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Abstract approved:

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Brian K. Bay

Thousands of children and adults suffer from fine motor skill deficits due to developmental disabilities or brain trauma. In order to acquire or reclaim these precision motor movements, occupational therapists work closely with each patient to develop the muscle memory required for completing tasks such as handwriting or drawing. Although successful, occupational therapy is expensive and can be embarrassing or frustrating for children and adults. Recent advancements in tactile based robotic simulation, also known as haptics, have provided an opportunity to experience low cost, three dimensional, forced virtual object interaction. The work presented in this paper takes advantage of current haptic technology in order to create a device which facilitates traditional occupational therapy techniques. An inexpensive, attractive, and versatile solution for handwriting training and rehabilitation was developed using a mechanical linkage connected to the Novint Falcon haptic device. Several phases of design resulted in a mechanical linkage which was conceptualized and manufactured.

Mechanical Linkage Design for Haptic Rehabilitation and Development of Fine Motor Skills

by
B. Taylor Streng

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APPROVED:

Major Professor, representing Mechanical Engineering

Head of the School of Mechanical, Industrial & Manufacturing Engineering

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Dean of the Graduate School

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B. Taylor Streng, Author

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1. INTRODUCTION

1.1 Motor Skill Disabilities

As education continues to drive advancements in technology and industry around the world, the importance of providing an opportunity in education for all children becomes increasingly apparent. Children with learning disabilities are often faced with significant disadvantages in the classroom compared to their peers. Despite these disadvantages many have succeeded in their academic endeavors through persistence and determination. The National Institute on Disability and Rehabilitation Research (NIDRR) published their findings relating to disability in the United States among adults and children. NIDRR reports that children and adults, ages 5 and up, with non-severe disabilities comprise approximately 10% (~30 million) of the population of the United States [1]. It is estimated that 6% of children in primary schools are diagnosed with Developmental Coordination Disorder (DCD) and experience significant difficulties learning to write and complete other fine motor skill related exercises (~1-2 million) [2].

A fine motor skill disability generally refers to the smaller, more precise single or multiple movements associated with the fingers, hands, and wrists [3]. These types of fine movements require acute coordination between muscles, tendons, and nerves. Individuals with these disabilities have traditionally relied on occupational therapists for the specialized training and assistance needed to overcome their disabilities, especially in the classroom. Despite the success of occupational therapy, many children feel embarrassed and inferior to their classmates because of the extra help they require. In addition, occupational therapy is expensive for the family or the school district providing for the student.

Adults suffering from the effects of stroke can experience fine motor skill disabilities due to the death of the tissue controlling these types of movements. Stroke is not uncommon among older adults; it is estimated that stroke is the leading cause of disability among older adults in Europe and the United States [4]. Occupational therapy is especially frustrating for adults because assistance is needed for tasks that were once completed easily. A more cost effective and convenient technique is needed for adults and children suffering from deficits in fine motor control.

1.2 Current Solution

Children who have difficulty developing the motor skills needed to control fine movements, such as those for writing or drawing basic geometric shapes, have succeeded through patterns of repetitive movement. Occupational therapists guide the student's hand over letters, numbers, and shapes to slowly help the student develop fine motor control. The same technique is used to help stroke victims. Physical therapists (PT's) and occupational therapists (OT's) work intensively with these patients to help them regain lost functions.

In addition to children with DCD and adults suffering from the effects of stroke, there are a large group of mildly disabled individuals who benefit from occupational therapy. Occupational therapy provides a way for an individual with a disability to work towards overcoming the disability and learning to perform everyday tasks. Through repetition and training the patient begins to view their disability merely as an obstacle, rather than a roadblock, and develop a means of achieving their goals.

1.3 Proposed Solution

The key component of occupational therapy techniques leading to student success has been training the brain and muscles to consistently generate the precise movements needed to formulate legible handwriting. This training has come almost entirely through repetitive, smooth, and controlled movements guided by the occupational therapist. Current advancements in technology have produced robotic devices that have the ability to generate movements with these characteristics. Developing a specifically designed mechanical linkage to act as a writing interface between the user and the robot could effectively simulate the experience provided through occupational therapy. This device will be more cost effective, convenient, entertaining and confidence building than traditional occupational therapy. These promising new robotic devices are more commonly known as haptic devices.

2. BACKGROUND

2.1 Current Haptic Technology

The word haptic generally refers to tactile, or touch based interaction with the environment. Haptic technology is associated with the vibrations, motions, or forces that are experienced by an individual through the sense of touch. These sensations are generated by a force feedback mechanism, called a haptic device. The haptic system in the human body refers to the ability of organs, muscles and tendons to sense their relative position to one another during tactile sensing. This biological process is known as proprioception [5]. These complex interactions and our ability to understand them better have opened the door for the recent advancements in haptic technology.

Wide varieties of haptic devices currently exist and have been used mostly for research and in the computer gaming industry. Haptic devices are currently being used as training tools and for surgical simulations around the world [6]. It is estimated that within five to ten years these devices will be in operating rooms assisting surgeons with remote operations [7]. In theory, a surgeon could be sitting in a room on the east coast performing surgery on a patient in a west coast hospital. The surgeon would have a real time video display and haptic surgical pen in the room with them. The surgeon could move the pen around and the precise movements of the pen would control a haptic device performing the actual surgery on the patient. In addition, the surgeon could have both visual and force based tactile feedback via the haptic pen.

This is possible due to the advancements in technology that allow the smallest differences in resistance between tendons, veins, muscles and bones to be detected by the haptic device and relayed almost instantaneously to the device in the surgeon's hand. The Freedom 7S produced by MPB Technologies and the Xitact IHP are high degree of freedom (DOF) devices that have been developed specifically for medical procedures [8,9].

In addition to the haptic devices mentioned, there are a variety of haptic devices that are available commercially. ForceDimension, Haption, Immersion, Moog FCS Robotics, Novint Technologies, Mimic Technologies, MPB Technologies, Quansar, SensAble Technologies and Mentice SA are the major companies that produce haptic devices and haptic interfaces. Some of the haptic devices produced by these companies are shown in Figure 2.1. ForceDimension is a Swiss company that has three different haptic devices, the 3DOF Omega, the 3DOF Delta, and the 6DOF Delta [10]. Haption is a French company that has created the Virtuose series of haptic devices [11]. Immersion, MPB Technologies, and Xitact have produced devices with wide ranges of applications in surgical operations [8,9,12]. SensAble Technologies developed the Phantom series of haptic devices, which was the least expensive haptic device that could be purchased commercially until Novint Technologies came out with the Falcon in June of 2007 [13,14]. Novint produced the first haptic device with a price tag which could compete with many of the other commercial gaming systems available today. The Novint Falcon can be purchased for under $200, which provides an opportunity for more people to experience the excitement of haptic technology.

Figure 2.1: A variety of haptic devices from several different companies developing haptic technology [8,10-15].

2.2 Previous Research in Haptic Handwriting Technology

Throughout the 1980's and early 1990's several groups of researchers began developing their ideas surrounding force feedback technology for a wide variety of purposes. Many of the previous and currently developed haptic devices take advantage of the pantograph linkage because of the magnification properties inherent with this style of linkage. The pantograph was first invented by Christoph Scheiner in 1603 and was developed primarily for the use of scaling images from one planar surface to another [16]. The lengths of each of the four links that create the pantograph can be adjusted to produce a magnification or reduction of the traced image. This has proven particularly useful for magnifying the traditionally small movements in the haptic workspace to larger movements often required for the application workspace.

One of the first haptic configurations to take advantage of the pantograph concept was developed by Vincent Hayward *et al* using a multi-objective optimization technique to determine an appropriate linkage that would meet specified design requirements [17]. Using a single value decomposition method to determine link lengths, the team developed the five bar pantograph based linkage shown in Figure 2.2.

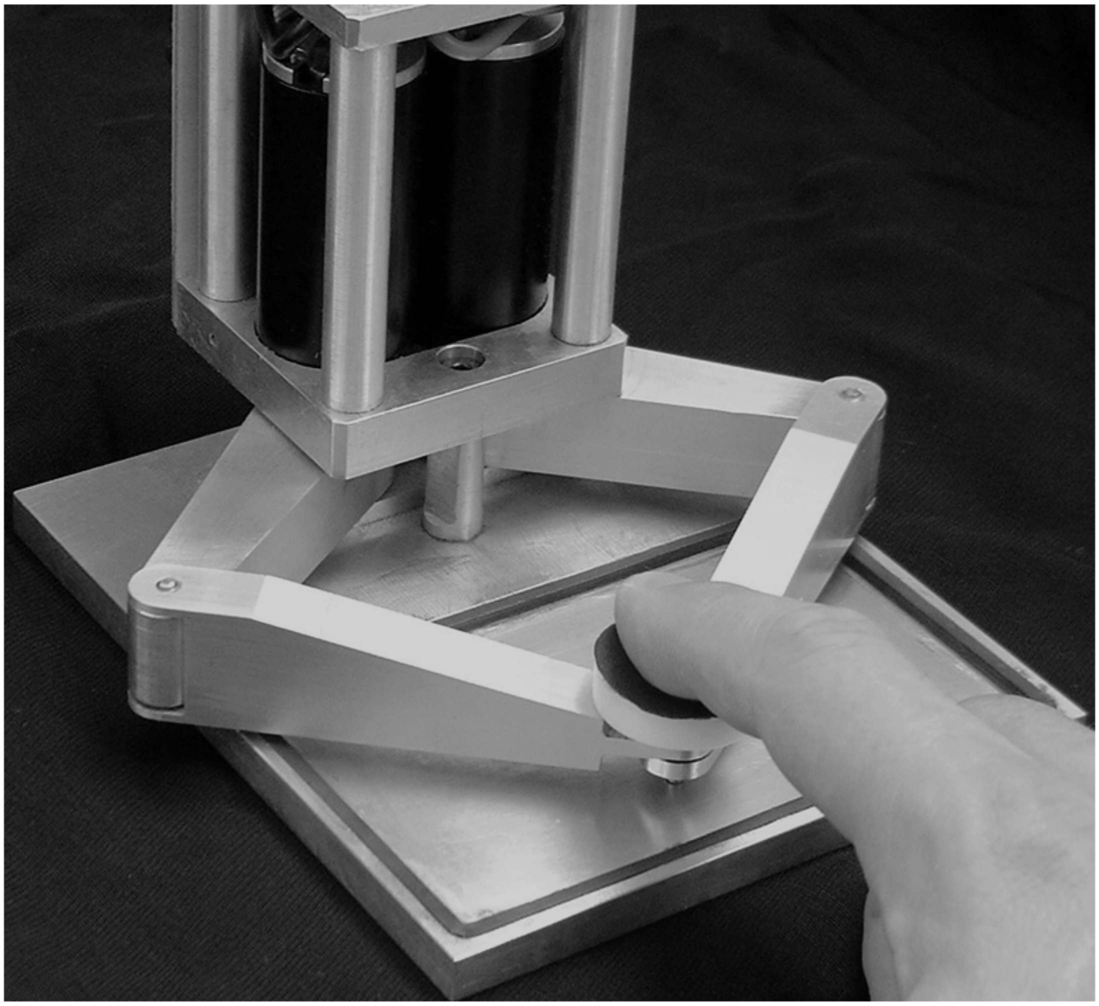


Figure 2.2: Result of Hayward *et al* multi-objective linkage optimization [17].

Leo Stocco *et al* use a culling algorithm to compute the global isotropy index of a wide variety of haptic interfaces [18]. The results are then compared analytically with one another and the most effective device is chosen to complete the optimization process. The Twin-Pantograph mechanism shown in Figure 2.3 proved to be kinematically superior to other haptic interfaces considered in the study.

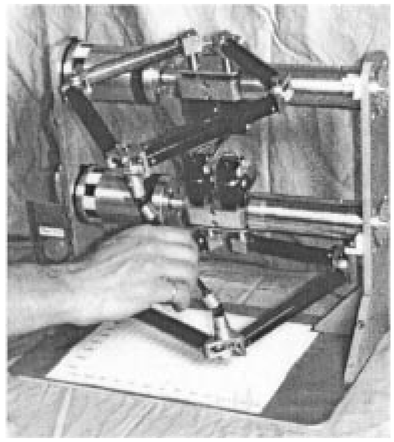


Figure 2.3: Optimal design conclusion from Stocco *et al* kinematic analysis of a haptic pen writing interface [18].

In addition to the devices presented above, many types of non-pantograph based handwriting tools have been developed to fulfill similar objectives. Jorge Solis *et al* developed the five bar linkage shown in Figure 2.4 to teach students how to write Japanese characters [19].

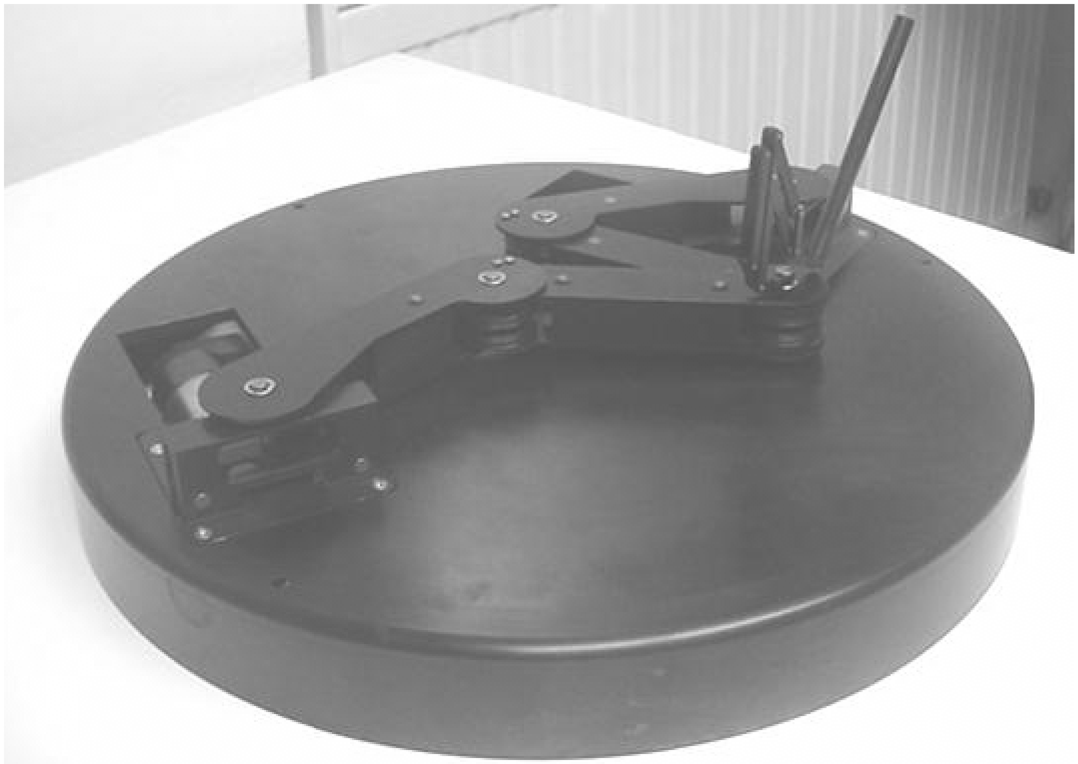


Figure 2.4: Linkage developed by Solis *et al* to teach Japanese handwriting using haptic technology [19].

The SensAble Technologies Phantom series has been used extensively for handwriting and rehabilitation studies. Figure 2.5A shows one of the original Phantom devices being used in a study completed by Srimathveeravalli *et al* comparing results between two different methods of assistance in tracing an unfamiliar symbol from the language of Tamil. Their study showed that providing a series of forces to the user's hand allowed the user to create a more accurate trace of the symbol than providing a series of positions to effectively channel the user's movements [3].

A similar project, shown in Figure 2.5B, uses the Phantom Omni specifically for handwriting training and assistance [20]. In this research, James Mullin *et al* developed a custom control algorithm that was completely compatible with the application programming interface (API) developed by SensAble Technologies for the Phantom Omni device. In addition to the control algorithm, the team developed a graphical user interface (GUI) that provided visual reinforcement for the user. Their research showed clearly articulated, consistent movements are achievable using the Phantom Omni. At the time, the Phantom Omni was a relatively low cost haptic rehabilitation device. The stylus used with the Phantom Omni is rather large and while this may be good for older stroke patients needing rehabilitation, younger children may have difficulty gripping the stylus or may feel uncomfortable holding such a large writing utensil [20].

A B

Figure 2.5: Two different haptic handwriting projects using different versions of the Phantom Omni haptic device [3,20].

2.3 Characteristics of Design

Understanding the complexities of the design process and knowing the techniques that lead to efficient design is of great importance in the undertaking of any design challenge. It is estimated that 85 percent of design problems are a direct result of inefficiencies in the design process [21]. Proper communication between the designer and the customer throughout the course of the design provides the essential building blocks to ensure design success. In addition, understanding the life cycle of the product and designing for manufacturability, assembly, reliability and testing are absolutely necessary. Approaching a design problem effectively not only saves time and money, but also creates a more robust, versatile and satisfying product.

Although systematic methods for obtaining design solutions have been developed, often decisions must be made throughout the design process which have significant affects on the outcome of the solution. This allows for a wide variety of solutions to a given problem, all of which have the possibility of satisfying the primary objective of the design. These design decisions are the result of excess design variables in relation to constraints. Design constraints and variables are derived specifically from the engineering requirements and customer requirements pertaining to the design problem. The excess of variables in comparison to constraints allows for definitive uniqueness in the design, which is difficult to find in most areas of engineering and science.

The design process, when broken into its most basic components, consists of a goal statement or objective function, product conception, testing, evaluation and production [22]. In most design situations the first step of the design process is absolutely the most critical. Properly identifying customer needs and the requirements placed on the design is one of the single most time and cost reducing steps in the design process. At this point in the process the design variables and constraints are specified. If these requirements are not identified properly, every part of the design process is affected. The result is unnecessary depletion of vital project resources.

After specification of the design problem, a significant amount of time is spent brainstorming and developing concepts that will provide the necessary function. Simulations or simple prototypes of various solutions are often generated and evaluated based on how well they satisfy the constraints and requirements imposed on the problem. Often important decisions are made in this phase requiring input from all individuals involved in the project. Effective communication is a necessity at this point in the process. Full-scale, functional prototypes are developed so testing and evaluation can be performed on the design that has been determined appropriate. Several iterations of re-design may be necessary to realize the most effective solution. The development of the linkage discussed in this research followed the approach described.

2.4 Previous MY SCRIVENER™ Work

Prior to the release of the Falcon by Novint Technologies, the most inexpensive haptic device commercially available was the Phantom Omni produced by SensAble Technologies. Obslap Research LLC and the National Institute on Disability and Rehabilitation Research formulated the MY SCRIVENER™ project with the goal of developing a writing assistive device using the Phantom Omni. The first phase of the MY SCRIVENER™ project involved several researchers from George Mason University working toward developing a solution with the Phantom

Omni. In order to avoid the task of creating extensive and complicated programming to interact with the Omni, the use of a recently developed haptic programming virtual interface was employed. This programming interface, named proSense and developed by Handshake VR Inc., used drag and drop based visual programming similar to the format used in LabVIEW to provide both novice and expert haptic programmers the ability to quickly and efficiently develop sense of touch based applications [23]. ProSense supported MATLAB based programming and produced haptic rendering algorithms corresponding to the positional differences between the actual location of the Omni stylus and the location defined in the MATLAB programming. Haptic rendering refers to the process of generating forces from information provided by the computer, which are executed by the haptic device to create a realized tactile object the user can feel [24].

Another benefit of the proSense Virtual Touch Toolbox was the Time Delay Compensation (TiDeC) technology developed by Handshake VR [23]. This ground breaking technology allowed seemingly instantaneous object collision detection. Previously, object collision detection was more of an iterative process because as the user moved into the object there was delay in the haptic rendering creating overshoot in force values. Due to the delay, the user unknowingly moves the stylus into the 3D virtual object and suddenly feels strong forces opposing the movement. These opposing forces drive the stylus away from the object and require a second attempt by the user to locate the periphery of the virtual object. The new TiDeC technology uses sophisticated movement prediction algorithms to detect possible object collisions and updates haptic rendering 1000 times a second, creating smooth, efficient, and accurate force rendering capabilities.

Using MATLAB coding to drive Simulink, another MATLAB based modeling program developed by MathWorks, and integrating with proSense, a well developed haptic handwriting letter sequence was generated by the group of researchers working at George Mason University. Their work provided the basis for the continuation of the project presented in this paper.

2.5 Motivation for Current Work

When the Falcon from Novint Technologies became a commercially available product there were several advantages of the device compared to the Phantom Omni. The three biggest advantages were the cost of the Falcon, the unprecedented smooth movement, and the freely downloadable open source haptic application programming interface (API) available from SenseGraphics and H3D. The Phantom Omni can be purchased for around $2300 dollars, where as the Falcon can be purchased for closer to $200. The low cost of the Falcon was the largest motivation for abandoning the work that had been done with the Phantom device. In addition, from a tactile perspective, the movements of the Falcon are smooth and continuous in comparison to the Phantom. The two main problems with the Phantom Omni device were a lack of fluidity in movements during handwriting letter generation sequences and the unmet requirement for versatility of the writing utensil. As can be seen in Figure 2.5, the user is limited to using only the writing utensil attached to the haptic device. This writing utensil more closely resembled a large marker and was not representative of most standard writing utensils such as a pen or pencil. The writing utensil was also not easily adapted for users from a variety of different age groups.

In addition to being inexpensive and producing consistent movements, the Falcon provided the opportunity to design a linkage that incorporated a wide variety of writing utensils. The Falcon also is equipped with a well written and versatile software development kit (SDK) in addition to the open source API from SenseGraphics and H3D as previously mentioned. The Falcon SDK is a solid programming platform that gives an advanced programmer the ability to work with the building blocks of haptic programming to develop both specific and highly complex haptic applications. The open source API available at the H3D website provides both novice and advanced programmers with easy access to hundreds of source code files that can be used to understand haptic programming structure and build graphics for haptic interaction [25]. All of the source files available in the API are built in C++ and use the Python programming language to provide dynamic interaction with graphics that are created in C++ or in the Virtual Reality Modeling Language (VRML) based environment called Extensible 3D (X3D) available from the Web3D Consortium [26]. The Falcon has a wide variety of resources that can be useful for all levels of programmers in developing the basic to the most complex haptic applications, another reason for using the Falcon as the force generator for the handwriting letters.

2.6 Customer Requirements

Working closely with Obslap Research LLC, a set of customer requirements was defined in order to properly identify the design problem. These customer requirements evolved throughout the project as the feasibility of each requirement was determined. The following is the list of requirements that were established after the first phase of the design process.

- Entire unit should fit easily on a medium sized desk space.
- Entire unit should be easily carried by a single individual.
- Force provided at the handle of the Falcon should be preserved and maintained at the writing utensil.
- Mechanism serving as the writing interface to the Falcon should be easily fabricated in a production style environment.
- Material required to build the mechanism serving as the writing interface should cost less than the Falcon.
- Compatible with both left and right handed individuals.
- Compatible with a wide variety of pen grippers and/or writing grip styles including the quadrupod grip, fist grip, lateral pinch grip, thumb wrap grip, and index grip. (See Figure 2.6)
- Must accommodate children and adults with fine motor skill and developmental disabilities.
- The writing interface mechanism must resist breaking, spills, and dust.

- Mechanism must demonstrate a magnification ratio of 1:2 from the haptic working volume to the writing working volume.
- Mechanism must have low-friction characteristics throughout the entire working volume and demonstrate smooth transitional movements.
- Writing attachment must easily accept/release BIC style writing pens.
- Writing pen must be capable of rotation to accommodate users with different pen angle preferences but maintain rigidity during operation of writing program.
- Falcon should be securely attached to the working surface during operation but be easily removed for transportation.
- Writing surface must sit securely in place during operation but allow for easy replacement of written work.
- Unit must be appealing for people of all ages and have a sleek, sharp look.
- Handwriting student should have both visual and auditory feedback from the device.
- Software and graphical user interfaces should be simple and easy to use.

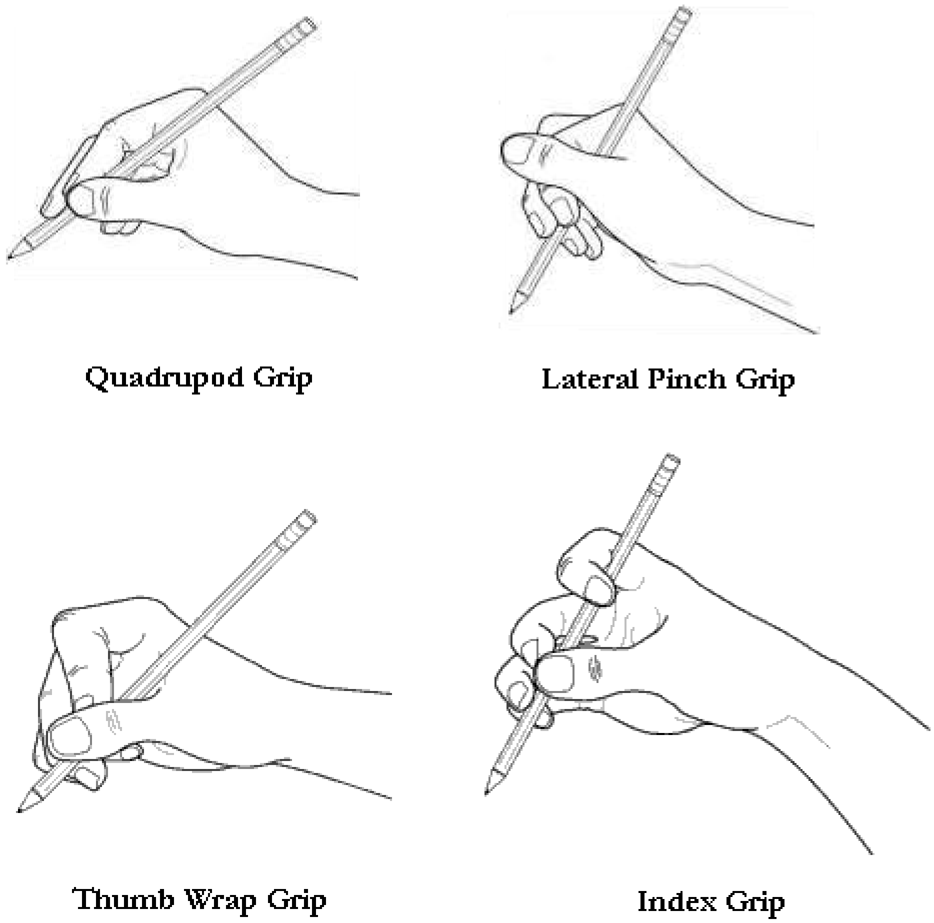


Figure 2.6: The most common gripping preferences for adults and children [27]. Other common grips are often a combination of the grips shown.

One of the original customer requirements was removed after the first phase of design. This requirement specified the mounting surface have the ability to rotate 180 degrees in the plane of the desktop and incline from 0 to 30 degrees off of the desktop. After the first prototype was generated it became obvious that this requirement was more of an inconvenience than beneficial and significantly added to the cost and weight of the entire unit, which were two of the design variables requiring minimization. These requirements for rotation and inclination of the Falcon base were eliminated, resulting in the very simple and inexpensive wood base that is currently used.

Originally the device needed to be capable of accepting both a pencil and a BIC style pen. After the first phase of clinical testing, it was determined that holding specific height tolerances at the tip of the pencil was very difficult due to the constant wear and dulling at the pencil tip. The BIC pen fulfilled the same function as the pencil, but did not exhibit the excessive tip wear characteristic of the pencil. Therefore, the requirement was changed to include BIC style pens only and avoid standard pencils. Based on the customer requirements, the project was divided into three different areas which were software design, designing the mechanism to create the necessary magnification from the haptic workspace to the writing workspace, and designing the handwriting utensil to interface with the magnification mechanism. As the design process progressed, the importance of constant interaction with the customer became obvious in order to achieve a successful design and balance design variables.

2.7 Mechanical Engineering Undergraduate Senior Project Work

The initial design steps of creating a mechanism to connect to the Falcon and fulfill the outlined customer requirements was given to a group of three mechanical engineering undergraduate students. The first design used a motion amplifying rod which would have involved adapting the electronics inside of the Falcon ball grip in order to assist attachment of the rod. It was decided to avoid modifying the electronics of the Falcon as this would void warranties and could damage vital electrical components. A second design idea was to use a specific type of mechanical linkage, called a pantograph, which as discussed in section 2.2 has already proved useful in a variety of haptic research applications. The properties of the pantograph and more information on the pantograph will be discussed in section 2.9. The horizontally mounted Pantograph linkage design is shown in Figure 2.7.

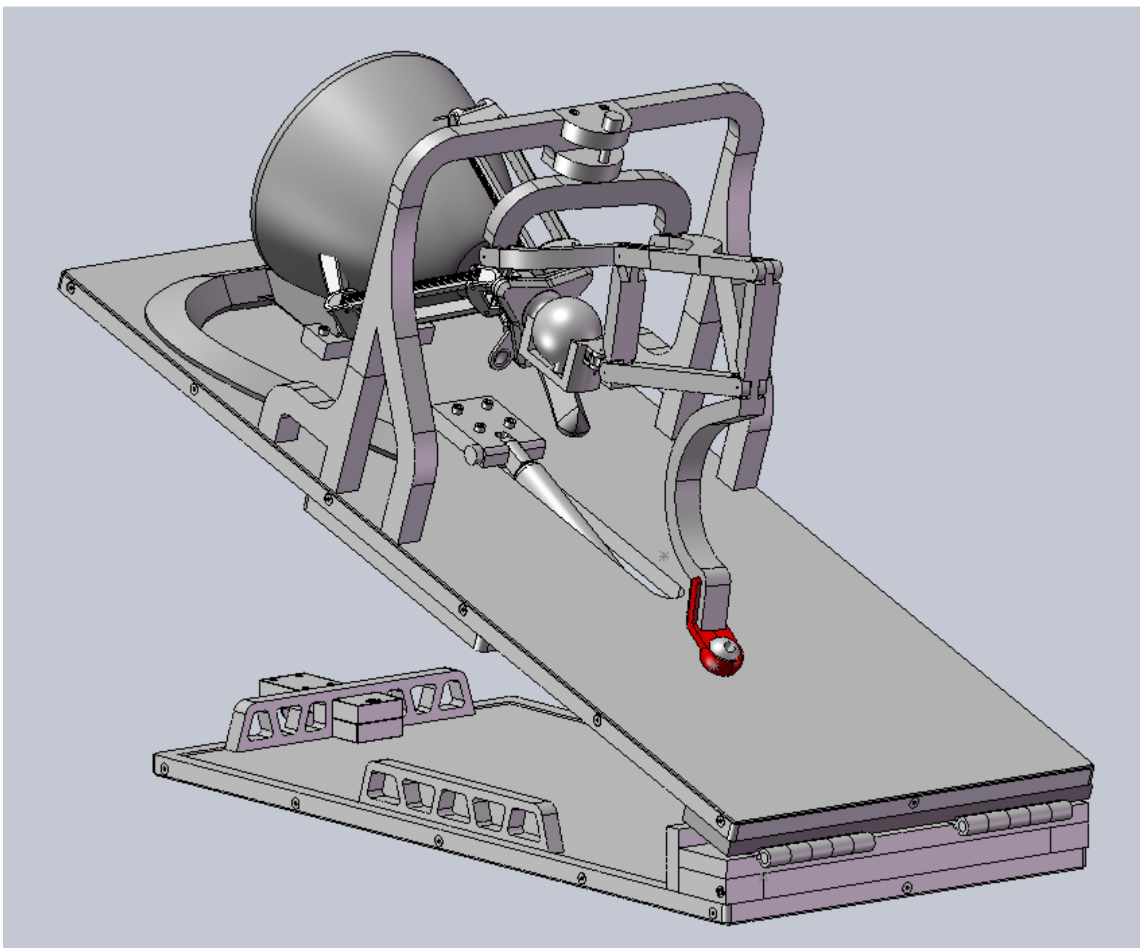


Figure 2.7: The horizontally mounted Pantograph linkage subject to original design requirements.

SolidWorks simulations of the horizontally mounted pantograph linkage produced promising results. At the end of this design phase several important problems were identified with the current design. The inclination and rotation of the mounting surface were no longer identified as important and made the device too costly and heavy, those requirements were eliminated as discussed in section 2.6. The linkage was made of high density polyethylene (HDPE) in order to keep weight and costs low. Machining HDPE and maintaining the needed tolerances proved to be difficult. As a result, the linkage joints were either too tight and drastically increased the friction in the linkage, or the joints were too loose which created lateral movement, making it difficult to control the tip of the pen precisely. Machining costs were high due to the complex geometries of the links and the time involved in machining the arch supporting the linkage. Material costs were high because of the amount of material needed for the base, supporting arch and links.

2.8 Industrial Engineering Undergraduate Senior Project Work

Developing the device to hold the writing utensil and fulfilling the associated customer requirements was given to a group of two industrial engineering undergraduate students. The red component and gray sphere assembly seen in Figure 2.7 was developed by the two industrial engineering students to mate properly with the linkage developed by the mechanical engineering students. This design allowed excellent control at the tip of the pen and provided easy angular adjustment of the writing pen. However, the design interferes with the tip of the pen and standard grip configurations for most individuals. It can be seen in Figure 2.7 that the optimal gripping position for this design would occur one-third to halfway up the shaft of the pen, this is not a standard gripping position. A second problem needing to be addressed with this design was securing the writing attachment assembly to the linkage. At this point, there was no fastening mechanism holding the two assemblies securely together, which resulted in the writing attachment falling out of the end of the linkage. A separate but equally important design problem involved securing the pen in the writing attachment, to ensure movements of the pen correspond directly to movements of the writing attachment and linkage. Overall, the undergraduate teams developed an elegant solution that successfully addressed several difficult customer requirements relating to the writing attachment and pen.

2.9 Pantograph Linkage

The pantograph was invented by Christoph Scheiner in 1603 and is a four bar linkage forming a parallelogram that takes advantage of spacing between the joints of the linkage to produce either magnified or reduced replication of an original drawing [16]. Figure 2.8 shows the basic configuration of a pantograph linkage for image magnification. Point A is fixed, point C is the point at which the original image is traced, and at point F the image magnification is produced.

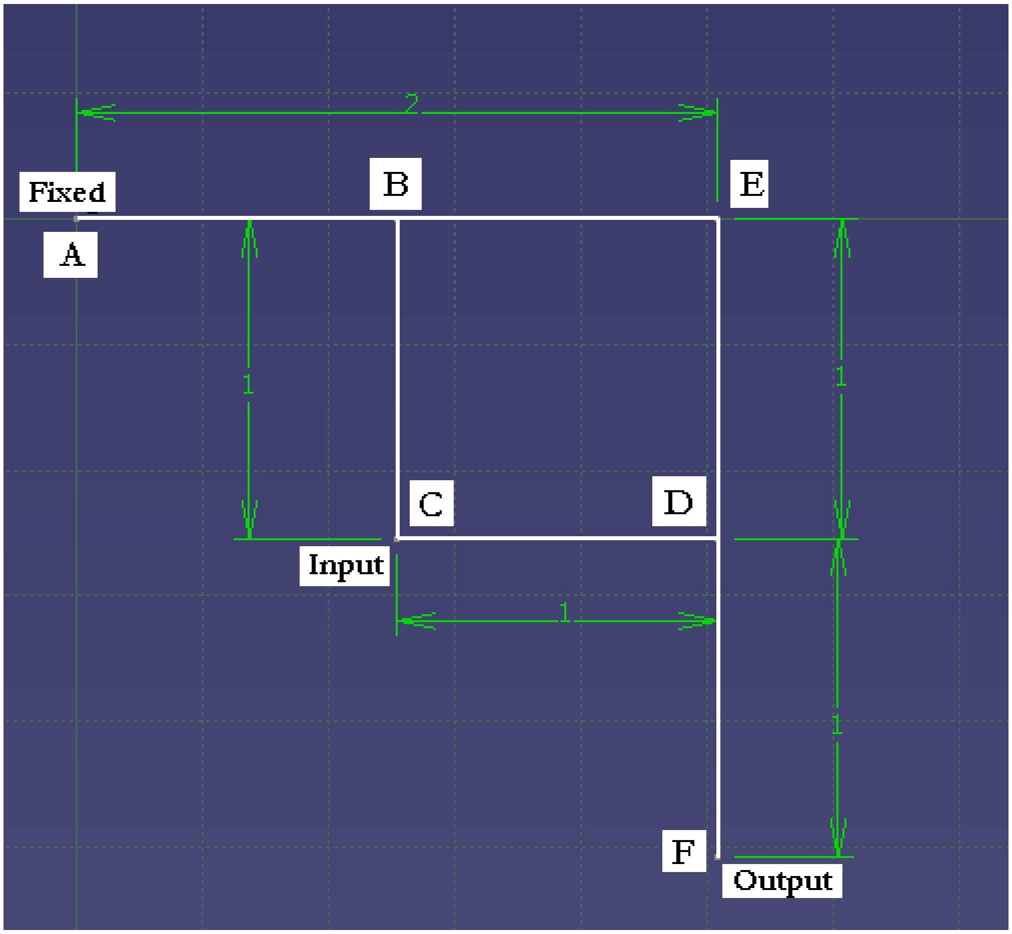


Figure 2.8: CATIA sketch showing pantograph linkage configured for magnification ratio of 1:2.

The pantograph four bar linkage can be easily manipulated to give the appropriate magnification or reduction. In reference to Figure 2.8, Equations (2.1) through (2.4) show the required link lengths for a specified magnification ratio [28].

$$\lambda = \text{Specified Magnification Ratio where } \lambda > 0, \text{ and } \lambda \neq 1 \tag{2.1}$$

$$\lambda * AB = AE \tag{2.2}$$

$$\lambda * ED = EF \tag{2.3}$$

$$\lambda * AC = AF \tag{2.4}$$

Equations (2.1) through (2.4) are derived from a linear algebra law called the distributive property of scalar multiplication in vector spaces [29]. The image translation characteristic of the pantograph linkage is the result of the parallelogram formed by points B, C, D, and E. The BCDE parallelogram creates two similar triangles which are proportional to each other by the specified magnification ratio. Figure 2.9 shows the BEF and B'DF similar triangles. These similar triangles provide identical movements at points C and F due to the parallel relationship between each of the links.

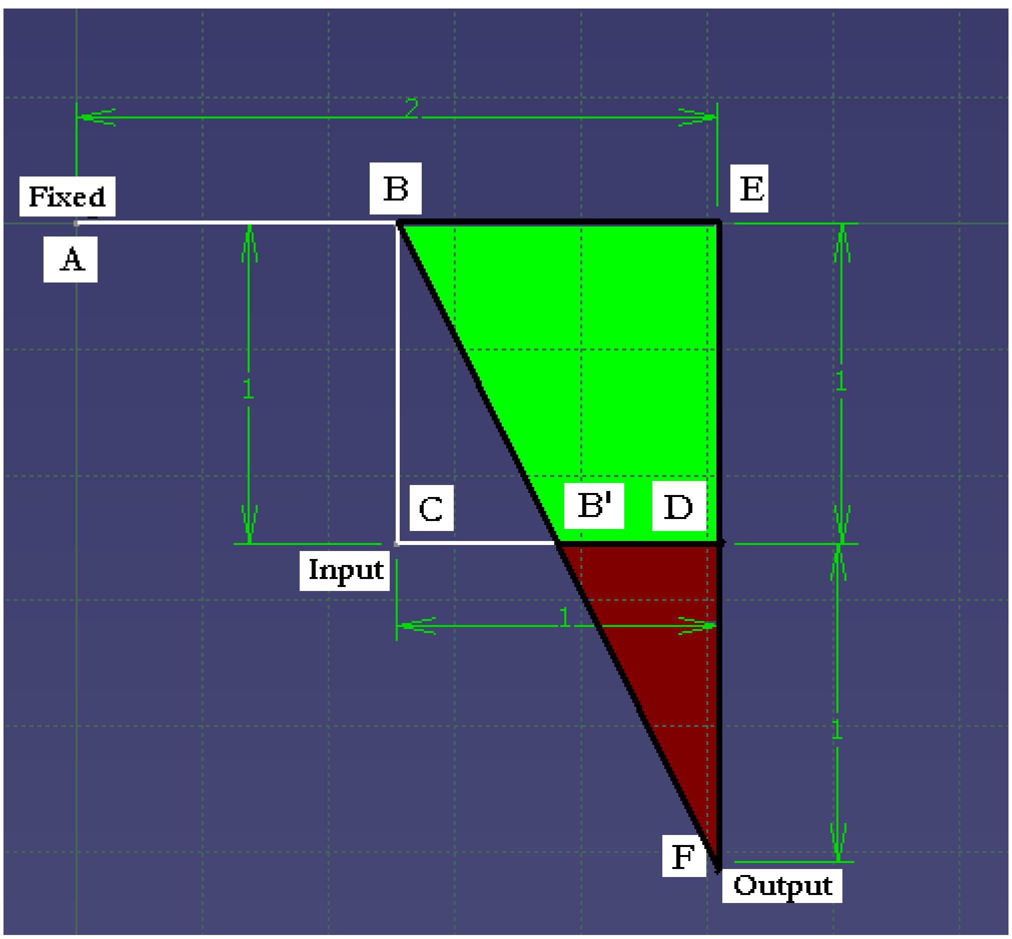


Figure 2.9: CATIA sketch showing the similar triangles which produce the identical and scaled movements at points C and F.

It is important to note that Equations (2.1) through (2.4) apply to both image magnification and reduction. However, in order to produce a reduced image from the linkage shown in Figure 2.8, the input and output points, C and F respectively, would need to be inverted. It is also important to consider the situations where λ is zero or one. A magnification value of zero does not make sense physically and should be avoided in Equations (2.1) through (2.4). A situation where magnification of one is desired eliminates the use of a pantograph completely and suggests using a single fixed link to produce a replica of the image. Figure 2.10 shows a pantograph linkage with $\lambda = 4$ and configured for magnification. The input and output links could easily be switched to provide a reduction configuration with $\lambda = 0.25$.

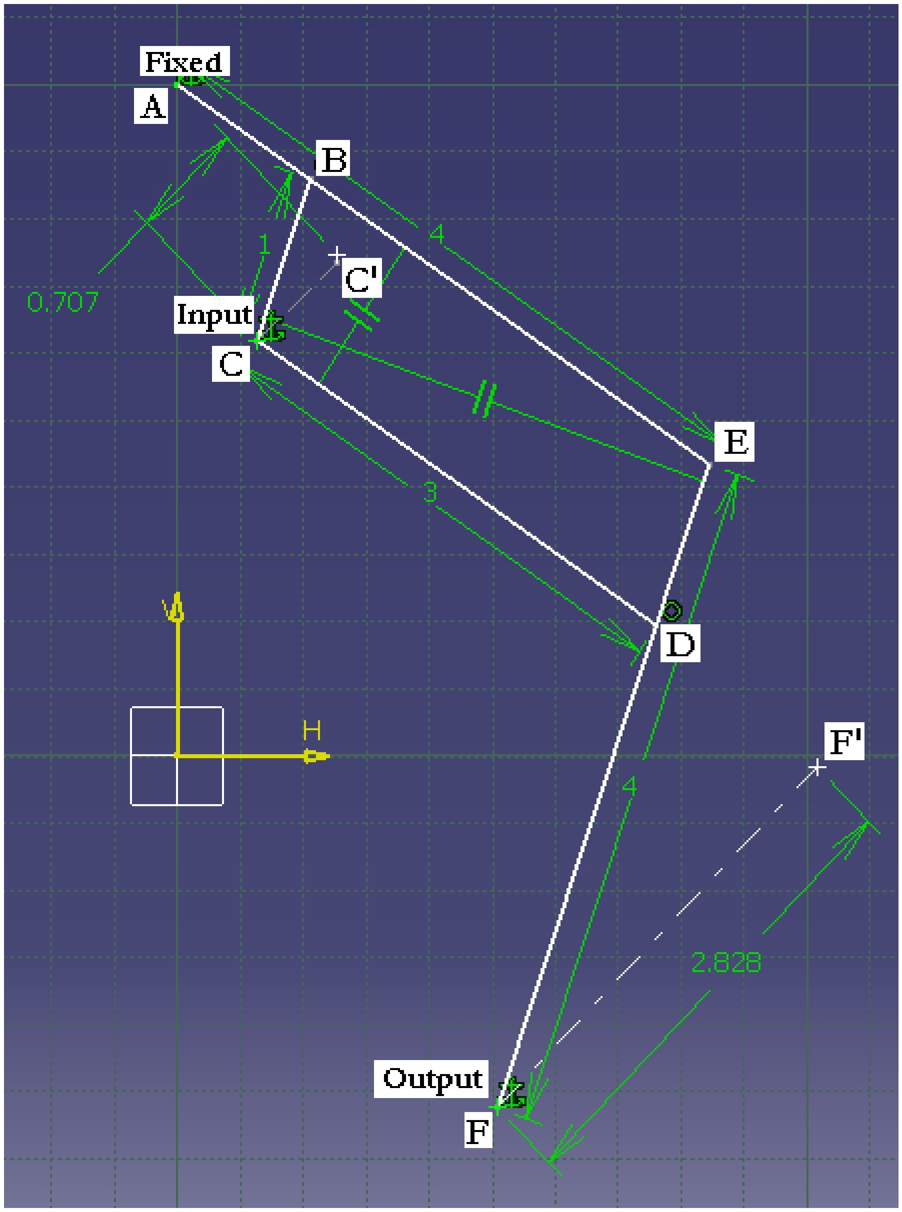


Figure 2.10: CATIA sketch demonstrating 1:4 magnification ratio of a simple diagonally sketched line.

An additional configuration of the pantograph can be useful in applications such as the clothes drying rack seen in Figure 2.12C and corresponds to magnification in the opposite direction of the traced movement, which can be thought of as negative magnification. With this configuration of the pantograph the traced image would appear upside down compared to the original image. In order to produce this negative magnification effect, point C of the pantograph is fixed instead of point A. Equations (2.5) through (2.7) should be used for generating magnification using the pantograph in the inverted orientation.

$$\lambda * AB = BE \tag{2.5}$$

$$\lambda * ED = DF \tag{2.6}$$

$$\lambda * AC = CF \tag{2.7}$$

The input movements occur at point F and the output movements occur at point A. As in the previous orientation of the pantograph, the λ value chosen for Equations (2.5) through (2.7) will produce λ magnification of the original image. However, with the linkage configured in this fashion the image will be inverted at the output link. Figure 2.11 shows the pantograph in this configuration creating the inverted image.

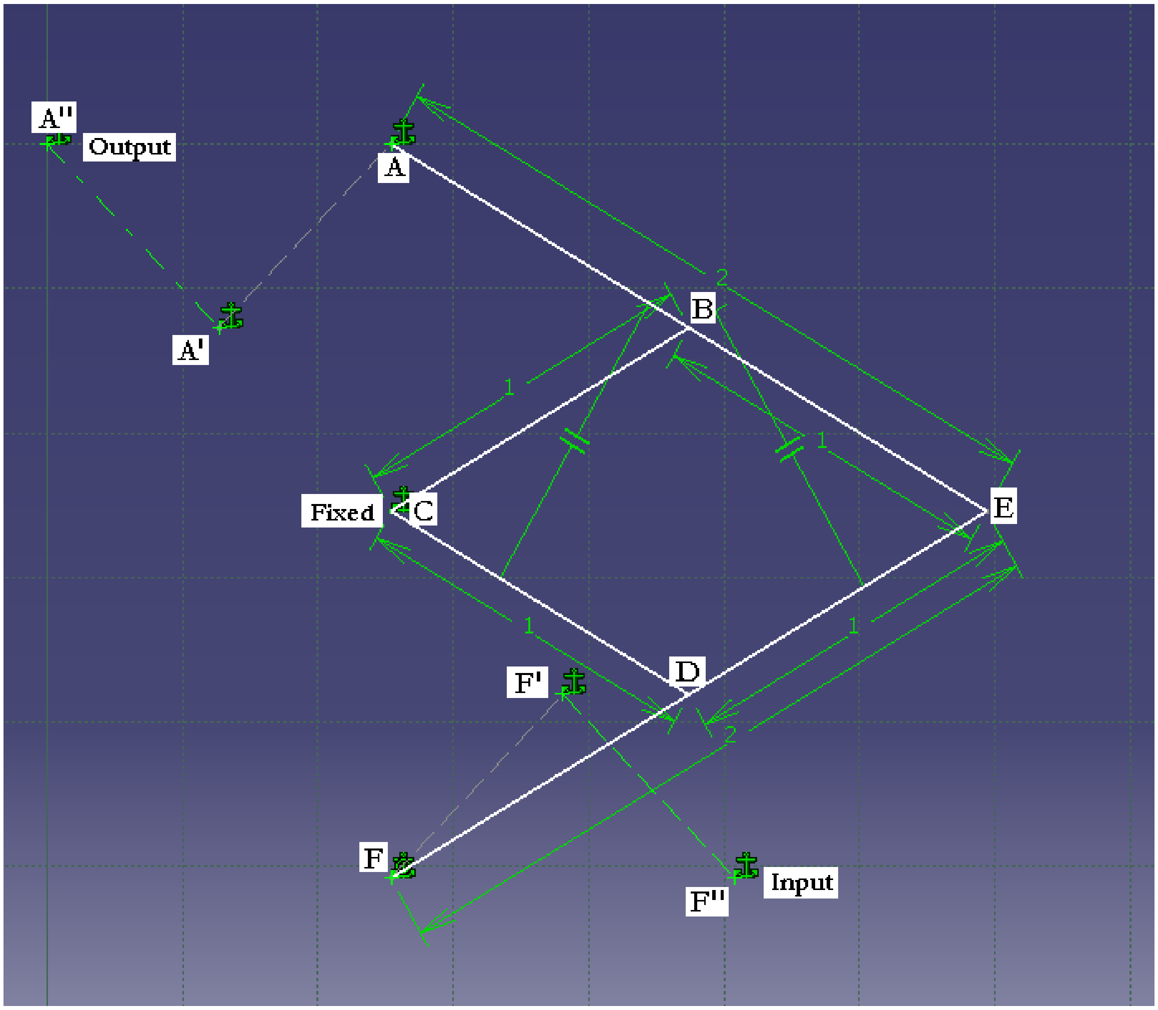


Figure 2.11: CATIA sketch showing the inverse 1:1 magnification configuration of the pantograph.

The four bar pantograph linkage is often found hidden in many modern mechanisms and machine design applications. The pantograph has been incorporated into the Delone exact circle-tracing sixbar mechanism for applications where exact circular motion is needed at specified distances from moving and fixed pivot points [22]. As Figure 2.12A shows, a pantograph is used in many styles of modern tram transportation designs across the world because the linkage ensures constant electrical contact between the tram and the transmission line. The pantograph is able to expand and contract easily in order to maintain an electrical contact despite slack in the line or inconsistencies in track elevation. Pantographs have also been incorporated into modern desk lamps and engraving machines. A pantograph used on an engraving machine can be seen in Figure 2.12B.

A B C

Figure 2.12: Various mechanisms utilizing the concept of the pantograph linkage [30-32].

3. SOFTWARE

3.1 Programming Haptic Letters

The Novint Falcon was chosen as the force providing mechanism for the MY SCRIVENER™ project because of its exceptionally smooth movements and low cost. In addition, the Falcon supported a well known and easily attainable application programming interface (API) called H3D. SenseGraphics AB developed this open source haptic software platform and made it available under the GNU General Public License (GPL) via registration at the H3D website [25]. H3D API provided extensive software support through online forums, direct access to source code files, and an informative software development manual. These resources facilitated the prototyping of basic haptic letter algorithms required for the success of the project.

H3D software uses the C++ programming language as the foundation for communication with the haptic device. The Python programming language and a 3D modeling environment, called X3D, are used to access the haptic commands developed in C++. Python and X3D provide a simple and effective method for developing haptic and virtual object interaction while avoiding complicated C++ haptic programming. The Microsoft Visual Studio 2005 integrated development environment (IDE) was used for executing H3D API. Figure 3.1 shows a letter created using X3D and H3D during initial prototyping for the software. The X3D file used to generate this letter is shown in Appendix A.

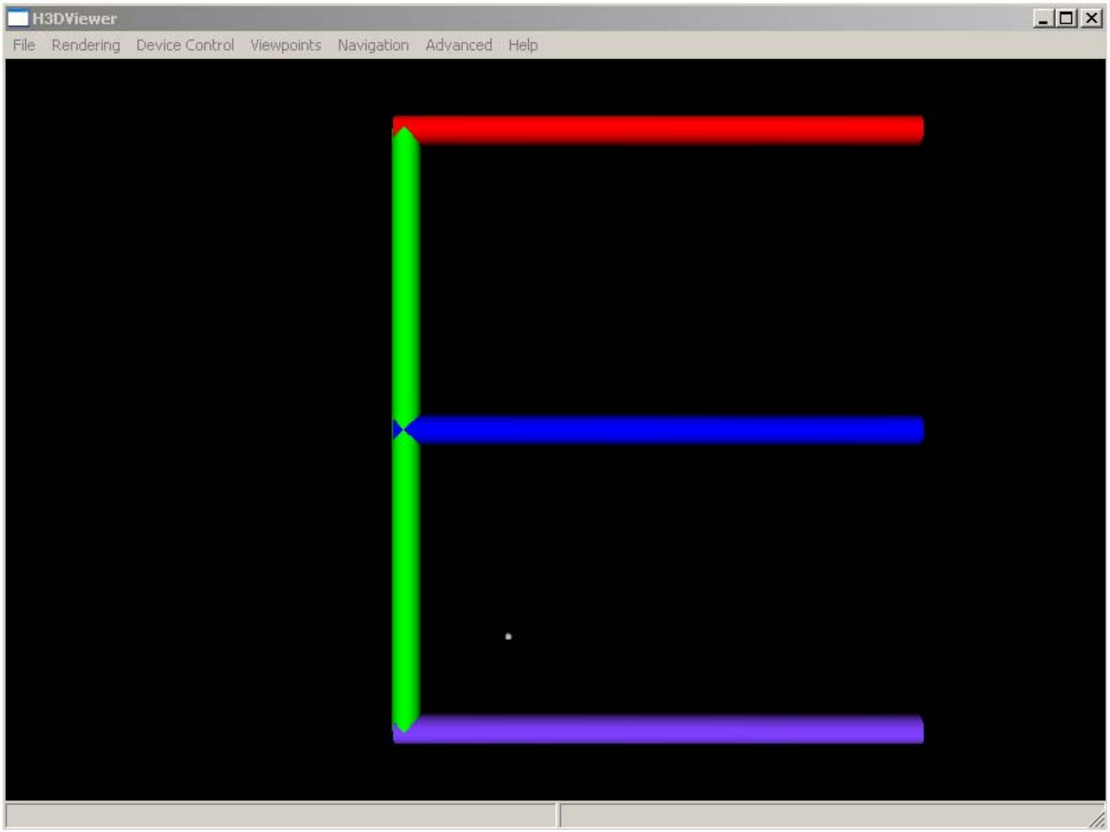


Figure 3.1: A simple "E" was created using X3D and H3D API during initial prototyping.

The programming algorithm prototype developed to generate haptic letters was derived from Hooke's law for a linear spring. Equation 3.1 shows Hooke's law for a linear spring.

$$F=-kx \tag{3.1}$$

F=Force

k=Spring Constant

x=(Falcon Handle Position-Spring Origin)

For this application, one end of the spring was connected to the haptic device handle and the other end of the spring was defined as the spring origin. The prototyping technique involved incrementing the origin of the virtual spring along a specified path in order to effectively pull the handle of the haptic device along this path. The incremental distances were specified at small values to create smooth transitions from one position to the next. Figure 3.2 shows Hooke's law as applied to the virtual spring.

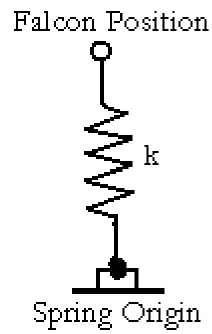


Figure 3.2: Showing basic linear spring model as described by Hooke's law.

A simple looping technique was used in Python to iterate the x, y, and z coordinates of the device through the desired path. The code developed and implemented for this technique is shown in Appendices B, C, and D. Unfortunately the programming prototype was not completely successful. Additional work was needed to provide more effective control over the haptic letter movements generated in the prototype.

The project was under a strict deadline for first phase completion due to clinical testing scheduled during summer 2008. The funding was available and it was determined necessary to consult advanced software engineers for assistance with developing the haptic letter programming for the Falcon. Lunar Logic, a custom web and software development company based in Eugene, Oregon, agreed to assign a team of software developers to provide the support needed for the project. Lunar Logic began development in C++ and used their programming experience to create the haptic letter algorithms.

The undergraduate seniors who were working on developing the mechanical linkage and writing attachment were no longer assigned to continue with the advancement of the linkage. Changes needed to be made to the linkage in order to create a more effective design and eliminate problems uncovered in the first phase of the design. The problems with the linkage and the solutions developed will be discussed in section four. The clinical testing during the summer required four separate haptic letter programs loaded on laptop workstations, each accompanied by a mechanical linkage.

4. LINKAGE DESIGN PHASES

4.1 Defining Linkage Dimensions

After developing the first linkage and experimenting with the Falcon, it became important to define an appropriate magnification factor for the linkage. Given the lack of control inherent in the Falcon handle and the volume of the Falcon workspace, the pantograph linkage was designed with a magnification value of approximately 2. This is consistent with the customer requirements stated in section 2.6. Using Equations (2.1) through (2.4) the original linkage prototype, shown in Figure 2.7, was analyzed to determine its magnification ratio. Dimensions AB, BE, BC, CD, and DE all showed values that were appropriate for a magnification of 2. Therefore, those dimensions were left as originally designed. Dimension DF of the original linkage was much larger than necessary and was reduced to reflect the desired magnification ratio. The distances between each of the appropriate points and corresponding magnification values are shown in Figure 4.1.

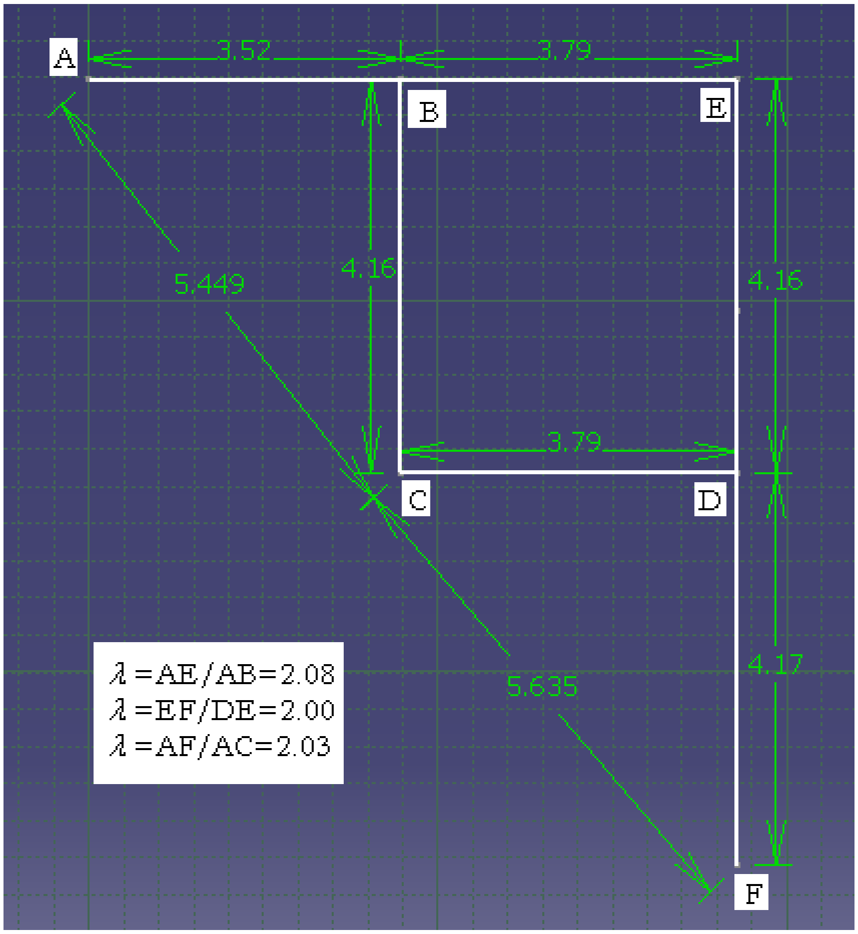


Figure 4.1: CATIA sketch of linkage dimensions chosen for magnification of ~2.

The dimensions shown in Figure 4.1 are measured from the center of each joint. The links lengths in each of the design phases were created slightly longer than the dimensions shown above to account for the diameter of the joint pin and bushing. After the programming was developed for linkage design A, it was imperative for successful letter generation that all further designs maintained the dimensions shown in Figure 4.1. The width and height of the links varied between each of the different design phases due to changes in the materials used and the addition of thrust bearings in the final two design phases.

4.2 Phase A Design

The first prototype of the mechanical linkage designed to interface with the Falcon haptic device, shown in Figure 2.7, provided important information about unforeseen problems during manufacturing, assembly, and operation of the linkage. One of the most troubling problems occurred in the joints of the linkage. Initial operation of the linkage demonstrated unexpected backlash occurring in the joints. Backlash refers to the amount of space between mechanically mated components which often results in lost function when motion of the mechanism is reversed [22]. The backlash created varying degrees of lateral movement which resulted in unsuccessful letter appearances. A culmination of small errors in the manufacturing and assembling processes was most likely the source of the backlash. Although these types of errors can be reduced, they cannot be eliminated completely in the manufacturing environment available for this project. Each link of the assembly was made from high density polyethylene (HDPE) to reduce weight; HDPE is flexible and provided dimensional instability which also contributed to the backlash. Figure 4.2 shows the dimensional mismatch at a linkage joint resulting in backlash. Large amounts of backlash make accurate translation of the Falcon movements virtually impossible.

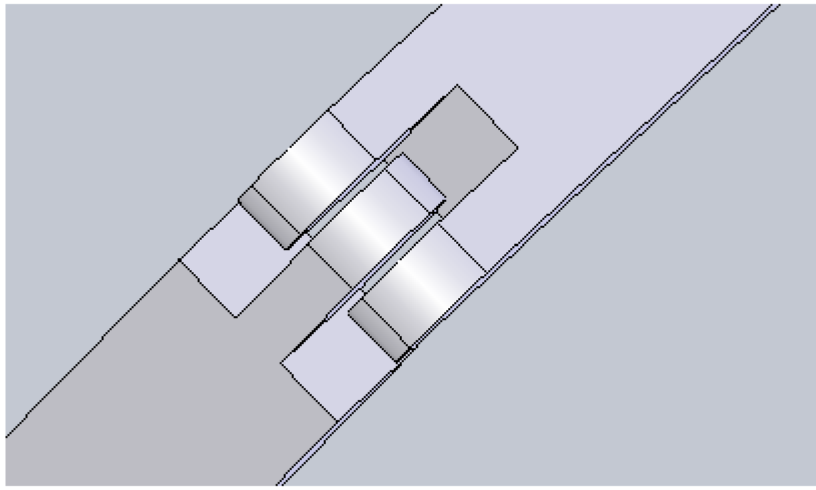
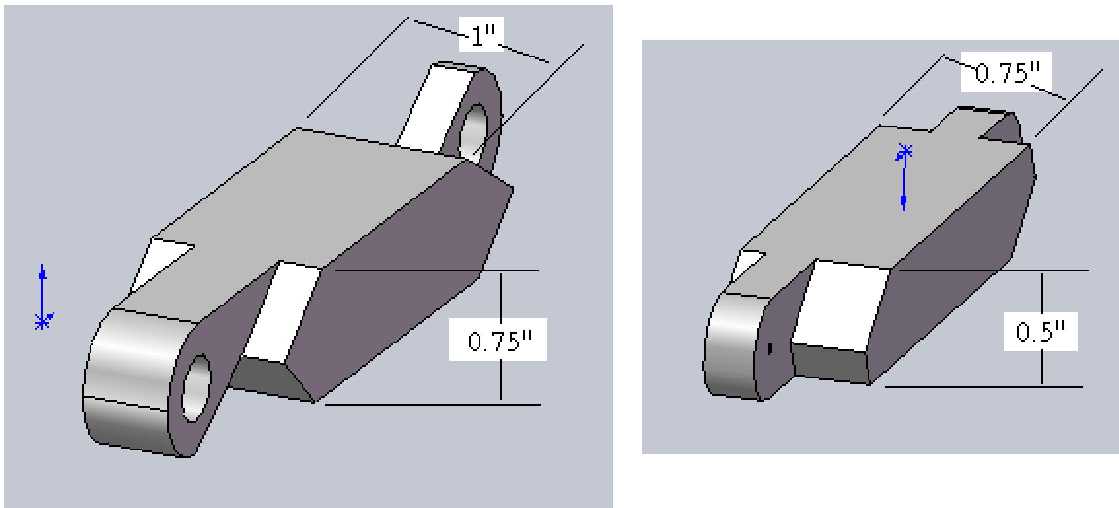


Figure 4.2: Shows the dimensional inaccuracy which produces backlash in the linkage joints.

Due to time constraints, it was not possible to perform a series of tests to determine the best solution for fixing the backlash in the linkage joints. As a result, two techniques were implemented to provide functionality to the current design. The first technique involved mounting the entire linkage vertically as opposed to the horizontal mounting configuration shown in Figure 2.7. The benefit of a vertical configuration over the horizontal configuration is the backlash in the linkage joints is restricted to the z-axis, or vertical movements only. Movement due to backlash is more tolerable when the pen is being applied or drawn away from the writing surface than in the x-y plane. Direct movement translation in the x-y plane is critical for successful letter appearance. The second technique involved increasing the width and height dimensions of each link by 0.25” which provided more rigidity for the links during the machining process. The original link and the modified link are shown in Figure 4.3 to demonstrate the increase in linkage dimensions.



Design A Link Original Prototype Design Link

Figure 4.3: Showing the increase in width and height dimension applied to all of the links in design phase A.

Another change from the design in Figure 2.7 was the addition of SAE 841 oil impregnated bushings to ensure smooth movements and low friction coefficients in each of the joints. Figure 4.4 shows the assembly of bushing and joint pin. The joint pin hole in design A has a diameter of 0.375” to allow for a bushing press fit. Sections of 0.25” drill rod pieces slide into the bushings and hold the joint together.

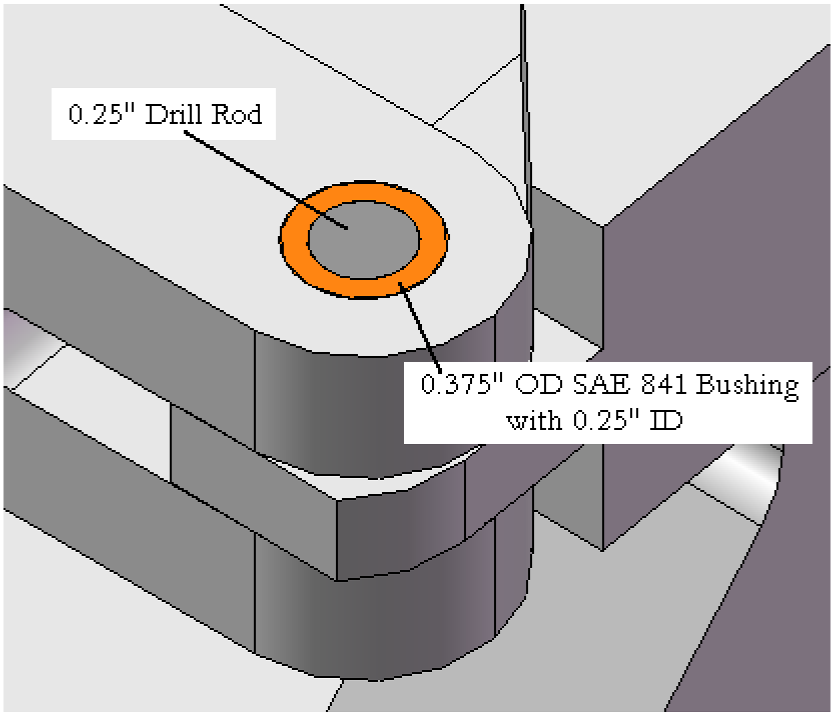


Figure 4.4: Showing implementation of drill rod and SAE 841 oil impregnated bushing to significantly reduce joint friction coefficients.

A cantilever clamping technique, shown in Figure 4.5, was used to successfully attach the spherical ball and pen writing attachment to the pantograph linkage. Prior to design A there was no method for fixing the writing attachment to the rest of the linkage because these two parts of the project were developed independently. In addition, the original writing attachment shown in red in Figure 2.7, provided no technique for clamping the spherical ball into position after the desired pen angle was achieved. This resulted in the pen angle changing as the haptic device executed the letter algorithm, producing inconsistent letter appearances. Design A fixed the writing attachment to the linkage and provided a means for fixing the pen angle when the haptic letter program was ready for execution. The cantilever clamping technique described is shown in Figure 4.5.

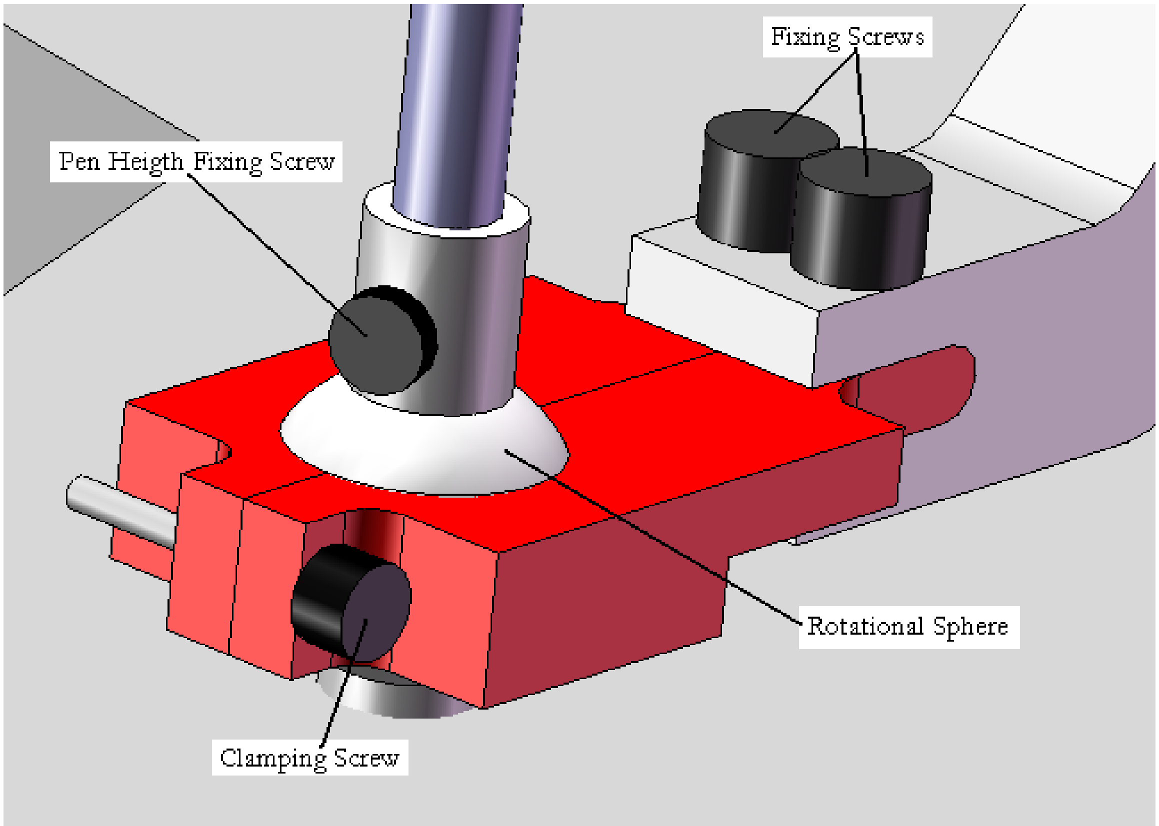


Figure 4.5: Showing the components of the cantilever clamping technique used to allow adjustment and fixation of the pen angle.

The changes outlined above resulted in the following improvements from the original prototype to design A:

1. Significant reduction in material costs
2. Significant reduction in machining time
3. Lower sensitivity to backlash in the linkage
4. Improved structural rigidity with larger link dimensions
5. Reduced joint friction coefficients using bushings

6. Fixed writing attachment to linkage

7. Cantilever clamping screw provides adjustment or fixation of pen angle

The assembled linkage of design A is shown in Figure 4.6 with link notation.

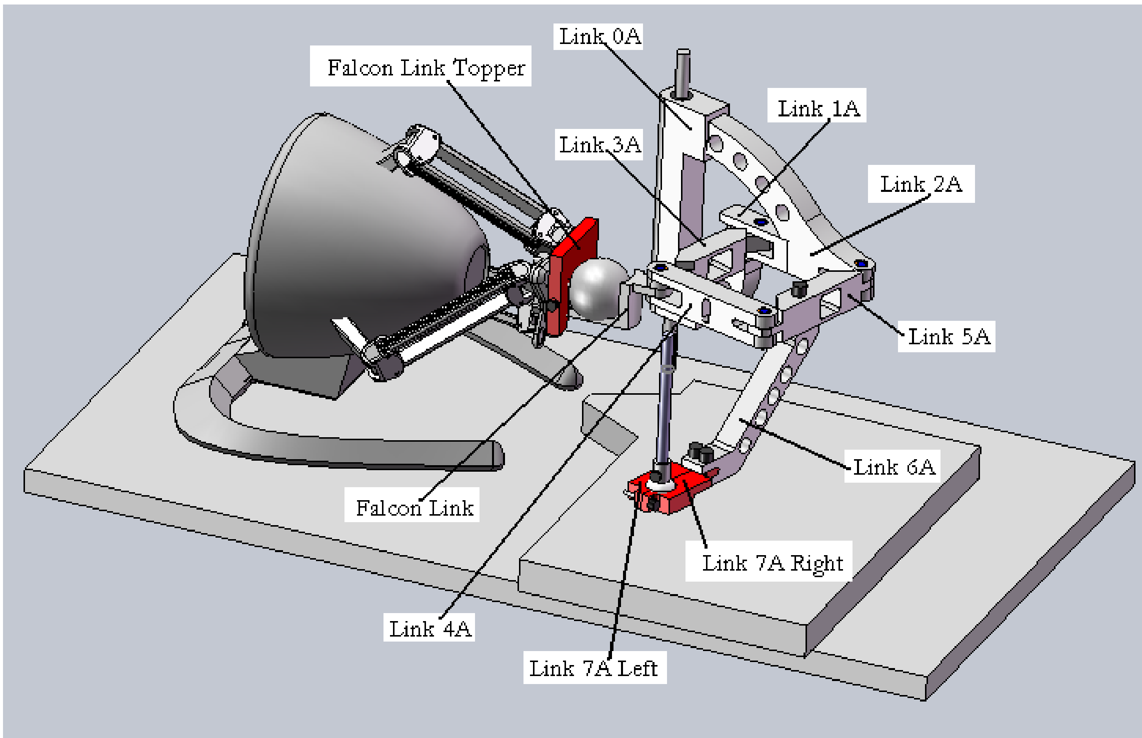


Figure 4.6: Showing the SolidWorks assembly of linkage A with link notation.

Linear ball bearings were used in Link 0A to allow smooth up and down movements of the linkage. Bushings were originally used for this purpose, but the weight of the linkage caused the bushings to pinch on the shaft and create unstable vertical movements of the linkage. The linear bearings also provide rotation to the linkage, allowing access to the entire writing workspace. Combination linear/rotary ball bearings would have been ideal in this situation, but this style of bearings is significantly more expensive than traditional linear ball bearings. Figure 4.7 shows the location of the linear ball bearings in the linkage assembly and a picture of the bearing prior to assembly.

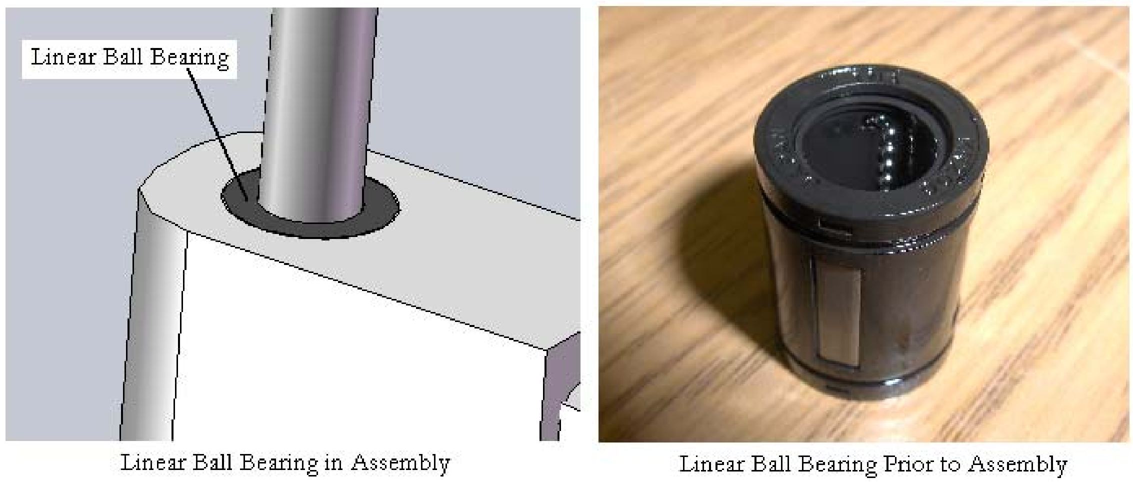


Figure 4.7: Linear ball bearing shown in assembly and prior to assembly.

4.3 Phase B Design

Several changes were made to the linkage design from phase A to phase B. One of the most significant differences between the two designs was the move from plastic to aluminum for the core links of the pantograph. The reason for creating these links out of aluminum rather than plastic was to increase the rigidity of the linkage and produce better tolerances during the machining process. Creating the core linkage out of aluminum also resulted in a more durable product for consumers. Thrust bearings were also introduced for the first time. Thrust bearings are designed to allow smooth rotation between two surfaces despite large axial loading conditions. Inserting thrust bearings into the joint spaces allowed for constant pressure on each link forming the joint, resulting in a joint that maintained smooth rotation and eliminated backlash.

Figure 4.8 shows the thrust bearings in the assembly of linkage B and a picture of the thrust bearings prior to assembly.

Thrust Bearings in Assembly Thrust Bearings Prior to Assembly

Figure 4.8: Thrust bearing shown in assembly and prior to assembly. A washer is placed on either side of the ball bearings to allow rotation even under large axial loading conditions.

Link 1A and link 2A shown in Figure 4.6 were created as one link in design B. In design B it was identified that there was no longer any need for these links to be created separately. Creating these links separately resulted in unnecessary assembly steps and compromised the structural integrity of the linkage. The angles on link 3A and link 5A were eliminated in order to increase the range of writing space the linkage could access. Redesigning link 3A and link 5A also significantly reduced the time required to machine these links. The Falcon link shown in Figure 4.6 was changed to incorporate a double shear joint as opposed to a cantilever style joint; this provided needed support at the joint. These design changes are outlined in Figure 4.9.

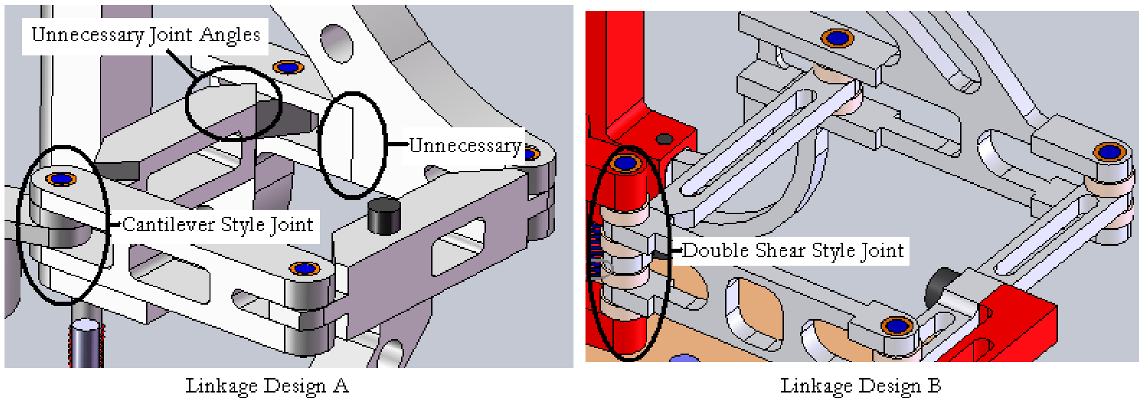


Figure 4.9: Showing differences between linkage design A and linkage design B.

Significant reduction in the size of each of the links can also be seen in Figure 4.9. More material was removed from each of the links in design B in order to reduce the weight of the aluminum linkage. It was important that removal of additional material did not compromise the structural integrity of the linkage. Link 6A was redesigned because it was determined that the link interfered with the user's ability to grip the pen close to the tip. The majority of standard writing grips are located near the tip of the writing device. The design implemented in linkage B allows both left and right handed users to grip the pen in several locations along the shaft. These changes can be seen in detail in Figure 4.10.

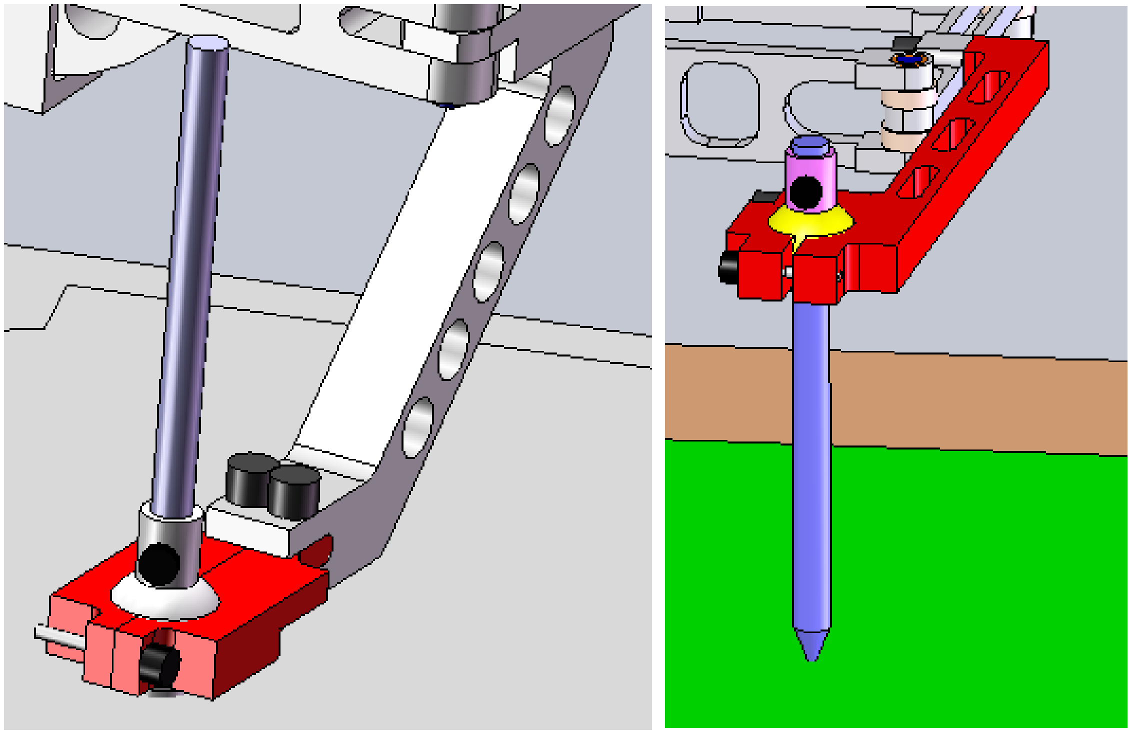


Figure 4.10: Showing the changes from design A to design B for attaching the writing device to the linkage.

The design changes described resulted in the linkage shown in Figure 4.11. The gray links in Figure 4.11 represent those made of aluminum and the red links represent those still made of HDPE.

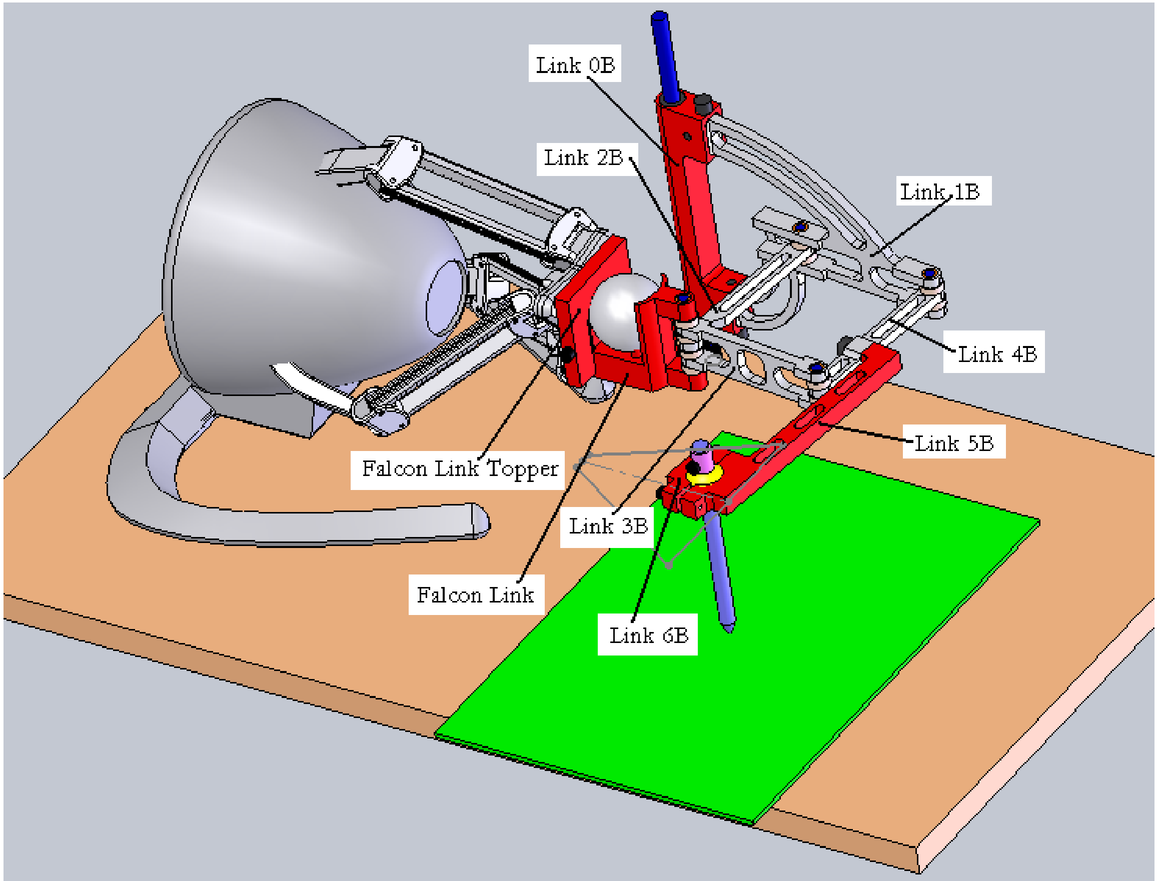
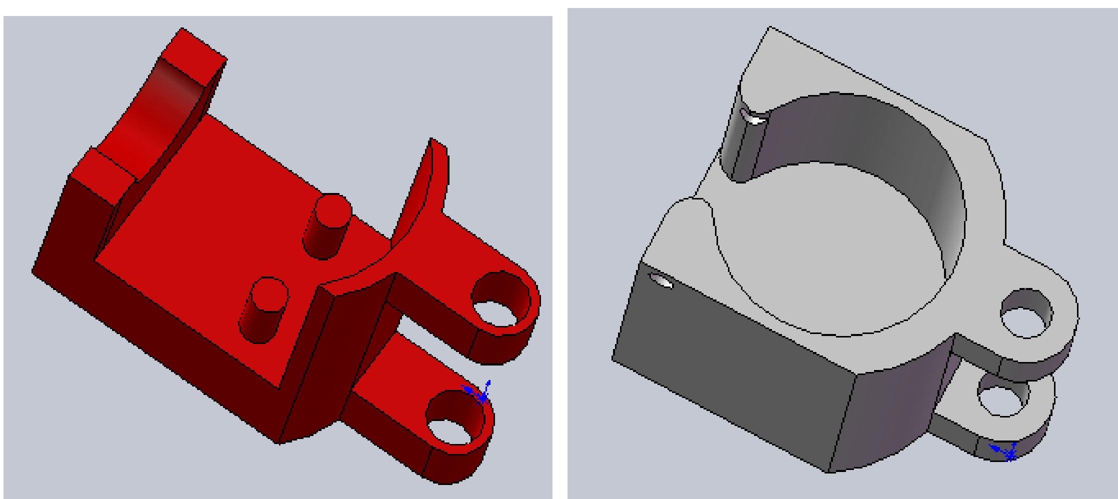


Figure 4.11: Showing the SolidWorks assembly of linkage B with link notation.

4.4 Phase C Design

After developing and testing design B, it was determined that two additional problems needed correction, resulting in a third phase of redesign. The first problem involved link 5B. Undesirable deflections were occurring in link 5B and both of the threaded holes were not withstanding necessary assembly steps. Using aluminum rather than HDPE, the excessive deflection was eliminated and the durability of the threaded holes was improved.

The second problem involved the Falcon link and Falcon link topper. These links were not providing the needed support for attachment to the Falcon handle. In addition, the Falcon link from design B was difficult to manufacture. A new Falcon link was developed which provided the needed support during attachment to the Falcon handle and was easy to manufacture. This design holds the Falcon handle securely in position after assembly. The Falcon link from design B and the new Falcon link, implemented in design C, can be seen in Figure 4.12.



Falcon Link From Design B　　　　Falcon Link From Design C

Figure 4.12: Showing the design changes made to the Falcon link between phases B and C.

A third improvement was implemented in design C to assist the Falcon in lifting the linkage during letter generation. Although the Falcon could easily lift the weight of the linkage, a simple spring was implemented to provide additional support for the Falcon. The spring was custom built by WB Jones Spring Company to meet the strict dimension and force producing requirements of the project. The spring provided the appropriate support for the Falcon during vertical movements. Figure 4.13 shows the spring as designed in SolidWorks and implemented during assembly.

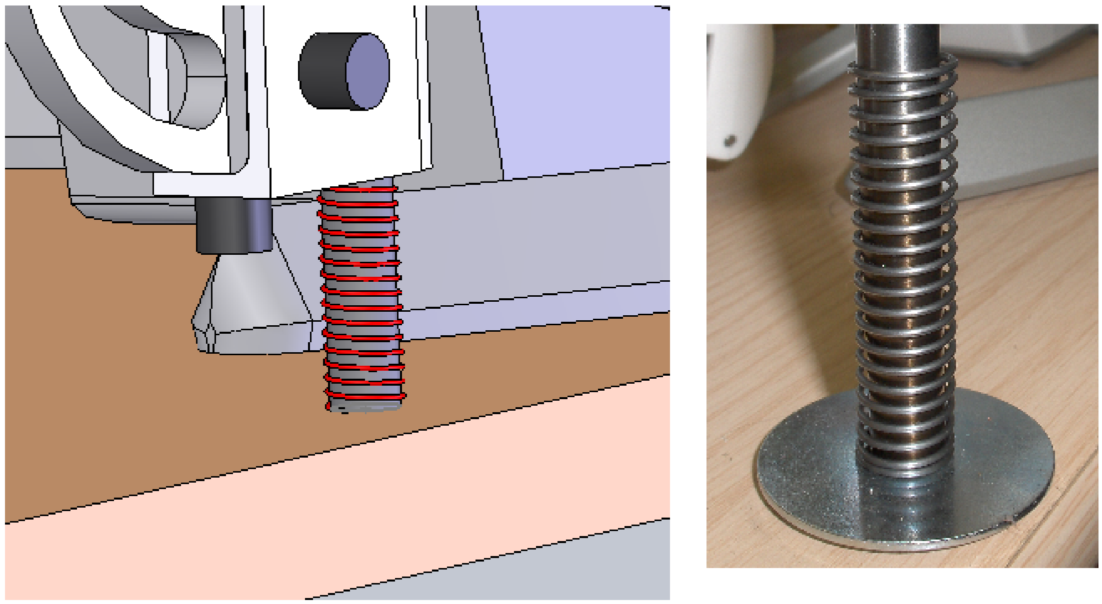


Figure 4.13: Showing spring implemented in design C to assist the Falcon when lifting the linkage.

The changes made in the third design phase resulted in the linkage shown in Figure 4.14. The white links are those machined from HDPE and the gray links are those machined from aluminum.

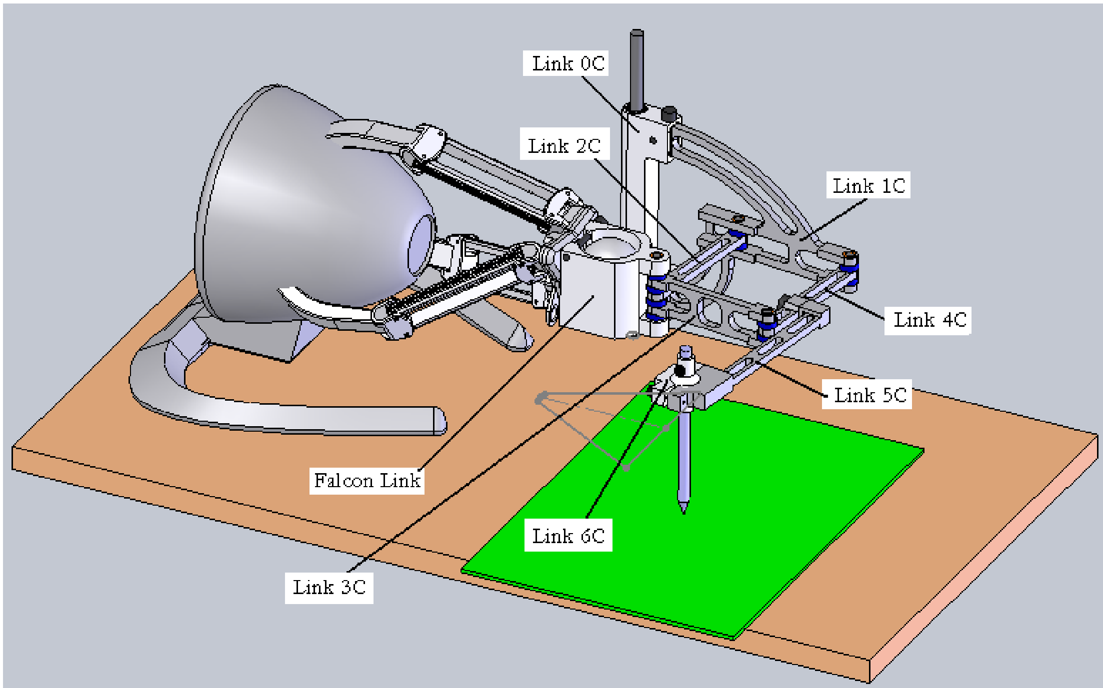


Figure 4.14: Showing the SolidWorks assembly of linkage C with link notation.

4.5 Design for Redesign

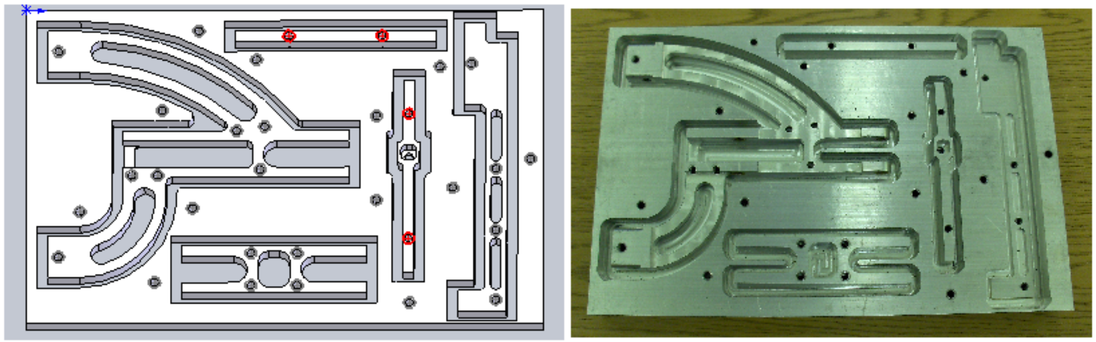
After completing three different phases of design, the importance of designing components to facilitate later stages of modification became apparent. In design C, any of the eight different components that make up the linkage can easily be modified without drastically affecting the other components in the system. This makes the redesign process much easier and also allows for simple correction of mistakes. If any of the links or linkage attachments were manufactured improperly, it could easily be removed and replaced. Eliminating unnecessary components, such as the Falcon link topper, reduces the complexity of the system and condenses the amount of work required in future design phases.

5. MANUFACTURING OPERATIONS

5.1 Fabrication and Minimizing Costs

Each link was manufactured out of one solid piece of aluminum or HDPE in order to decrease the total amount of machining time required. Most of the machining time is consumed during setup of the machine, so reducing the number of setup procedures is critical. Given the complex geometry of some of the links, it was particularly difficult to find the optimal arrangement of the links for minimizing wasted material. Additionally, since vice jaws secure the material into position, some material needed to be left near the edges in order to avoid interference between the endmill and the jaws of the vice.

When creating complex parts in a manufacturing environment, mounting these parts and holding them in position during machining can be difficult. It is often necessary to create a fixture that facilitates the automated machining process. For this project, a simple aluminum plate functioned as the fixture during manufacturing of linkage design C. The aluminum plate provided a way of fixing each of the links during machining to avoid violent interaction between the milling cutter and free floating links. Two identical aluminum plates were used during the CNC machining process. A top plate was used to machine the links, and a bottom plate was used to fix the otherwise unrestrained links. Figure 5.1 shows the part both in SolidWorks and just after the first set of CNC milling operations.



A SolidWorks drawing of link fabrication B CNC link fabrication-Link 5C is not shown

Figure 5.1: Showing arrangement of links for fabrication. Image B shows the aluminum fixture plate located below the fabrication plate. Link 5C is not shown in image B.

The machined links were oriented as shown in Figure 5.1 to minimize the amount of material waste and reduce machining time. The holes seen in image A and B of Figure 5.1 are clearance holes for 8-32 socket head cap screws. The holes in the fixture plate are tapped so that the socket head cap screws can be tightened down to hold the top piece of aluminum in position during machining. The screws also help reduce chatter during machining. Chatter is the physical representation of vibrations in machined material. Chatter often results in material which has a rough and undesirable appearance. Chatter creates unnecessary noise and can significantly decrease tool life. The red circles in image A of Figure 5.1 are reminders that the heads on these screws must be ground down to less than 0.25" because standard socket head cap screws stick out into the path of the tool.

5.2 EdgeCAM

EdgeCAM is a computer aided machining (CAM) program that facilitates communication with a CNC machine. EdgeCAM provides the user with the ability to import a variety of computer aided design (CAD) files or simply create a new part in EdgeCAM. Virtual machining operations are created in EdgeCAM and assigned to sequences for CNC machine execution. EdgeCAM provides a simulator, which allows the user to visualize the tool path of the machine and ensure proper execution of milling cycles. For this project, the SolidWorks part file shown in Figure 5.1A was loaded into EdgeCAM. Figure 5.2 shows the EdgeCAM simulation environment.

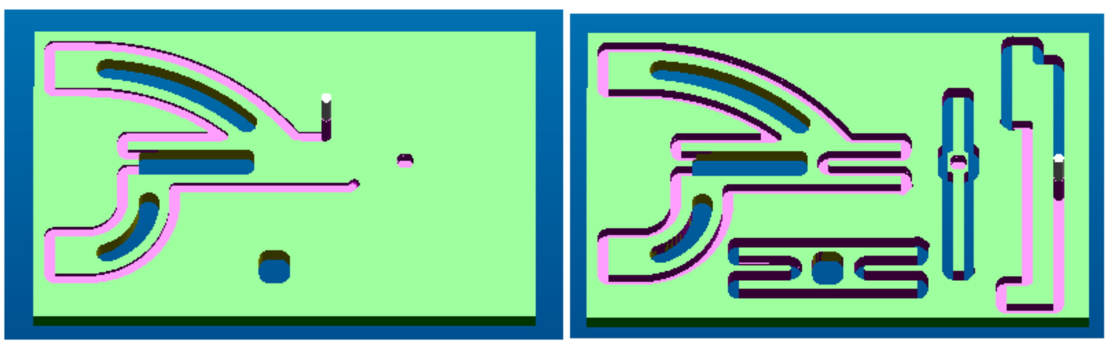


Figure 5.2: Showing the EdgeCAM simulation environment providing visual feedback of milling tool path prior to CNC machining of the parts.

EdgeCAM was not only used to create each of the links, but it was also used to generate the curved ends on each of the links, the male and female mates between links 4C and 5C, the male and female mates between links 0C and 1C, and the Falcon link. EdgeCAM is complex and took significant time to learn, but was necessary to create the complex geometries of the linkage developed in this project.

5.3 CNC Machines

Three different CNC milling machines were used throughout the course of this project. The two larger CNC machines, Fadal VMC 4525 and Fadal VMC 15, were used for machining the links out of stock material. The smaller Bridgeport CNC machine was used for all of the additional CNC work that needed to be done on the links after they were manufactured on the large CNC machines. The large CNC machines have maximum spindle speeds of 10,000 revolutions per minute and have the capability to feed at over 50 inches per minute. The Bridgeport machine has a maximum spindle speed of near 3,000 revolutions per minute. Both Fadal machines can handle programs with thousands of lines of code. The code generated for milling the links out of the aluminum was over 3,000 lines. The larger machines were the obvious choice for this milling program because of the reasons stated above. The Bridgeport machine is easy to set up and operate, so it was very useful for rounding small corners or machining pockets in the links. The three different milling machines are shown in Figure 5.3.

Fadal VMC 4525 Milling Machine

Bridgeport CNC Milling Machine

Fadal VMC 15 Milling Machine

Figure 5.3: Showing the three different milling machines used to create the links.

6. CLINICAL TESTING

6.1 Summer Writing Camp at Shenandoah University

During June and August of 2008 a clinical evaluation of the MY SCRIVENER™ project was scheduled at the Boys and Girls Club of the Northern Shenandoah Valley [33]. Deborah Marr, associate professor and director of Shenandoah University's Division of Occupational Therapy, organized the clinical trials in conjunction with Obslap Research LLC [34]. A total of six complete design A phase linkages were produced to accommodate the group of children participating in the study. The clinical trials lasted a total of six weeks. The children were evaluated at the beginning and the end of the six week session. The children had the opportunity to work with the MY SCRIVENER™ device twice a week. The goal of the study was to determine how the haptic device affected the legibility of the student's handwriting after six weeks of working with the device. Three of the six linkages that were produced at Oregon State University are shown in Figure 6.1.

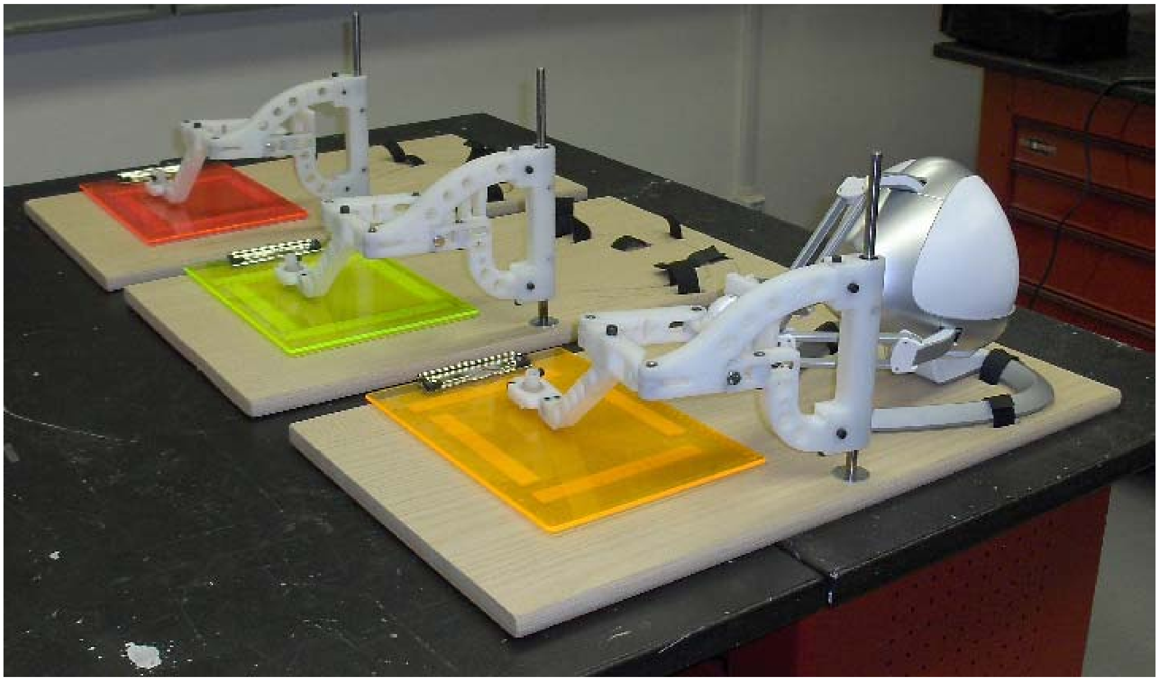


Figure 6.1: Showing three of the six linkages constructed for the July and August 2008 summer writing camp in Virginia.

The results from the summer writing camp provided the motivation for design phases B and C. As discussed in section four, the linkage was exhibiting unwanted amounts of deflection and the backlash in the joints became an obvious problem. It was determined that making the links out of aluminum would decrease the amount of deflection during operation and create a more effective product. The attachment of the writing device was established as a problem for the children because they could not grip the pen close to the tip. The attaching arm, link 6A, also got in the way for most right handed users. Figure 6.2 shows the writing attachment and the gripping problem generated from the design.

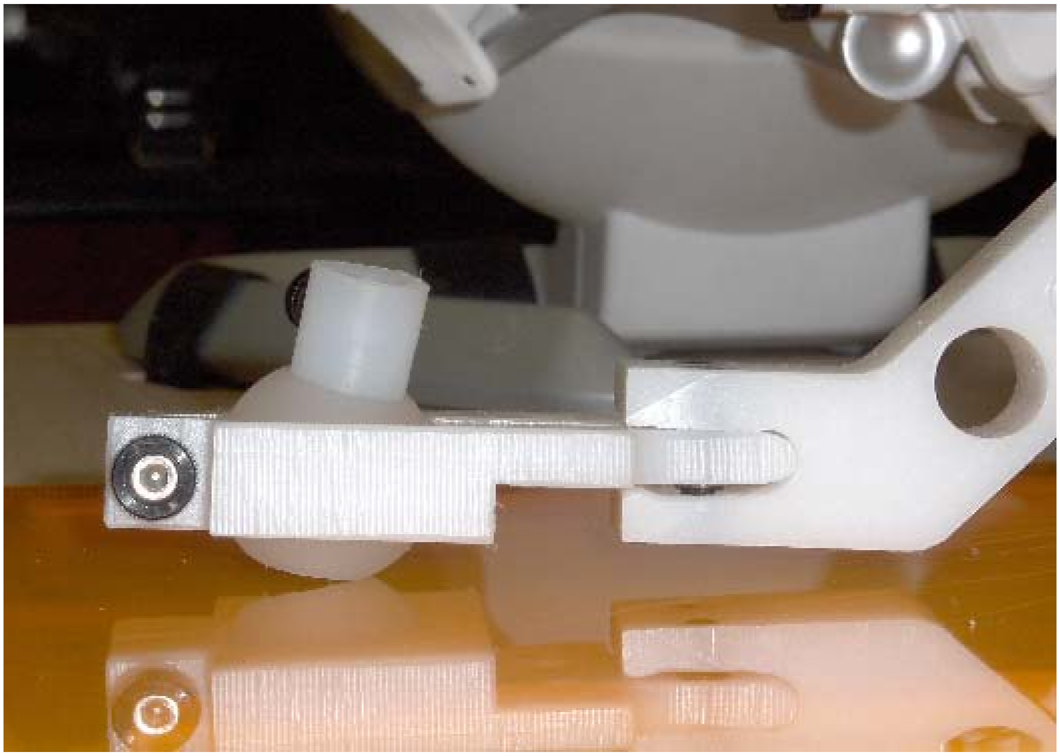


Figure 6.2: Showing the problems with linkage design A that became apparent after the first round of clinical testing in summer of 2008.

Development of the linkage progressed through two additional design phases before the deflection and gripping problems were eliminated. The final linkage design, phase C, is shown in Figure 4.14 as a SolidWorks assembly file. This linkage successfully improved on the design challenges encountered in the phase A design. The next round of clinical testing will provide important information regarding the success of design phase C. The constructed linkage for design phase C is shown in Figure 6.3.

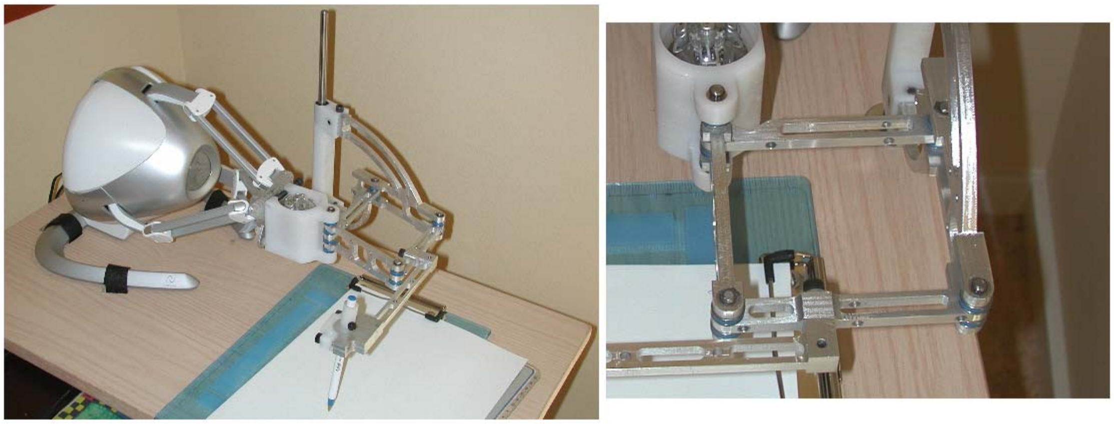


Figure 6.3: Showing the final assembly of the phase C linkage.

7. RESULTS

7.1 Current Linkage

The linkage shown in Figure 6.3 is the result of the final design phase. Future clinical tests may reveal problems with the current design that will need to be addressed with subsequent design phases. There are small problems with the haptic programming algorithms that will need to be analyzed in more depth by the next team of programmers in order to create a more robust programming package. All of the identified customer requirements were met and the company funding the project, Obslap Research LLC, is excited about the current design phase. The ability of the device to draw well formed letters is critical. Figure 7.1 shows several different letter sequences created by the MY SCRIVENER™ device.

Figure 7.1: Showing letters drawn by the Falcon programming and the final linkage design (phase C).

One of the most interesting problems with the letters generated by the final design occurs in line five of Figure 7.1, which spells the word “MOM”. The difference between the first M and the second M in “MOM” is significant. The second M looks much better than the first M. Although not as noticeable in the other lines, there is some slight misalignment in the first letter of each word. The first O in “OSU” appears more closed at the top than the O in “MOM” and “DOG”. The first T in “TEST” appears slightly misaligned when compared to the second T. The specific reason for this error was not completely investigated, but could be the result of a programming issue. A second reason for this error could be due to slight distortion of the letters in the far left portion of the writing workspace.

7.2 Satisfaction of Customer Requirements

The customer requirements listed in section 2.6 provided a rubric for evaluation of the final linkage design shown in Figure 6.3. Some of the customer requirements were difficult to quantify and were appropriately evaluated with the help of Obslap Research LLC. Each of the customer requirements from section 2.6 has a corresponding performance evaluation shown in Table 7.1.

Table 7.1: Showing the customer requirements and a performance evaluation corresponding to the phase C linkage design.

Customer Requirements	Design C Data	Performance Evaluation
Fits on medium size desk space	~16"x30"	Requirement Satisfied
Carried easily by a single person	~15 pounds	Requirement Satisfied
Force preservation	Yes-Not Numerically Tested	Requirement Satisfied
Easily fabricated in production environment	No Numeric Data	Assume Satisfied
Material cost must be less than Falcon cost	~$85	Requirement Satisfied
Left and right handed compatibility	Yes	Requirement Satisfied
Compatible with different gripping styles	Yes	Requirement Satisfied
Accomodating	Yes-User Tested	Requirement Satisfied
Resists breaking, spills, and dust	Yes-Spills Untested	Requirement Satisfied
Magnification ratio	~2	Requirement Satisfied
Low-friction and smooth movements	Yes-User Tested	Requirement Satisfied
Accepts BIC style pens	Yes	Requirement Satisfied
Accomodates various pen angles	~+45 to -45 in X or Y Plane	Requirement Satisfied
Secure Falcon attachment/easy removal	Yes-Falcon/Velcro Tested	Requirement Satisfied
Secure writing surface/easy paper exchange	Yes-Velcro/Clipboard Tested	Requirement Satisfied
Appealing	Yes-User Tested	Requirement Satisfied
Visual and Auditory Feedback	Yes-User Tested	Requirement Satisfied
Software is easy to use	Tested-Small Glitches	Requirement Satisfied

Numeric data was collected from the linkage shown in Figure 6.3 and recorded in Table 7.1. Several of the requirements that did not produce numeric results were evaluated through user interaction and feedback via Obslap Research LLC. The ability to easily produce the linkage in a production environment was assumed satisfied due to limitation of available testing resources. Aluminum die casting each of the links would be an efficient way for manufacturing the links in a production environment and would eliminate dimensional tolerance issues. At that point, the links could easily be shuffled through a series of operations for assembly. The entire unit was not tested for liquid spills. However, it can be assumed that the Falcon will be much more sensitive to spills because of its delicate electronics than the aluminum linkage.

An experiment could have been preformed to obtain numeric data that measured the forces translated from the Falcon to the writing utensil. This was not determined necessary because there were no obvious decreases in the forces transmitted. Small software glitches were rare occurrences and seem to be more noticeable among certain letters, as shown in Figure 7.1. The final dimensions of each link can be obtained from the layout drawings shown in Appendix F. The distance between linkage joints remained as shown in Figure 4.1.

A complete kinematic analysis of the linkage was performed using SolidWorks to verify that the linkage could access the entire 8” by 10” writing workspace. SolidWorks provided the capability to completely simulate the movements of the linkage to ensure the writing workspace was maximized. The results of this kinematic analysis, shown in Figure 7.2, confirm the linkage maximizes the writing workspace.

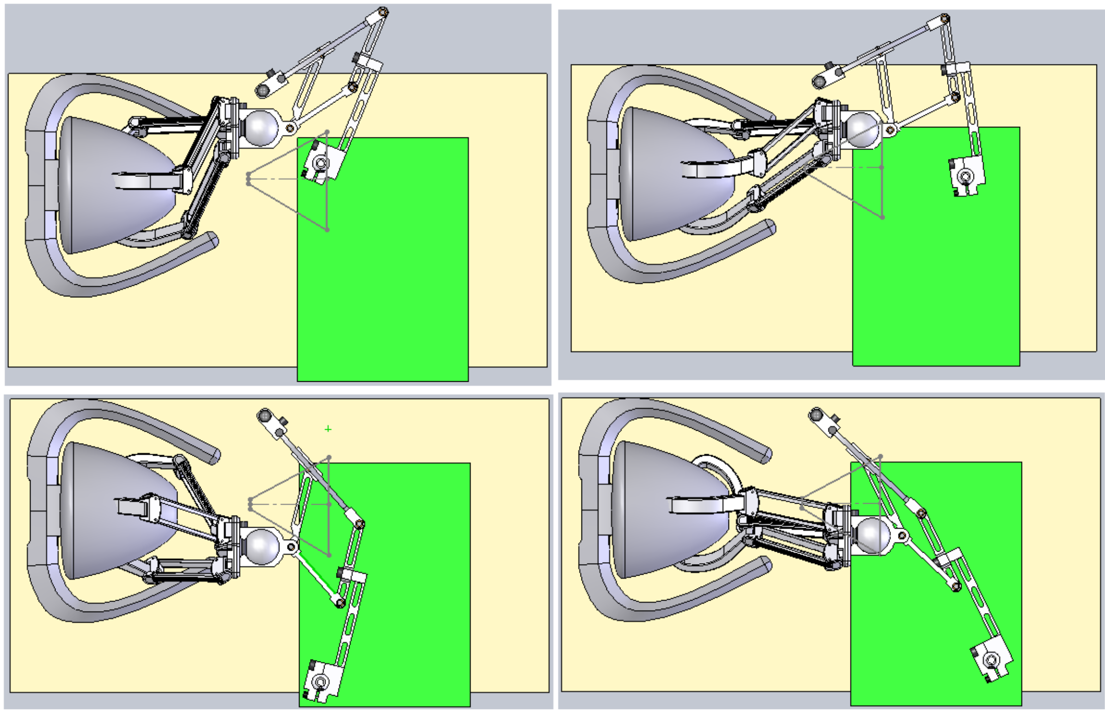


Figure 7.2: Showing the Falcon and linkage in each of the four corners of the writing workspace.

7.3 Haptic Letter Generating Software

Lunar Logic developed a complete graphical user interface (GUI) and software platform for generating haptic uppercase and lowercase letters of the alphabet and numbers from zero through nine. The user interface to the programming is easy to use and provides handwriting training for students. Handwriting testing exercises are available as well. Figure 7.3 shows the GUI developed by Lunar Logic to accompany the haptic letter algorithms.

Figure 7.3: Showing the GUI developed by Lunar Logic.

8. CONCLUSIONS

8.1 Future Work

The origin of the letter misalignment discussed in section 7.1 should be analyzed in more depth. The haptic programming should be carefully examined to ensure consistent letter generation is being achieved. Improving the reliability and efficiency of the programming is necessary for successful deployment of the product. Continual feedback from clinical trials is essential, as these often reveal unforeseen problems in the design. Future work may be required when results from the next round of assessments shed light on faults in the design. Ultimately, the design will be implemented in a production style manufacturing environment. Analysis of each step in the machining process is needed in order to determine the most effective method for creating the linkage from a mass production perspective. Alternatives to machining such as creating cast aluminum links should also be considered when integrating the design with large scale manufacturing operations.

8.2 Project Summary

The increasing population of people affected by fine motor skill disabilities provides an opportunity for the development of rehabilitation and learning assistive devices. The benefit of a cost effective, convenient and confidence building alternative to occupational therapy is needed. Realization of these alternatives is being driven by current advances in haptic technology and affordable access to haptic hardware. This project investigated several different types of haptic devices developed for a wide variety of applications and proposed a new solution using the Novint Falcon haptic device. Through multiple design iterations and data gathered based on user feedback, a successful product was generated called MY SCRIVENER™. The clinical trials conducted during the summer of 2008 provided the testing and evaluation necessary to develop the final two phases of the design. The changes made at each phase of the design are outlined in section four. Although future clinical trials may result in additional improvements to the design, the work presented in this paper has laid the foundation for continued success.

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APPENDICES

A. X3D CODE FOR "E"

The following X3D code was used to generate the colorful "E" shown in Figure 3.1.

```
<?xml version="1.0" encoding="UTF-8"?>
<Group>
  <Transform translation='-0.1 0 0'>
  <Shape>
    <Appearance>
      <Material diffuseColor="0 1 0"/>
    </Appearance>
   <Cylinder DEF="CYLINDER" radius = "0.01" height="0.4" />
  </Shape>
  </Transform>
  <Transform rotation='0 0 1 1.57' translation='0.068 0.2 0'>
  <Shape>
    <Appearance>
      <Material diffuseColor="1 0 0"/>
    </Appearance>
    <Cylinder DEF="CYLINDER" radius = "0.01" height="0.35" />
  </Shape>
  </Transform>
  <Transform rotation='0 0 1 1.57' translation='0.068 0 0'>
  <Shape>
     <Appearance>
      <Material diffuseColor="0 0 1"/>
     </Appearance>
    <Cylinder DEF="CYLINDER" radius = "0.01" height="0.35" />
  </Shape>
  </Transform>
  <Transform rotation='0 0 1 1.57' translation='0.068 -0.2 0'>
  <Shape>
     <Appearance>
      <Material diffuseColor="0.5 0.25 1"/>
     </Appearance>
    <Cylinder DEF="CYLINDER" radius = "0.01" height="0.35" />
  </Shape>
  </Transform>
</Group>
```

B. C++ CODE FOR SOFTWARE PROTOTYPE

The following code was written by SenseGraphics AB and used for development of the software prototype discussed in section 3.1.

```
//////////Scopes in SpringEffect.cpp////////////////////////////////////////////////////////
//    Copyright 2004-2007, SenseGraphics AB
//////////////////////////////////////////////////////////////////////////////////////////////
#include <H3D/SpringEffect.h>
#include <H3D/H3DHapticsDevice.h>

using namespace H3D;

// Add this node to the H3DNodeDatabase system.
H3DNodeDatabase SpringEffect::database(
                                       "SpringEffect",
                                       &(newInstance<SpringEffect>),
                                       typeid( SpringEffect ),
                                       &H3DForceEffect::database );

namespace SpringEffectInternals {
  FIELDDB_ELEMENT( SpringEffect, position, INPUT_OUTPUT );
  FIELDDB_ELEMENT( SpringEffect, force, INPUT_OUTPUT );
  FIELDDB_ELEMENT( SpringEffect, springConstant, INPUT_OUTPUT );
  FIELDDB_ELEMENT( SpringEffect, startDistance, INPUT_OUTPUT );
  FIELDDB_ELEMENT( SpringEffect, escapeDistance, INPUT_OUTPUT );
  FIELDDB_ELEMENT( SpringEffect, active, OUTPUT_ONLY );
  FIELDDB_ELEMENT( SpringEffect, deviceIndex, INPUT_OUTPUT );
}

/// Constructor
SpringEffect::SpringEffect( Inst< SFVec3f     > _position,
                            Inst< SFVec3f     > _force,
                            Inst< SFFloat     > _springConstant,
                            Inst< SFFloat     > _startDistance,
                            Inst< SFFloat     > _escapeDistance,
                            Inst< SFBool      > _active,
                            Inst< SFInt32     > _deviceIndex,
                            Inst< SFNode      >  _metadata ) :
  H3DForceEffect( _metadata ),
  position( _position ),
  force( _force ),
  springConstant( _springConstant ),
  startDistance( _startDistance ),
  escapeDistance( _escapeDistance ),
  active( _active ),
  deviceIndex( _deviceIndex ),
  haptic_spring( new HAPI::HapticSpring() ) {

  type_name = "SpringEffect";

  database.initFields( this );
```

```
  position->setValue( Vec3f( 0,0,0 ) );
  force->setValue( Vec3f( 0,0,0 ) );
  springConstant->setValue( 100 );
  startDistance->setValue( 0.01f );
  escapeDistance->setValue( 0.01f );
  active->setValue( false, id );
  deviceIndex->setValue( 0 );

}

// TODO: remove counter when Sensable fixes the bug with invalid positions
// at startup. HLAPI reports the wrong position for the first couple of loops
// which can cause the spring to be added even though it should not.
int counter = 0;

void SpringEffect::traverseSG( TraverseInfo &ti ) {
  if( counter < 5 ) {
    counter++;
  } else {
    if( ti.hapticsEnabled()  ) {
      int device_index = deviceIndex->getValue();
      H3DHapticsDevice *hd = ti.getHapticsDevice( device_index );
      // the tracker position in local coordinates.
      const Vec3f &pos =
        ti.getAccInverseMatrix() *
        hd->trackerPosition->getValue();
      const Vec3f &spring_pos = position->getValue();
      H3DFloat distance = ( pos - spring_pos ).length();
      if( active->getValue() ) {
        if( distance >= escapeDistance->getValue() ) {
          active->setValue( false, id );
          force->setValue( Vec3f( 0, 0, 0 ) );
        } else {
          haptic_spring->setPosition( ti.getAccForwardMatrix() * spring_pos );
          haptic_spring->setSpringConstant( springConstant->getValue() );
          ti.addForceEffect( device_index, haptic_spring.get() );
          Vec3f f = (Vec3f) haptic_spring->getLatestForce();
          force->setValue( f );
        }
      } else {
        if( distance <= startDistance->getValue() ) {
          active->setValue( true, id );
          haptic_spring->setPosition( ti.getAccForwardMatrix() * spring_pos );
          haptic_spring->setSpringConstant( springConstant->getValue() );
          ti.addForceEffect( device_index, haptic_spring.get() );
        }
      }
    }
  }
}
```

C. PYTHON CODE FOR SOFTWARE PROTOTYPE

The following code was written using the Python programming language and used for development of the software prototype discussed in section 3.1.

```
from H3D import*
from H3DInterface import *

class SpringForce( TypedField( SFVec3f, ( SFBool, SFVec3f )  ) ):
  def update( self, event ):
    routes_in = self.getRoutesIn()
    active = routes_in[0].getValue()
    position = routes_in[1].getValue()
    if (active):
        for i in range( -0.0005, -0.05, -0.0001 ):
            return position + Vec3f( -0.0015, i, -0.00009 )
    else:
            return position + Vec3f( -0.00145, -0.0005, 0.00141 )

springForce = SpringForce()

class SpringForce1( TypedField( SFVec3f, ( SFBool, SFVec3f )  ) ):
  def update( self, event ):
    routes_in = self.getRoutesIn()
    active = routes_in[0].getValue()
    position = routes_in[1].getValue()
    if (active):
        for i in range( 0.001, 0.05, 0.001 ):
            return position + Vec3f( 0.0007, i, -0.00061 )
    else:
            return position + Vec3f( 0.0007, 0.001, -0.00061 )

springForce1 = SpringForce1()
```

D. X3D FILE FOR SOFTWARE PROTOTYPE

The following X3D file was used to provide dynamic interaction between the C++ code and Python code used for development of the software prototype discussed in section 3.1.

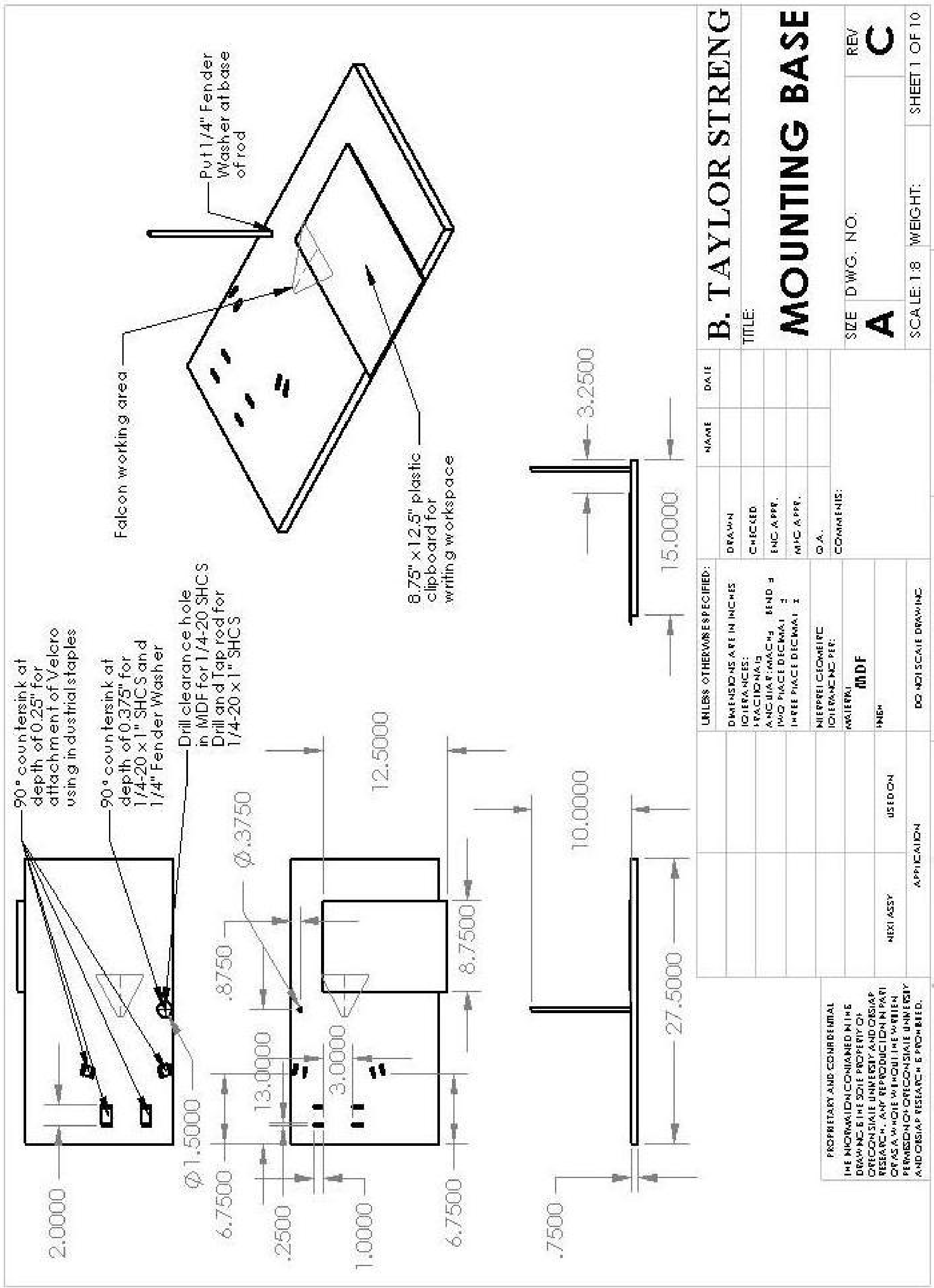
```
<Group>
  <Transform translation="-0.005 0 -0.15">
      <Shape>
    <Appearance>
      <Material diffuseColor="1 0 0" transparency="0.5"/>
    </Appearance>
    <Sphere DEF="SPHERE" radius="0.02"/>
      </Shape>
  </Transform>
  <ForceField force="0 0 0"/>
  <SpringEffect DEF="SPRING" position="-0.005 0 -0.15" startDistance="0.04" escapeDistance="0.00005" springConstant="300"/>
  <SpringEffect DEF="SPRING1" position="-0.15 -0.05 -0.009" startDistance="0.04" escapeDistance="0.00005" springConstant="300"/>
  <PythonScript DEF="PS" url="springeffect3.py" />

  <ROUTE fromNode="SPRING" fromField="active" toNode="PS" toField="springForce"/>
  <ROUTE fromNode="SPRING" fromField="position" toNode="PS" toField="springForce"/>
  <ROUTE fromNode="PS" fromField="springForce" toNode="SPRING" toField="position"/>

  <ROUTE fromNode="SPRING1" fromField="active" toNode="PS" toField="springForce1"/>
  <ROUTE fromNode="SPRING1" fromField="position" toNode="PS" toField="springForce1"/>
  <ROUTE fromNode="PS" fromField="springForce1" toNode="SPRING1" toField="position"/>
</Group>
```

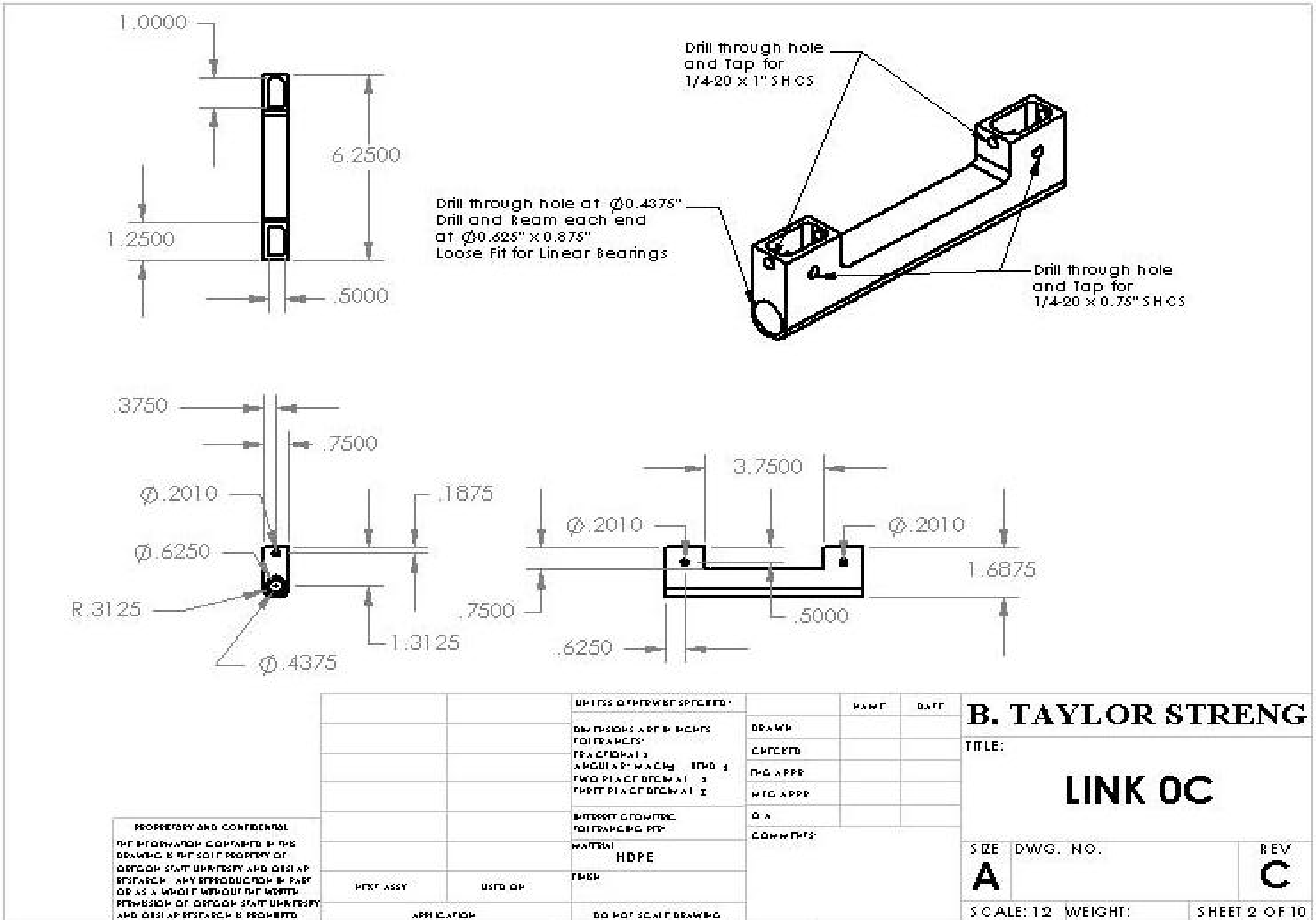
E. LIST OF MATERIALS

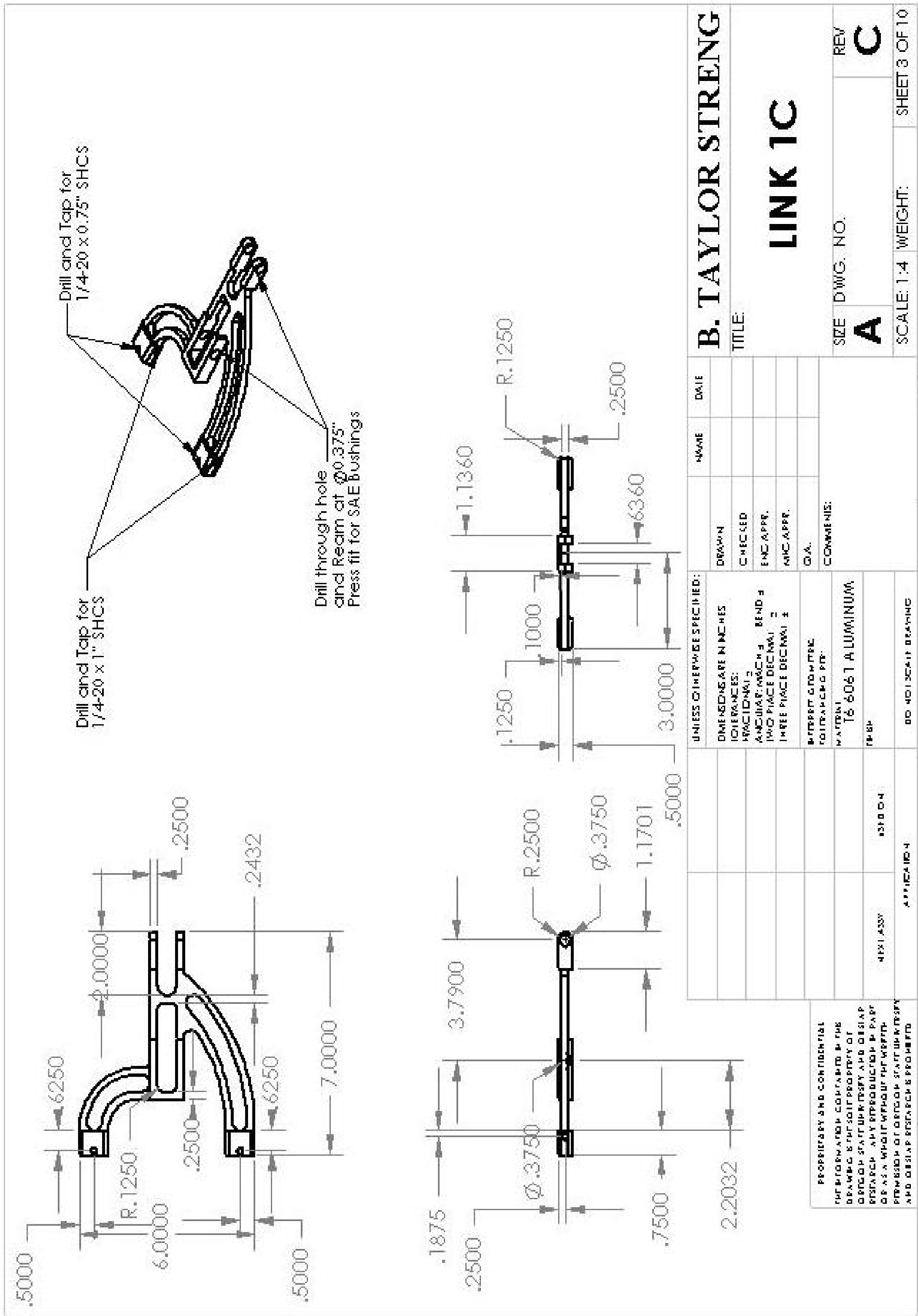
This table shows a list of the materials needed in order to construct one MY SCRIVENER™ linkage.

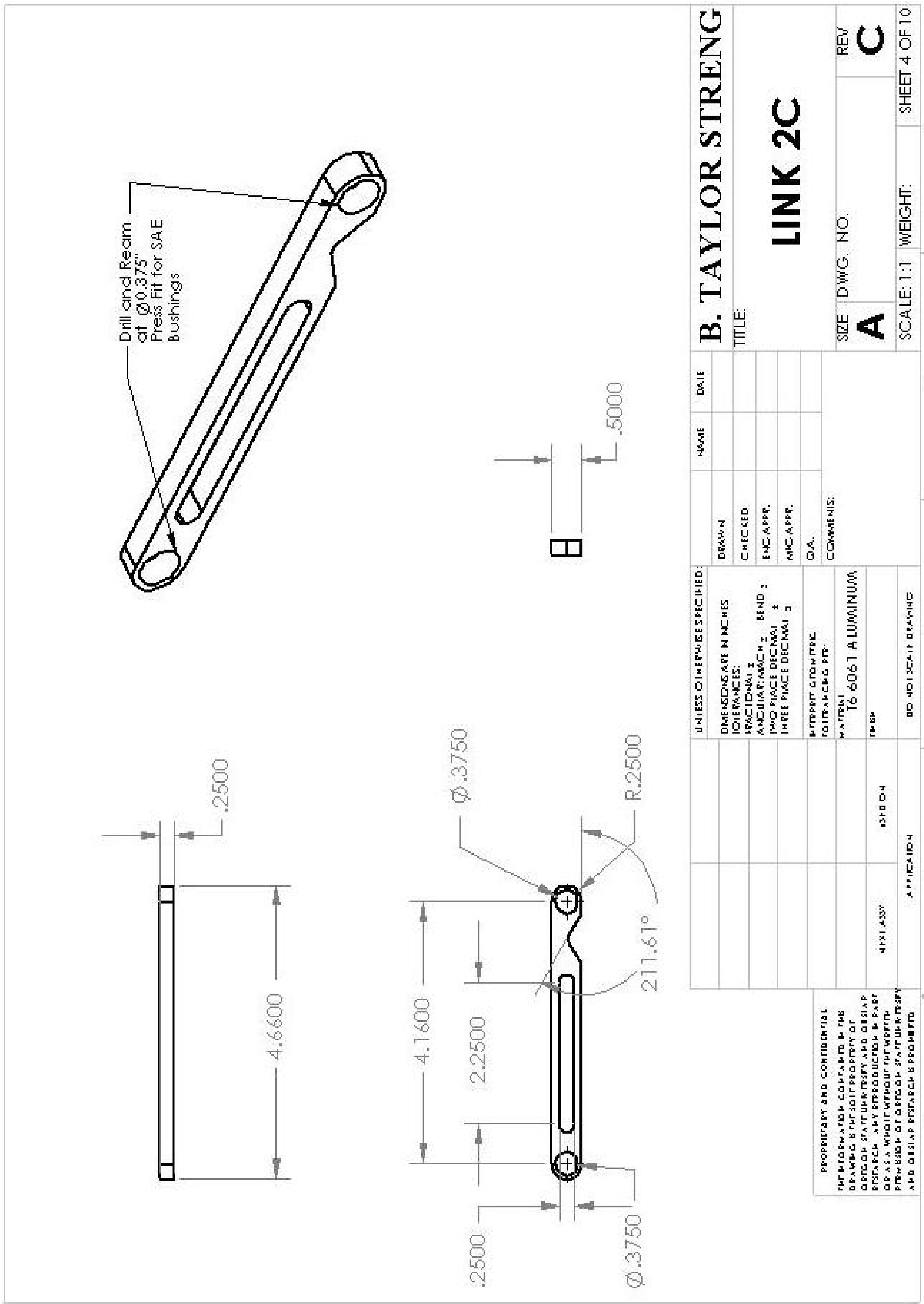
MATERIAL DESCRIPTION	DIMENSIONS	QUANTITY
T6 6061 Aluminum (For Making Links)	7" x 12" x 0.5"	1
T6 6061 Aluminum (For Fixturing Plate)	7" x 12" x 0.5"	1
SAE 841 Bronze Oil Impregnated Sleeve Bushing	0.375" OD x 0.25" ID	14
A2 Tool Steel Tight Tolerance Rod	0.25" OD x 6" Long	1
A2 Tool Steel Tight Tolerance Rod	0.375" OD x 10" Long	1
Carbon Steel Ball Thrust Bearing	0.5625" OD x 0.25" ID	10
Self Aligning Closed End Linear Ball Bearing	0.625" OD x 0.375" ID x 0.875" Long	2
Steel External Retaining Rings	0.25" ID	8
White Delrin Spherical Ball	1" Diameter	1
All Purpose Nylon Hook and Loop Velcro with Plain Back	2 Feet Long x 1" Width	1
All Purpose Nylon Hook and Loop Velcro with Sticky Back	3 Feet Long x 1" Width	1
Plastic Head Thumb Screw with Socket Drive	#6-32 x 0.90625" Long	1
Ultra High Molecular Weight Polyethylene rod	0.5" OD x 2" Long	1
High Density Polyethylene (For Plastic Links)	4" x 12" x 0.75"	1
High Density Polyethylene (For Falcon Link)	3" x 2.5" x 2"	1
Plastic Head Thumb Screw	#4-40 x 0.25" Long	1
BIC Style Pen With Hard Plastic Casing	Standard	1
Zinc Plated Fender Washers	1.25" ID x 0.25" ID	2
Socket Head Cap Screws	1/4-20 x 0.75" Long	4
Socket Head Cap Screws	1/4-20 x 1" Long	3
Socket Head Cap Screws	1/4-20 x 1.25" Long	1
Compression Spring	Wire Size=0.041" Wire Type=228 Free Length=3.25" OD=0.6035" ID=0.5215" Coils=25.52 Active Coils=23.52 Max Load=2 lbs. Rated=1 lb./in.	1
Medium Density Fiberboard (MDF)	15" x 27" x 0.75"	1
Standard Plastic Writing Clipboard	8.75" x 12.5"	1

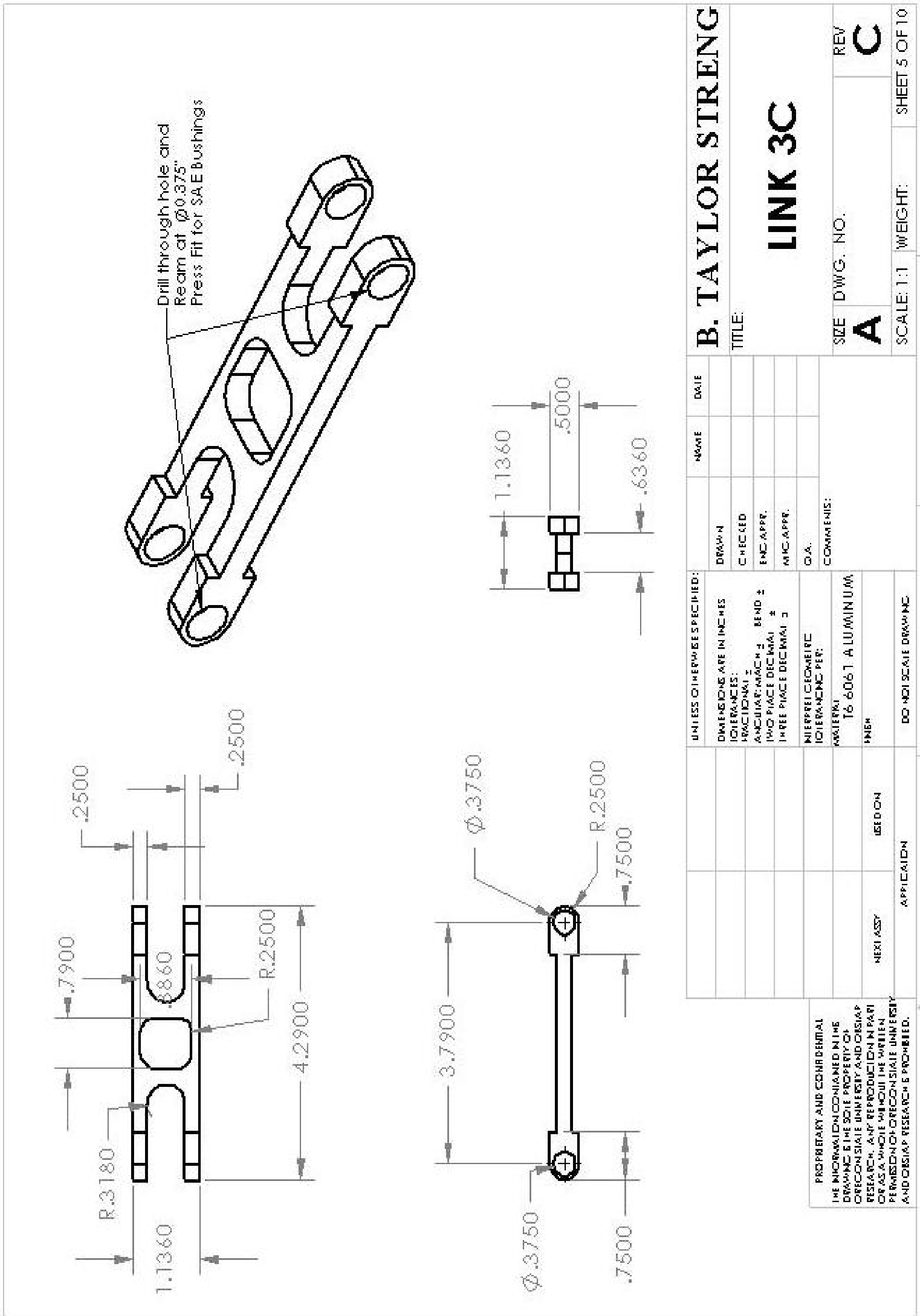
F. PHASE C LAYOUT DRAWINGS

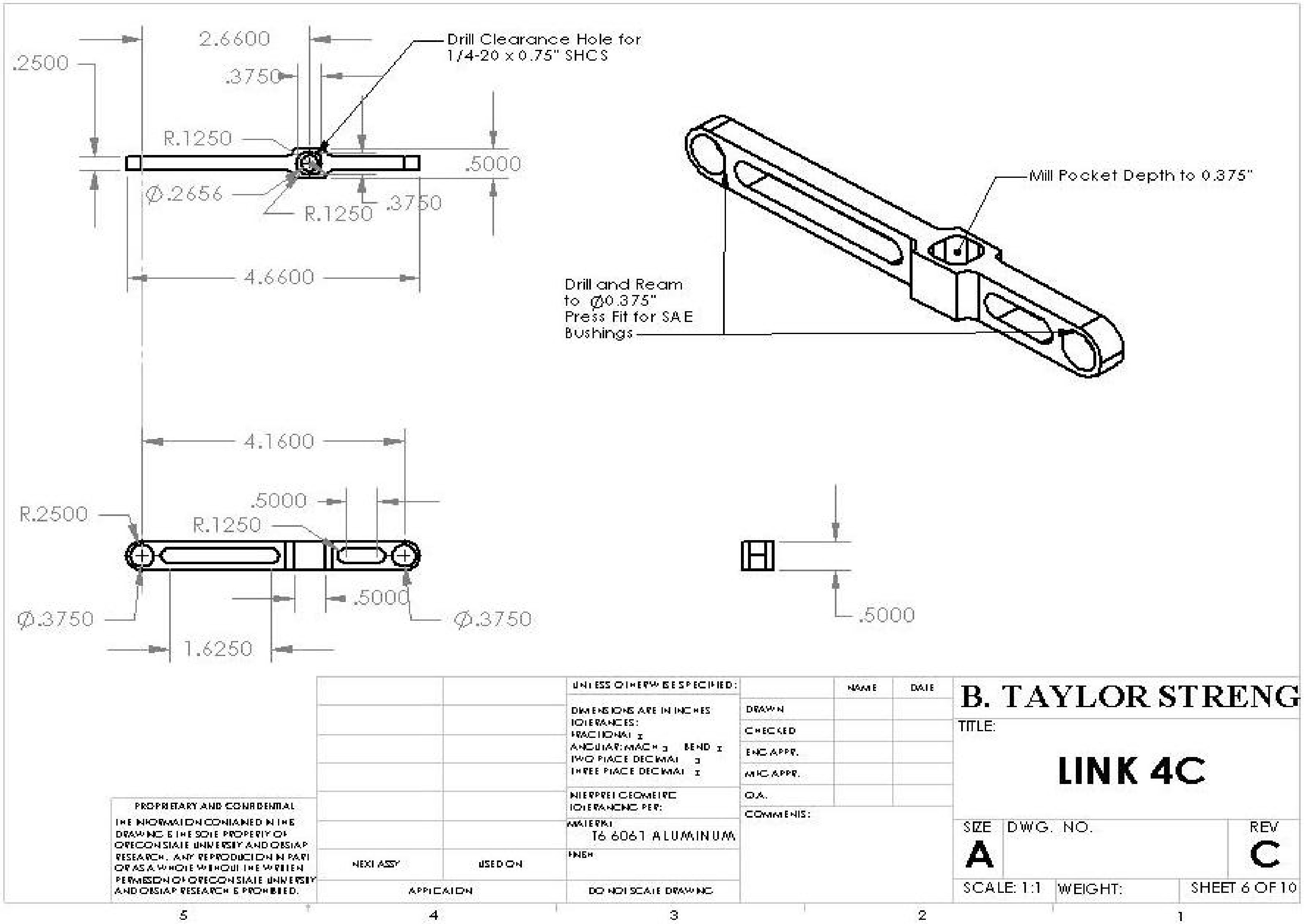


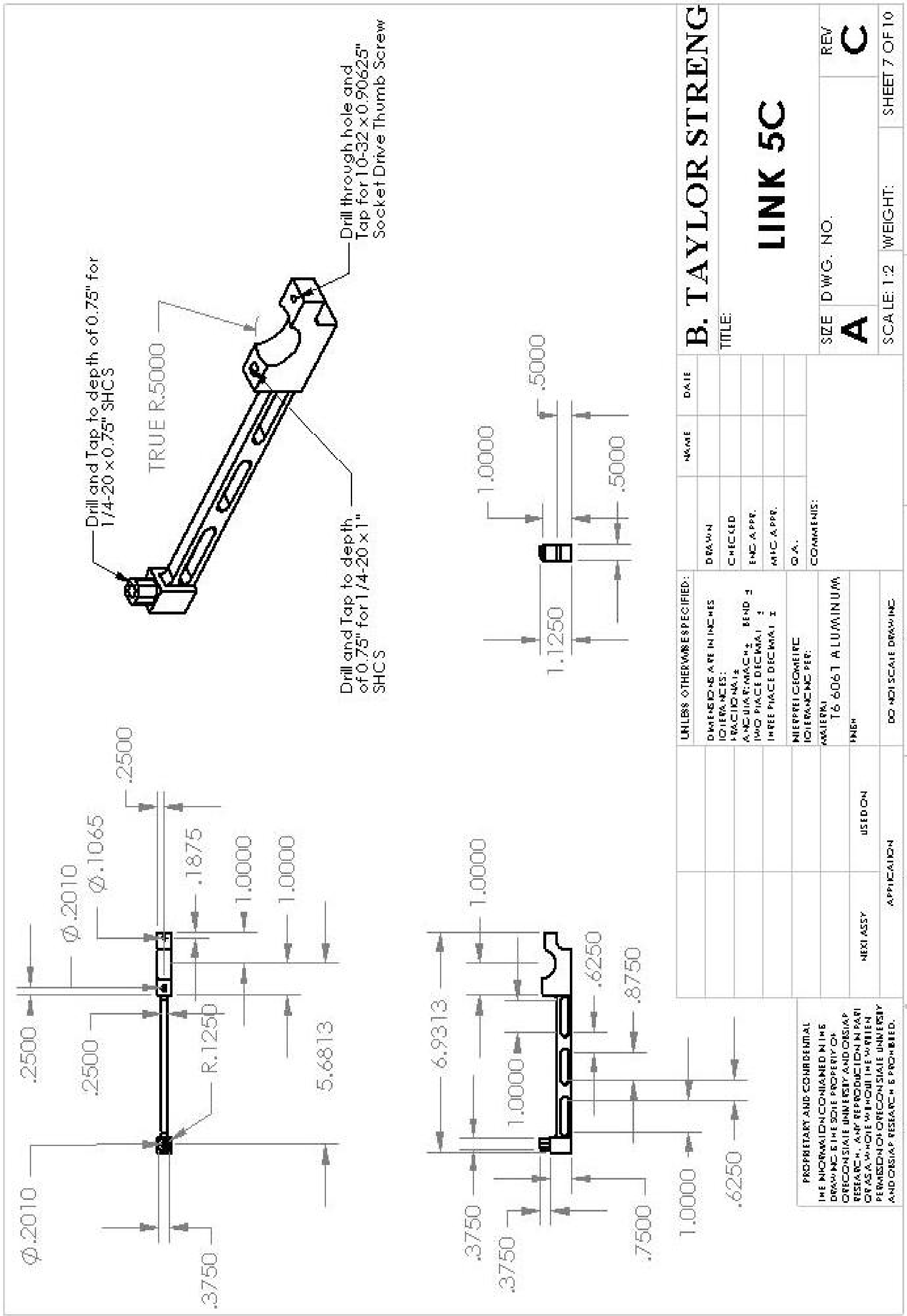

1.0000
6.2500
1.2500
.5000
Drill through hole at Ø0.4375"
Drill and Ream each end
at Ø0.625" x 0.875"
Loose Fit for Linear Bearings
Drill through hole
and Tap for
1/4-20 x 1" SHCS
Drill through hole
and Tap for
1/4-20 x 0.75" SHCS
.3750
.7500
Ø.2010
Ø.6250
R.3125
Ø.4375
.1875
1.3125
3.7500
Ø.2010
Ø.2010
1.6875
.7500
.5000
.6250
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
MATERIAL
HDPE
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
B. TAYLOR STRENG
TITLE:
LINK 0C
SIZE
A
DWG. NO.
REV
C
SCALE: 1:2
WEIGHT:
SHEET 2 OF 10

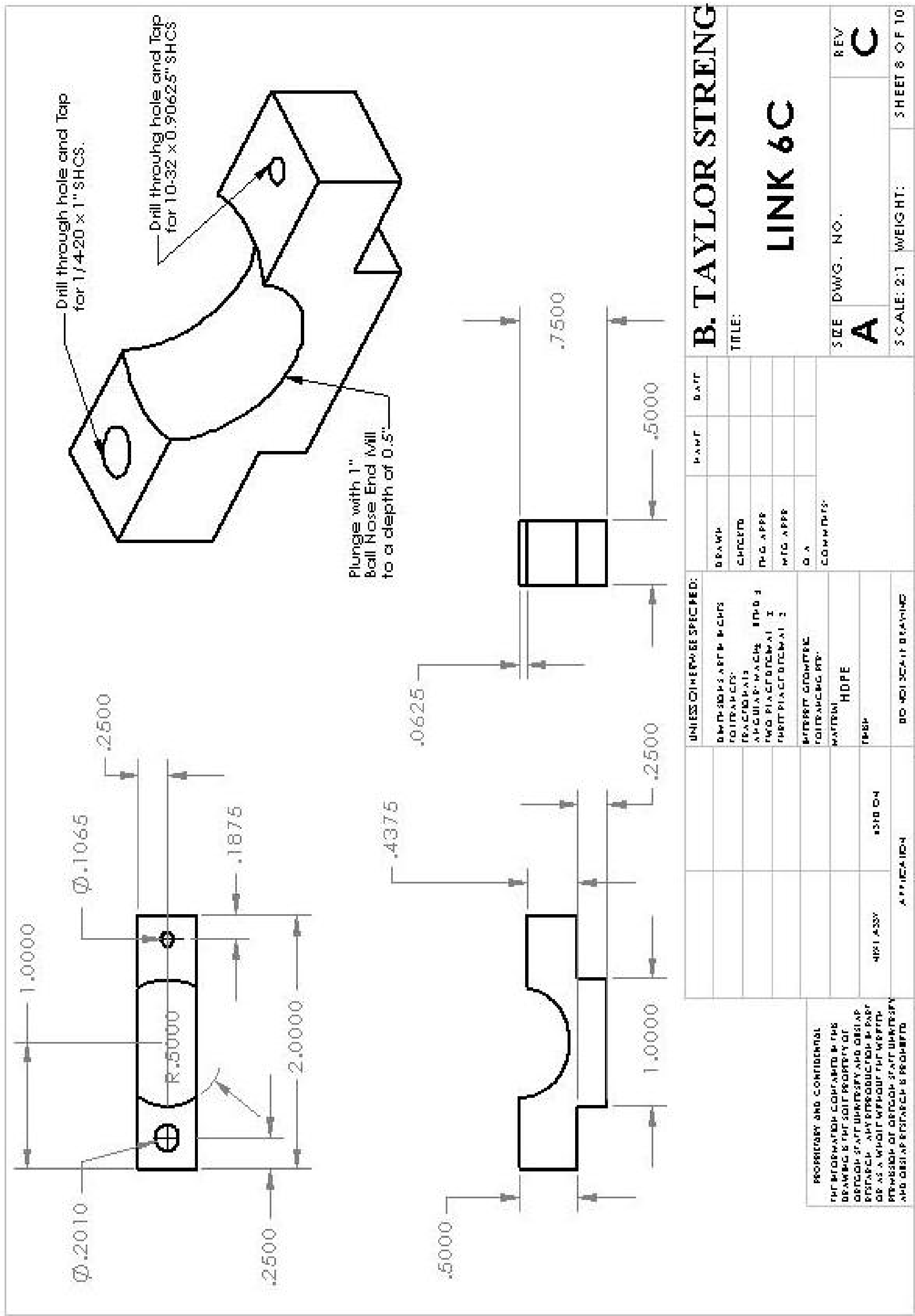

B. TAYLOR STRENG
TITLE:
LINK 1C
SIZE A
DWG. NO.
REV C
SCALE: 1:4
WEIGHT:
SHEET 3 OF 10
Drill and Tap for 1/4-20 x 0.75" SHCS
Drill and Tap for 1/4-20 x 1" SHCS
Drill through hole and Ream at Ø0.375" Press fit for SAE Bushings
UNLESS OTHERWISE SPECIFIED:
MATERIAL
T6 6061 ALUMINUM
FINISH
DO NOT SCALE DRAWING
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
.5000
6.0000
R.1250
.2500
.6250
2.0000
.2500
.2432
7.0000
3.7900
R.2500
Ø.3750
1.1701
.5000
.1875
.2500
.7500
2.2032
.1250
3.0000
.1000
.6360
1.1360
.2500
R.1250

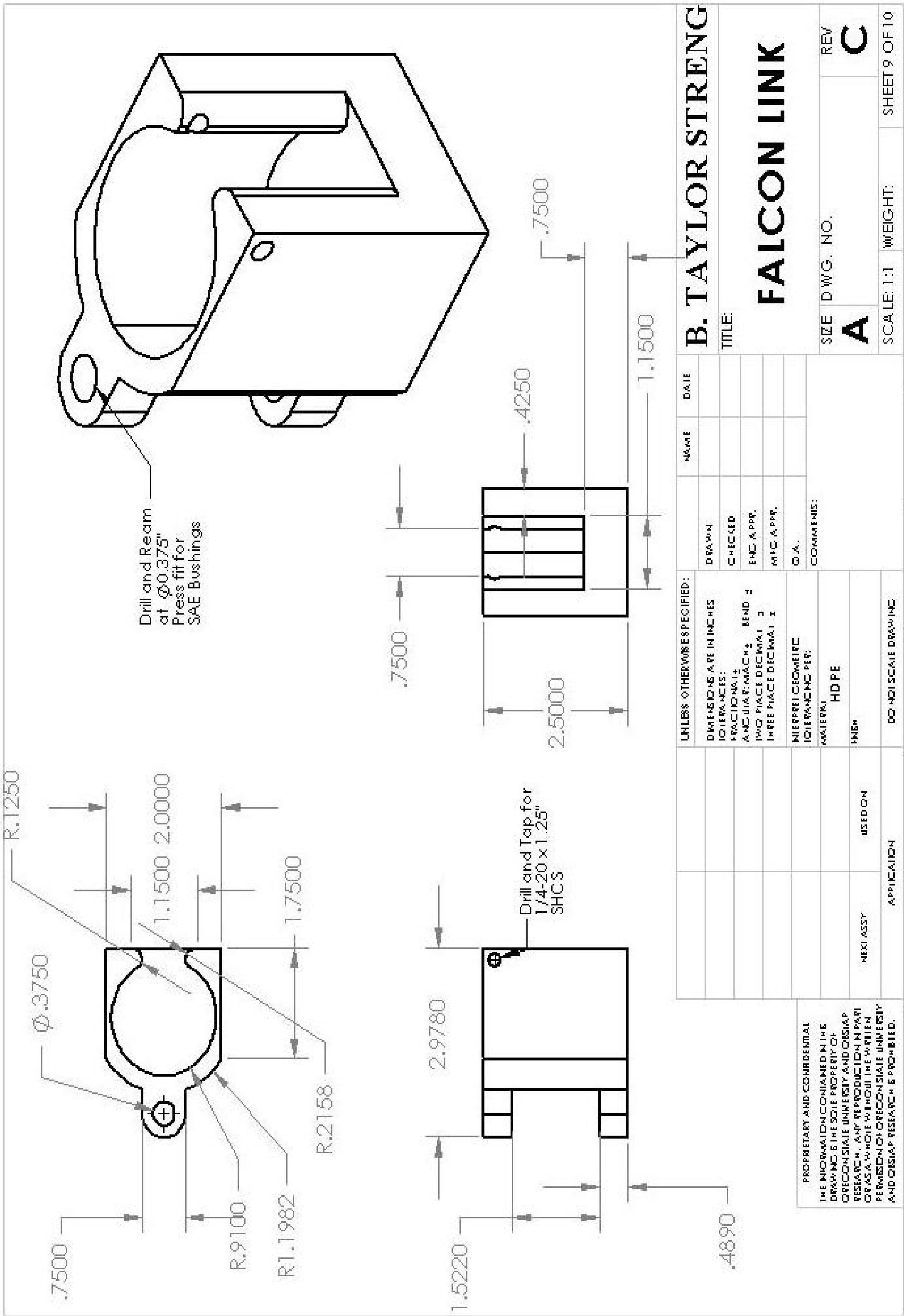

Drill and Ream at Ø0.375" Press Fit for SAE Bushings
.2500
4.6600
Ø.3750
R.2500
4.1600
2.2500
211.61°
.2500
Ø.3750
.5000
B. TAYLOR STRENG
TITLE:
LINK 2C
T6 6061 ALUMINUM
SIZE
A
DWG. NO.
REV
C
SCALE: 1:1
WEIGHT:
SHEET 4 OF 10


Drill through hole and
Ream at Ø0.375"
Press Fit for SAE Bushings
.2500
.2500
.7900
.3860
R.2500
R.3180
4.2900
1.1360
Ø.3750
R.2500
.7500
3.7900
Ø.3750
.7500
1.1360
.5000
.6360
B. TAYLOR STRENG
TITLE:
LINK 3C
SIZE
A
DWG. NO.
REV
C
SCALE: 1:1
WEIGHT:
SHEET 5 OF 10
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
T6 6061 ALUMINUM
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL

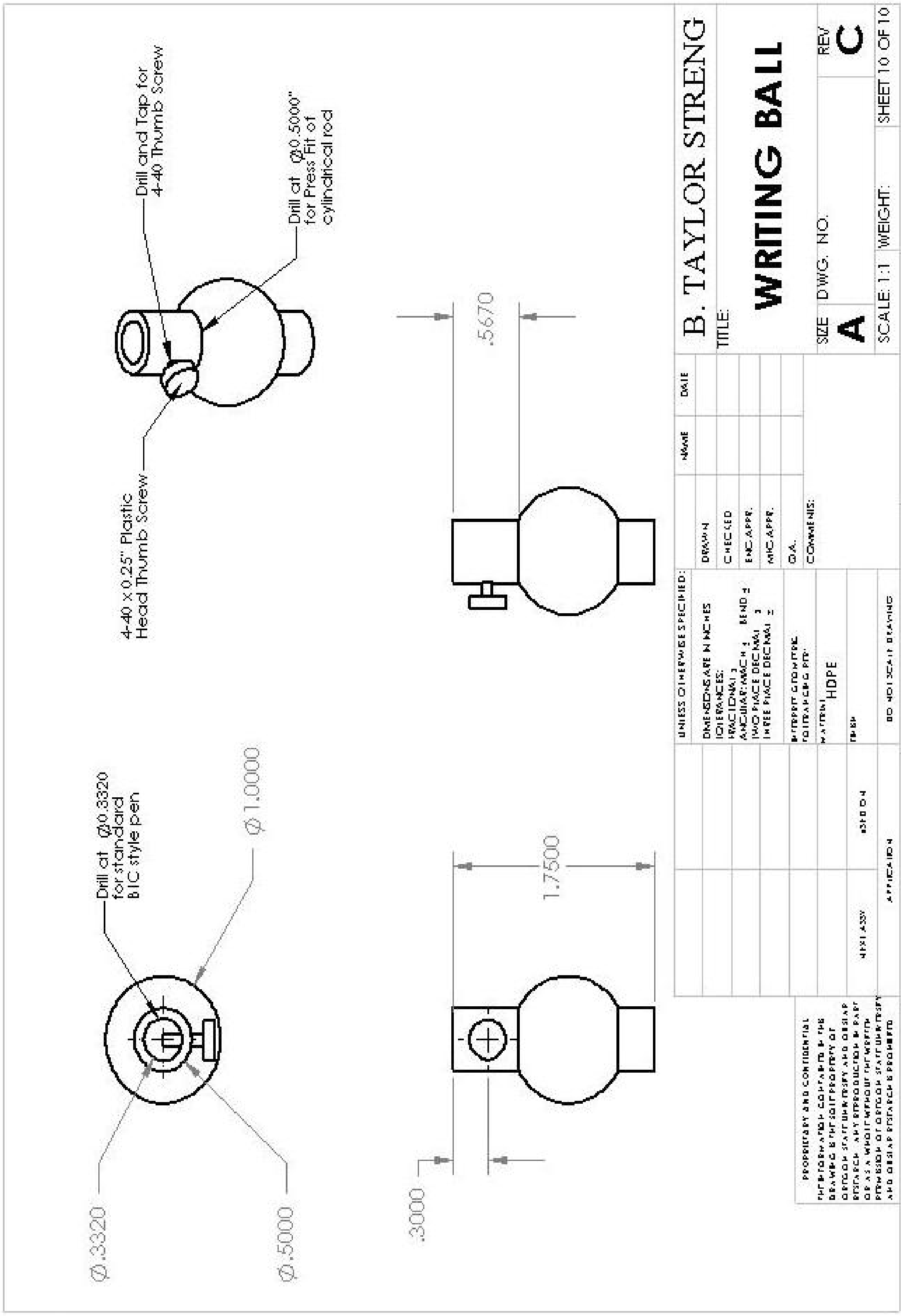

2.6600
.2500
.3750
R.1250
Ø.2656
R.1250
.3750
.5000
4.6600
Drill Clearance Hole for 1/4-20 x 0.75" SHCS
Mill Pocket Depth to 0.375"
Drill and Ream to Ø0.375" Press Fit for SAE Bushings
4.1600
R.2500
.5000
R.1250
Ø.3750
.5000
Ø.3750
1.6250
.5000
PROPRIETARY AND CONFIDENTIAL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
T6 6061 ALUMINUM
FINISH
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
B. TAYLOR STRENG
TITLE:
LINK 4C
SIZE
A
DWG. NO.
REV
C
SCALE: 1:1
WEIGHT:
SHEET 6 OF 10
5
4
3
2
1


B. TAYLOR STRENG
TITLE:
LINK 5C
SIZE A
DWG. NO.
REV C
SCALE: 1:2
WEIGHT:
SHEET 7 OF 10
T6 6061 ALUMINUM
Drill and Tap to depth of 0.75" for 1/4-20 x 0.75" SHCS
TRUE R.5000
Drill through hole and Tap for 10-32 x 0.90625" Socket Drive Thumb Screw
Drill and Tap to depth of 0.75" for 1/4-20 x 1" SHCS
Drill and Tap to depth of 0.75" for 1/4-20 x 1" SHCS
Ø.2010
Ø.1065
R.1250
5.6813
6.9313


1.0000
Ø.2010
Ø.1065
.2500
R.5000
.1875
.2500
2.0000
Drill through hole and Tap for 1/4-20 x 1" SHCS.
Drill throuhg hole and Tap for 10-32 x 0.90625" SHCS
Plunge with 1" Ball Nose End Mill to a depth of 0.5"
.4375
.0625
.5000
.7500
1.0000
.2500
.5000
UNLESS OTHERWISE SPECIFIED:
HDPE
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
B. TAYLOR STRENG
TITLE:
LINK 6C
SIZE
A
DWG. NO.
REV
C
SCALE: 2:1
WEIGHT:
SHEET 8 OF 10
5
4
3
2
1



B. TAYLOR STRENG
TITLE:
FALCON LINK
SIZE
A
DWG. NO.
REV
C
SCALE: 1:1
WEIGHT:
SHEET 9 OF 10
Drill and Ream at Ø0.375" Press fit for SAE Bushings
Drill and Tap for 1/4-20 x 1.25" SHCS
Ø.3750
R.1250
1.1500
2.0000
1.7500
R.2158
R1.1982
R.9100
.7500
2.9780
1.5220
.4890
.7500
2.5000
.4250
1.1500
.7500
UNLESS OTHERWISE SPECIFIED:
HDPE
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL


Drill and Tap for 4-40 Thumb Screw
Drill at Ø0.5000" for Press Fit of cylindrical rod
4-40 x 0.25" Plastic Head Thumb Screw
.5670
Drill at Ø0.3320 for standard BIC style pen
Ø1.0000
1.7500
Ø.3320
Ø.5000
.3000
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
HDPE
DO NOT SCALE DRAWING
B. TAYLOR STRENG
TITLE:
WRITING BALL
SIZE
A
DWG. NO.
REV
C
SCALE: 1:1
WEIGHT:
SHEET 10 OF 10
PROPRIETARY AND CONFIDENTIAL