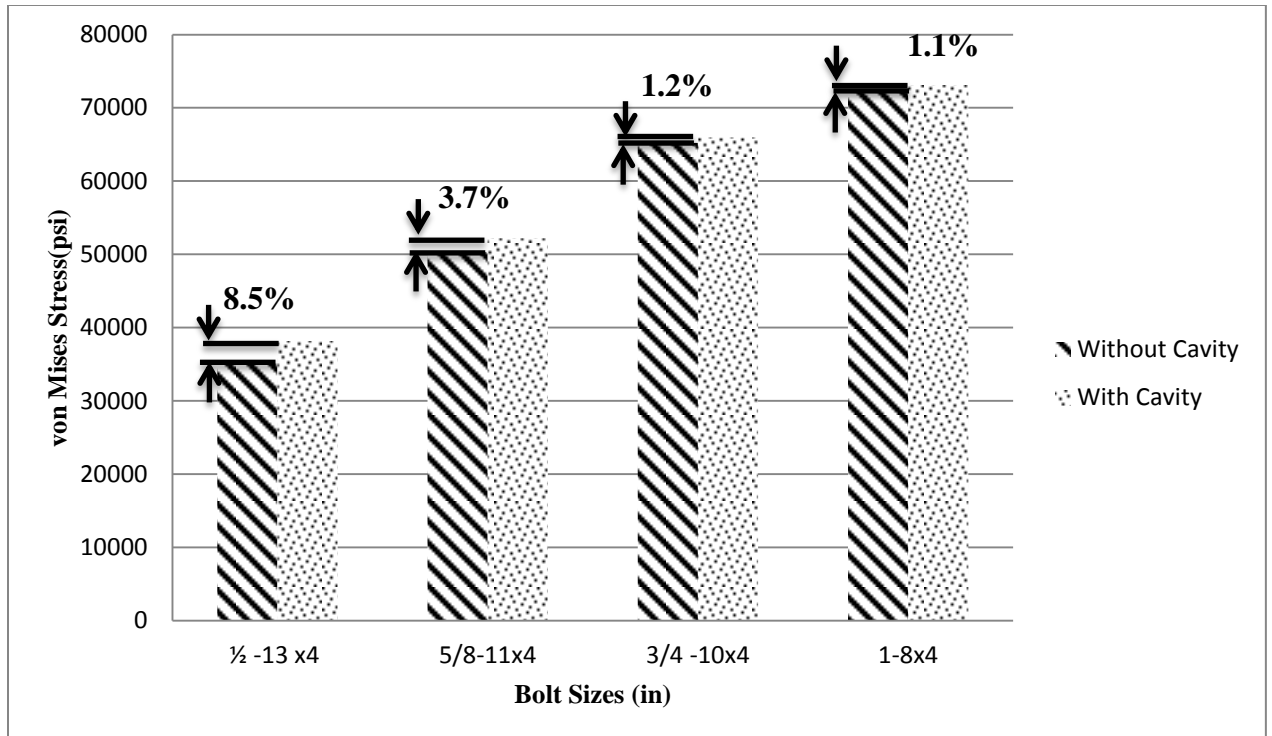
Figure 24. Maximum von Mises Stress Value around the head area for different sizes bolts with and without cavity

As shown in the results, the cavity in visual indicating fasteners increases the stress concentration. However, its effect compared to its advantage of removing the discrepancy between torque and clamping force is negligible. This effect diminishes as the bolt diameter increases. Considering the fact that their design tension is always 25% below the proof load of the bolt and the results gathered from simulations, it can be concluded that the strength reduction as a result of modification can exist in smaller bolt and definitely negligible for bolts larger than ½" diameter.

After studying the proof of concept of visual indicating fasteners and understanding the fact that the modifications done on these fasteners do not lower the strength of the bolts a lot, it was necessary to outline a reliable manufacturing process for these fasteners. As mentioned earlier, the quantity of fasteners in industry is tremendously large. Thus any proposed technology should have the capability of

being mass produced. In the following chapters of this work, the proposed manufacturing process and the design of the automated assembly line for visual tension indicating fasteners is discussed.

Chapter 3: Process Engineering for High Resolution Visual indicating fasteners

3.1 Required Process Steps for manufacture of High Resolution Visual indicating fasteners

The High Resolution (HR) Visual indicating fastener is composed of several subsystems and components that all require their own processing methods. Some best principles as well as unsuccessful methods will be presented in this section in an effort to better focus on the areas that were considered mainly for designing the automated assembly line. In order to design any automated assembly line, the hand assembly must initially be done. Manufacturing process presented here is based on the experience gained from hand assembly of these products.

Visual Indicating Fasteners are made by modifying existing bolts in a machining process. The bolts are purchased mainly from Fastenal. These bolts are mainly SAE J428 Grade 5 with standard Rockwell Hardness between 25-34 HRC, proof strength of 85ksi, yield strength of 92ksi and ultimate strength of 120ksi [1].

Step1: The first step in this process is machining the regular bolts. The cross section of this cavity is shown in Figure 25. The consistency in the tolerances of machining is a main factor in this step. One of the main manufacturing issues with bolts is the eccentricity of the head of the bolt to the shank. Due to the nature of manufacturing bolts, the hexagonal head bolt can have this issue. Since the bolt is held from the shank in order to machine the cavity, there is a chance of having the cavity off center with respect to the center of the shank.

33
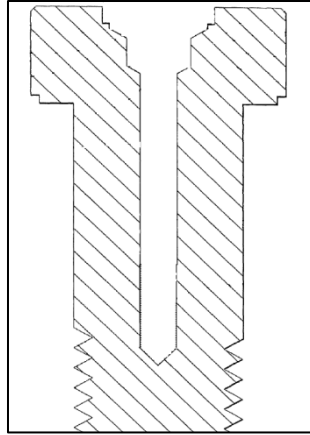
Figure 25. Cross Section of Machined Cavity [25]

Step2: HR Visual indicating fasteners should be under the design tension during the manufacturing process. Therefore, putting the HR Visual indicating fasteners under tension is the first thing to do in the assembly process. There are different methods of putting bolts under tension in industry; however, making sure the load applied is accurate is challenging. Skidmore tensioners, bolt extractors, etc. instruments are off the shelf products for doing this. These methods are costly and the range of the bolts they can elongate is limited. Therefore coming up with a method for tensioning the bolt was an important task in this project.

Step3: There are different methods for bonding the pin into the cavity such as threads, press fit, adhesives. Having threads might not work due to the dimension and manufacturing limitations. Press fit is known as a process which needs tight tolerances in order to have mass production. Therefore, using a type of adhesive that can hold the shear stress between the pin and the bolt cavity is critical. As shown in Figure 26 , adhesive should be dispensed at the bottom of the cavity.

Figure 26. Loctite603 Dispensed at the bottom of cavity [25]

Step 4: The pin with the silicone washer needs to be put into the cavity after the adhesive is dispensed in the previous step. Due to the physical shape of the cavity it is important to make sure that the pin is all the way down into the cavity, as shown in Figure 27.
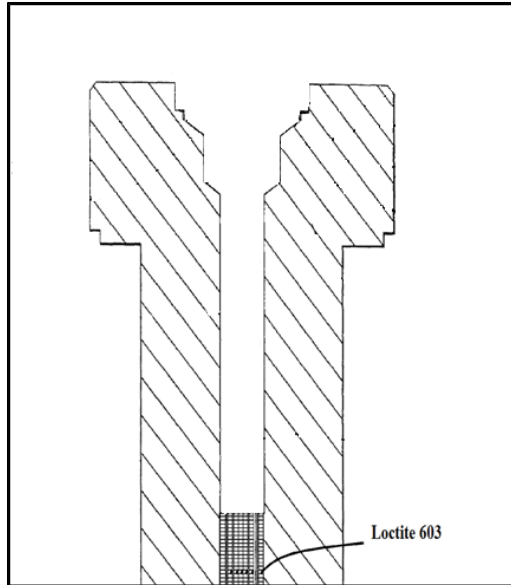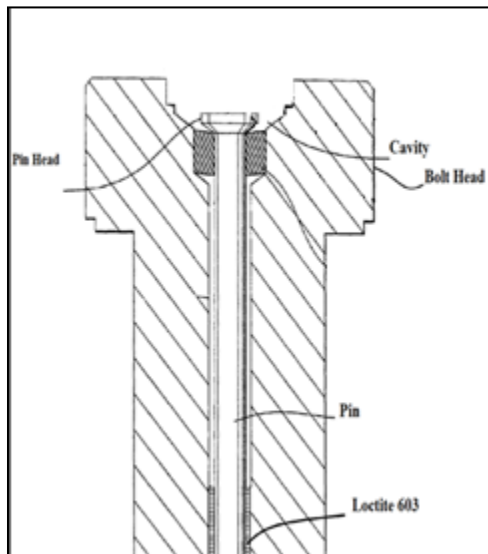

Figure 27. Pin and washer placed in cavity [25]

Step 5: Three different components, window assembly, microindicator and pin are attached together by using a room temperature vulcanizing (RTV, elastomer sealant). This component has a critical role to the optical appearance of Visual indicating fasteners. The quality of application of RTV depends on the volume, the state of cure, the age of the RTV and concentricity of dispensing with pin head.

The volume of the RTV has traditionally been very important to control. Improper amounts of RTV have been claimed and/or suspected to cause multiple assembly flaws which will be discussed later in this work. The first controlled shot of RTV is dispensed on the top of the pin head as shown in Figure 28.
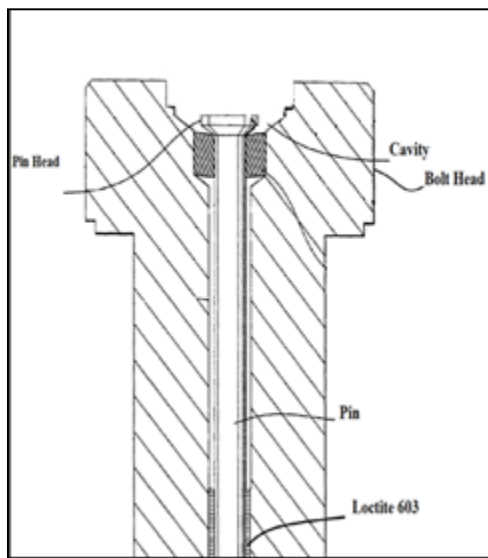
Figure 28. Dispensed RTV on top of pin's head [25]

Step 6: The microindicator will be put on top of the pin head, as shown in Figure 29. The microindicator is manufactured by Stress Indicator in an automated machine which has its own quality assurance process that is sufficiently developed for effectiveness, albeit not for speed. Therefore this critical component has become relatively stable and predictable. In designing the automated assembly line, the subsystem responsible for picking up the microindicator and dropping it in the bolt

should be able to do the tasks in the cleanest form in order to minimize any marks on the surface of the microindicator, since it directly affects the final quality of the product.
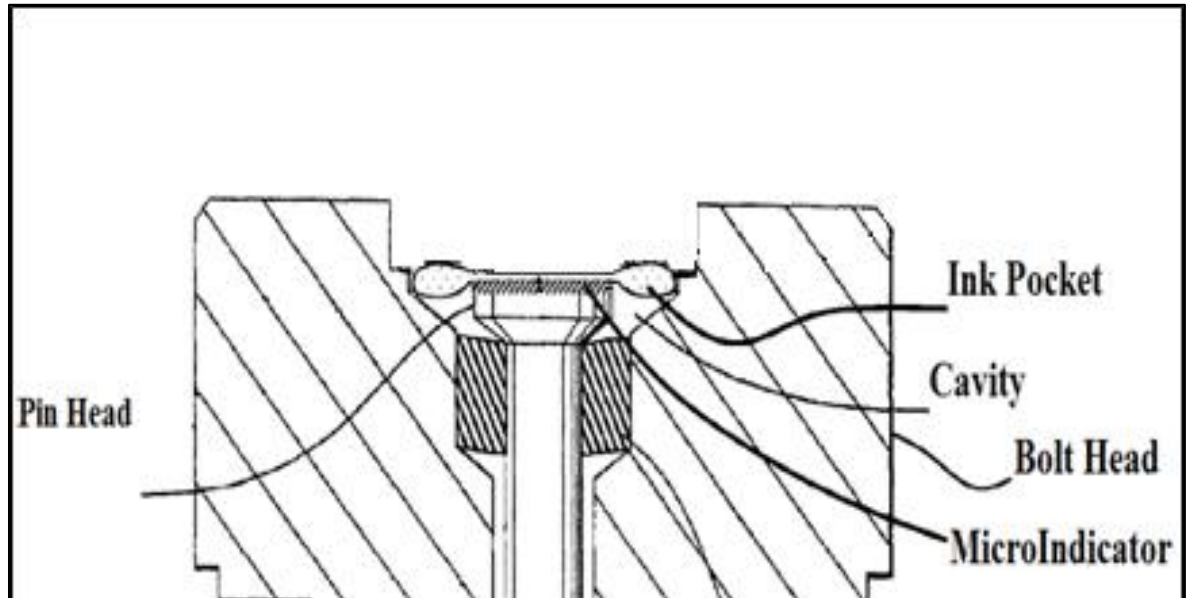
Figure 29. Microindicator Dropped [25]

Step 7: After putting the microindicator on the head of the pin, another shot of RTV should be dispensed in order to attach the window assembly to the microindicator. It is shown in Figure 30. In the manual assembly process, the second shot of RTV would be dispensed on the bottom surface of the window assembly since it would be make it easier for the operator. It is critical to make sure that the RTV is dispensed at the center, and with the same amount dispensed earlier during the process on the pin head.
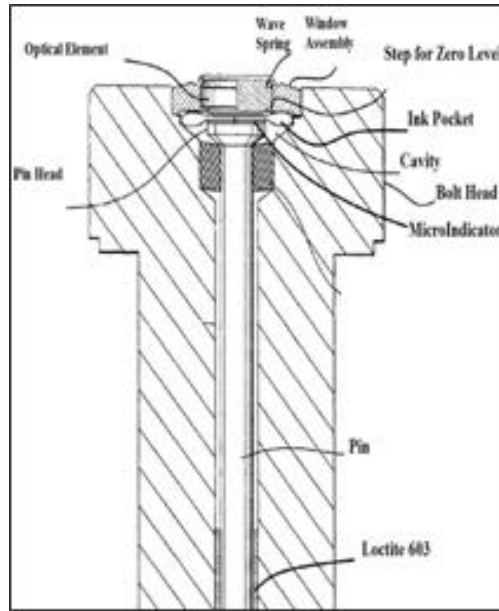
Figure 30. RTV Dispensed on Top of Microindicator [25]

Step 8: The HR window ring assembly is made of up three components: the window ring, the window, and the wave spring. It is a stacked assembly that starts with the window ring, then window, then wave spring. The window ring is then crimped using a pneumatic lever press with appropriate tooling. The crimping is designed to fold a steel lip over to create a closed compartment for the wave spring to compress against. The compartment height directly impacts the working height of the wave spring and thus the initial force to start deflection.

Putting the window assembly on the microindicator is the last component of this assembly line. As shown in Figure 31, all of the components are placed in the cavity. However, staking the window assembly and curing the RTV are the main two tasks that can change the behavior of the Visual indicating fastener greatly. During the hand assembly, staking is done at three different locations at three different times which causes some flaws that will be discussed in the next section of this work. With

respect to results gathered from hand assembly of this step, integrating three main tasks of pushing the optical element (in the window assembly), curing and staking is defined as the ultimate goal for this step. The limited space (1/2" diameter cavity) and high amount of force in order to deform the edges around the cavity in order to lock the window assembly in the bolt can make the design of this subsystem the most challenging one among the rest.
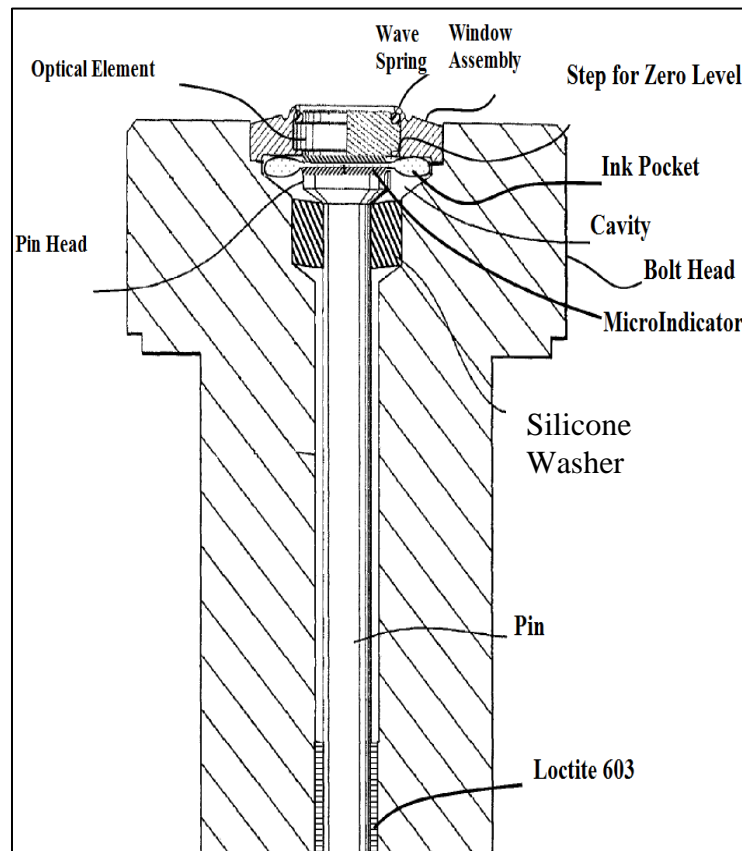
Figure 31. Assembled Components of Visual indicating fastener [25]

Step 9: Releasing the load and unloading the HR Smart Bolt from the system. By experience, it is found that releasing the load gradually results in a better quality for visual indicating fasteners. The main reason for this phenomenon can be the curing period of the Loctite603. If the pin is not completely bonded to the bolt at the

end of the manufacturing process, releasing the load suddenly can shift the pin location.

3.2 Manufacturing Issues with HR Visual Indicating Fasteners

Based on proof of concept tests conducted as a part of this thesis and those conducted at the collaborator's facility, different flaws are observed, which can cause high rejection rates. Based on the initial tests conducted, these flaws are listed and explained in the details in the following section.

Room temperature vulcanization **B**lemish (**RB**) flaw exhibits a behavior where "under-tension" pin color is visible even though all around that point may be the desired uniform grass green. This issue can be seen in Figure 32. Conceptually this can be visualized as islands protruding from a body of water on a miniscule scale. These "Islands" are believed to be created by two sources. The first and most common is partially cured/solidified RTV which will be discussed more in details in future sections.
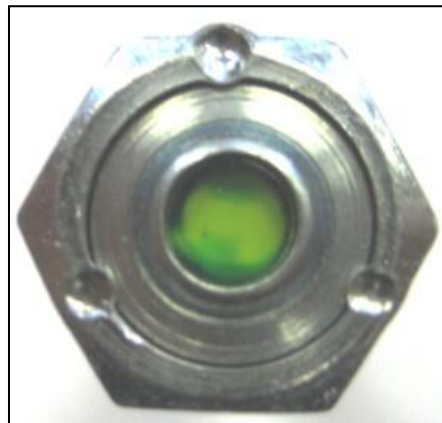
Figure 32. Blemish Issue

The location that the RTV is being dispensed is critical. **R**TV **O**ff center (**RO**) is a problem of concentricity which is present with too little volume. The RTV fails to

flow completely over the pin head/window. The color of the pin head is then able to show through while the rest of the pin head is properly darkened. This is a very noticeable and unattractive flaw that can hinder the indicator's effectiveness. "RO" are therefore almost always rejected and rebuilt (if possible).

Even though "RO's" are a consequence of too little or misplaced RTV, too much RTV could also be a problem. The excessive dispensing of RTV is suspected to cause flaws like "BL's", "OT", "UT", and perhaps NF's. The "BL" flaw stands for Blush which is characterized by a generally uniform "pool" of fluid that remains between the pin and the window even when the bolt is unloaded. The fluid can be pressed out of the way temporarily by pushing on the window but it will flow back in when the force is removed. The flaw is conceptualized as a puddle that is more prone to form with large amounts of RTV, shown Figure 33.
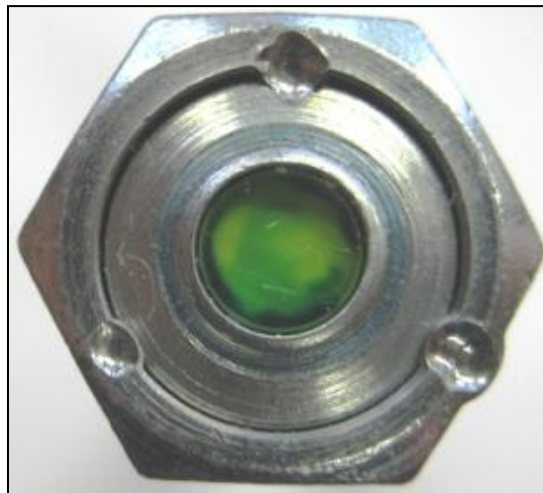
Figure 33. RTV Off Center Issue

Although the microindicator has its own quality assurance process, it still might create some problems. The contamination by dust/metal particles and microindicator fluid is a temporary state that can be cleaned off if noticed. If this is not done, these particles will affect the uniformity of the viewing window and affect

perceived quality in the end user. This is to be avoided but small particles alone are usually not grounds for rejection. Noticeable creases in the microindicator can show up as Cosmetic Blemishes (CB) and be grounds for rejection. CB's are not always rejected and it generally depends on the severity of the flaw. Microindicator fluid on the outside of the envelope is not tied to a specific flaw but could negatively influence the peel/bonding strength of the RTV on the microindicator's walls. This small amount of fluid could also be absorbed by the solidified RTV causing slight darkening of appearance but this has been rarely noticed if ever.

Another common problem with HR Visual indicating fasteners is the Gradient (GR), shown in Figure 34. The window ring sub assembly, as explained earlier, consists of three components. The pneumatic lever press is used to crimp the window ring. The force applied by this press is really critical because that is how the thickness of the window is defined. An overly thick window ring assembly can create too small of a reaction spring force, slippage/erratic behavior of the window, and improper protection from contaminants in to the window ring subassembly that could disturb functionality. The last issue that can occur with the window ring subassembly is uneven distribution of force along deflection. The wave spring is a single turn gap type wave spring with three waves. The size of the gap is proportional to force and perhaps could be a better measure of spring force than the thickness of the window ring. The uneven distribution of force along deflection could be the biggest cause of developing a "GR". The gradient is the most common cause of rejection of the HR Visual indicating fastener. The severity of a gradient is wide ranging from a slight difference in shade to Over Tension/ Under Tension in the same window. This

potentially confusing flaw affects the functionality and perceived quality of HR Visual indicating fasteners and is therefore very important to avoid.
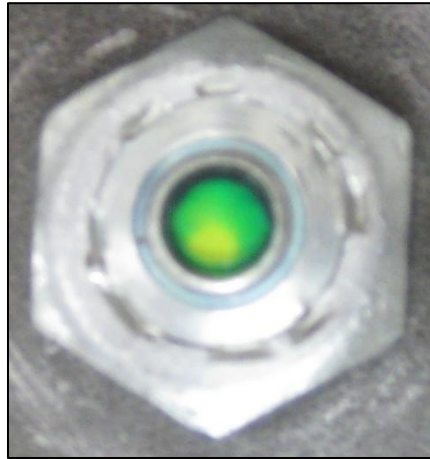
Figure 34. Gradient Issue in Visual indicating fasteners

After identifying all of the flaws and assembling issues involved with HR Visual indicating fasteners manual assembly line, coming up with a way of setting up experiments in order to find out the cause of each flaw was challenging. Due to the large number of variables in the assembly, keeping all of them constant and testing one variable is difficult. Controlling the variations in the manufacturing process should be done by the automated assembly line in order to completely eliminate human errors.

The cause and effect (fishbone) diagram helps visually display the many potential causes for effects during a manufacturing process. The constructed fishbone diagram shown in Figure 35 breaks down the possible causes of the main three problems of blemish, blush, and gradient.
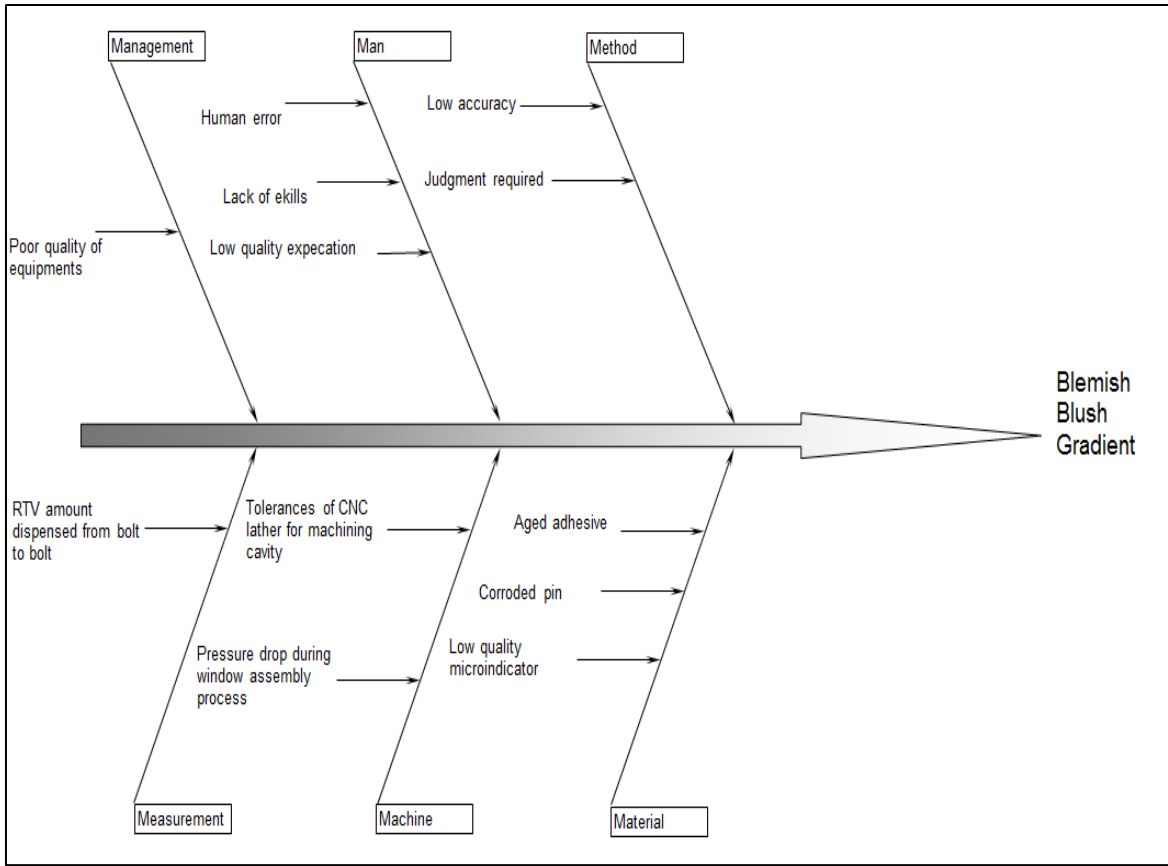
Figure 35. Fishbone Diagram for manufacutring process of HR Visual tension indicating fasteners

In the next sections of this paper, different experiments and approaches used in order to understand the cause of each flaw and the methods used to design an automated assembly line to eliminate these issues are discussed.

Chapter 4: Automated Assembly Line for HR Visual indicating fasteners

4.1 Advantages of Automated Assembly Lines

Assembly work has a very long history. Ancient people already knew how to create a useful object composed of multiple parts. However, the objective of modern assembly processes is to produce high quality and low cost products. A number of important ideas have been developed to facilitate assembly work. First of all, assembly parts are standardized. Parts of the same type must be subject to the same specifications. This also implies uniform part quality. Parts from different sources then can be put together as a finished product. Another progress in the history of assembly manufacturing is the division of the assembly job. If an assembly task has a long process time or involves too many parts, the work may be broken into a number of smaller tasks (done by subsystems). Each task builds a part of the assembly. By progressively adding parts to an assembly, a finished item is produced. Since each task has a relatively limited content, skill can be developed in a short time. Thus, assembly speed may be increased and quality improved. In many cases, non-assembly operations may be needed. For instance, parts preparation, inspection, and testing operations may be introduced to assure the product quality level, and facilitate assembly work [13-14].

Since an assembly is composed of multiple parts and parts are assembled by multiple operations, material flow becomes relatively complex. On the other hand, moving physical material is a rather simple mechanical task, as compared with the assembly task. Operator productivity can be further improved by introducing a dedicated material-handling system and letting operators concentrate their efforts on

assembly tasks where skills are needed. As a consequence, automated material-handling systems have become very popular in modern assembly line. Manufacturing cost is reduced due to prompt material delivery, smaller space requirement, better inventory accountability, less handling damage, and less labor. Due to the existence of unknowns and uncertainty, line design often becomes a philosophical problem. On the other hand, line design is a very practical problem which can greatly influence the product cost. Since a company's ultimate goal is to make profit, line design cannot be treated as an isolated engineering problem. It must be considered as a part of the entire business plan [13-14].

One of the important aspects of assembly is the simplification of the work into minute elemental this has been appreciated for generations, even before Adam Smith presented a paper on the subject in 1776. Apart from some isolated effort, it was left to Henry Ford to apply the principle in a scientific manner. Henry Ford's system, introduced in 1913, gave us what was perhaps the first progressive assembly line, the forerunner of the present day motorcar assembly tracks with the basic idea of one man on job [13].

Since 1913, no other major development, other than robotic assembly, has occurred in assembly technology for the specialist manufacture. There have been minor improvements, such as synthetic time studies to improve individual performances, techniques in assembly line balancing to obtain an even distribution of the work content, and the use of hand and power tools to assist the operators in their tasks. Isolated companies have established development sections undertaking the design and manufacture of assembly machines to meet their own requirements and

have forged ahead, but there has been no interchange of ideas. This is obviously a slow and expensive process but, until there is an established machine tool industry available to bring forward a range of standard equipment to meet all the varied conditions which apply, this sort of individual effort must continue.

The need to have assembly machinery is vital to the manufacturer of specialized products such as Visual indicating fasteners. It is the one area which can show the greatest saving of labor in the production departments. The followings are some of the reasons for having an automated assembly line for HR Visual indicating fasteners besides the fact that it can eliminate the issues in manufacturing of HR Visual indicating fasteners manually which were mentioned earlier.

1) Reduction of cost
2) Improvement of quality
3) Reduction of operator fatigue
4) Elimination of special skills
5) Elimination of safety hazards
6) Operations which are impossible or almost impossible for the human operator
7) Technical achievement

Considering the advantages of an automated assembly line for products that require highly reliable and repeatable quality products and knowing the facts about hand assembling of HR Visual indicating fasteners, it was decided to:

1) Develop a reliable manufacturing process for HR visual indicating fasteners by refining the originally proposed process further.

2) Automate the manufacture process in order to increase the reliability and rate of production.

4.2 System Design

In order to evaluate the performance of each concept, the fabrication and testing steps should take place. After generating and selecting concepts, the semi-automated physical prototype setups for all of the subsystems of the assembly line of HR Visual indicating fasteners are done. This chapter describes the embodiment design and the system design of this assembly line.

Setups were developed through a combination of hand sketch design and hand calculations with solid modeling and analysis also performed through Pro-Engineer software. Design objectives were to establish modular subsystem architecture while satisfying all specified target specifications, functional requirements and design criteria. Appropriate component design and selection was performed to meet the criteria of Design for X (DFX), or:

1) Design for Manufacturing
2) Design for Assembly
3) Design for Maintenance
4) Design for Cost

It is important to highlight that specifications of each component chosen or designed often show themselves to be extensively detailed, but nonetheless considered. In this chapter as well as chapter of detailed design only some of these specifications are shown.

4.2.1 Design Elements

To build an automation system in a modular way, it is necessary to have a minimum amount of custom design and make the design as standard as possible. In order to have a standard design, getting off-the-shelf products and using these in the subsystem can benefit in different ways. This approach has many benefits, including ease of replacement of defective and worn-out parts, cost savings due to standardization, shorter design times and more rapid implementation of the machine. This catalog approach was taken to further develop the prototype setups. Pneumatic components, hydraulic systems, structural support components, linear motion hardware were used to mechanize and automate actions necessary to satisfy the prototype functional requirements.

4.2.2 Pneumatic Components

Use of pneumatic components offers a number of benefits almost always preferred by the automation industry. Pneumatic automation can save manufacturers a lot of money in a variety of ways. With pneumatic automation, manufactured parts are:

- Drilled from many angles at once

- Held firmly during the manufacturing process

- Assembled at maximum speed with great accuracy

- Manufactured with less waste than standard manufacturing processes

In addition to money savings, pneumatic automation has many other benefits that help the process run smoothly:

- Simple design and control with ON-OFF controls

- Reliable with a long operating life

- Storage-compressed gas can be stored, which enables the machines to be used even in the event of a power outage

- Safety-very low chance of fire and machines are designed to be overload safe

For the systems in design, commonly available pneumatic components such as actuator air cylinders and gripper mechanism were used to provide the required process actuation or motion. The main criteria for using the actuators were the force, stroke length of the actuator, and available mounting position to name a few. Clippard Minimatic and SMC Pneumatics[18] are the main two manufactures of the pneumatic systems that were used for this system.

FIGURE 36. Left: Clippard Pneumatic Cylinders, Right: SMC Pneumatic Cylinders

4.2.3   Motion Hardware

There are different mechanisms used in machinery for linear and rotational motion. Lead screw, gear and belt assembly, slider and bearings are the common off-

of-shelf products. For systems with long travel distance and high load capacities, lead screws are preferred. There are a lot different types of ACME screw and nut assemblies that can be used with respect to the required application. ACME screws, shown in Figure 37 , are manufactured with centralizing thread form to prevent wedging. Nuts including bronze, plastic and anti-backlash styles are matched with over 110 screw diameters and leads. ACME screw lead accuracies are as following:

- Rolled +/- 0.0003" per inch

- Milled +/-0.002" per ft.

- Ground +/-0.0005" per ft.

Proper lubrication is the key to continued performance and reliability of ACME screw assemblies. E-100 and PAG-1 sprays made by Nook Industries [17] can maximize life of any ACME screw assembly.

Figure 37. ACME Screw Assemblies

4.2.4 Structural Support Components

One of the most common structural framing and off-of-shelf product in automation industry is 80/20 Inc.[16] products. Different components of 80/20 products are shown in Figure 38. These products offer ease of component mounting and adjustment, they can be fastened together to accommodate most industrial applications without the need of expensive fabrication equipment. T-slotted aluminum extrusions, joining brackets, different methods of fastening as well as dynamic modules are offered in a variety of shapes and sizes to match the desired design application. Offered in a number of metric and fractional forms, T-slot aluminum extrusion beams were used to create the necessary prototype frame work. Extrusions could be machined down to the length required and then connected using a combination of a screw, T-nut and supporting brackets. For ease of adjustment, the T-nut is able to slide within the T-slot of the profile while also creating a sufficient clamping force when tightened with a screw and locked in place. For all of the 80/20 products, the screws used are ¼"-20 which makes the design of the system more standard and easier for maintenance purposes.
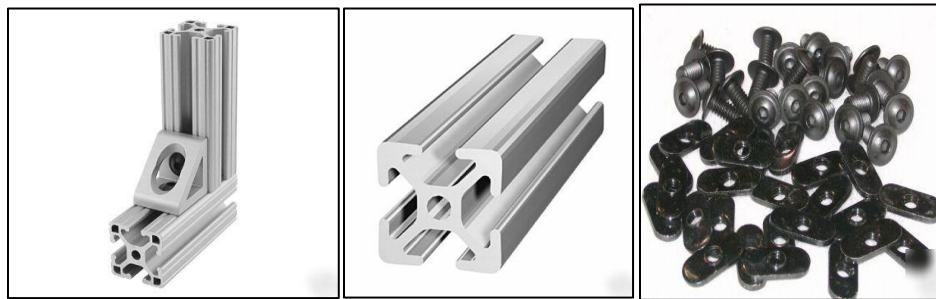

Figure 38. Left: T-Slot Extrusion and Joining Bracket; Middle: T Slot Extrusion (1010 Model); Right: 1/4"-20 Screws and Nuts

4.2.5   *Hydraulic Components*

The basic idea behind any hydraulic system is very simple: A force that is applied at one point is transmitted to another point using an incompressible fluid such as oil. The force is almost always multiplied in the process. In any industrial application where a large amount of force is required, hydraulic system is preferred. One of the most common hydraulic system components, are hydraulic cylinders or hydraulic plungers. The piston travels in a cylinder and is actuated by the force of fluid.

ENERPAC[19] provides the largest selection of cylinders and lifting systems, fully supported and available almost everywhere in the world. Different applications such as lifting, pushing, pulling, bending or holding, in most industrial and commercial work environments use hydraulic systems made by ENERPAC. There are different general purpose cylinders available in hundreds of different mechanical or hydraulic cylinder configurations. As it is shown in Figure 39 , different types of hydraulic cylinders are: single acting, hollow plunger, or low height.

Figure 39. Left: Single Acting, Middle: Hollow Plunger, Right: Low Height Cylinders

In any hydraulic system, there is a need for hydraulic pump in order to inject the fluid (oil) into the cylinders. ENERPAC combined the widest selection of high pressure hydraulic pumps available with reliability, durability and built-in safety to make it easy to find the right pump for any application requiring applied force.

Different types of hydraulic pumps are: Manual pumps, Electric pumps, Air Hydraulic pumps, Gasoline pumps as shown in Figure 40.

Figure 40. (a) Manual Pump (b) Electric Pump (c) Air Hydraulic Pump (d) Gasoline Pump

4.3 Layout of the Assembly Line

For automating any manufacturing process, it is important to understand the steps that are done during the hand (manual) assembly process. After understanding the steps and the required tasks in order to get a "good" Visual indicating fastener out of the process, as shown in Figure 42, the functional decomposition chart is developed. In this chart (or system), it is assumed that the bolt is stationary through the whole process [15].

HR Smart Bolts Manufacturing Process

- Load Machined Bolts on the System
- Apply Design Tension to the Bolt
- Dispense Loctite 603
- Is the Loctite Dispensed — No → Release the load → Clean the bolt and Start again!
- Yes → Drop the Pin & Washer
- Dispense RTV(Loctite5033)
- Is the RTV Dispensed Correctly? — No → Clean the head of the pin and purge
- Yes → Drop MicroIndicator
- Dispense RTV(Loctite5033) → Drop Window Assembly → Secure Window Assembly → Release the load & unload the Bolt
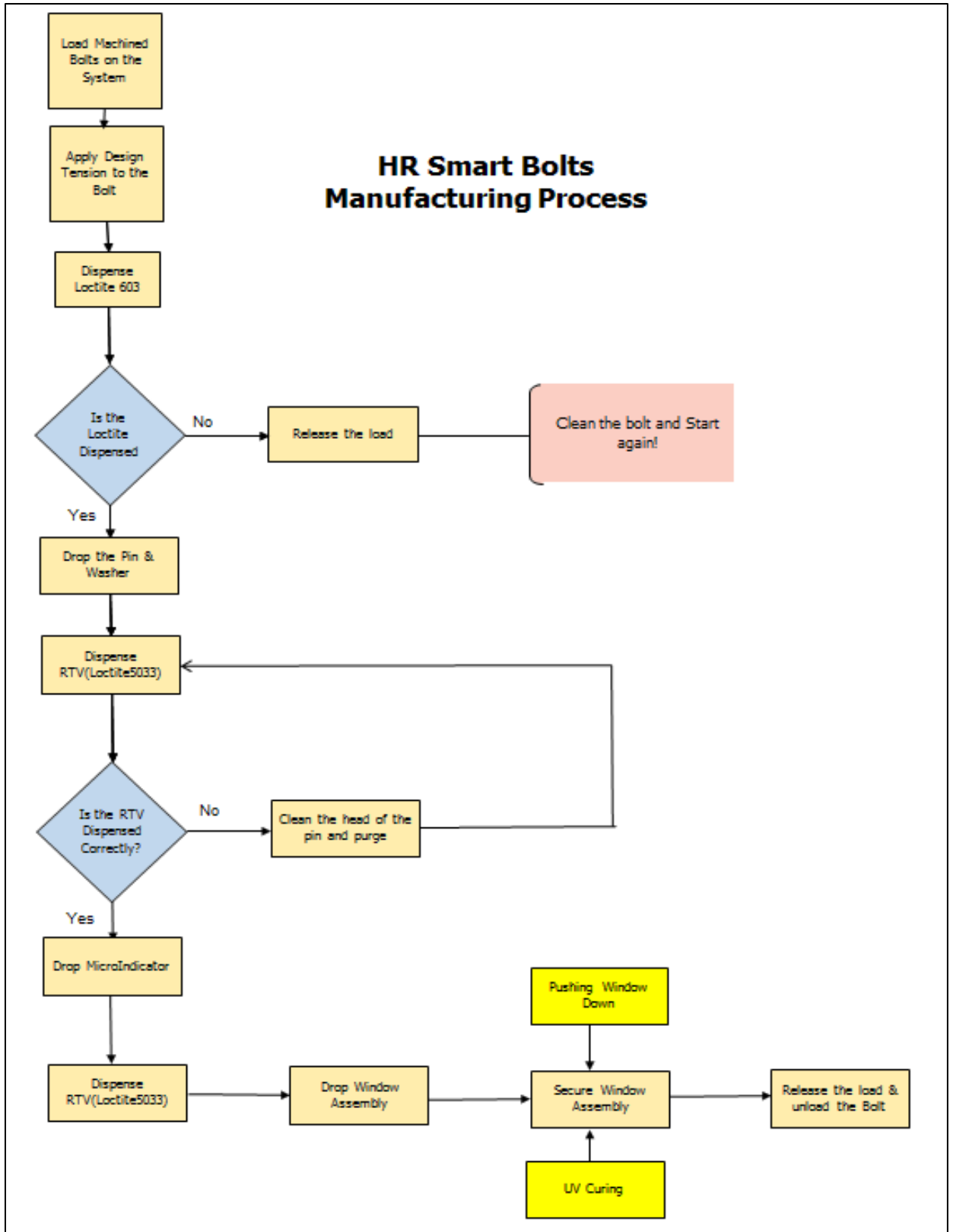- Pushing Window Down
- UV Curing

Figure 41. HR Manufacturing Process

As mentioned in the process engineering of HR Visual indicating fasteners, these bolts should be under design tension while manufacturing. This fact causes many challenges in the design of the assembly line for HR Visual indicating fasteners. The general guideline of having subsystems stationary cannot be applied to this project. The range of the loads that need to be applied to different types of bolts is from 5000lbs to 90000lbs. Due to high load requirements on the product, the part being made needs to be stationary and subsystems should be moving. Therefore the following sketches or concepts that are shown in Figure 42 and 31 cannot be used.
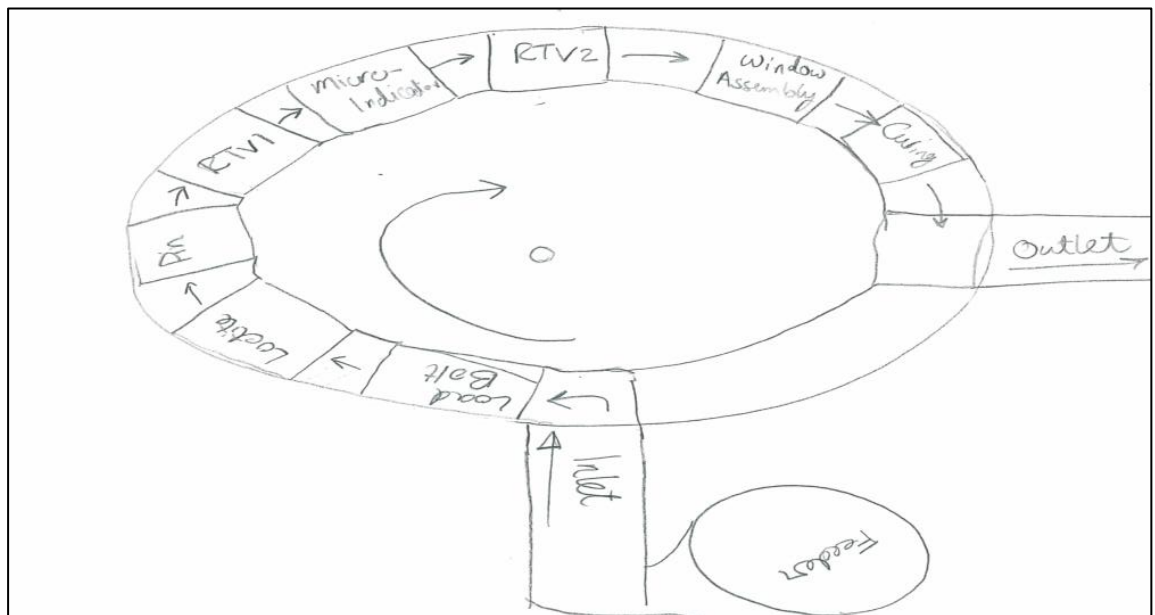

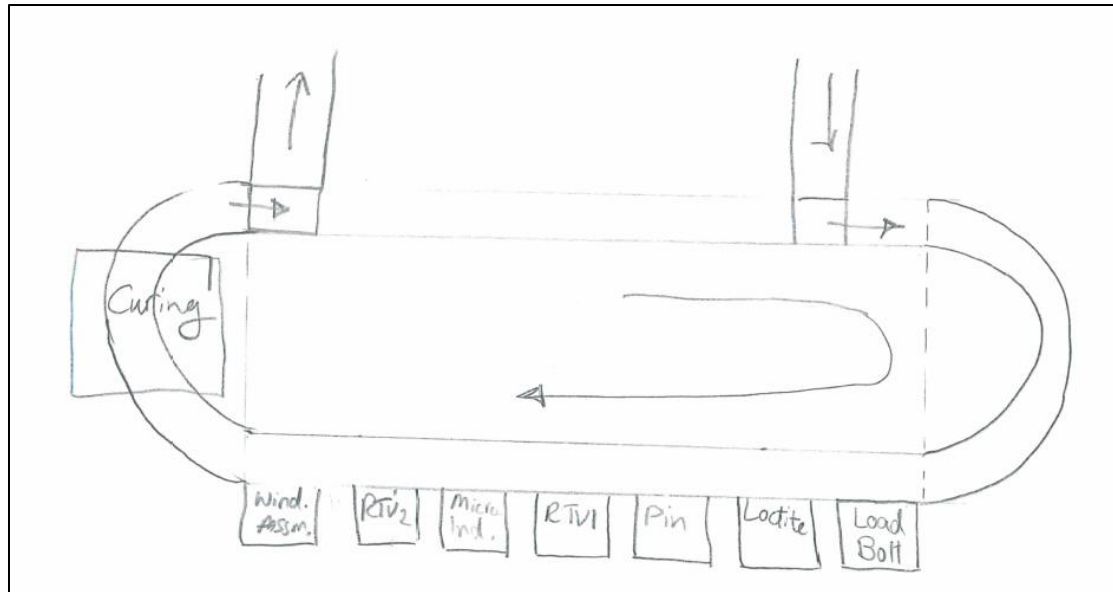Figure 42. Sketch of Circular Layout of Automated Assembly Line

Figure 43. Sketch of Oval Layout of Automated Assembly Line

The system we decided on is designed such that the subsystems travel across the bolt head driven by a precision ACME screw. Upon reaching the bolt head each subsystem performs its specific task. Most subsystems occupy a 2"x6" space. The whole system can be categorized into stationary subsystems and moving subsystems.

The only two stationary subsystems are the tensioning and staking systems. They are kept stationary due to the high load requirements for the functions they perform on each bolt. An H-Frame press is used in order to apply large forces.

The moving subsystems move to the top of the bolt and stop at the required location in order to perform their function. In order to have an accurate control system that can tell the system to stop exactly at the required location, a stepper motor is used. The stepper motor rotates the ACME screw which causes the subsystems to move forward and backward. The main reason for using the ACME screw is the minimum amount of backlash. ACME screws are usually used where repeatable positioning accuracy is required. Steel ACME screw and bronze ACME nuts are

combined to provide the optimum performance available in this type of lead screw. The highly burnished surface finish of the ACME screw and low friction bronze nuts yields a smoother, less abrasive action than conventional cut ACME screws. Improved wear and surface properties insure users a longer service life and quitter operation, requiring less power in a wider variety of application. Figure 44 shows the general layout of the moving subsystems.
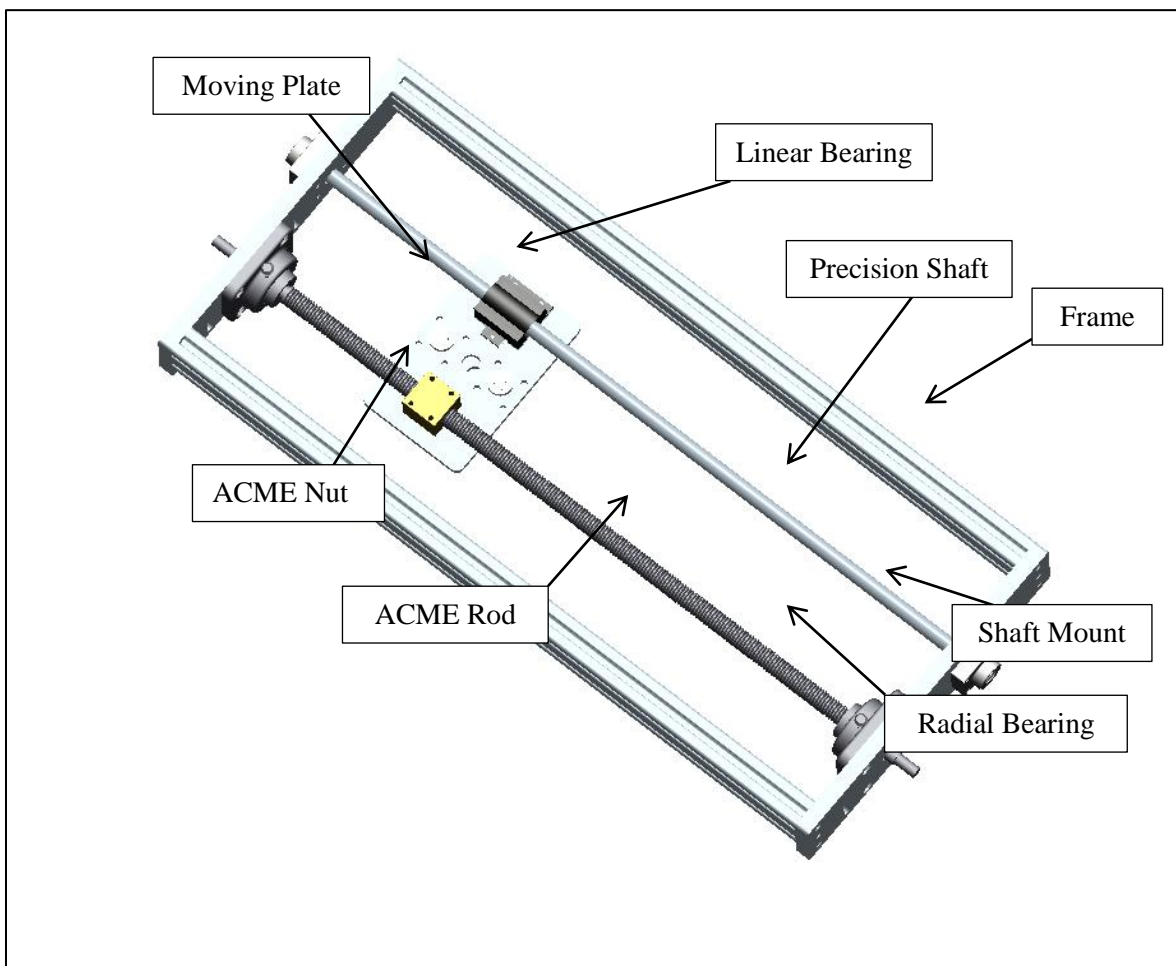

Figure 44. CAD Drawing of Moving Subsystem

The weight of the assembly in the prototype came out to 2.4lbs and the moment arm about which the weight of the moving assembly acts on the lead screw is

59

1.84 inches. Hence the total moment of the moving assembly about the lead screw is 72oz.in. Since a greased contact between the bronze ACME nut and the steel lead screw is used the coefficient of static friction of 0.16 results in a requirement of 11.5oz.in of torque to overcome the static friction.

The motor selected for the current prototype application is a stepper motor BM34-1694 by Advance Micro Systems (AMS) with a minimum step angle of 1.8 degrees which serves the accuracy requirement of automation assembly. The motor was selected in such a manner that it could be used in the full scale model of the 'Visual indicating fastener Assembly Line' by only increasing the input voltage to the motor. The motor is controlled by providing an input step where every step corresponds to 1.8 degrees. Thus 200 steps correspond to one rotation which translates to 0.10" displacement of the moving assembly. The minimum resolution attained by the current motor is 0.0005". For the current prototype a 48V power supply produces enough torque (approx.3.25Nm or 460 oz.in) to overcome the static and dynamic friction between the lead screw and the ACME nut. This moves the lead screw at a speed of 0.25 inches per second, the targeted design speed for the prototype assembly system.

The current motor selected can provide a maximum torque of 6.5N.m (4.8lb.ft) at 300 rpm that gives a factor of safety of 1.27. The motor was purchased along with a compatible driver and controller from AMS that requires a 12V dc power supply. The programming for the motor was carried out with AMS Cockpit, a free software provided by AMS where programming is based on ASCII commands. The programming is based on simple positive or negative increment in steps for the

motor and appropriate wait times between different subsystems. This cycle is put into a loop to execute a finite number of times.

To control the solenoid actuated pneumatic valves for the individual subassemblies; an Arduino Uno micro controller is used. A push button mounted on the moving subassembly will be actuated as soon as the subassembly reaches the starting position. This triggers a series of solenoid actuated valves timed in order to match the motor speed to reach the various subsystems at the precise time.

In the following chapters of this paper, each of the stationary and moving subsystems is explained in details. The subsystems are as following:

a. Stationary Subsystems:

      i)   Tensioner Subsystem

      ii)   Staking Subsystem

b. Moving Subsystems:

      i)   Loctite 603 Dispenser

      ii)   Pin and Washer Drop System

      iii)   RTV (Loctite 5033) Dispenser

      iv)   MicroIndicator Drop System

      v)   Window Assembly Drop System

4.4 Detail Design

4.4.1   Tensioner Subsystem

As mentioned in the manufacturing process of the HR Visual indicating fasteners, while assembling the components the fastener should be under design tension. This is a way of calibrating the bolt to that design tension and defining a reference location for the window assembly. The term "design tension" is defined by the following equation:

$Design\ Tension =$

$(safety\ factor) \times [Proof\ Strength\ \times Tensile\ Stress\ Area\ of\ the\ bolt]$

Eq. 15

In practice, the design tension of a Visual indicating fastener will be the tension where the color of the bolt changes. As shown in the equation, this tension is always in the elastic region and has a safety factor which leaves room for the operator in cases where they over tighten the bolt. With respect to the different sizes of bolts given and applications, the range of design tensions are found to be from 5000lbs to 90000lbs. Due to the high load requirements and considering the fact that Visual indicating fasteners should be under tension during assembling process, it becomes challenging moving the bolt around during the assembly process while it is under tension. Generally in any automated assembly line, the subsystems or workstations are stationary and the product will be transferred to different locations on the system. This general guideline could not be used for this specific system due to the large weight of the system that will be putting the bolt under tension. Therefore, this subsystem is designed to be a stationary subsystem which has the bolt in it. The main

task of this subsystem is putting the bolt under a known value of design tension and making sure that it will maintain the load till the end of the process.

One of the challenges in designing this subsystem is making sure that the load applied to bolt is a uniaxial load (symmetric with respect to the center axis of the bolt) and accurate. It is important to note that using torque wrenches is not allowed in this process since the main goal of this product is to eliminate torque discrepancy. There are different technologies available in industry for bolt tensioners. One of the most common ones is the Skidmore Wilhelm bolt tensioner, shown in Figure 45. Skidmore Wilhelm [20] setup works based on a hydraulic mechanism. Tightening a fastener inserted into to the Skidmore Wilhelm creates pressure, which is transmitted through hydraulic fluid to a gage. The gage gives a direct reading equivalent to fastener tension in force units. Although this system has a high accuracy, they occupy a large space due to their large envelope volume besides their high cost. Automating the process of changing the spacer, nut, etc. could be close to impossible if this setup is used. Skidmore cannot be used for longer bolts either. Thus, for an automated assembly line that manufactures multiple or different length bolts the main goal is to carry out the operation on several bolts simultaneously, Skidmore cannot be the best solution.

Figure 45. Skidmore Bolt Tensioner

Another available solution in industry is Hydraulic Nuts, mainly manufactured by SKF. Using an SKF hydraulic nut facilitates easy and quick application of the high drive-up forces required for mounting bearings. These systems are suitable where space is available such as pressure vessels in power plants, or wind turbines. However these systems are heavy and take a large amount of space. They require a good amount of operator's input in order to set them up.

Figure 46. Left: Sketch of Cross Section of SKF Hydraulic Nut, Right: SKF Hydraulic Nut in Application

Therefore designing a system that can apply an accurate amount of tension to multiple bolts that can have different diameters and lengths was necessary. After studying available options in industry and brainstorming new concepts, it was decided

to use the same concept of the test setup explained in this work. As explained earlier, the selected concept involves mounting the bolt between a stationary and a movable plate and stretching the bolt by moving the movable plate. In order to transfer the load effectively to the bolt, bronze drill bushings and precision rods were used to provide smooth vertical translation of the plate. These bushings were press fit into the plate to provide a sliding fit with the precision rods, enabling the plate to travel freely along the precision rods. Two hydraulic cylinders were attached to the plate using the outer threads on the cylinder and the threaded holes on the plate. Prescribed loads can be applied by using the hydraulic pump. To ensure that the frame was rigid enough to be able to handle the reaction forces, reaction forces and moments were calculated. It was found that the design was inadequate and subsequently pillars were added under the fixed plate to support the reaction forces and prevent possible deformation of the fixed bottom plate. This design is created in Pro/E and shown in Figure 47.
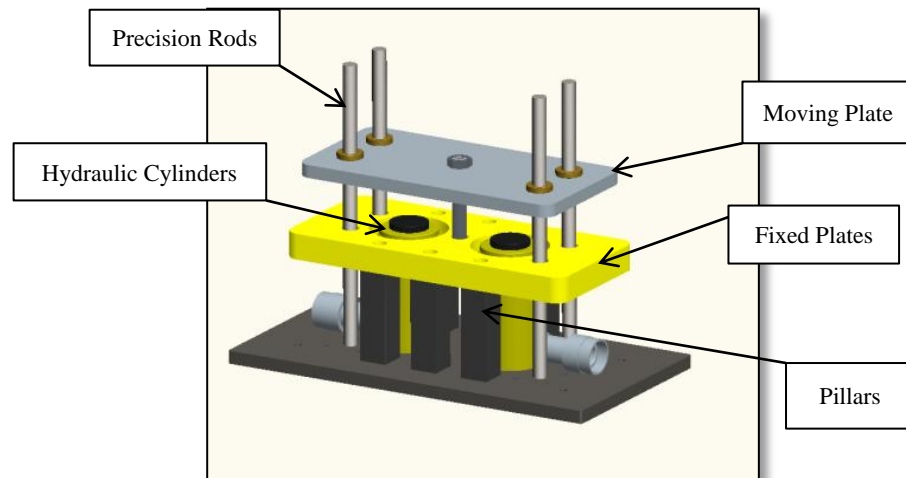

Figure 47. 3D CAD Representation of the Test System

Before fabricating the subsystem, different elements of the system were analyzed using the commercially available Pro/Engineer software. Results were

examined and parts were strengthened as needed. Figure 48 shows example results from the finite element analysis (FEA) for the fixed bottom plate, one of the key components of the setup. Due to the force transferred from the bolt and nut, the plate was expected to undergo deformation. FEA results ensured that the plate was rigid enough for the application and that the bolt will undergo intended deformation.
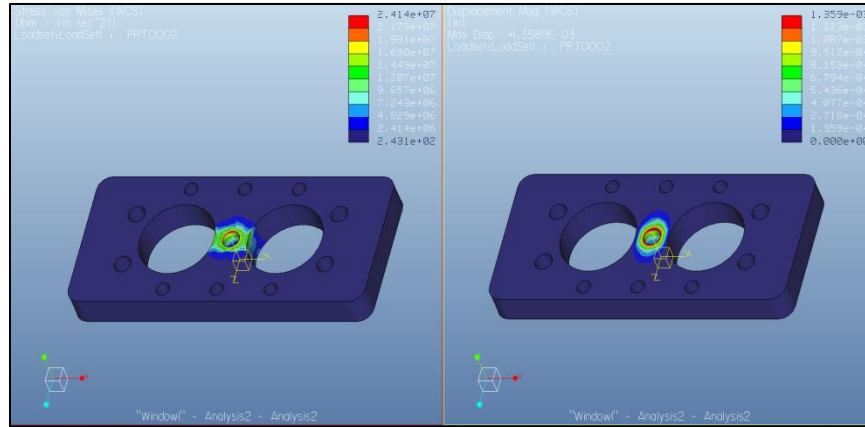

Figure 48. Left: Stress Concentration, Right: Displacement Concentration

After ensuring that all of the components in the setup can handle the reaction forces and tension will be directly and symmetrically applied to the bolt, the setup is fabricated and tested as shown below.

Figure 49. Physical Prototype of Tensioner Subsystem

4.4.2   Pin Drop Subsystem

The steps for automating the manufacturing process of visual indicating fasteners are divided into subsystems, each of which performs a specific task. One of these subsystems is the pin subsystem. In essence, this is the system responsible for properly inserting the pin into the tensioned bolt. The steel pins have two different lengths of 1.75" and 2". They come preassembled with a silicone washer as shown in Figure 41.
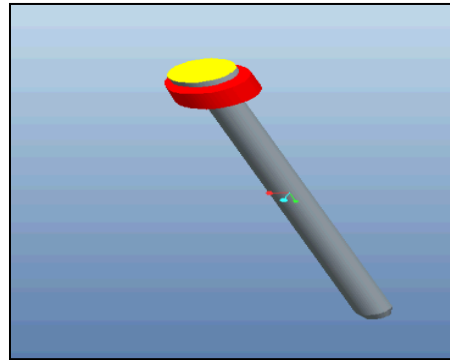

Figure 50. Steel Pin & Silicone Washer

<u>*Test Setup:*</u> The success of this subsystem largely depends on the gripper design. There are many unknowns involved in this procedure that could jeopardize the integrity of the design. These unknowns, including other factors of the design have to be known and corrected for the subsystem to be successful. A test setup is then created to simulate the pickup and dropping mechanism of the pin into the bolt. The test setup for the subsystem is shown in Figure 51.
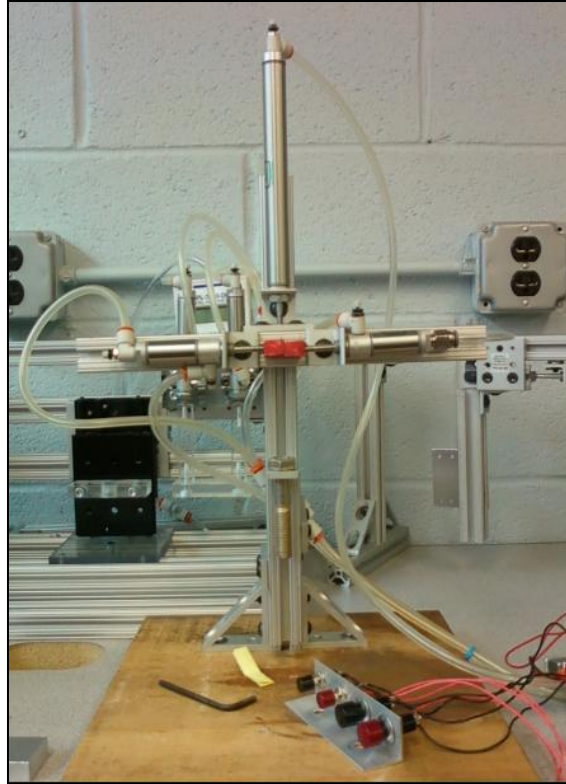
Figure 51. Pin Subsystem Test Setup

Having a separate gripper for the pin puts more control in the picking up and dropping off process. There is, as a result, no need for extra programming steps for back and forth motions. The design of the grippers allows for rejection, hence eliminates the potentially damaging situation that might arise in the event of a rejection. Another concern is the pin dropping mechanism. To say with certainty that the proposed gripper design would result in a successful drop the majority of the time will require experimental proof. Therefore the experiments and calculations are done on the design of grippers.

The critical component of the setup (and the concept) is the gripper design. The grippers are shaped as "V" shape vices for better gripping of the pin (the pin is gripped on via the rubber). The critical dimension for this design is the side length,

which was calculated to be 7mm (0.275in). The 3D CAD representation of the gripper is shown in Figure 52.
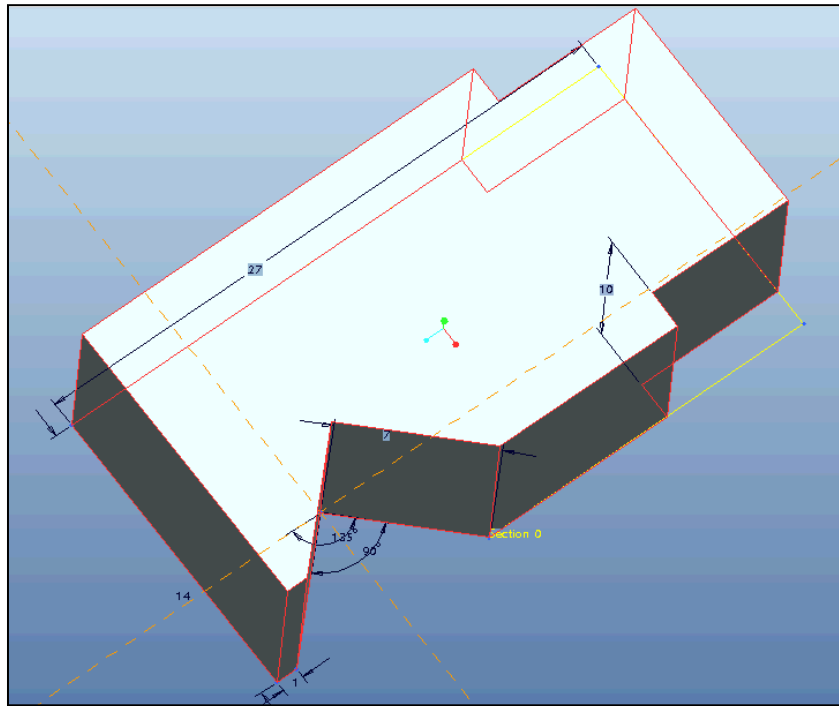
Figure 52. CAD Representation of the gripper

The experiments are quantitative (recorded success rate of a drop) and qualitative (behavior of the system) in nature. The experiments performed are:

- ➢ Straight drop success rate (slow & rapid signals)
- ➢ Slant drop success rate (slow & rapid signals)
- ➢ Offset drop success rate (slow & rapid signals)
- ➢ Critical release height (slow & rapid signals)

Figure 53 shows to help one better understand the terminologies used in the comments section of the experimental data are shown.

The initial test setup has two pneumatic actuators. In order to properly simulate the drop, the setup was modified to include a third actuator, as shown in Figure 51. The three pneumatic actuators are tasked as follows:
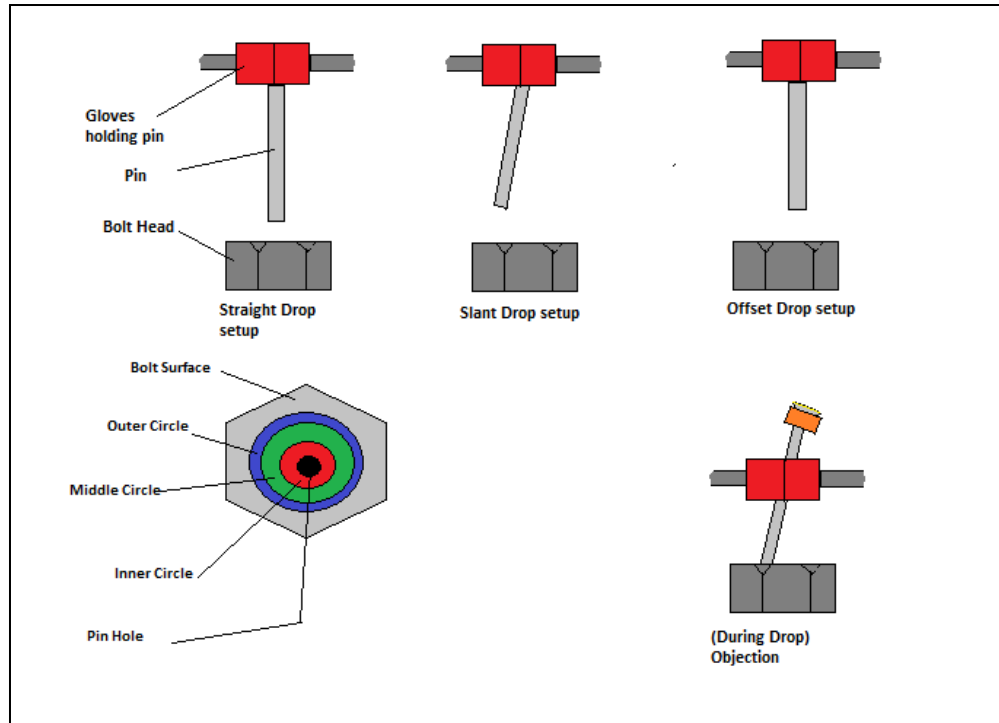
i)   Two of them with grippers attached to their tips to simulate the gripping action of the pneumatic grippers. They are both actuated using the same solenoid in order to have the symmetrical force around the silicone washer. This is exactly how the SMC parallel grippers work.

ii)   The third actuator holds the first two via a common bar for a vertical motion to simulate the linear actuator in the concept. The stage has two attachments: one to hold a pin for picking up, and the other to hold a bolt in place for the dropping. These attachments are easily swapped when needed.

The actuators are controlled by solenoid switches which are activated electronically with the push of a button. Hence the speed of the operation can be controlled: by giving rapid signals, a dropping sequence can be accomplished in as little as one second. Hence the speed of the operation can be controlled: by giving rapid signals, a dropping sequence can be accomplished in as little as one second. After running the experiments, it was found the defective rate of this system is about 1.5%.

Final Concept: After finalizing the design of grippers for gripping the pin from silicone washer, different concepts were introduced based on the target specifications defined for this subsystem. Although these concepts are similar in the sense that they will be doing the same function (picking up the pin from the silicone washer and dropping it) they use different equipment for doing that. Figure 54 and 46 show the final concept chosen for this subsystem.
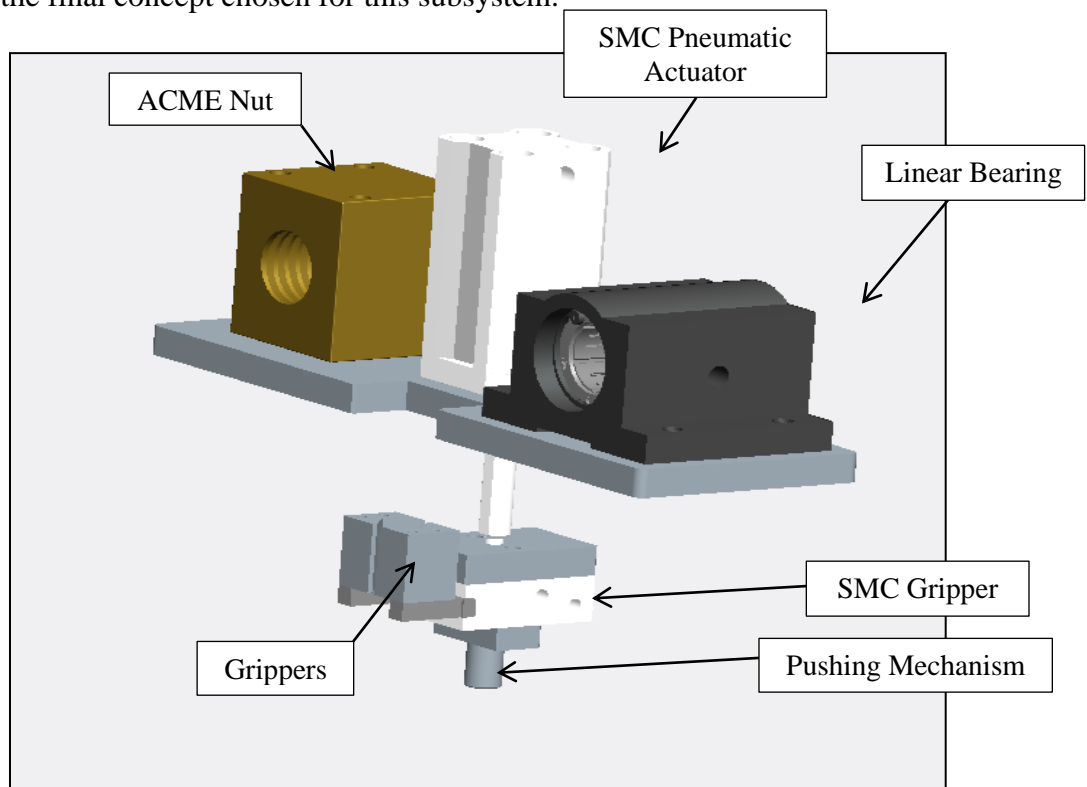
Figure 54. 3D CAD Representation of Pin Drop System

Figure 55. Physical Prototype of The Subsystem

In this system there are two SMC Pneumatic actuators used. The vertical pneumatic cylinder (NCQ2KB12-30DM) is a non-rotating piece that is chosen to bring the pin down. The subsystem, like other moving subsystems, moves as a result of the ACME screw rotation. The pin is held by the pneumatic gripper (MHZA2-6D1). Once the subsystem arrives at the top of the bolt head, the pneumatic cylinder extends, partly inserting the pin into the bolt. The gripper then releases the pin, which drops into the bolt. There is a hammering stud underneath the gripper which does the hammering should it be needed.

4.4.3　Adhesive Dispensing Subsystems

In the manufacturing process of HR Visual indicating fasteners, there are two types of adhesives used. The first adhesive is meant to bond the pin to the bolt at the very bottom of the cavity. Although there are some other methods proposed such as threaded bond, press fit; experimentally using Loctite 603 has given the best results. The other type of adhesive used is known as a Room Temperature Vulcanization (RTV) adhesive. The specific type of this RTV is known as Loctite 5033. The main purpose of this adhesive is to attach the head of the bolt, microinidicator and window assembly together. Therefore, one of the main requirements for it is to be transparent. Although RTV adhesives cure at room temperature, in the manufacturing process of HR Visual indicating fasteners the UV curing method is chosen in order to cure the RTV in a shorter amount of time, which will be explained in more details in the staking subsystem section.

Among the moving subsystems, Loctite 5033 and Loctite 603 are the most critical components. The reason for that is the number of variables they involve and the inconsistencies found while manufacturing Visual indicating fasteners manually. In the following section the experiment and studies done in order to simulate the interface between the pin, microindicator and window assembly are discussed. Based on the results and conclusions gathered from these studies, concept generation and selection is done.

4.4.3.1   Loctite 5033 Dispensing Subsystem

In order to conceptualize the RTV subsystem, the variables affecting the behavior of this adhesive in Visual indicating fasteners should be defined clearly. Therefore, a test setup was designed and fabricated. The idea behind the test setup is to have an apparatus that is able to accurately dispense RTV On/Off center, as well as press the window with the desired force needed.

Test Setup: By considering these two specifications, conceptualizing and fabrication of this setup is done. The apparatus, as shown in Figure 56, is made with simple and basic design components. The moving mechanism of the two plates made testing quick and efficient, minimizing the time required to complete a test (critical to avoid hardening of RTV during assembly). The pressing plate material is made of PMMA clear plastic allowing for UV curing when the window is pressed down. Special attention was paid to ensure the structure had no vibrations/oscillations which are known to skew experimental data. The EFD dispenser is used to dispense the RTV which is a critical factor (both the amount and velocity) [21]. EFD settings currently used for HR Visual indicating fastener manual production were unchanged, allowing for a repeatable and consistent RTV shape that is constant for all experiments.
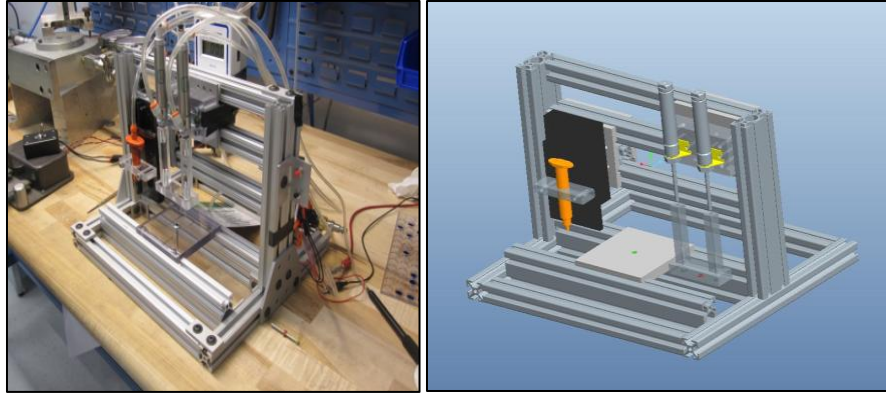
Figure 56. RTV Dispensing Apparatus

After purging the EFD a couple of times in order to get the fresh part of RTV out of the syringe barrel, Figure 57 shows a good sample of RTV dispensed on microindicator.

Figure 57. Good Sample for RTV Shot on Microindicator

This apparatus allows for the possibility to vary four essential variables:

    i. Amount of RTV dispensed

    ii. Location of RTV

    iii. Pressing force of the window (by varying cylinder pressure)

    iv. UV curing time

Given that there are four variables at play, only one is changed at a time while keeping the other three constant, to allow us to isolate and highlight the impact of that variable on the overall behavior of the bolt. Sin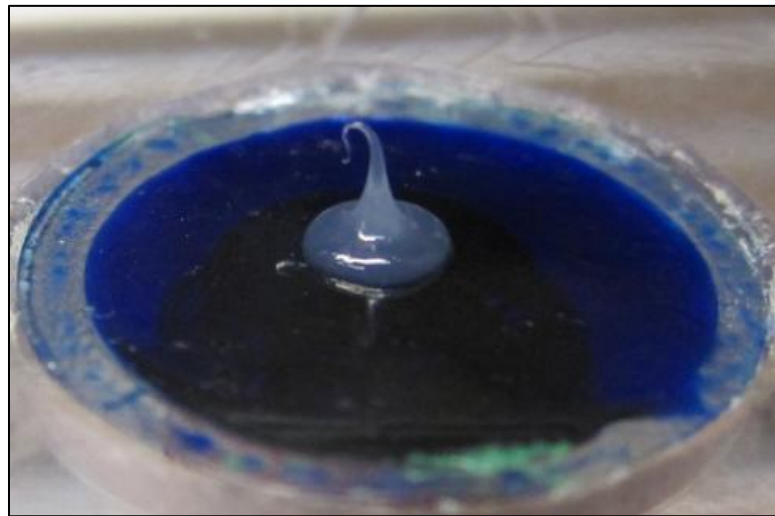ce there are many variables involved in the manufacturing process of HR Visual indicating fasteners, partly due to the number of components involved and partly due to the way the bolt is assembled, this experiment allows for a better understanding of how important each variable is and how much weight or impact it carries. This can help isolate the critical variables from the less important ones, allowing us to invest more time and resources to better understand them and use them as our engineering constrains in the design of the automated assembly line.

Throughout the different tests, a few patterns started becoming apparent. Curing time plays a significant role in reducing the blemishes (RB), blushes (BL), but high curing time (240 s) also caused grading (GR). When curing time was increased from 60 sec to 240 sec, we no longer had any permanent markings when pulling on pin. Color change was uniform and would go back to yellow (no load color) when at rest compared to a permanent color spotting as well RB formation at the lower curing time. One possible explanation could be that RTV is not curing fast enough after only 60s of curing time. When tension is released, the internal components are moving at different rates, possibly causing an RB and BL. On the other hand, a curing time of 240s is causing a solidification of RTV enabling the GR effect.

The location of RTV did have a significant impact on overall performance of bolt even though the current amount of RTV dispensed by the EFD spreads enough to cover most of the microindicator surface. Again, curing time played a significant role.

When cured for only 60s, formation of BL and RB was noticeable when pin was pulled leaving a permanent RB defect under no load. This phenomenon was not present at a curing time of 240s.

The preliminary test results are in agreement with predictions based on previous assumptions concerning the reasons for defects. The ability to replicate the outcomes ensures that the factors causing unwanted effects are understood and can be eliminated from the production process and automation assembly.

In conclusion, it can be deduced that both RTV location and curing time are responsible for many of the defects that can be seen in an HR Visual indicating fasteners. It was shown that off center RTV dispensing is linked to BL and RB while an increased curing time causes GR. It must be noted that other factors might be responsible for these defects to appear. This can include but is not limited to, window assembly geometry, microindicator eccentricity, crimping of window, tension loss as well as other factors.

Final Concept: After understanding the problems which were introduced earlier in this work in more detail and finding the causes of these results, concept generation and selection for this subsystem took place. Besides the fact the design of this system had to fit with the guidelines defined in the system design procedure, considerable attention was given to:

1) Centering the dispensing location

2) Amount of RTV

3) Required Pressure to Dispense the RTV by using EFD dispensing systems

As shown in Figure 58 and 50, CAD drawings based on hand sketches were generated for the RTV subsystem and the system was fabricated. This system is using two pneumatic cylinders in order to bring down the plate which is holding the RTV syringe (or barrel). Due to the design of the whole system and the height offset requirements, the pneumatic cylinders are used. The pneumatic cylinders will be at the closed position until the subsystem arrives at exactly the center of the bolt. Then the pneumatic cylinders get actuated by using the solenoids and bring the syringe plate down. When the syringe is at the required location (known X, Y, Z location), the EFD dispenser gets actuated and it dispenses the correct amount of the RTV at the correct location. Before asking the system to move, the syringe plate needs to be brought to the closed position by closing the pneumatic cylinders.
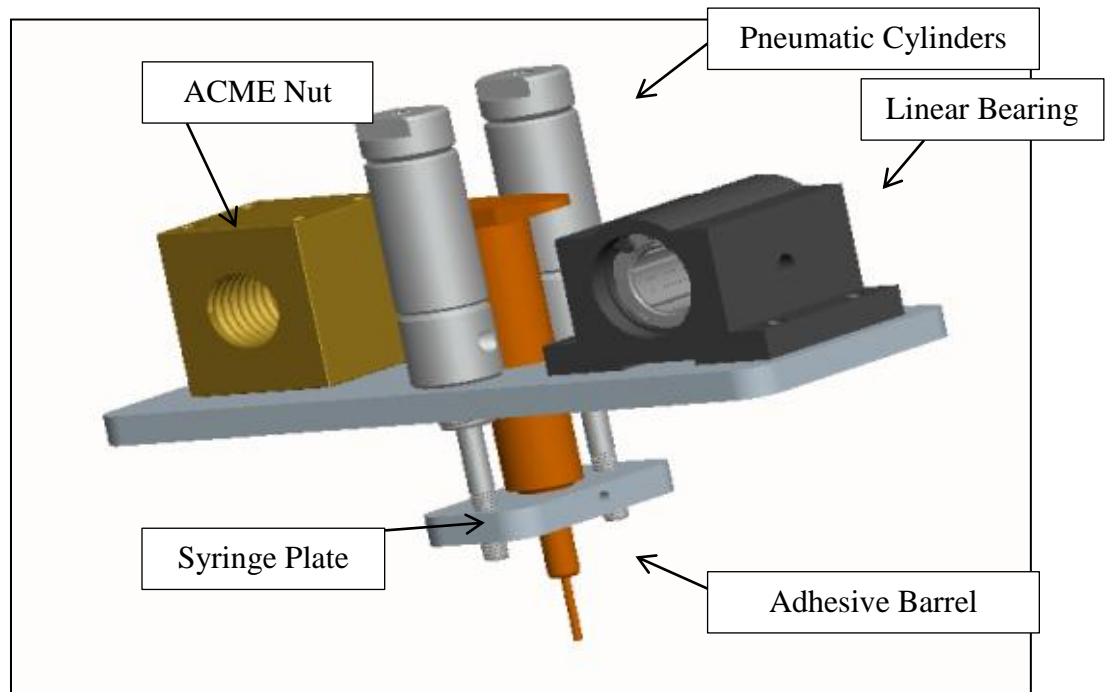

Figure 58. 3D CAD Representation of Loctite 5033 Dispensing Subsystem

Figure 59. Physical Subsystem

4.4.3.2   Loctite 603 Dispensing Subsystem

The Loctite 603 subsystem had to follow the same guidelines given with RTV in the sense that dispensing the adhesive at the center is critical. The other factor that can affect the behavior of the bond between the pin and the bolt is the amount of adhesive dispensed. Due to the nature of the design, an HR Visual indicating fastener can be non-functional if the bond at the interface of the pin and cavity is not done correctly. Some features that can make an HR Visual indicating fastener non-functional are mentioned in the Table 7.

Table 7. Effect of Loctite 603 on Final Quality of HR Smart Bolt

Test Configuration	Effect on the Bond	Result on HR Smart Bolt
Dispensing More Than Required	Larger Surface Area for the Bond (More shear force on the pin)	Changes Color Before Design Tension
Dispensing Less Than	Weak Bond	Non-responsive Bolt

Required

Dispensing Off Center	Bond at a higher point on the pin	Permanent Blemish

As shown in Figure 60, the amount of Loctite 603 should be enough so that when the pin is inserted it will not come out of the bottom of the cavity.
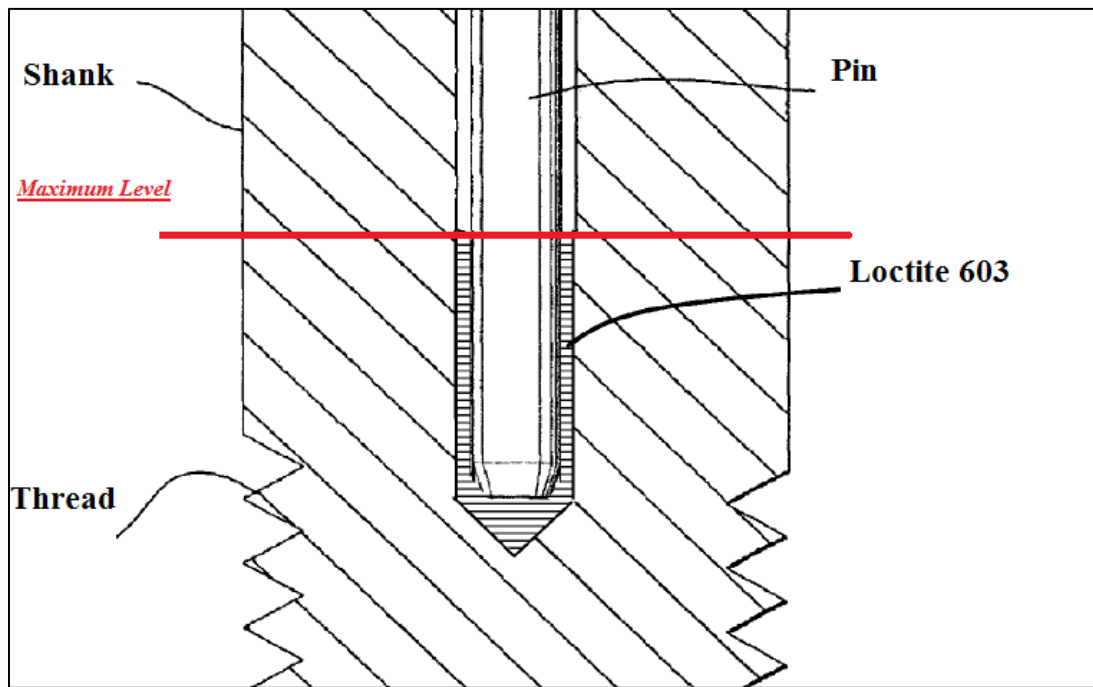
Figure 60. Maximum Level of Loctite 603

Same concept of RTV dispensing subsystem is used to design the Loctite 603 subsystem. One plate should be used in order to hold the syringe and the two pneumatic cylinders will be used to bring the plate up and down. Since the adhesive needs to be dispensed exactly at the bottom of the cavity, the stroke length of these actuators is critical. However, in order to be able to reach the bottom of the cavity for the bolts which are machined for 2" pins SMC pneumatic actuators are selected because they are more impact and take minimum space while having the required

stroke length(2 inch). In Figure 62, the CAD drawing and physical subsystems are
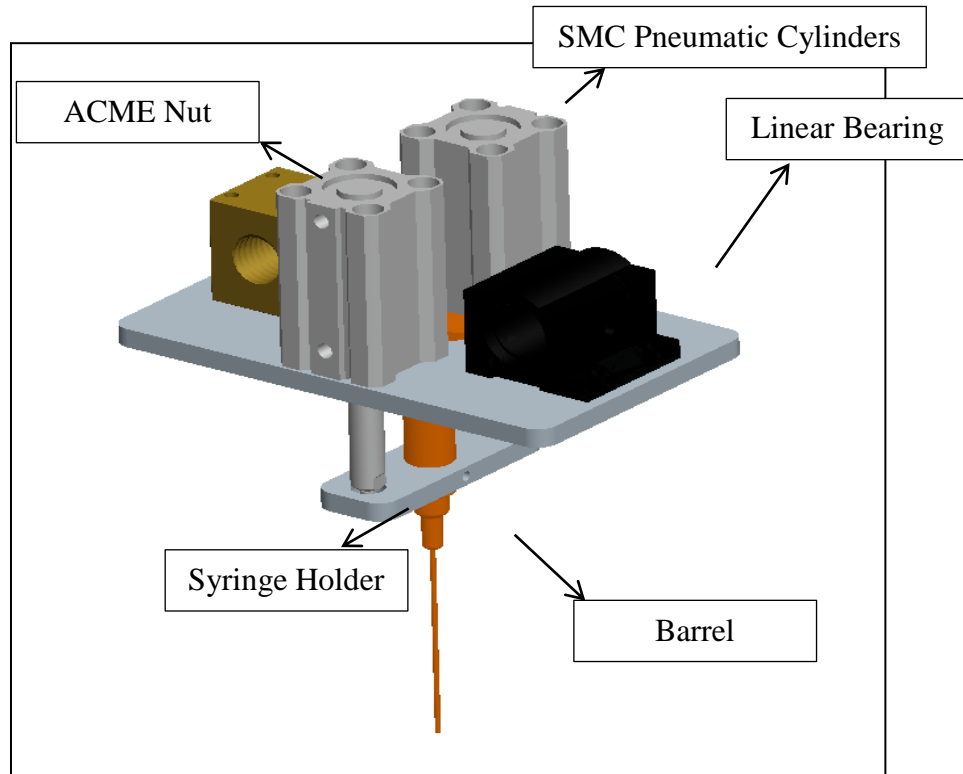shown.
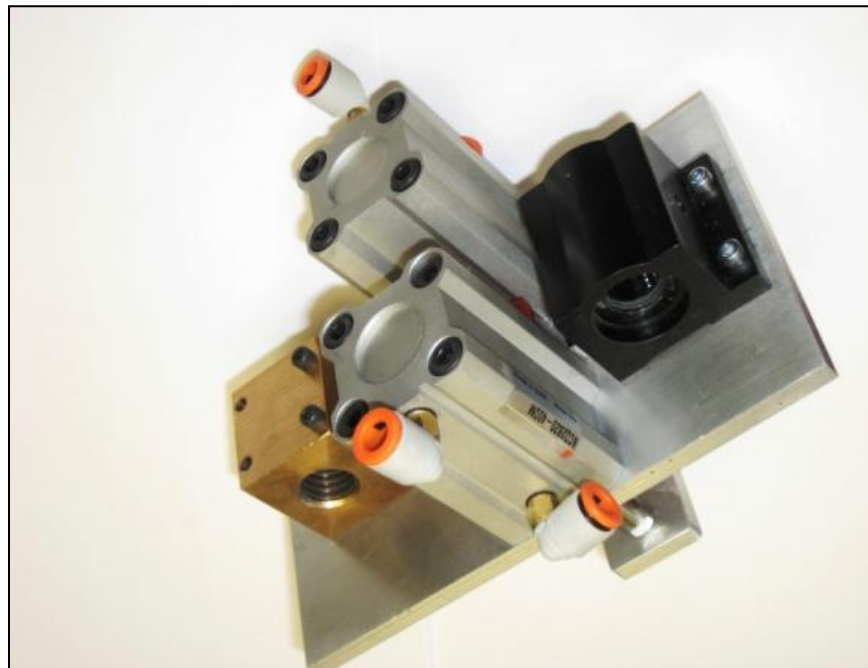

Figure 61. CAD Representation of Loctite 603

Figure 62. Physical Prototype of Loctite 603

4.4.4   *Pick & Place Subsystem for MicroIndicator & Window Assembly Ring*

Suction pressure is a very popular method of picking and placing various objects. Suction cups are usually used as grippers, which are between the pneumatic circuit and the item which is being moved. Many industries have tried using magnets as a source of moving metal objects but there are multiple problems with this method. One of the main problems with magnets is the difficulty in orienting the object exactly how you want it. With suction cups this is easily possible. Another big problem is if using any material other than a ferrous metal the magnet will not be able to move it. The suction cup is able to move a wide variety of materials other than metal. Even certain factors that could come into play such as very hot products, electric sensitive computer components and not wanting to leave marks on the product are addressed with the use of suction cups. But the main problem for suction cups is finding the required suction pressure to hold the object.

Suction Cups are a popular choice when it comes to various types of assembly processes. They are mainly used to move parts of high heat, move plastic products without leaving marks, and diffuse static buildup on electronic components. In each application suction cups must be set to the proper suction pressure so that they do not harm the product or part they are moving for assembly. Most cases it is hard to move injection molded plastic parts without leaving an invisible mark; this is not the case with suction cups. Also, when moving very hot glass pieces it can be hard to handle and have your holder not melt while still having a good grip. When assembling a computer package one of the difficult parts is being sure that there is no static buildup

introduced to the system which could damage other components, dissipative Nomastat suction cups are able to diffuse the static buildup making it safe to assemble. Therefore suction cups are chosen in order to pick up microindicator and the window assembly. In order to choose the correct size and model of the suction cup, the following equation is used:

$$S = \frac{D_s^2 P_u c}{125.44m}$$

The minimum diameter of the suction cup is calculated to be 10.6 mm. However this is not standard size suction cup in the market. The next size closest to this is a 10.9mm suction cup, which is chosen for this system. The height of the suction cup is 10mm. The safety factor was solved to be 3. A general rule is to have a safety factor of at least 2 for horizontal lifts and a safety factor of at least 4 for any tilting application. The weight and the required pressure for the pneumatic circuit, shown in below, are found by the following equations.

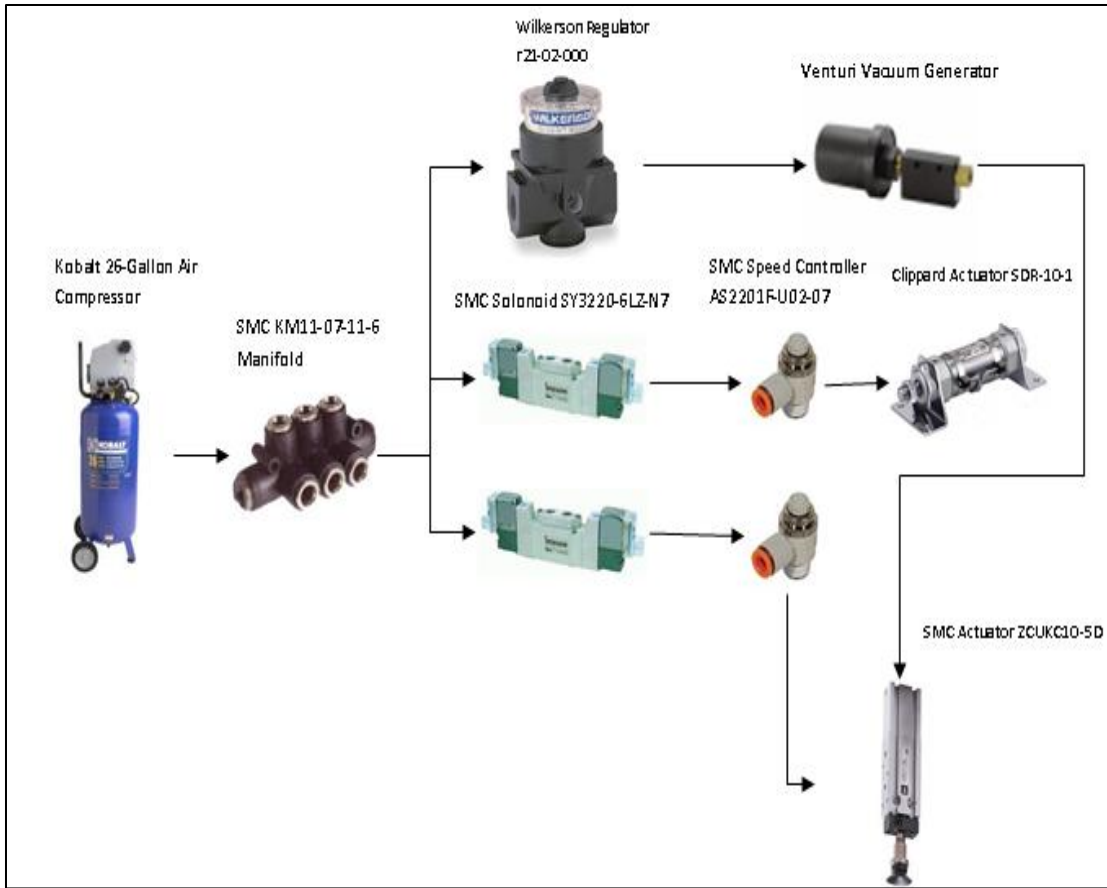$$F = m \times g$$

$$P = \frac{F}{A}$$

Figure 63. Pneumatic Circuit for the Test Setup of Suction Subsystem

The pneumatic cylinder chosen is manufactured by SMC (ZCUKC10-5D). This pneumatic cylinder has the suction feature at the tip of its stroke which makes the design more impact. The figure below shows the three different types of suction cups that are used and tested in order to find out the best performance for picking the microindicator and window assembly up. The red suction cup (U10-SI) is a red silicone. The black suction cup (F10-NBR) is made of nitrile with a diameter of 10mm and height of 10.6mm. Finally the clear suction cup (B1.5-14-SIT) is made of translucent silicone with a diameter of 10.9mm and height of 15.8mm. The suction cup on the right was chosen since it had the best performance compared to the others in that it did not jam the microindicator and did not drop the window assembly either.

Figure 64. Left: Silicone Suction Cup, Middle: Nitrile Suction Cup, Right: Translucent Silicone Suction Cup

After choosing the correct suction cup and the SMC actuator, the hand sketch for this subsystem was drawn and put in ProEngineer. After doing the embodiment design of this subsystem, the actual prototype is fabricated. This process is shown in the following pictures.
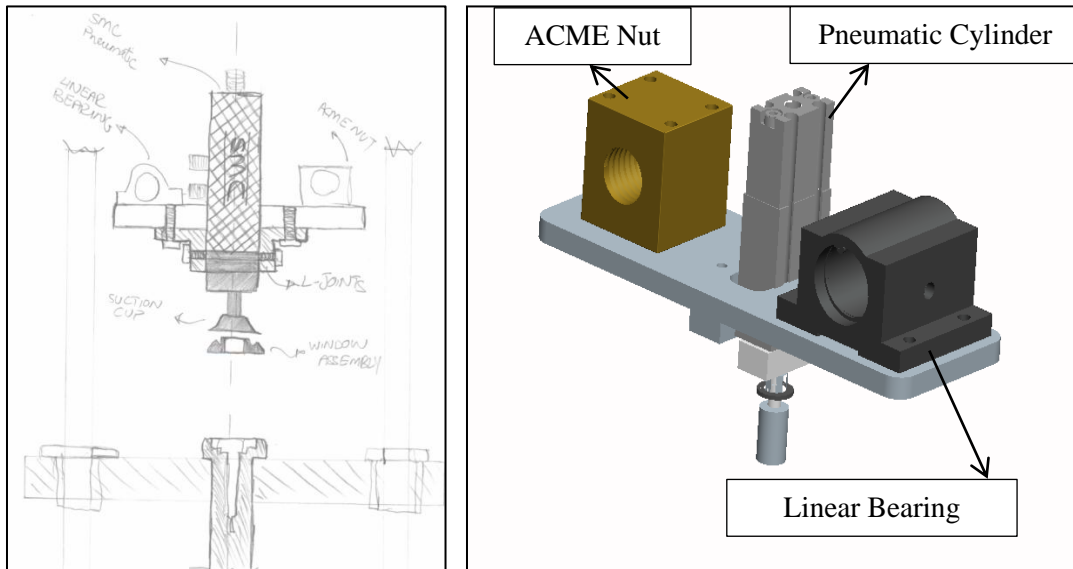

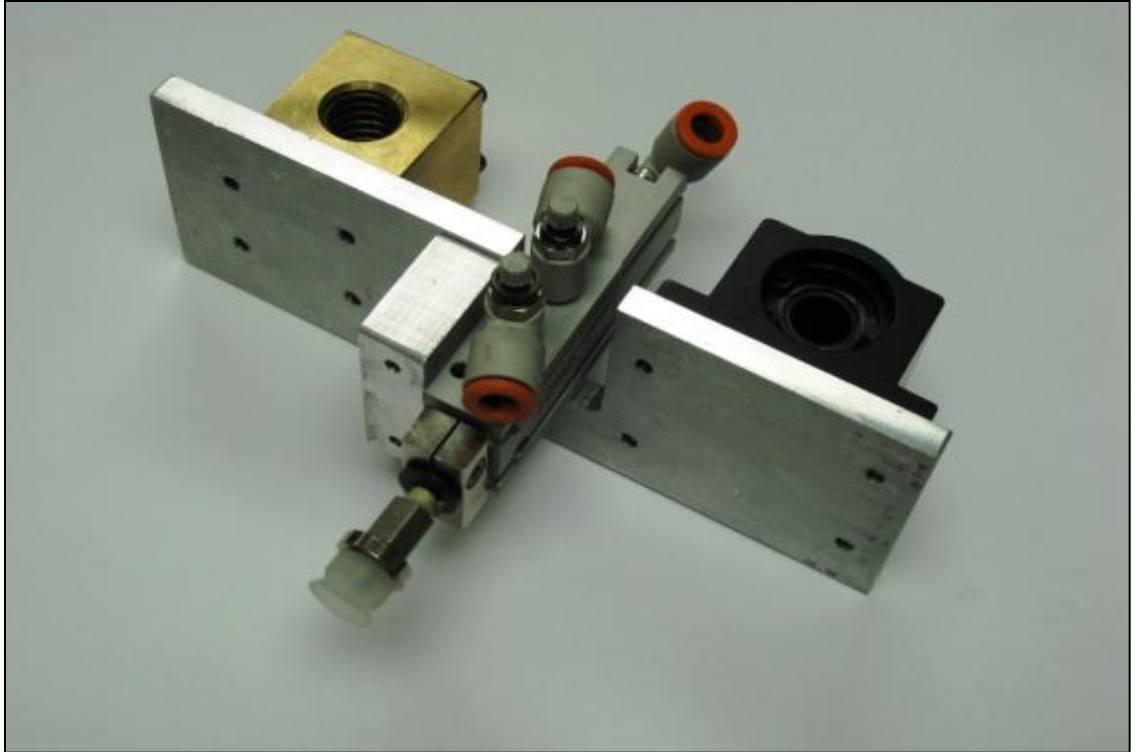**Figure 65. Left: Hand Sketch of Suction Subsystem, Right: CAD Prototype of Suction Subsystem**

Figure 66. Physical Suction Subsystem

4.4.5   Staking Subsystem

In design of a subsystem the number of functions that should be accomplished and the embodiment design with respect to other subsystems define the complexity of a design. The staking subsystem in this machine was definitely the most challenging subsystem compared to other systems. There are three main tasks for this subsystem that needs to take place at the same time:

i)   Pushing the Optical Element Down (i.e. compressing the wave spring)

ii)   Staking the head of the bolt

iii)   Applying UV light to cure the adhesive

In the process of manufacturing HR Visual indicating fasteners it was explained earlier that when all of the components and adhesives are in place and dispensed. They should be locked in-place. However, it is at this stage of the process where the "zero-level" of the window assembly needs to be defined. Therefore, making sure that the optical element in the window assembly is pressed down, compressing the wave spring to the maximum displacement is critical. By experiment, it is shown that if this task is not done properly, there will be blushes in the bolt causing darker color when there is no load applied. Figure 67 shows how the optical element is aligned with respect to other components while staking.
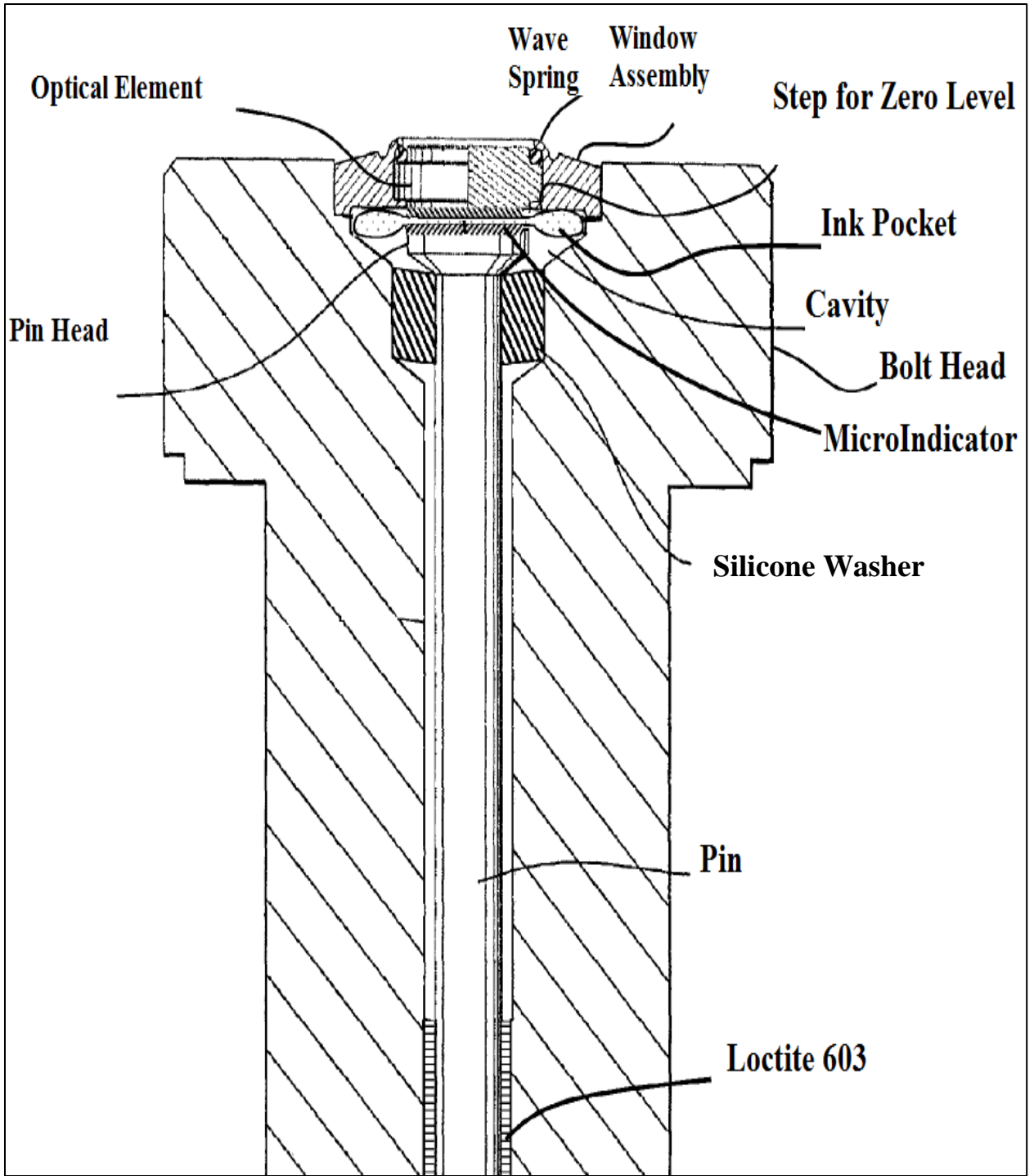
Figure 67. Cross Section of Cavity and Internal Components in HR Smart Bolt

While pushing the optical element down, the circle around the window assembly on the bolt head needs to be deformed in order to lock all of the components in that position. The final product quality directly depends on this part of the process. Tolerances in this part of the design play an important role, therefore it is important to design a tool that can be easily manufactured and be repeatable.

The third function of this subsystem is curing the RTV dispensed in the previous steps by using the ultraviolet light (UV light). To do this, spot curing method is mainly used due to limited accessibility to the adhesive. The specific instrument used for UV curing is Spot Cure B6 model manufactured by Kinetic Inc. The SpotCure-B6 high intensity LED UV adhesive curing light is designed for bench-top use in various industrial applications. The system consists of an input wall switcher, power console and curing probe. The standard curing probe is 405nm wavelength (Black) with optional probes available in 365nm (Purple) and 460nm (Blue) wavelengths. The functionality of SpotCure-B6 is software driven by an onboard micro-controller [22]. A built-in external switch control input is provided to permit the unit to be controlled by a foot switch, PLC or other device. The Spot Curing B6 instrument is shown in Figure 68.
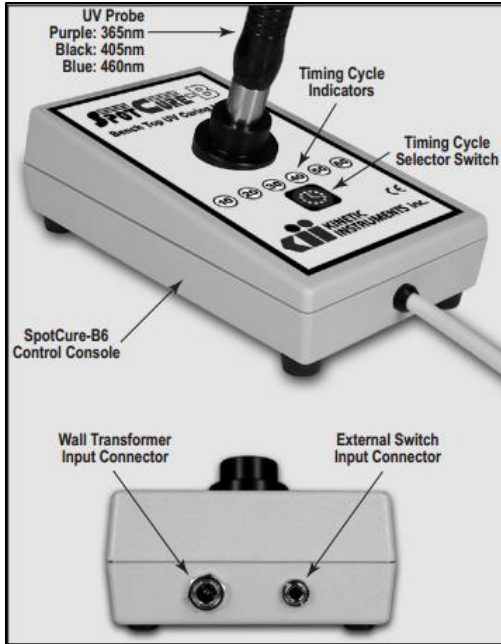
Figure 68. UV Spot Curing Instrument

Designing an adapter that can be mounted on the curing instrument and be attached to the staking tool is done too which is shown in Figure 69.
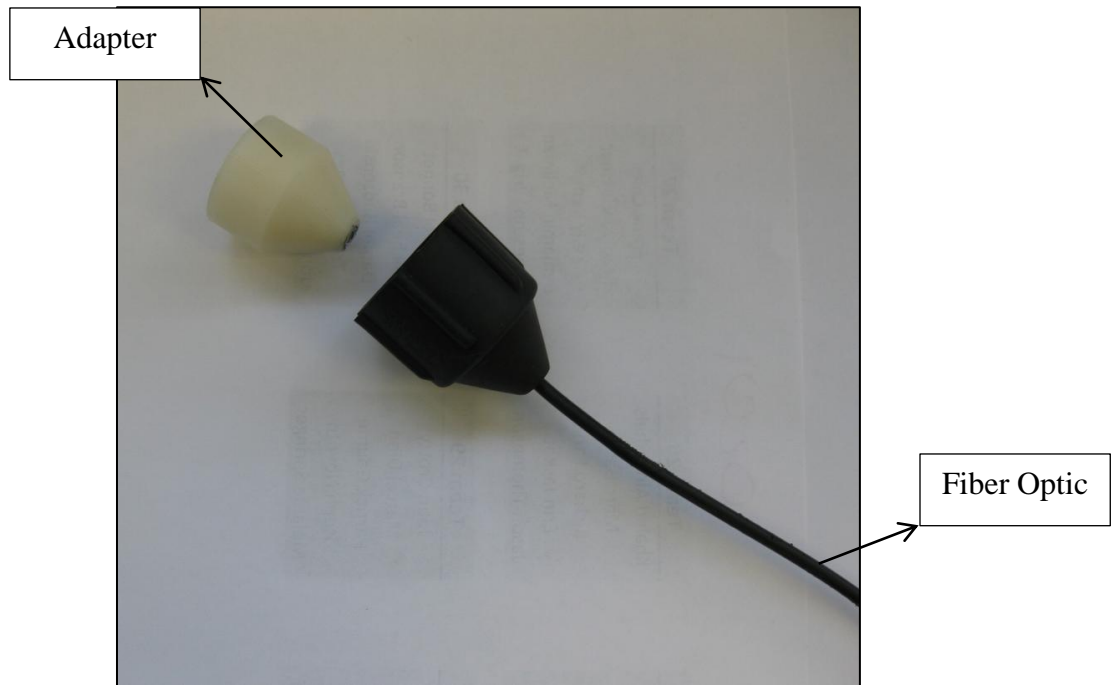
Figure 69. Adapter & Fiber Optic

Test Setup Prior to designing the staking tool, we conducted some experiments using hand staking. During the hand assembly process of HR Visual indicating fasteners, it was found that one of the main sources of the gradient issue is due to doing staking at three different times. The following figures show the design of semi-automated assembly system that was used during the hand assembly.
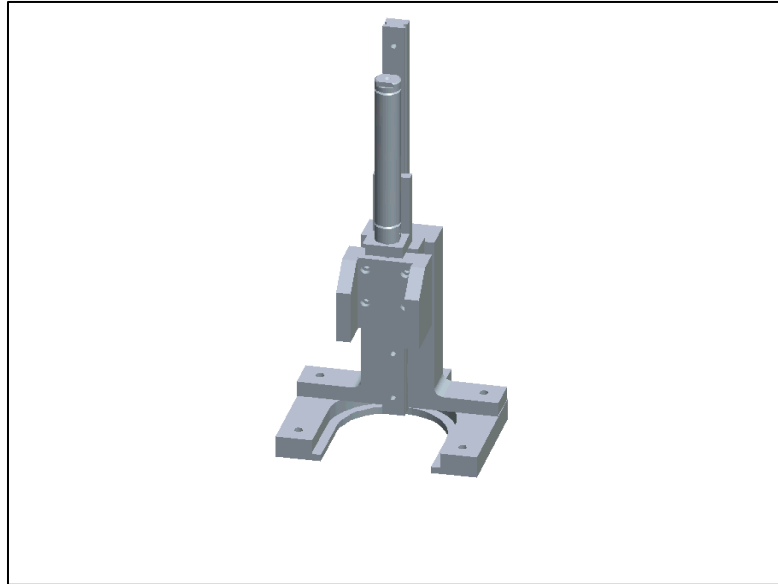
Figure 70. First Design of Semi-Automated Staking System
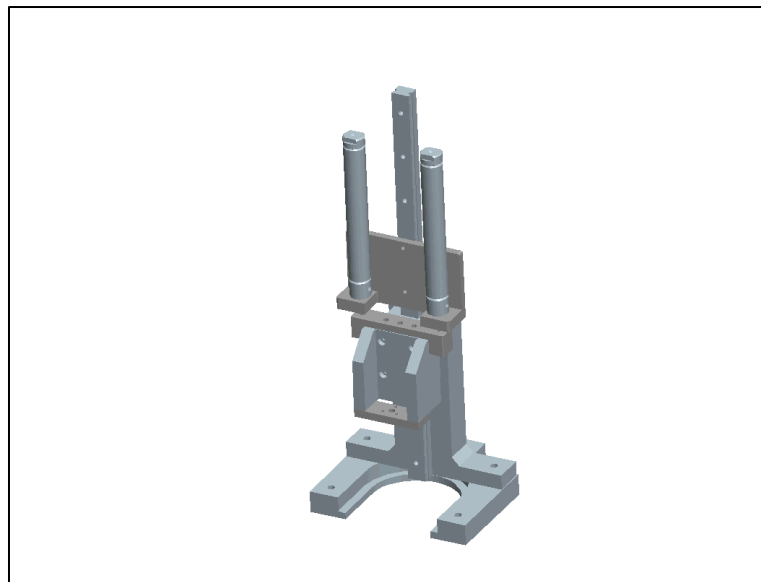
Figure 71. Second Design of Semi-Automated Assembly Staking System

In order to choose the right pneumatic cylinders, the force needed was calculated with respect to the data sheet given by Smalley Steel Ring Company for the wave spring. By knowing the spring constant of the spring (k=100 lbs./inch) and the required displacement (x=0.010 inch), the force required to push on the window in order to bring it to the lowest position is calculated and found to be 1lbs, solving through the basic spring equation.

$$\mathbf{F = k\Delta x}$$ Eq. 19

Since the required load was very small, almost any type pneumatic cylinder that could provide the required stroke length could be used.

In Figure 70, the first design of this system is shown. The operator has to bring the pushing plate down, using the pneumatic actuator and locate the staking tool, shown in Figure 72, and hammer the top part of the tool in order to stake it.
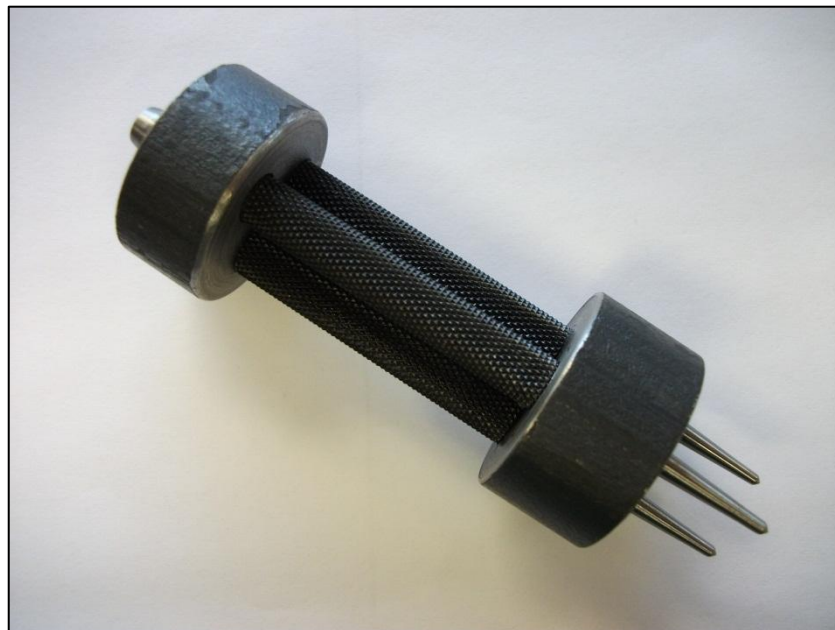
Figure 72. Manual Staking Tool

However, in order to create more space and increase the level of comfort for the operator the second design was done. In the second design, the operator has more control on the alignment of the staking tool and could apply the force more concentric. The main purpose of designing this system was to understand the effect of staking three different locations simultaneously and correlating that with the issues introduced earlier, more specifically the gradient issue. After getting the experimental results, it was concluded that staking the head of the bolt with a tool that can do the task simultaneously was necessary. Therefore, the next step of the design was trying to calculate the force required to deform the head of the bolt and design a fully automated subsystem for these tasks.

Final Concept After finding the force required to deform the head of the bolt, a tool needed to be designed that can resist this amount of stress and have a minimum wear rate. In the following figure the hand sketch of the general concept is shown. In this setup, central spring is used in order to push the optical element down while fiber optics is used in order to pass the UV light to the RTV. Staking is done simultaneously for four different arcs around the head of the bolt.
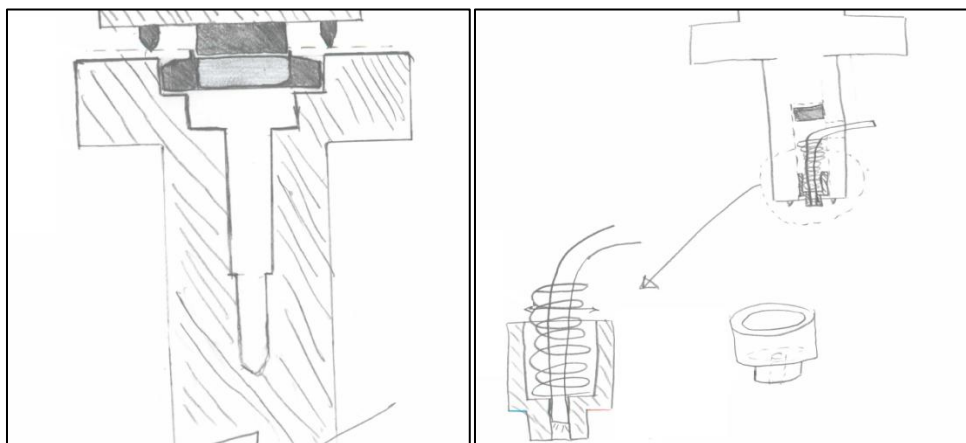
Figure 73. Hand Sketched of Initial Concepts for Staking Tool

After feasibility tests, in order to finalize the exact dimensions the 3D representation is prepared in ProEngineer. The material used for the staking tool is A2 tool steel, which is heat-treated and cooled down by air. A very fine grain structure results in superior-quality steel. Compared to O1 tool steel, this material has better wear resistance, which means it can hold a sharper cutting edge. Compared to D2 tool steel and other high-carbon or high-chromium steels, this material offers better machinability. It is ideal for making thin parts that are usually prone to cracking during heat treating. The yield strength of this material is 55ksi with Brinell Hardness Number (BHN) of 215. After heat treatment it can reach maximum Rockwell hardness of C62-C65. Straightness tolerance is 1/8" per 5 feet [23]. Figure 74 and 66 show the CAD representation and the fabricated piece.

Figure 74. CAD Representation of Staking Tool

Figure 75. Physical Staking Tool

The finite element analysis is done on the tip of this tool by using ProEngineer Mechanica simulation in order to find the safety factor of the design. In Figure 76, the stress concentration on this tool is shown. It can be seen that the maximum von Mises stress on the tip is around 100MPa.
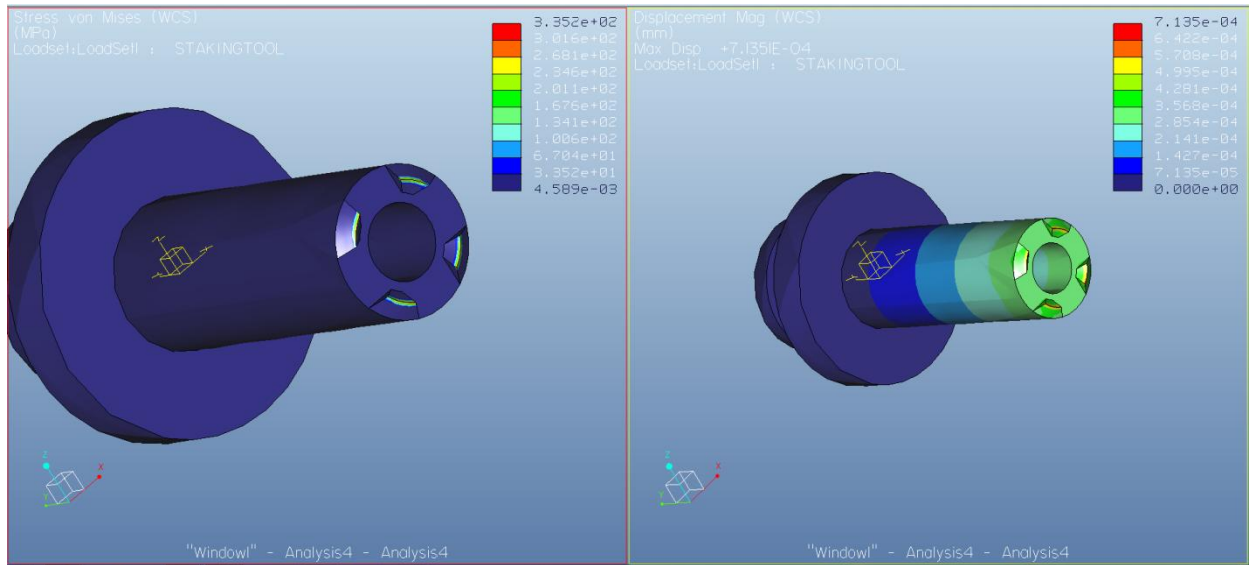
Figure 76. Finite Element Analysis on Staking Tool, Left: von Mises Stress Concentration, Right: Displacement Concentration

It is important to note that this tool will be applying large amount of forces on the head of bolts (especially case hardened ones) in order to clamp the window assembly in its place. Therefore, designing a frame that can handle the reaction forces due to staking is important. In order to minimize the cost, H-Frame bench press is used as the general frame of the system where the staking tool is attached to the hydraulic cylinder of it. This press has a capacity of 10ton. Figure 77 and 69 show the H-Frame chosen.

Figure 77. H-Frame Bench Top Press

Figure 78. Overall Dimensions of H-Frame Bench Top Press

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4.5 Integrating Subsystems to Final Prototype

After designing and fabricating all of the moving and stationary subsystems, each one of them were tested individually to make sure the concept is feasible. By assembling all of the subsystems next to each other, it was realized that the moving subsystems can be integrated into one moving plate that can carry all of them. In Figure 79, the optimized design of the moving subsystems is shown. Since there are only two ACME nuts and two linear bearings used and all of the subsystems (thread holes, grooves, etc.) are based on the edge of the plate, this design has minimized the tolerance stack up of the system to +/- 0.005".
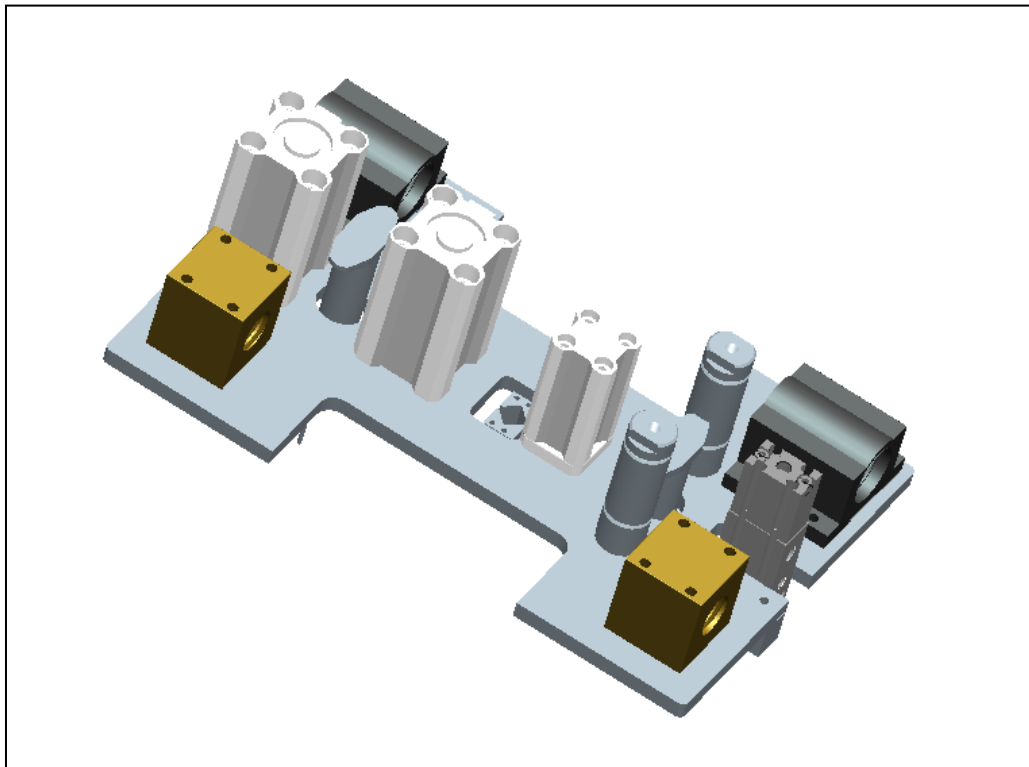
Figure 79. 3D CAD Representation of Integrated Moving Subsystem

In the following paragraphs general design for assembly of the final prototype is discussed. One of the general guidelines of design for assembly is "minimizing the

number of fasteners". This guideline is maintained for most of this design. The frame of the moving subsystem is assembled using ¼"-20 socket head machine screws. Frame is made out of aluminum extrusion from 8020 company. In Figure 80 and 77, the two stationary subsystems (tensioner and staking subsystems) are shown. The H-Frame Press with capacity of 10ton is used in order to be able to resist the reaction force of the staking process.
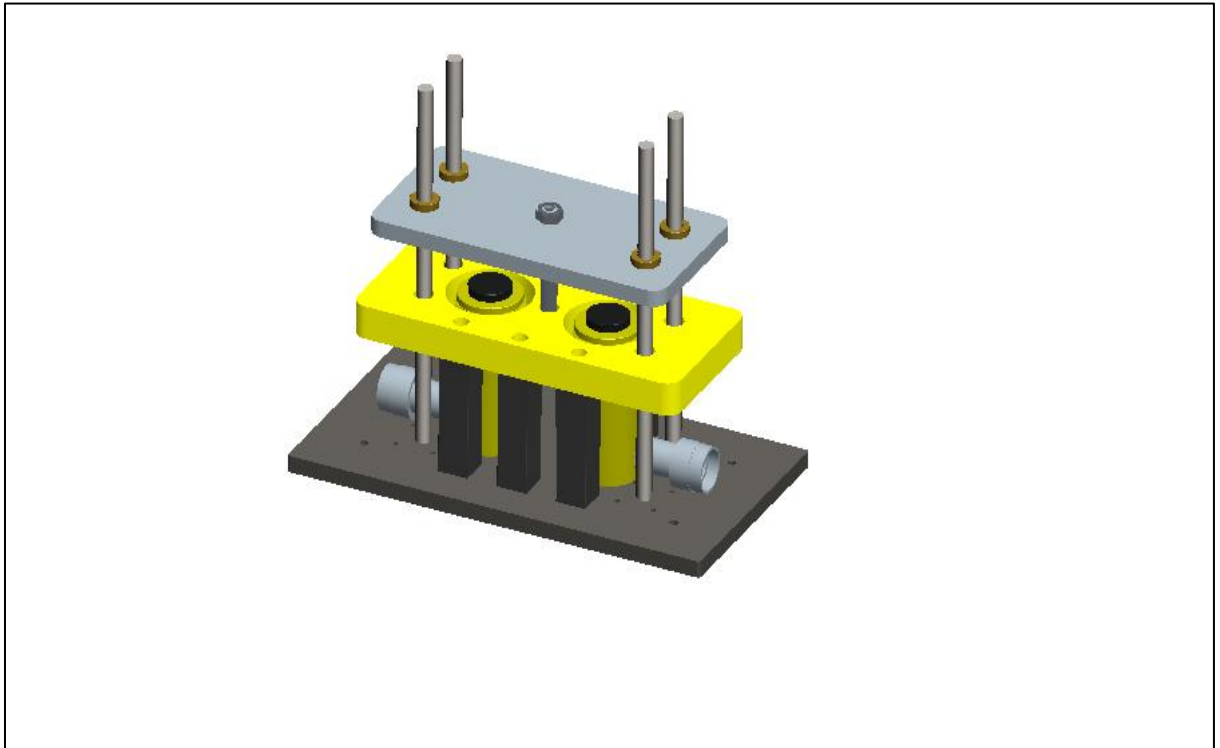
Figure 80. 3D CAD Representation of Tensioner Subsystem
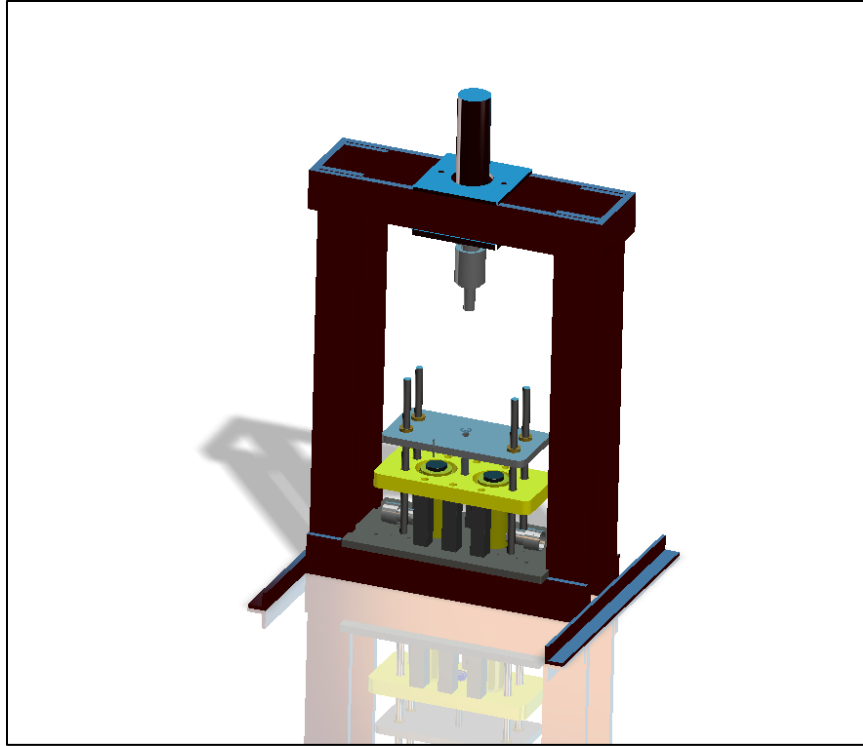
Figure 81. 3D CAD Representation of Tensioning Subsystem and Staking Subsystem

The moving subsystem, shown in Figure 82, has a modular design so it can be assembled separately from the stationary subsystems. This can help the operator for maintenance. The moving plate shown in Figure 80 earlier can be assembled to the frame of the moving system by 6-32 machine screws that can attach the ACME nut and linear bearing to the threaded holes on the plate.
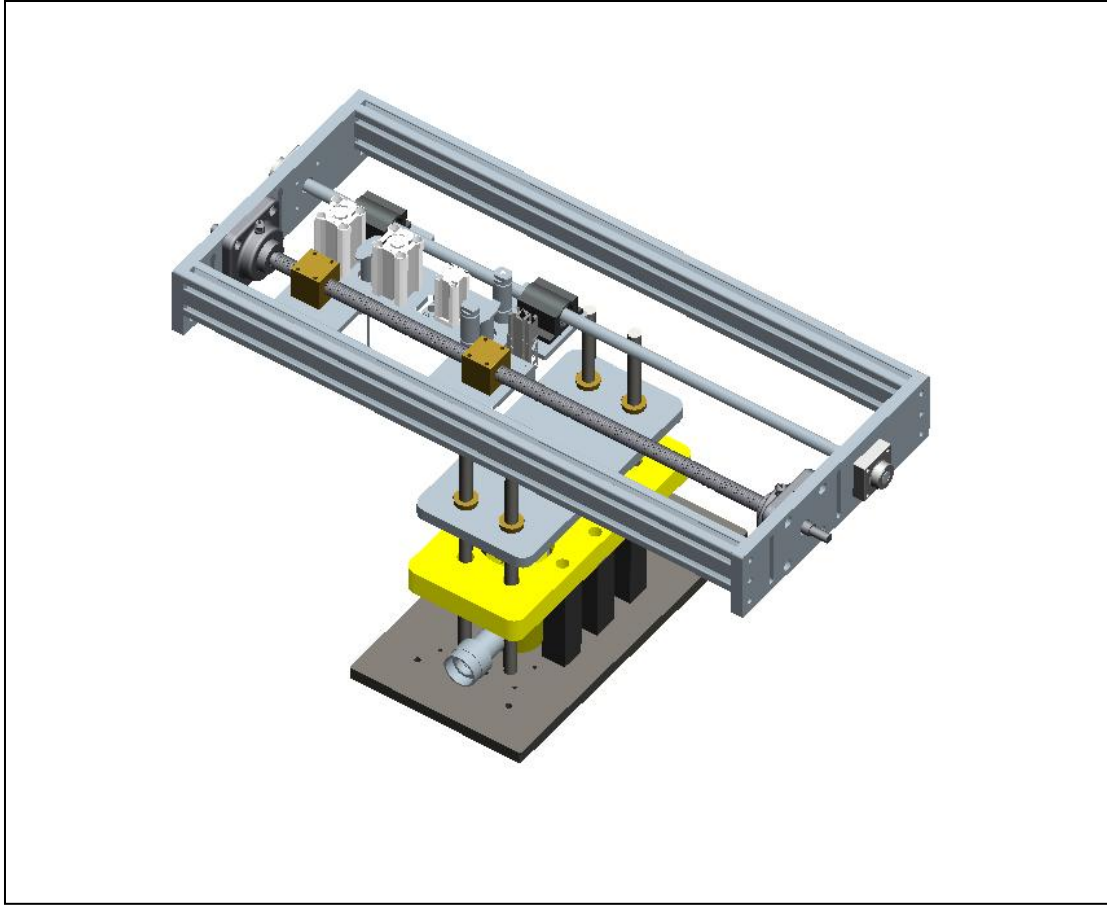
Figure 82 CAD Representation of Moving Subsystem

As shown in Figure 83, the location of the moving system is known with respect to the H-Frame press by using the mechanisms designed. The detailed exploded views, pneumatic and hydraulic systems, and assembly instructions are provided in the Appendix.
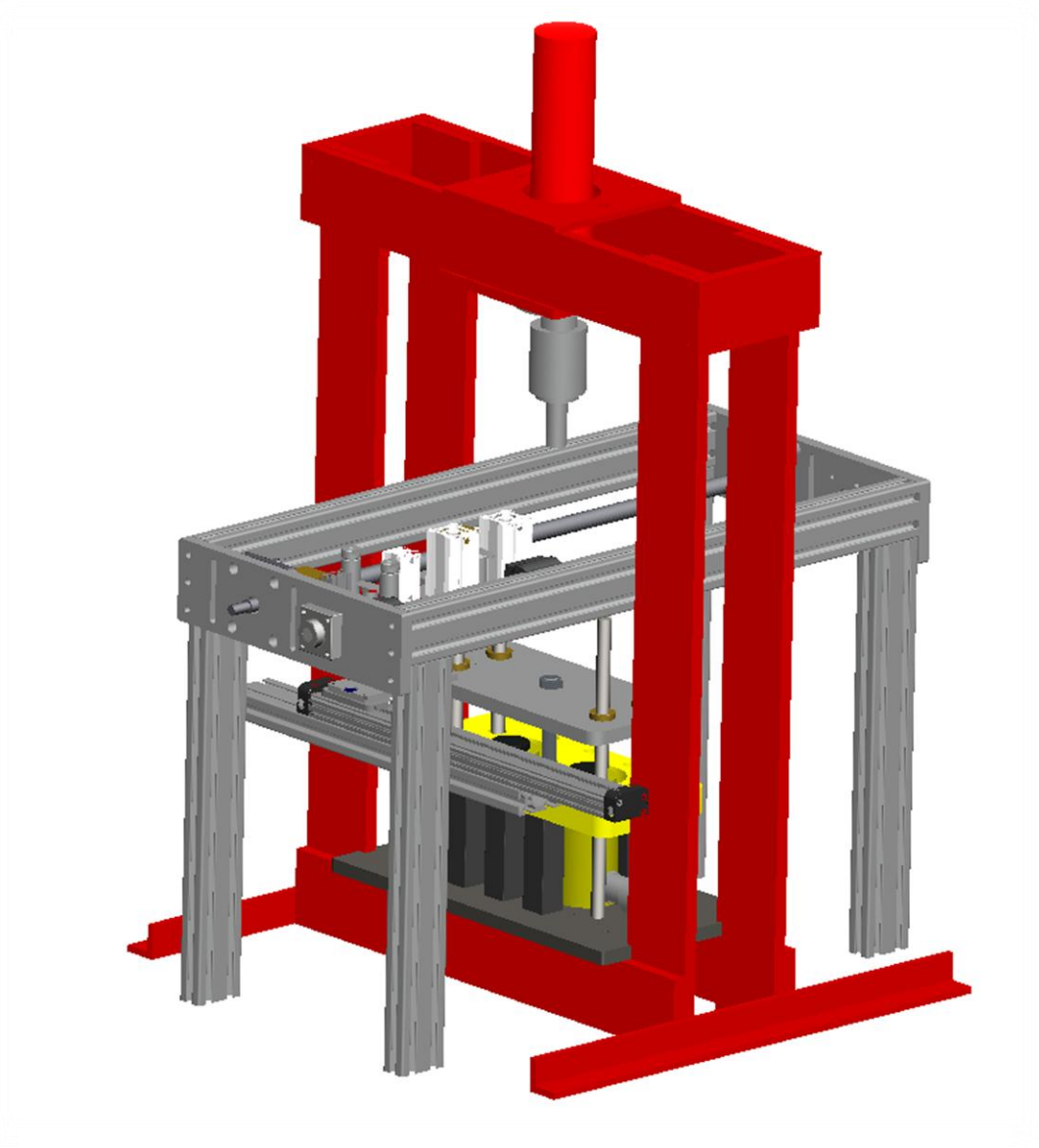
Figure 83. CAD Representation of Final Prototype

4.6 Outcomes of the Final Prototype

After designing and fabricating the final prototype, it was necessary to manufacture HR visual indicating fasteners in order to test the quality and make sure the introduced flaws are resolved. By automating this process, all of the human errors involved with hand assembly are eliminated, consequently increasing the reliability and consistency of visual indicating fasteners' quality. The following table shows the flaws introduced earlier in this thesis and the how the automated assembly line is fixing the issue.

Table 8. Solutions to Introduced Flaws in the manufacturing process of HR visual indicating fasteners

Flaw	Caused by	Fixed by
Blemish	RTV off center	±0.005" Accuracy in the dispensing subsystem
Blush	Inadequate force applied on the window ring	Using an integrated staking mechanism
Accurate Design Tension	Skidmore Calibration Issue	Consistent tensioning Subsystem
Gradient	Staking at three different locations	Staking and curing simultaneously

Besides the fact that the introduced flaws are mostly fixed by design of this prototype, the process time to manufacture these fasteners has been halved. In the hand assembly, this process could take up to 8 minutes however we have been able to make HR visual indicating fasteners that are following all of the expected qualities in 4 minutes. After identifying the main manufacturing issues, creating FMEA chart that can summarize all of the issues and determine the effect on the system of each potential failure was necessary. The severity and occurrence and detection rates for failure were chosen based on the experience gained throughout the hand assembly of these fasteners.

Process Function/ Requirements	Potential Failure Mode	Potential Effect(s) of Failure	S e v	Potential Causes(s)/ Mechanism(s) of Failure	O c c u r	Current Process Controls -Prevention -Detection	D e t e c	R. P. N.
Tensioning the Bolt	Pressure Drop During the process	Inaccurate Design Tension	7	Not Calibrated Hydraulic System	3	Level used for moving plate	2	42
Pick up the Microindicator	Microindicator jamming	Damaging the final quality of the bolt	3	Adjusting the regulator to a higher pressure in pneumatic system	4	Regulators accessible to the user to check before the process	5	60
Pick up the Pin	Not enough gripping force	Disturbing the manufacturing process.	1	Adjusting the regulator to a lower pressure in pneumatic system	4	Regulators accessible to the user to check before the process	5	20
Dispensing Loctite 603	Dispensing inaccurate amount	Inaccurate Design Tension	7	EFD System Failures	2	Pressure Gage and chart provided	4	56
Dropping Pin	Not pushed to the bottom of the cavity	Inaccurate Design Tension	7	Tolerance stack up between the bolt cavity and pin	3	Machined to +/-0.005" tolerance	4	84
Dispensing Loctite 5033 (First Shot)	Dispensing inaccurate amount	Blemish	5	EFD System Failures	2	Pressure Gage and chart provided	4	40
Dropping MicroIndicator	Dropping it during the travel	Disturbing the manufacturing process.	1	Pressue Drop in Pneumatic System	4	Regulators accessible to the user to check before the process	5	20
Pick Up the Window Assembly	Not enough suction	Disturbing the manufacturing process.	1	Pressue Drop in Pneumatic System	4	Regulators accessible to the user to check before the process	5	20
Dispensing Loctite 5033 (Second Shot)	Height offset due to microindicator thickness	Blemish	5	Tolerance Stack up between the stationary and moving subsystems	3	Machined to +/-0.005" tolerance	4	60
Drop the Window Assembly	Pushing the window assembly into the cavity	Gradient	5	Tolerance Stack up between the stationary and moving subsystems	3	Machined to +/-0.005" tolerance	4	60
Pushing the window down	Applying off center force	Gradient	5	Misaligned Spring	5	Accessible to the operator	2	50
Staking the head of the bolt	Misalignment with respect to the center of the bolt	Damaging the window assembly	7	Hydraulic Cylinder Misalignment during travel	4	Level used for moving plate	2	56
Curing the adhesives	Intensity Loss	Blush	5	Fiber Optics	5	Intensity test performed before each trial	4	100
Release the load on Bolt	Sudden Load Release	Permanent Blush	5	Operators' Error	4	Shown in the instruction manual	5	100

FIGURE 84. FMEA Chart for Manufacturing HR Visual Tension Indicating Fasteners

Since the RPN value for all of the process functional requirements were below

150, it was decided that there is no need for redesigning. After testing this prototype

and being able to have a more reliable process, design of an automated assembly line for mass production of these fasteners was assigned as the next goal for this project. The design of this system is shown in the following chapter.

Chapter 5: Additional Work Accomplished

5.1 Full Scale Design

The main objectives regarding the manufacturing process and design of HR Visual indicating fasteners are accomplished by automating the process and the experiments done on the fabricated prototype can verify the fact that the production of HR Visual indicating fasteners are reliable and repeatable. However, in order to have a mass production the full scale automated assembly line is designed too.

5.1.1   System Design

The full scale design is based on the concepts introduced and tested in the prototype. The subsystems were taken from conceptualization stages to detail design to finalized subsystem design prototypes. Based on final design generated, subsystems were integrated together to simulate process assembly using 3D CAD solid modeling, and troubleshoot if necessary. After the design was shown to be successful, documentation necessary for component purchase, component manufacture, assembly and operation of the system was prepared as demonstrated previously. Resulting documentation will be handed over to the sponsor for system manufacturing.

The full scale design assembly line is capable of manufacturing three Visual indicating fasteners simultaneously under 5minutes. The system can manufacture different sizes and types of bolts. Any type of bolt from 7/16” to 1 ¼” in diameter and from 2 ½” to 10” in length can be manufactured. The system is designed in a way that can be adjustable easily by the operator before starting the process. The architecture

of the system is based on the H-Frame press as seen in Figure 85 due to the same reasons explained for the prototype.
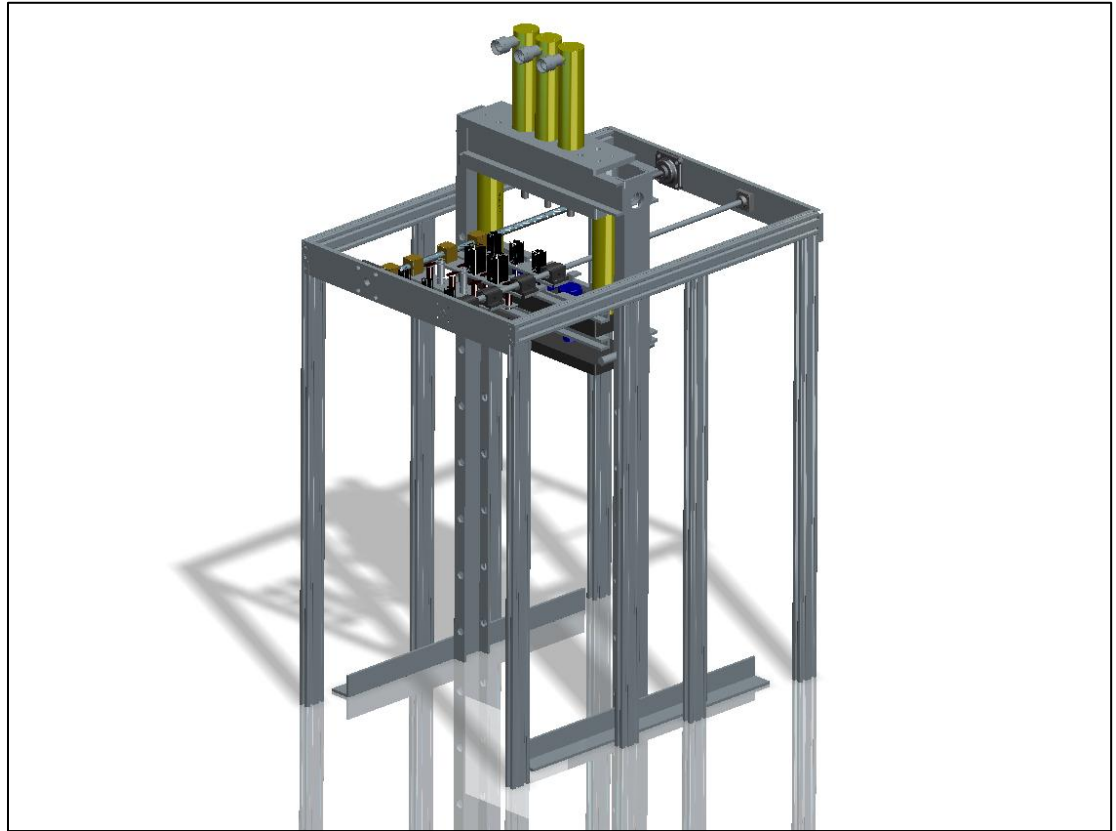
Figure 85. CAD Representation of Full Scale System

5.1.2   Detail Design

The tensioning subsystem has been modified compared to the prototype design in order to increase the range of length and diameter that it can make. Larger hydraulic cylinders (10" stroke length) are used in order to take advantage of force capacity and stroke length. The top plate in this system is maintained stationary and the bottom plate will be pushed down by the hydraulic cylinders in order to apply tension on the bolts. One of the advantages of this design is the constant height offset

between the head of the bolt and the tip of subsystems. Tensioning subsystem can be seen in Figure 86.

Concept of moving subsystems in the full scale design is very similar to the fabricated prototype. The only difference is the fact that there are three bolts manufactured at the same time, correspondingly there will be three adhesive dispensers, suction cups, pin drop mechanisms. Due to maintenance purposes and larger size, the moving subsystems are modular and are not assembled on one common plate. Technical drawings and detailed information about this system can be provided upon request. In Figure 87, individual subsystems can be seen.
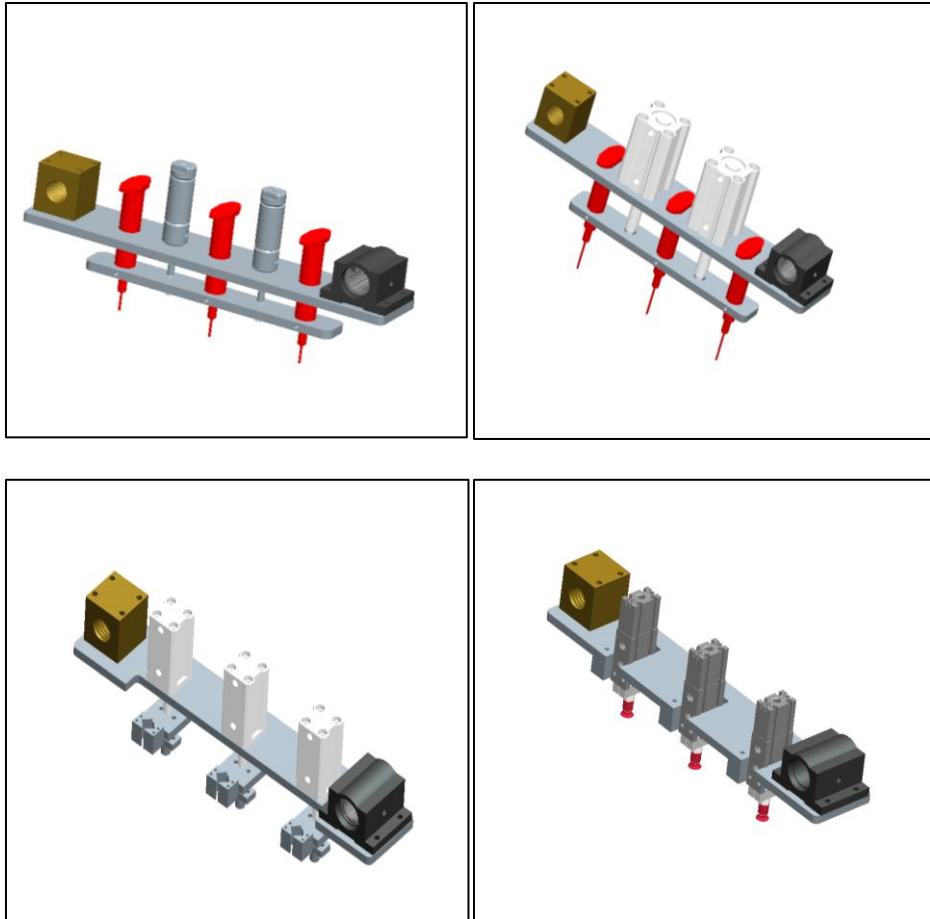
Figure 87. Individual Moving Subsystems for the Full Scale Design

Chapter 6: Conclusion

The discrepancy between torque and clamping force in bolted joints has been an unsolved issue during the past decades in industry. Although there are many correlations, guidelines about specifics of a bolted joint, assessing if a joint is tight or not is challenging. In this work, the novel concept that can directly measure tension on bolted joints is discussed. Visual indicating fasteners' concept relies on a basic concept of bolts in joints. These fasteners are able to visually indicate if a joint is tight or not, by changing the color. In this thesis, this feasibility of this concept is tested and results are provided. After proof of concept tests for visual indicating fasteners, the manufacturing process for them was developed. With respect to the experimental results gathered from hand assembly process, the flaws and issues were studied individually. Three main problems exhibiting while making these fasteners manually were: blemishes, blushes and gradient. In this study, an automated assembly line that can manufacture the HR Visual indicating fasteners with a high rate of production and higher rate of reliability and repeatability was designed. The fabricated prototype is capable of manufacturing ½"-13 bolts for any length available in the market and rate of production of 5 minutes per bolt. We believe this design eliminated effects of hand assembly on final quality of the product.

After running experiments on the fabricated prototype, the full scale automated assembly line was fully designed. The full scale is capable of manufacturing any bolts from 7/16" to 1 ¼" in diameter and with length range of 2" to 10". By scaling up the size of the system, the rate of production has been tripled compared to the prototype. The full scale machine will be able to manufacture one HR Visual indicating fastener

per minute. For the full scale system, the sponsor is responsible for installation of the completed system onto the factory floor to initiate the automated assembly line.

Additional studies were presented on the concept of Visual indicating fasteners. The guidelines and correlations between the color on the bolt and the corresponding tension and torque were experimentally gathered and the correlations were presented. The provided color charts can be used for any application of Visual indicating fasteners in industry. The finite element analysis is done on the effect of the modifications on strength of the bolt. It was found that the as the diameter of the bolt increases the effect of the cavity decreases.

We expect that the concept of the visual tension indicating fasteners described here will improve the reliability and safety of bolted joints. The manufacturing process and system designed, based on our results from testing, will help companies to commercially manufacture such bolts reliably and at good production rates. For future work, the studies on the effect of temperature on Visual indicating fasteners are necessary. The microindicator and the adhesives used in these fasteners limit the temperature range that they can be used in. Another potential study can be verifying the ASME codes and guidelines on Pressure Vessels and Bolted Joints using Visual indicating fasteners.

Appendix

Reservoir

Double Acting Cylinder

Single Acting Cylinder

Solenoid Actuated Pneumatic Valve

Pressure Regulator

On/Off Switch

Splitter Fitting

Vacuum Actuator

Suction Subsystem

Pin Subsystem

Gripper

Slider Subsystem

Loctite Subsystem
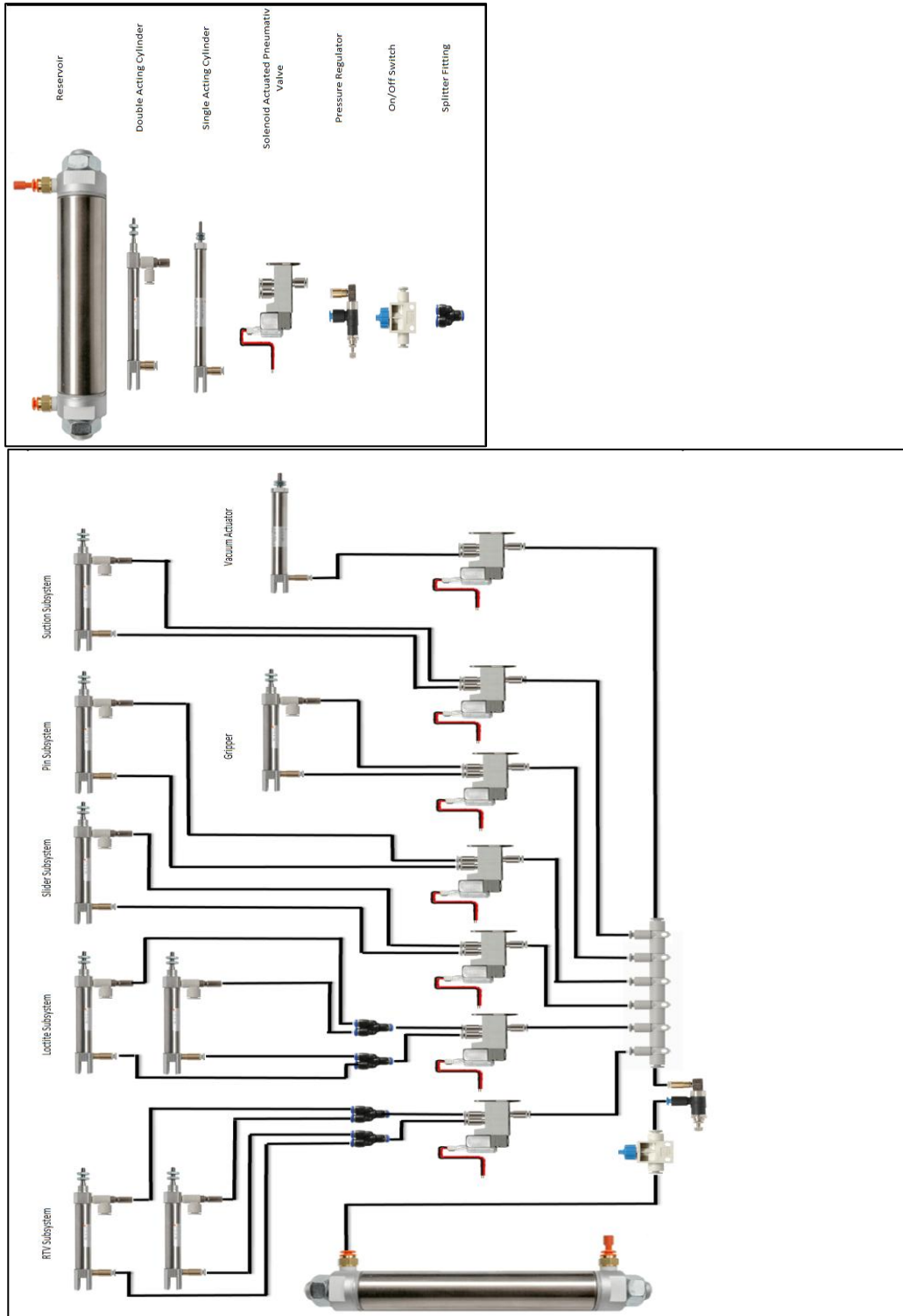
RTV Subsystem

FIGURE 88 Pneumatic Circuit Diagram

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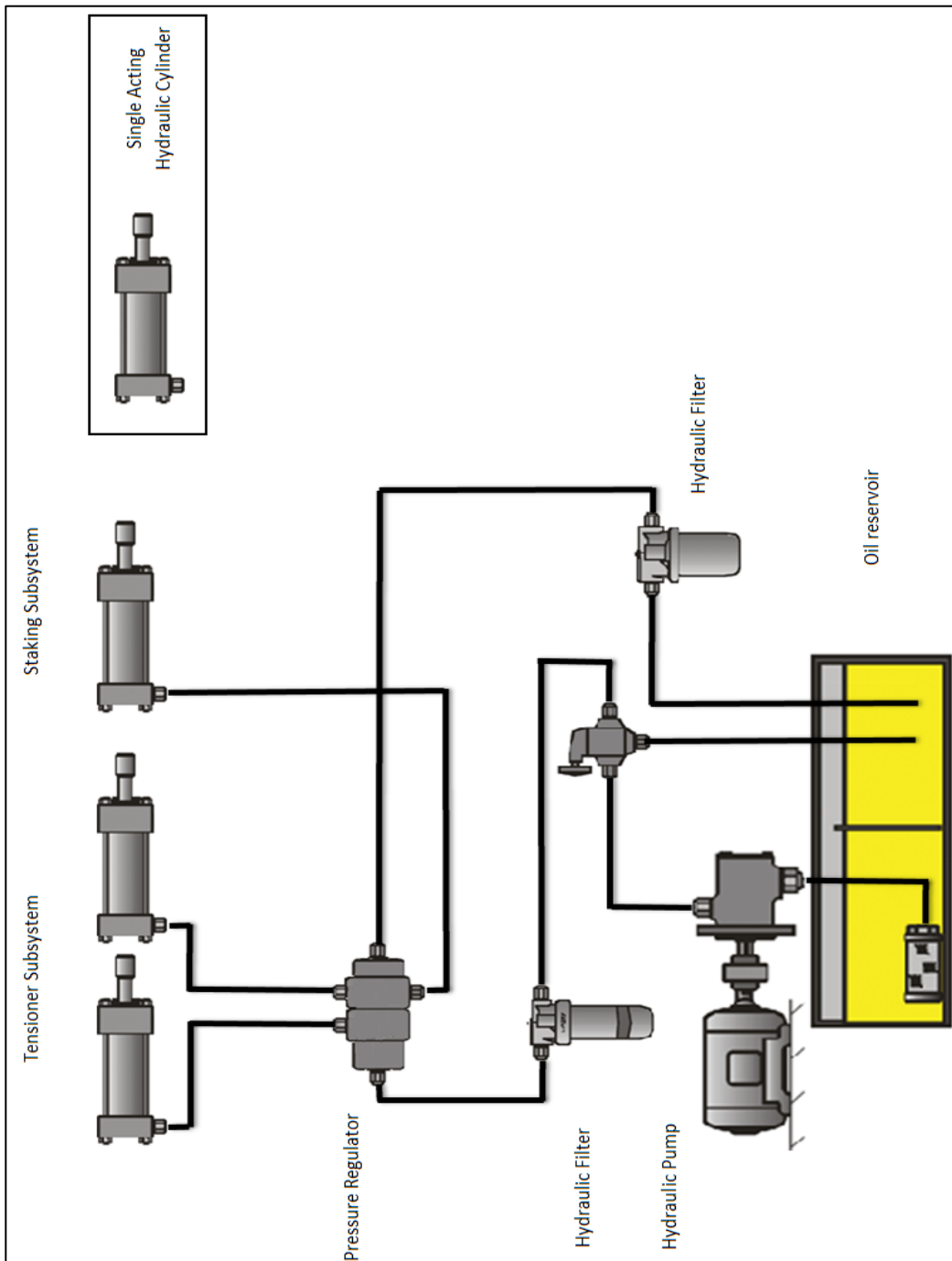
FIGURE 89 Hydraulic Circuit Diagram

113
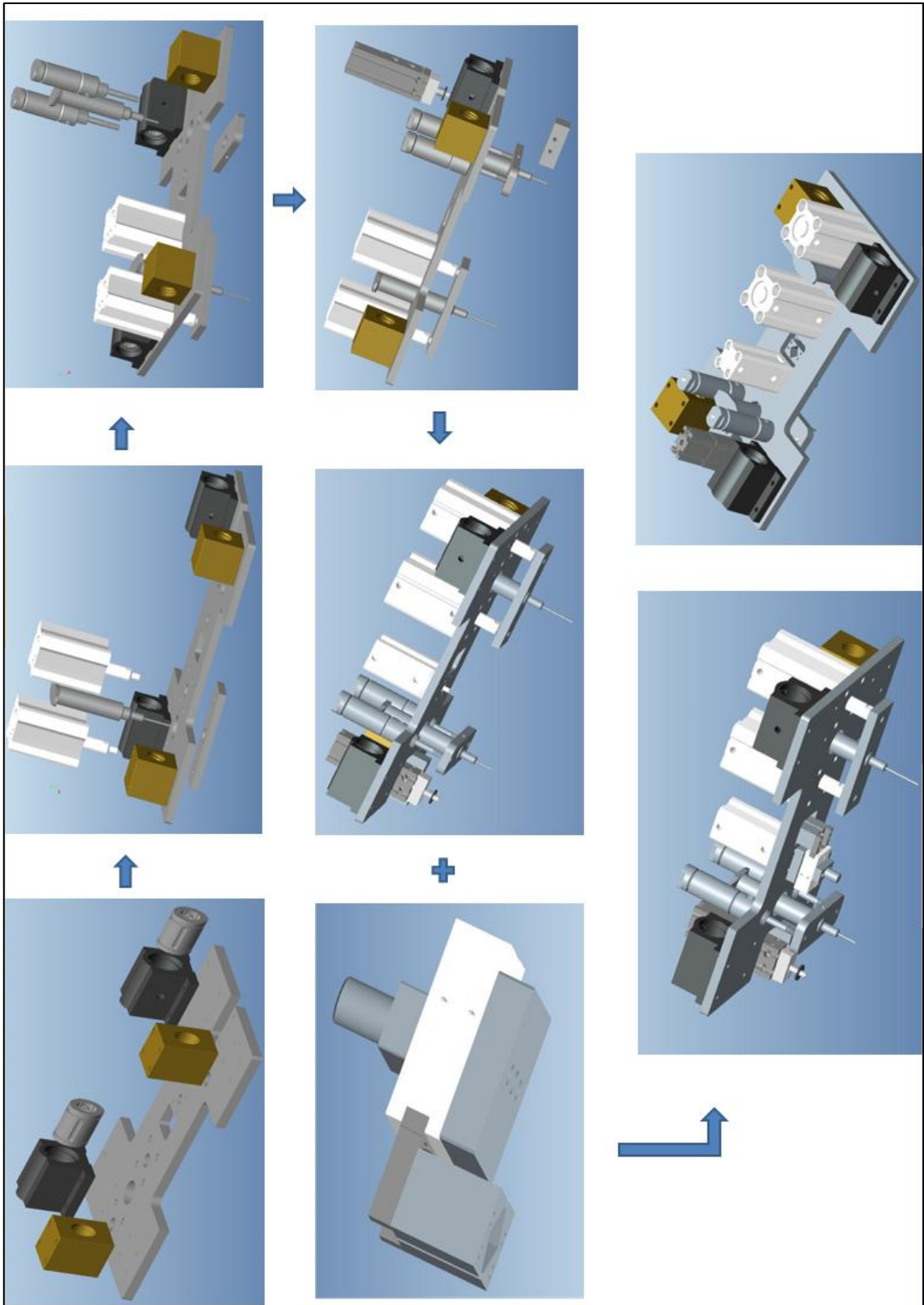
FIGURE 90 Assembly Process of the Moving Subsystems

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Order	Part Name	Quantity
10	7/16"-20*7/8" Screws	8
9	1/4"-20*1" Screws	12
8	8-32 Screws	8
7	ACME Rod	1
6	Precision Rod	1
5	24" 8020 Double	2
4	Mounted Bearing	2
3	Support Plate	2
2	Shaft Mount	2
1	13.5" 8020 Double	4
	Bill of Materials for Moving Assembly	
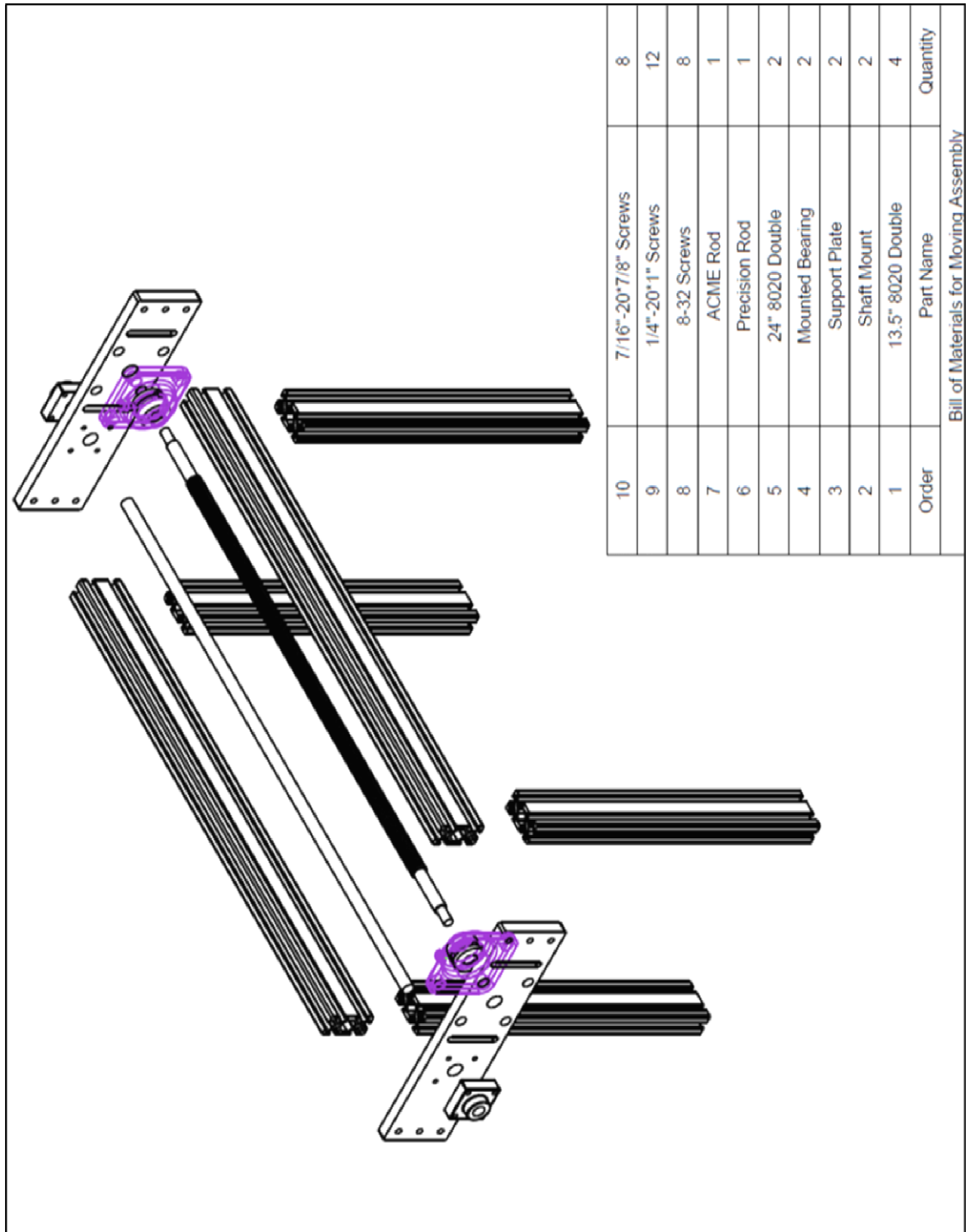
FIGURE 91 Exploded View and Bill of Material for Moving Subsystem

Order	Part Name	Quantity
7	Hydraulic Plate	1
6	Top Plate	1
5	Top Ring	1
4	Bottom Plate	1
3	Bottom Ring	1
2	Staking Tool Holder	1
1	Staking Tool	1
Order	Part Name	Quantity
Bill of Materials for Hydraulic Assembly		
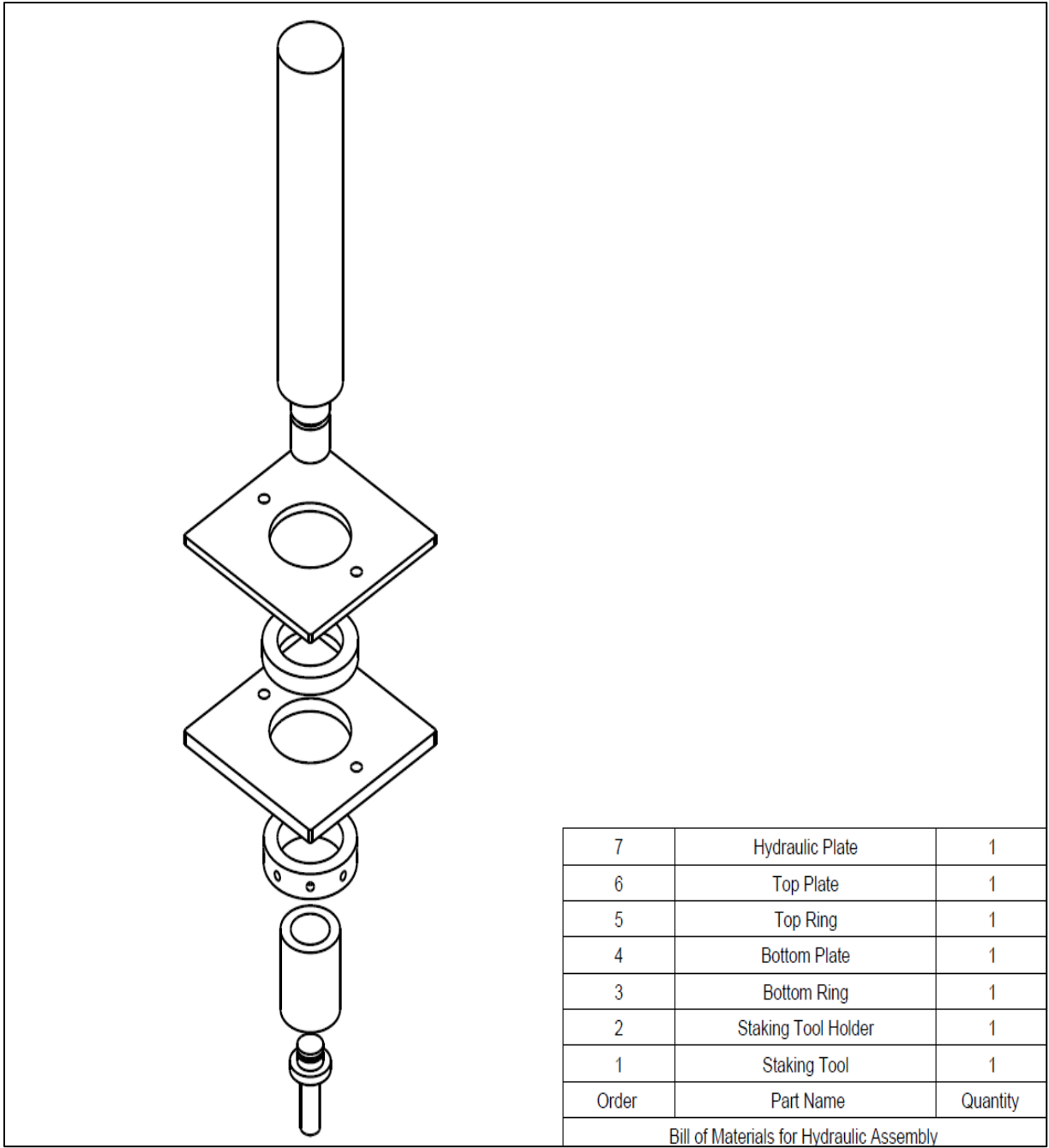
FIGURE 92 Exploded View and Bill of Material for Hydraulic Assembly of Staking Subsystem

Order	Part Name	Quantity
11	5-40 Screw	2
10	8-32 Screw	2
9	1/4"-20*2 1/2"(2.5") Screw	2
8	6-32 3/4" Screws	4
7	6-32 1 5/8"(1.625") Screws	4
6	ACME Nut	1
5	SMC Pneumatic Actuator	1
4	Inner Bearing	1
3	Linear Bearing	1
2	Modified Moving Plate	1
1	Side Plate	1

Bill of Materials for Suction Assembly
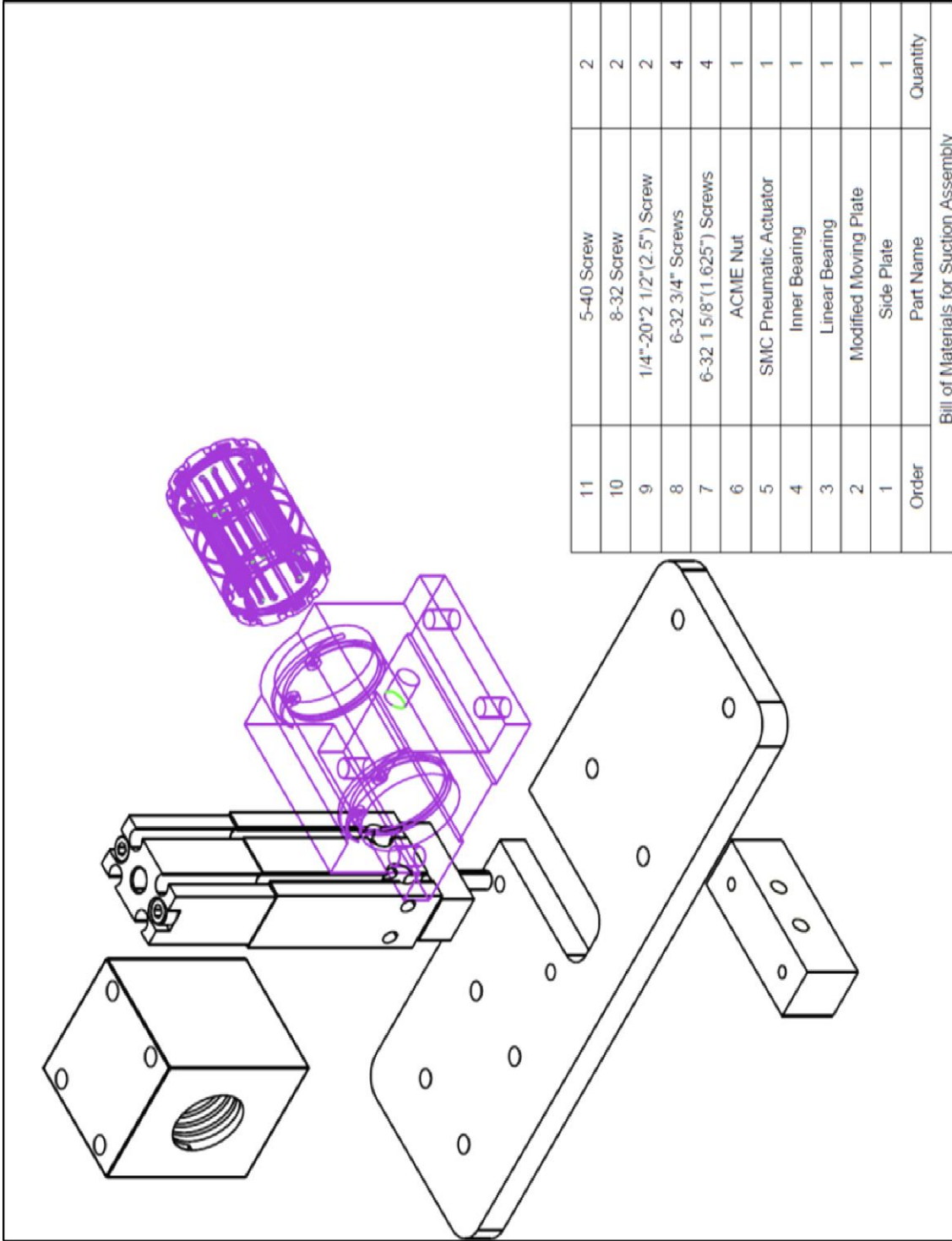
FIGURE 93 Exploded View and Bill of Material for Pick and Drop Subsystem of Microindicator and Window Assembly

Order	Part Name	Quantity
12	5-40 Set Screw	1
11	1/4"-20*2 1/2"(2.5") Screw	8
10	6-32*3/4" Screws	3
9	6-32*1 5/8"(1.625") Screws	4
8	ACME Nut	1
7	Inner Bearing	1
6	Modified Linear Bearing	1
5	SMC Pneumatic Actuator	2
3	Syringe Extension	1
2	BB Plate	1
1	Syringe Plate	1
	Bill of Materials for Loctite Assembly	
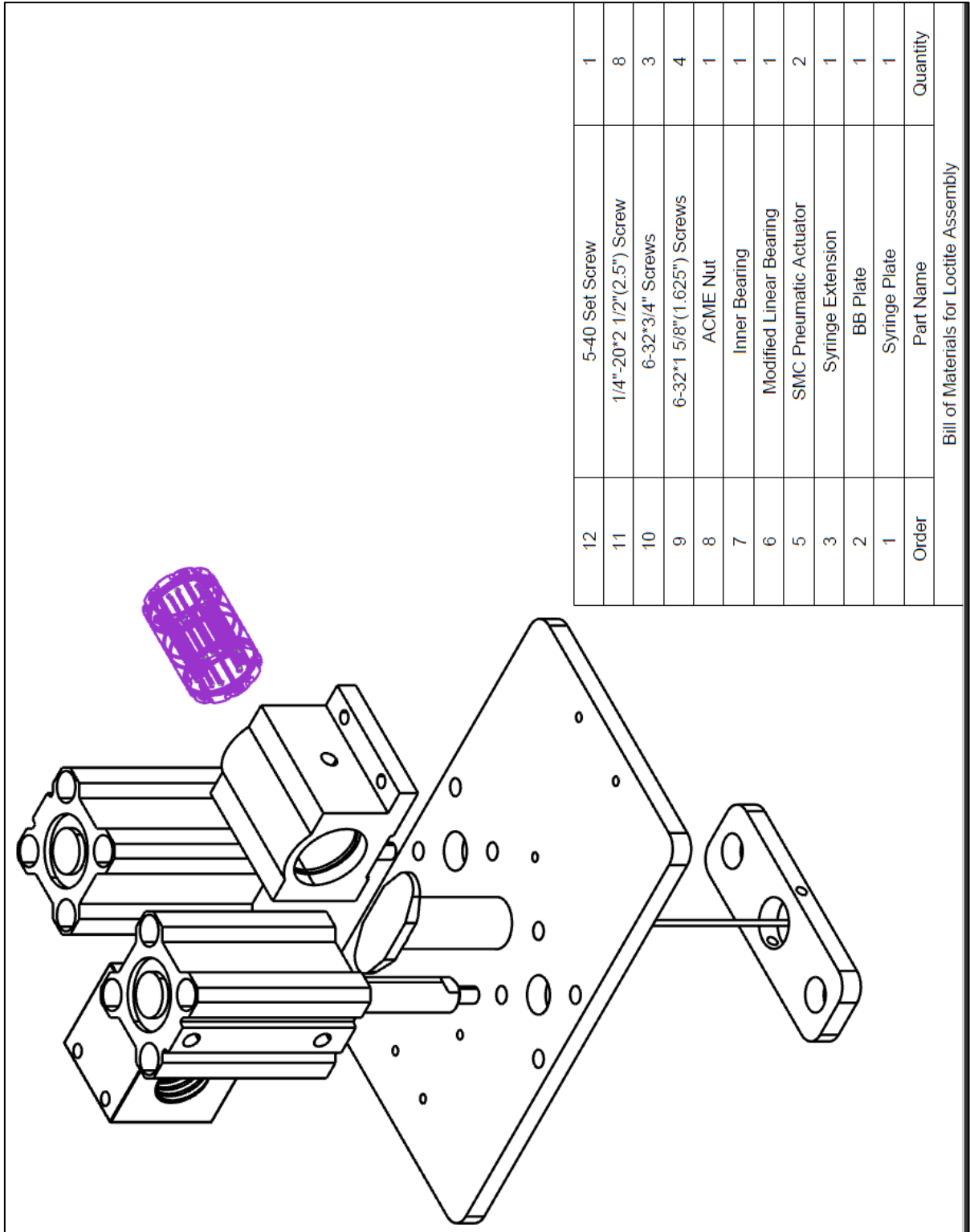
FIGURE 94 Exploded View and Bill of Material of Loctite 603 Dispensing Subsystyem

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Order	Part Name	Quantity
10	5-40 Set Screw	1
9	6-32*3/4" Screws	4
8	6-32*1 5/8"(1.625") Screws	4
7	ACME Nut	1
6	Syringe	1
5	1/2" Air Cylinder	2
4	Inner Bearing	1
3	Linear Bearing	1
2	Dispensing Plate	1
1	Syringe Plate	1
	Bill of Materials for RTV Assembly	
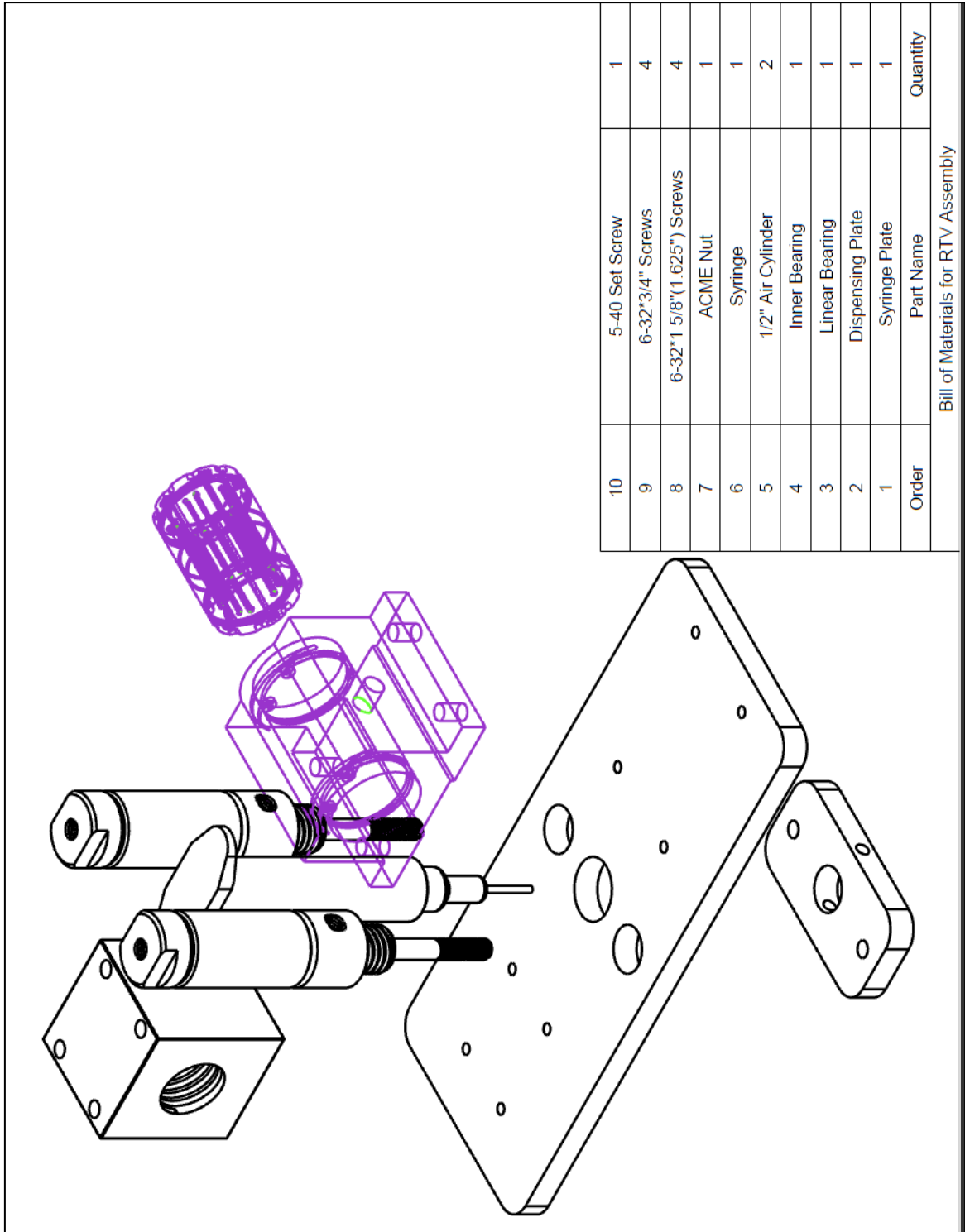
FIGURE 95 Exploded View and Bill of Material of Loctite 5033 Dispensing Subsystem

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Glossary

T	Torque (lbs.ft)
F	Clamping Force (lbs)
p	Pitch of thread
D	Diameter of the bolt shank (in)
μ_s	Friction coefficient on the thread surface
μ_w	Friction coefficient on the nut bearing surface
α	Half of the thread angle profile
d_w	Diameter of nut bearing surface (in)
d_h	Diameter of the bolt insert hole (in)
D_v	Equivalent Diameter (in)
K	Nut Factor
s	Safety Factor
D_s	Diameter of Suction Cup (in)
P_u	Vacuum Pressure in the system (psi)
c	Number of Suction Cups
A	Suction Cup Area (in^2)
P	Pressure (psi)
m	Mass (lb)
g	Gravity ($\frac{ft}{s^2}$)

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