DEVELOPMENT OF MECHANICAL SYSTEMS FOR AUTOMATED MEDICAL SLIDE SPECIMEN STORAGE AND RETRIEVAL

By

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ABSTRACT

Applying automation to any system or process has the capability of improving reliability and efficiency, and reducing cost and amount of human time/labor necessary. The concept of automation applied to the medical field is especially promising and intriguing considering that improving medical systems can save the lives of patients. The Intelligent System and Automation Laboratory at the University of Kansas has created a prototype machine with the goal of making the process of medical slide specimen storage and retrieval fully automated in order to make clinical laboratories and other similar laboratories better at processing specimens and diagnosing patients.

In order to achieve this goal, the machine required three subassembly systems to be designed and integrated together. The specimen storage and retrieval is based on medical slides being stored from and retrieved into 20 slot slide folders. The first subsystem, known as the Folder Movement System, was designed to move these slide folders into position for the second system, known as the Folder Opening/Holding System, to take over and open the slide folders. The third system, known as the Slide Movement System, is then free to manipulate the slides into or out of the folders. A storage and slide inventory system was also developed.

Each system was tested and proven to be effective and reliable individually. While the individual subsystems have been proven to be reliable, the integration of these systems is not reliable enough to achieve a fully automated storage and retrieval process. While this prototype has shown success further development is necessary to reach the ultimate goal of full automation. This prototype machine provides an excellent platform for future progress towards making automation a standard in the medical field.

ACKNOWLEDGEMENT

I would like to first thank my graduate advisor, Dr. Terry Faddis. Without his guidance and support this project would not have been possible. I would also like to thank Gavin Strunk for his help and guidance throughout the whole project. He was the other half of the project team with me and without him this project never would have been completed. I would also like to thank my other two committee members Dr. Carl W. Luchies and Dr. Bedru Yimer for their time, consideration and effort in this thesis defense process.

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1. INTRODUCTION

1.1 MOTIVATION

With the development of new technology and processes comes the ability to develop newer, more efficient systems and methods of carrying out tasks. The rapid development in robotics and similar technology related to automated processes opens up the possibility of automation to be applied to many different types of fields. It is only natural that automation and robotics would have endless possibilities for application in the medical field [1]. Human tellers were replaced by automated machines at banks and automated switch boards replaced human telephone operators, so why not carry this idea into a medical environment [2]. Human beings are flawed instruments. They get tired and they make mistakes. Robots however "are steady untiring instruments." They are capable of "doing tasks over and over again with precision without error" [3]. The main benefits of using automation for medical application "are not only the reduction in cost to producing an end product but the improvements in quality of the medical process and increased safety to patients" [2,3].

In the medical field, it is very often necessary to archive and retrieve specimens of a patient's cells or tissues in order to diagnosis and treat a patient. A single hospital may generate up to a million specimens in a given year. After specimens have been prepared many of them are shipped off to clinical laboratories (pathology, immunology, etc.) for processing, analysis and storage. Therefore these laboratories are typically handling a very large number of specimens that must be moved back and forth between large storage areas. Even a medium sized lab handles ~2500 specimens a day, whereas the large labs will deal with a lot more than that [2]. As of 2008, clinical laboratories generated up to 70% of medically relevant data used in the management of patients and yet are plagued by large numbers of medical specimens that need to be processed in a timely fashion [4,5]. Presently many of these labs utilize a primitive method of storage and retrieval in which everything is done manually by an employee [6]. The storage procedure calls for the employee to manually place each specimen on a tray, to stack the trays while specimens are processing, to categorize specimens after processing, to move the categorized specimens to a second location for long-term storage, and to prepare a record of where the specimen is stored. Other storage methods even require an additional step of positioning the specimen in a certain orientation so that it can be processed and then returned to a tray. The retrieval procedure is perhaps even more tedious and time consuming. An employee must look up the location in which a specimen is stored in the relevant records, go to the location, search manually to match the physical location with the recorded location, pull out specimen, and record the specimen as “checked out” or “removed” [6] .

Another issue is finding space for storage. Clinical labs only have a certain amount of space available to house their storage units based on workplace regulations so, frequently, lab specimens must be thrown out to make room for new specimens coming in or additional space must be built.

There are many flaws with this current system. It is labor intensive, tedious, time-consuming, inefficient, and error-prone [6]. Often the full attention of a lab technician is required and finding specimens is difficult during the procedure as there is frequently no intermediate record of where the specimen is between being stored and retrieved. There is also an inherent danger to the technician since they must sometimes handle dangerous and infectious specimens [6]. These flaws can lead to serious concerns. Loss, damage or mismanagement of specimens could have grave consequences to patient care, criminal prosecutions, and research objectives. This could lead to liability issues like malpractice or privacy violations. Potentially the worst consequence is that the “time-consuming steps delay the diagnosis or treatment of a patient” [4].

1.2 BACKGROUND ON EXISTING APPLICATIONS OF RELATED MEDICAL AUTOMATION

Automation in clinical laboratories got its start in the early 1980’s when robotic technology had advanced enough to be viable for specimen handling [2,4]. Since then many different versions of clinical automation have been developed. Generally speaking most of them address the pre-analytical phase (preparing the specimen for analysis) because it is the most labor intensive aspect of the clinical lab and therefore has the potential for yielding the greatest investment return [4]. Recently though, there has been a push to develop the storage and retrieval phase of clinical automation. Combining automation in this phase with automation in the other phases, to achieve a fully automated clinical lab process, is the end game.

There are already several examples of designs for automated specimen storage that have been very successful. Since December2003, the ARUP Laboratory at the University of Utah has been using a fully automated storage system that they call AS/RS. Utilizing a two robot setup, specimens are removed from the refrigerated storage area via a conveyor system and then individual specimens are placed into racks based on the request of the operator. From the previous manual method that ARUP used to use, the AS/RS has increased the total capacity of the lab from 400,000 specimens to 2.3 million. This storage system has also significantly increased productivity and efficiency. The overall retrieval time for a 30 tube rack is 2.5 minutes and the system is capable of handling 4000 specimens an hour [6,7].

The company Beckman Coulter sells a much smaller but commercially available storage system. Similar to the AS/RS, Beckman’s Coulter Specimen Stockyard system stores specimens in carriers and then individual specimens are moved into retrievable racks based on the operator's request [8,9]. Since 2007, this Specimen Stockyard has been in use at the Singapore General Hospital [10]. In the case of these examples, the term "specimen" refers to a medical sample stored within a test tube. So the technology developed by these companies can only apply to specimens contained in test tubes. These test tubes and their corresponding storage racks are much easier for manipulation than other forms of specimen containers.

1.3 SLIDE VALET OVERVIEW

The Slide Valet is a prototype that was designed and built by the Intelligent Systems and Automation Laboratory at the University of Kansas. This prototype serves as a proof of concept for a fully automated machine capable of storing and retrieving from storage, mass quantities of medical specimens. In regards to this project, a "specimen" refers to a medical slide that has been prepared using a fixing agent to secure a medical specimen to the slide itself. As this machine is only a prototype, preliminary design guidelines were set on a smaller scale that could later be applied on a larger scale. Certain hospitals can generate up to a million specimens each year. This prototype machine has a maximum storage capacity of 58 slides.

As stated previously, the Slide Valet has two functions: storage and retrieval. As a part of the automated storage process slide folders containing slides are manually put into the machine then the control program is opened and the machine is started. For the retrieval process, the doctor is able to open up the control program, choose the slides he wishes to retrieve and then tell the machine to run. The automated process is based around the slides being held in slide folders. It is also based on an inventory system which tracks the location of each individual slide. For the storage procedure, the medical slides are removed from the slide folder, scanned into the inventory and then moved into the storage area. The retrieval procedure is essentially the opposite of this as slides are removed from storage, scanned out of the inventory and placed into the proper slide folder.

These procedures require several smaller steps to achieve. For this reason the Slide Valet is subdivided into 3 major subassemblies: the Slide Movement System, the Folder Movement System and the Folder Opening/Holding System. Figure 1.3.1 shows a top view schematic of the Slide Valet including these subassemblies. The Slide Movement System is required for the purpose of removing the slides from the slide folders, scanning them into the inventory and then finally moving them into storage. It also serves the purpose of moving slides from storage,

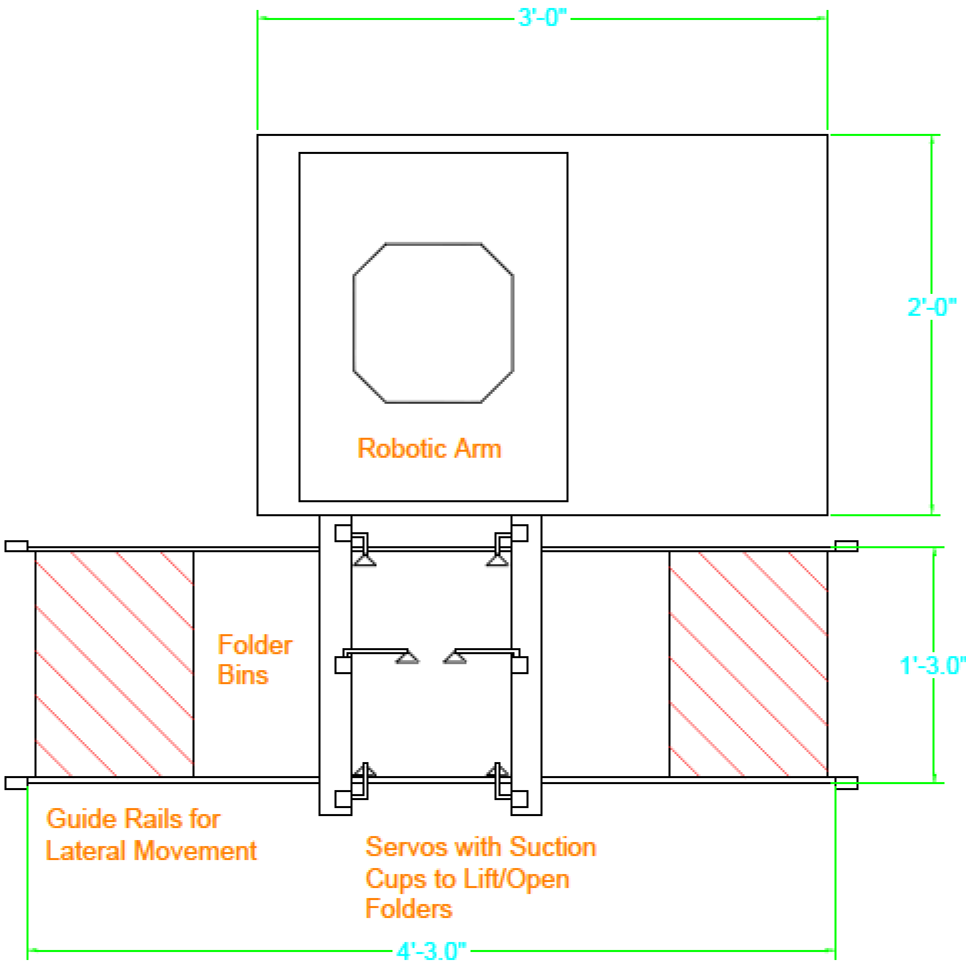


Figure 1.3.1: Slide Valet Top View

scanning them out of the inventory and moving them back into a slide folder. The Folder Movement System is used to move the active folder around based on its status: holding slides to be stored, empty, or holding slides that were just retrieved. The Folder Opening and Holding System serves the purpose of opening the slide folders so that slides can be added or removed. It also works in conjunction with the Folder Movement system to hold the active folder and help move it to the appropriate position based on its status.

For good reason, automation has become very desirable for different medical applications. It offers major advantages in accuracy, speed, convenience, and cost. Improvements in the overall process throughout a clinical lab can have a very significant impact. This is especially true for clinical labs and hospitals considering that "consistency, ease of use, and time to diagnosis can mean the difference between the life and death of a patient" [11].

Although for this specific project the application is for the storage and retrieval of medical slide specimens, the system and methods used can be applied to the storage and retrieval of any other types of specimens. These other specimens include but not are not limited to geological specimens, biological specimens, criminal evidence specimens, etc. From a medical standpoint, this design can also be used in other diagnostic applications aside from just clinical labs. Many hospitals do testing in house rather than sending specimens off to a clinical lab. This setup at a hospital requires the same type of storage that is required for a large clinical lab just on a smaller scale. One of the major benefits of the Slide Valet system is that it can be scaled to for use in a small hospital.

The benefits of automation are so compelling that there is a strong initiative to standardize automation in the clinical lab industry. Standardization would allow for lower cost and easier implementation which would allow hospitals and clinical labs of all sizes and budgets to have an automated system. On the horizon lies the standardization of automation in clinical laboratories but to get there requires developing this automation technology to the point where it is ready to be standardized. [12,13]

2. DESIGN AND DEVELOPMENT OF THE SLIDE VALET

2.1 FOLDER MOVEMENT SYSTEM

The Folder Movement subsystem is designed to manipulate the slide folder positions so that the appropriate folders are in the correct position for slides to be either stored or retrieved. The main components of this system are the belt system with a stepper motor, the actuator system and the bin system to actually hold the folders.

Figure 2.1.1: Slide folder with 20 slide capacity

Medical slides are typically stored in folders, Figure 2.1.1, that hold up to twenty slides. For this reason it was necessary to design the machine around the usage of these slide folders because the slides would need to be stored into and retrieved from these folders. Another key factor was that the folders would be manually placed into and removed from the machine by the operator. Based on these factors, a three bin system was designed to incorporate the

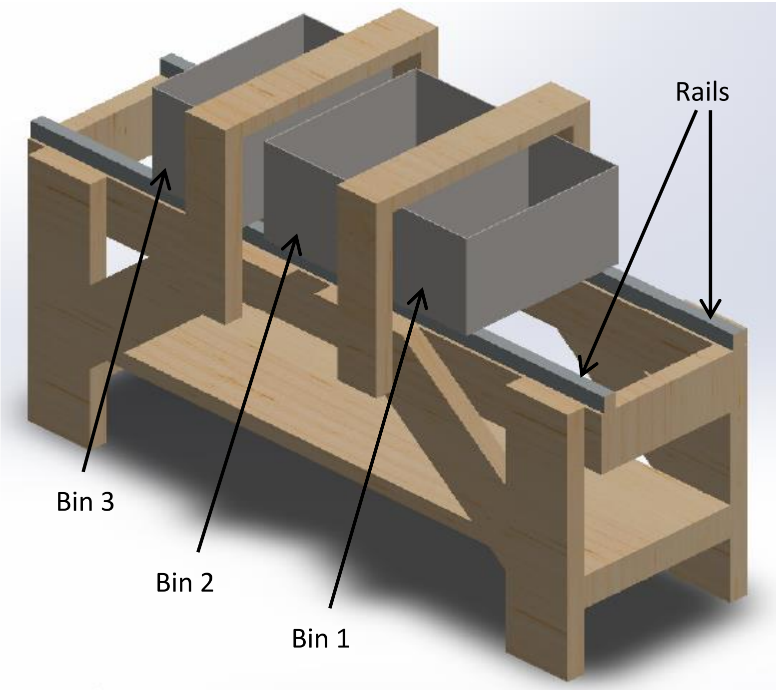


Figure 2.1.2: Bin frame with 3 bin system

usage of the folders into the machine.

This bin system is displayed in Figure 2.1.2. It is supported by a simple wooden frame which forms the main structure of the Slide Valet. The bin furthest to the right (Bin 1) is the loading bin. Slide folders containing slides that are meant to be put back into storage are placed in this bin. The furthest left bin (Bin 3) serves the purpose of holding the folders that have retrieved slides in them. The middle bin (Bin 2) is the empty folder bin. As soon as a folder has been emptied, the now empty folder is stored in the middle bin. Folders are pulled from this bin to be filled with slides that the operator wishes to retrieve. All three bins are bolted to each other via steel pieces on the underside of the bins, Figure 2.1.3, so they move with each other as the belt system is operated.

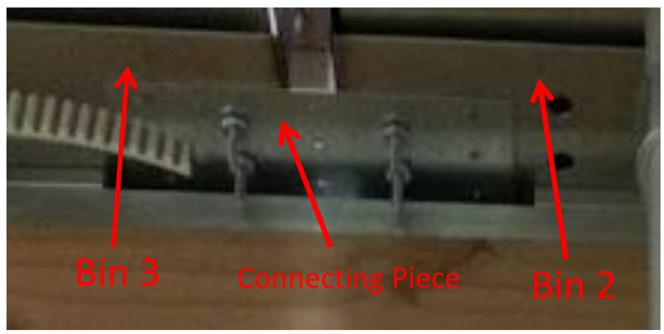


Figure 2.1.3: Bin connection piece

The bins themselves are made from .125" Stainless Steel bent to form the bin structure. The dimensions of the bins were determined from the size of the slide folders. The height of the bins was designed at 9" to allow for up to twenty four .375" thick slide folders to be stored in each bin at a time. The inner dimensions of the bin allow for a .125" clearance between the inside of the bin and the outside of each slide folder. On the bins, two of the sides opposite one another have openings running the entire height of the bin so that the stack of folders can be easily grabbed and slid out from the bins by the operator. The bottom of the bin is open to allow for an actuator to move up and down inside the bins. A rectangular piece of .125" steel is placed in the bottom of each bin underneath the stack of slide folders. A piece connected to the top of the actuator (shown later in Figure 2.1.7) pushes on this steel piece, which moves the folder stack up and down. On one side of the bottom of the center bin, the belt is fixed to that bin by a bracket. On the other side of the center bin, the belt passes through a guide bracket, Figure 2.1.4, with two stacked ball bearings. The belt is tensioned and only makes contacts with the ball bearings which allow the belt to move smoothly through the bracket as the motor moves the system in one direction or the other.

Figure 2.1.4: Bin belt bracket

The belt and actuator systems serve the purpose of moving the folders into the correct positions for slides to be stored and retrieved from them. In 3D coordinate system terms, the belt system translates the folders side to side in the ± y-axis while the actuator moves the folders up and down in the ± z-axis.

The belt system is designed to move the appropriate bin into position on top of the actuator system. Two slider pieces with three

Figure 2.1.5: Overview of Belt System

roller bearings (shown in Figure 2.1.5) are attached to the bottom of each bin. These slider pieces then translate along two linear rails used to guide the bins from side to side. As seen in Figures 2.1.2 and 2.1.5, these linear rails are mounted to the wooden frame underneath the bins. This slider and linear rails were chosen almost solely for their reliability and low cost. The loading of the slide folders on the bearings was not a concern as a maximum loaded bin (24 folders with all slides) weighs no more than 30 lbs. and the chosen sliders have a load capacity of 850 lbs. A control system which incorporates three slotted optical switches was used to control the position of each bin. A slotted optical switch consists of a photoemitter and photodetector sensor with a gap, or slot, between them. When an opaque object is passed between the emitter and the sensor, the beam is broken and the state (On/Off) of the switch is changed [14]. For this project, a simple zip tie was attached to each bin as the object used to trip the optical switch. The three switches are mounted to the wooden frame at appropriate places along one side of the linear rail. When a certain operation is designated by the controller, the belt system will turn the stepper motor in the appropriate direction to move the desired bin into the correct position. When the correct bin has moved to the desired position the corresponding optical switch is triggered and the stepper motor is shut off.

For the linear actuator system, two types of actuators were considered: pneumatic and electric. Both types of systems would fit within the Slide Valet base frame structure and would not require the complications of a hydraulic system. Therefore the actuator selection was based on speed, force, stroke length, complexity of controls and precision of position. Pneumatic actuators are known for providing higher force and higher speed at a lower cost and smaller physical area [15,16]. For this project, speed was a low priority factor in distinguishing between electric and pneumatic options because fast actuation was not a necessity for the system. The maximum weight that the actuator would need to push up and down would be the weight of 24 slide folders filled with 20 slides each which is a maximum of 30 lbs. so producing a large amount of force was also not a concern. A major factor in the actuator selection ended up being the necessary stroke length. Each slide folder is .375” thick and each bin was designed to hold 24 folders. In the scenario that only 1 folder is present in a bin at a certain time the stroke length would need to be a minimum of 9 inches to push that folder up and out of the bin.

The other major factor became positional precision. Electric actuators provide more precise positioning for all positions including those that are mid-stroke. Because air is compressible, a pneumatic actuator is susceptible to undesired movement which will change the position when a force is applied down on it [16]. Although the weight of the folders was not large, this was taken into consideration because of the effect it could have on the overall automated process. Pneumatic actuators are also subject to disturbances coming from leakages in valves and time-varying payloads [17]. Any amount of movement from the actuator could result in a change in vertical position of the slide folders. This could have led to a failure in the Folder Opening/Holding Subsystem as they relied on a near constant folder position to operate correctly. It could have also resulted in a failure in the Slide Movement Subsystem’s robotic arm grabbing the slides out of the folder since this system was based on absolute coordinates relative to the robot’s position.

When the actuator was run out all the way, the actuator rod was subject to some small side loading which the actuator was not equipped to handle. So the rod became unstable and wobbly. This was a concern because the actuator rod would shift to the side enough to misalign the stack of folders with the bin underneath it. So when the rod was retracted the slide folder stack would sometimes get caught on the top of the bin it needed to go down into. This concern was fixed with the addition of metal channeling pieces that were welded to the tops of the folder bins to ensure that the folders were channeled back into the bins as the actuator rod was retracted. These pieces are shown in Figure 2.1.6.

Figure 2.1.6: Folder Bins with channeling pieces

Several factors were taken into account when considering the type of power source in the actuator system. In the event of a loss of compressed air the pneumatic actuator would fall down and lose its position. The electric actuator has the advantage in this regard because it uses a linear screw system. If the system were to lose power it would retain its position regardless. The other disadvantage of a pneumatic actuator is the need for an air compressor as the source of power. Electrical power is standard anywhere, whereas compressed air is not.

The complexity of control for both alternatives ends up being about the same. The actuator has a simple operation. When the red and black wires are connected to the corresponding terminals on the power supply the actuator begins to extend. When the wires are switched the actuator begins to retract. Therefore the control circuit for this simply requires a Double Pole Double Throw Relay or equivalent circuit. The complication arises when the actuator needs to stop. For this reason the addition of a Single Pole Single Throw Relay or equivalent circuit is necessary to create a neutral position that will stop the flow of electricity and hold the actuator position. A similar design would be necessary to control the pneumatic actuator but would control which valves are open/closed to control air direction (rather than electricity) in the actuator [17].

In order for the actuator system to be able to interact with the folders inside the bin, a pusher piece was designed. This piece (shown in Figure 2.1.7 below) connects to the top of the actuator rod and applies the actuator's force evenly across the bottom of the folder stack. This pusher piece was made from several pieces of bent steel that were then welded together.

The active folder refers to the folder that slides are placed in or removed from. In order to ensure the repeatability and reliability of the process, the position of the active folder must be the same every time for the folder opening system. For this reason it was necessary to develop a way

Figure 2.1.7: Overview of Actuator System

to tell the actuator system how far it needed to raise or lower the stack of folders. This was accomplished through the use of a limit switch and an infrared distance sensor. The limit switch is used to tell the actuator system where the bottom limit of the actuator stroke is, so it is mounted on the actuator mount underneath the bin. This limit switch also provides a safety device for movement of the bins. When the limit switch is triggered the actuator stops retracting and the belt system is free to move the bins around. The distance sensor is mounted on a post above the folder stack, Figure 8, and uses reflected infrared light pulses to determine the distance to an object. In the case of the Slide Valet when the infrared sensor reaches a predetermined distance, the actuator stops extending so that the Folder Opening System can operate.

2.2 FOLDER OPENING/HOLDING SYSTEM

Figure 2.2.1 below shows the layout for a typical 20 slide folder. The slide folders have two covers that must be opened to access the slides they contain or to allow slides to be placed in the slide folders. Therefore a system had to be designed to open the slide folder covers. This Folder Opening System was designed to do this by incorporating a vacuum system along with a servo motor system. The vacuum system is used with suckers to grab the slide folder covers for manipulation and the servo motor system is used to rotate the

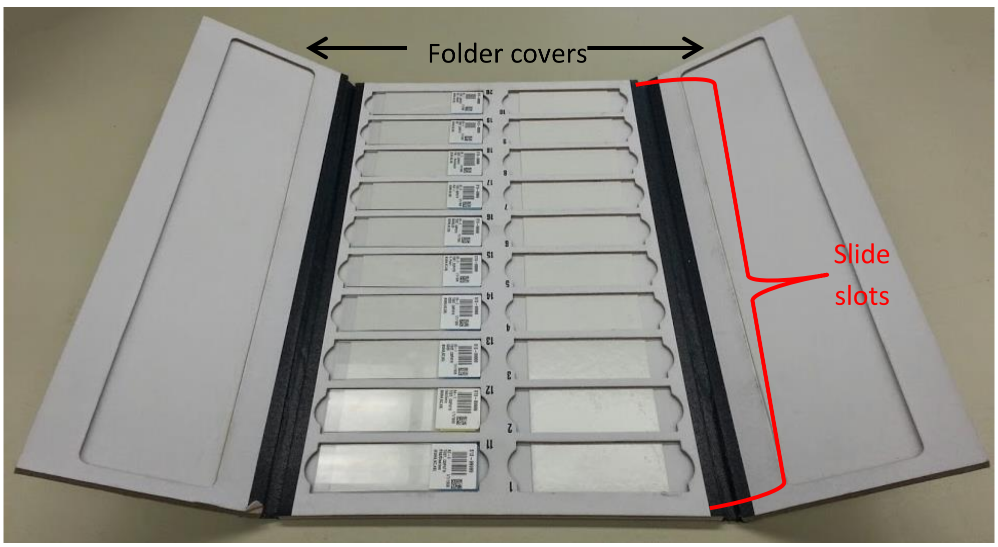


Figure 2.2.1: Overview of Slide Folder Layout

covers open or closed (See Figure 2.2.4). The vacuum sucker pieces needed to attach towards the middle of the folder, as far away from the folder cover hinge as possible. The servo motors are mounted on the Bin System frame. Servo arms were designed to connect the sucker pieces to the

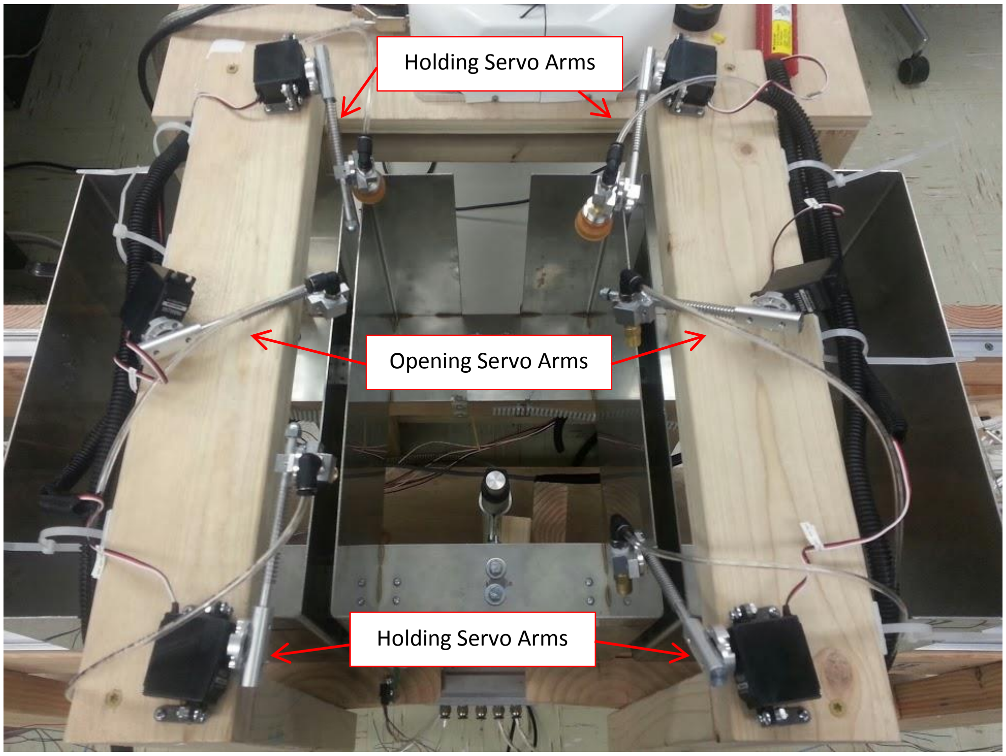
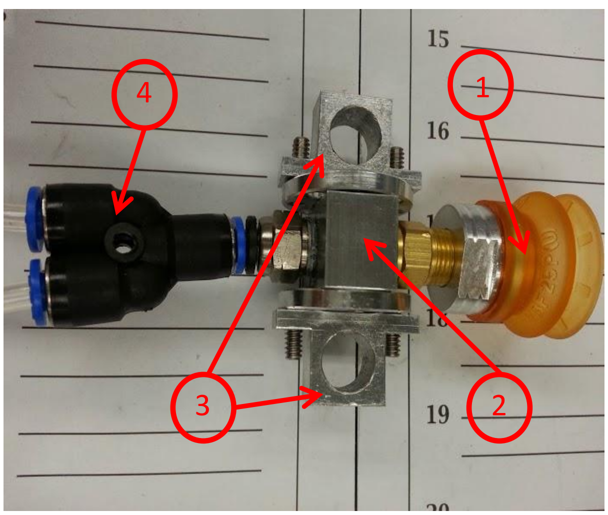


Figure 2.2.2: Original Layout for Folder Opening and Holding

servo motors. These servo arms would allow for the sucker pieces to attach to the folder covers towards the middle and away from the cover hinge. The sucker pieces were connected to the vacuum system through a manifold. This manifold was also connected to a mounting piece that was then connected to the servo arm. As Figure 2.2.2 shows, for the orginal design of the Folder Opening System, two of these servo arm assemblies were mounted in the middle of the mounting arm directly across from one another while four more of these arm assemblies were mounted at each corner to be used by the Folder Holding System.

Due to the changing geometry, the sucker pieces created an arc when rotating the folder cover open or closed. Therefore the mounting piece, that connects the servo arm to the sucker, had to slide up and down on the servo arm. The initial solution was to let the force the folder exerted on the sucker piece move the sucker piece up or down the servo arm as the servo rotated the cover open or closed. The hole in the sucker mounting piece had a very small clearance with the servo arm shaft that it slid on. For this reason, the friction between the two parts was too much so the folder would then begin to lift off the stack. There were several other issues with this design as well. The design had the sucker piece cantilevered off of the servo arm. This created additional friction when the sucker piece needed to slide up or down. Also the vacuum hose was much more rigid than anticipated and tended to pull the sucker piece to one side which then created even more friction.

The second solution to this problem was to make the mount hole larger, press fit a bushing into the hole and then lubricate the servo arm shaft. This solution mitigated the problems



Part Identification:

1. Sucker Piece
2. Manifold v2
3. Mounting Pieces v2
4. Quick Connect Piece
5. Servo Arms
6. Servo Motors
7. Dual Tubing

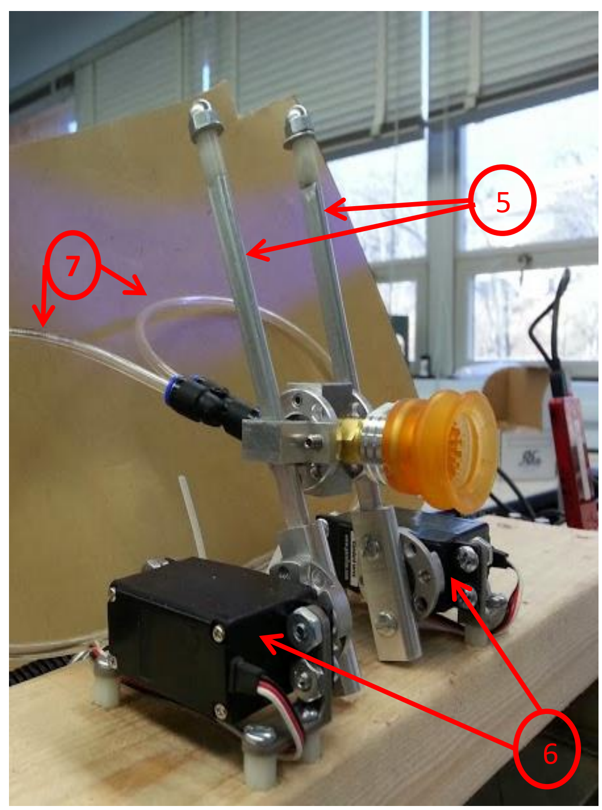


Figure 2.2.3: Overview of the Servo Arm Assembly for the Folder Opening System

with the initial design but reliability was still an issue. The third and final solution, shown in Figure 2.2.3, was to remove the bushing from the hole to make a larger clearance between the hole and the servo arm shaft. This alleviated a lot of the friction issues between these two pieces. Also the first two designs only incorporated two servos. The final design uses four servos; two servos for each of the two sucker pieces.

The manifold piece was redesigned so that two mounting pieces could attach to it. With this design the sucker piece is no longer cantilevered and its weight is supported by two servo arms.

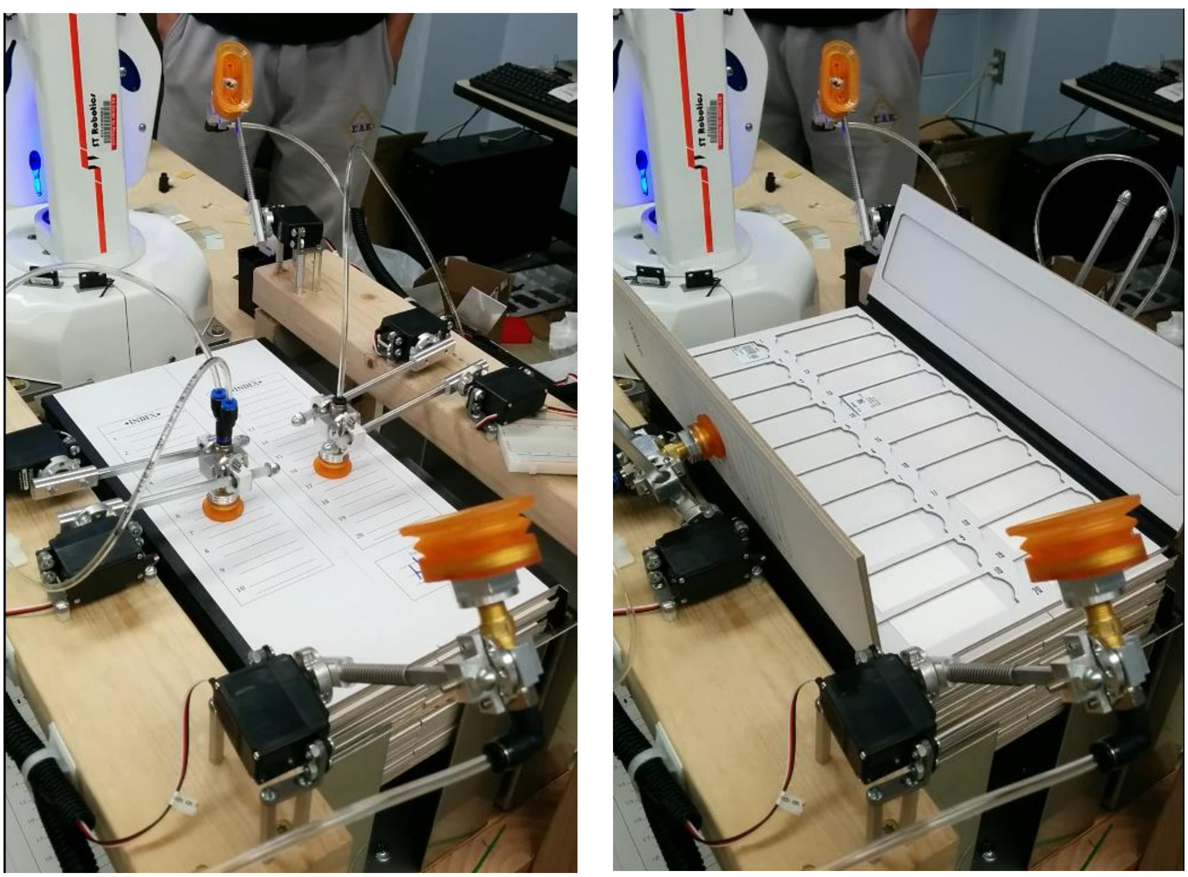
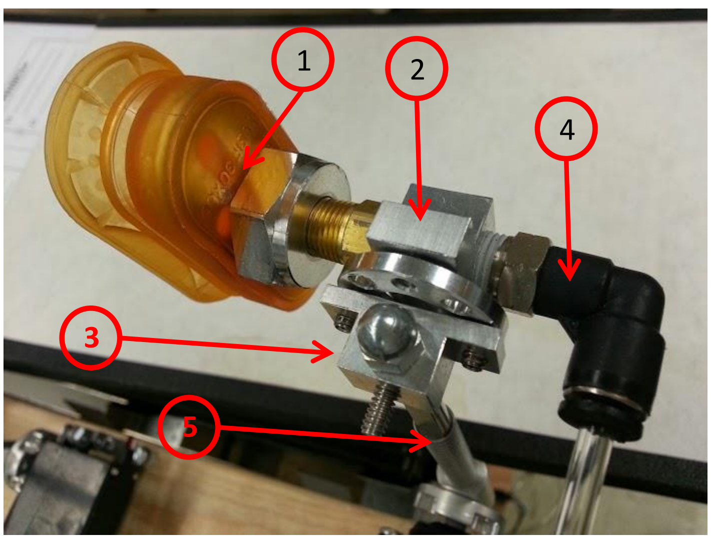
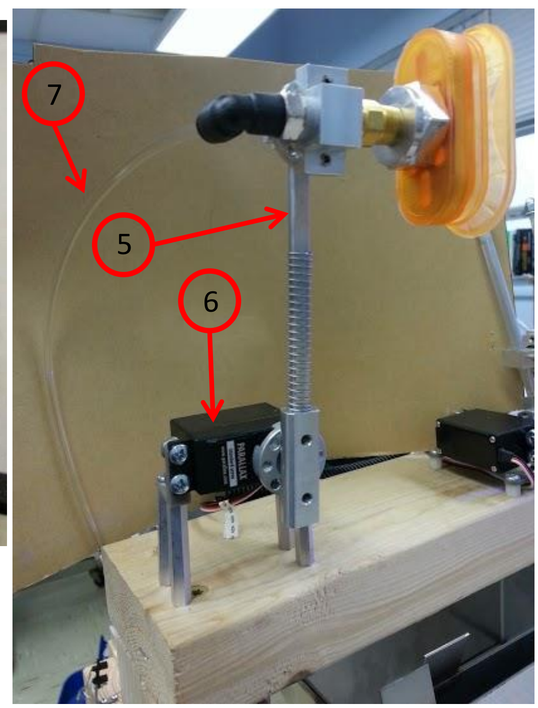


Figure 2.2.4: Overview of the Final Design for the Folder Opening and Holding Systems. The picture on the left depicts the system attached to the folder covers and the picture on the right depicts the system after it has finished opening the folder covers.

This also helps to alleviate some of the effects of the vacuum hose's rigidity. This hose issue was alleviated even more by adding another hose to each sucker piece and then mounting the hoses to the frame at an ideal orientation based on the way the hose tended to pull. The duel hoses then effectively canceled each other out and had a minimal effect on the sucker piece's sliding action. For the servo arm pieces, the manifolds and the mounting pieces, aluminum was chosen because it is lightweight, inexpensive and easily machinable. Figure 2.2.4 shows the finished Folding Opening System when it is engaged on the active folder and when it has successfully opened the covers for the active folder.

The Folder Holding System uses a very similar design to the initial design for the Folder Opening System. The only difference is that the mounting pieces did not have to slide up and down the servo arm shaft. For this reason a set screw was threaded into the mounting piece





Part Identification:

1. Sucker Piece
2. Manifold
3. Mounting Pieces
4. Quick Connect Piece
5. Servo Arm
6. Servo Motor
7. Single Tubing

Figure 2.2.5: Overview of the Servo Arm Assembly for the Folder Holding System

keeping it stationary on the servo arm. The servo arm assemblies for the Folder Holding System are show in Figure 2.2.5. This system uses two of these servo arm assemblies mounted cattycorner from one another on the frame, shown in Figure 12. When this system is activated, the servo arms rotate into position with the vacuum system on and the suckers are engaged with the slide folder on opposite corners. The system will then hold the active slide folder suspended as the Folder Movement System is free to move the rest of the folders until the correct bin is in position. The Folder Holding System will then be deactivated and the active folder will fall into the appropriate bin.

Servo motors were chosen as the method of rotating the folder covers open. Servos are easily programmable and easily interfaced with other electrical systems. A 180 degree standard Parallax servo motor provides the ideal angular range for this application as the motion for opening a folder cover requires a maximum of 135 degrees of rotation. Servo motors use a pulse width modulation communication method for control. In the case of the Parallax servo, a high 5.0 Volt pulse, sent at a constant 100 Hz, moves the motor. The duration of this high pulse tells the servo what angular position to rotate to. For the Slide Valet, the pulse width modulation is controlled through the use of a MOSFET switch in the circuit for each servo. The servo motors also provide 38 oz.-in. of torque which is more than enough to rotate the entire servo arm assembly and the folder covers. Servo motors also hold their position well as long as the control signal is continually supplied. The gearing on the servo is also high precision for smooth operation and no backlash.

Two main types of vacuum pumps are commonly available: Multi-stage mechanical pumps or Venturi pumps. There are a wide variety of designs for multi-stage pumps. All multi-stage pumps have several stages with a variety of moving parts depending on the design of the pump and are typically powered by an electric motor. These moving parts are very susceptible to clogging as dirt or other debris is sucked into the pump. When the pump begins to clog, the vacuum pressure of the system decreases. These pumps incorporate filters to help with this issue but often still have to be stopped for maintenance or to replace the filter. Another issue with the mechanical pumps is that the movable parts all combine to make a significant amount of noise.

Venturi pumps provide a solution to all these issues. Venturi pumps work by forcing compressed air through a nozzle which creates a vacuum based on the Venturi Effect [18]. Because the air only flows down the chamber, there are no moving parts necessary. For this reason the only source of noise is from the air flow so venturi pumps are much quieter than mechanical pumps [19,20]. The venturi pump chosen for the Slide Valet also utilizes an integrated silencer to reduce the noise level even more. The Slide Valet is designed to be used in a lab or hospital environment therefore keeping noise at a minimum is very important. The fact that the venturi pump has no moving parts also means that no heat is generated. It also requires fewer parts which allows it to be smaller and lighter than an equivalent mechanical pump. The design of the Venturi pump also significantly reduces the level of clogging that occurs and does not require a filter [19,20]. The pump chosen for this project has a filter to help prevent clogs even further. From a reliability and maintenance standpoint, all these factors make the Venturi pump a better option for this application.

Mechanical pumps can also take a significant amount of time to create a vacuum once they have been started and/or they can possibly continue to produce a vacuum after they have been turned off. Mechanical pumps are better suited for a continuous application where the pump is needed for a long period of time. Venturi pumps have a fast response and create a vacuum as soon as compressed air is supplied and will stop creating a vacuum as soon as the compressed air is shut off [19,20]. This was important because the in order to effectively manipulate the slide folders the vacuum system for the Slide Valet needs to go quickly from off to on and vice versa.

The only drawback with the venturi pumps versus the mechanical pump is that a source of compressed air is needed.

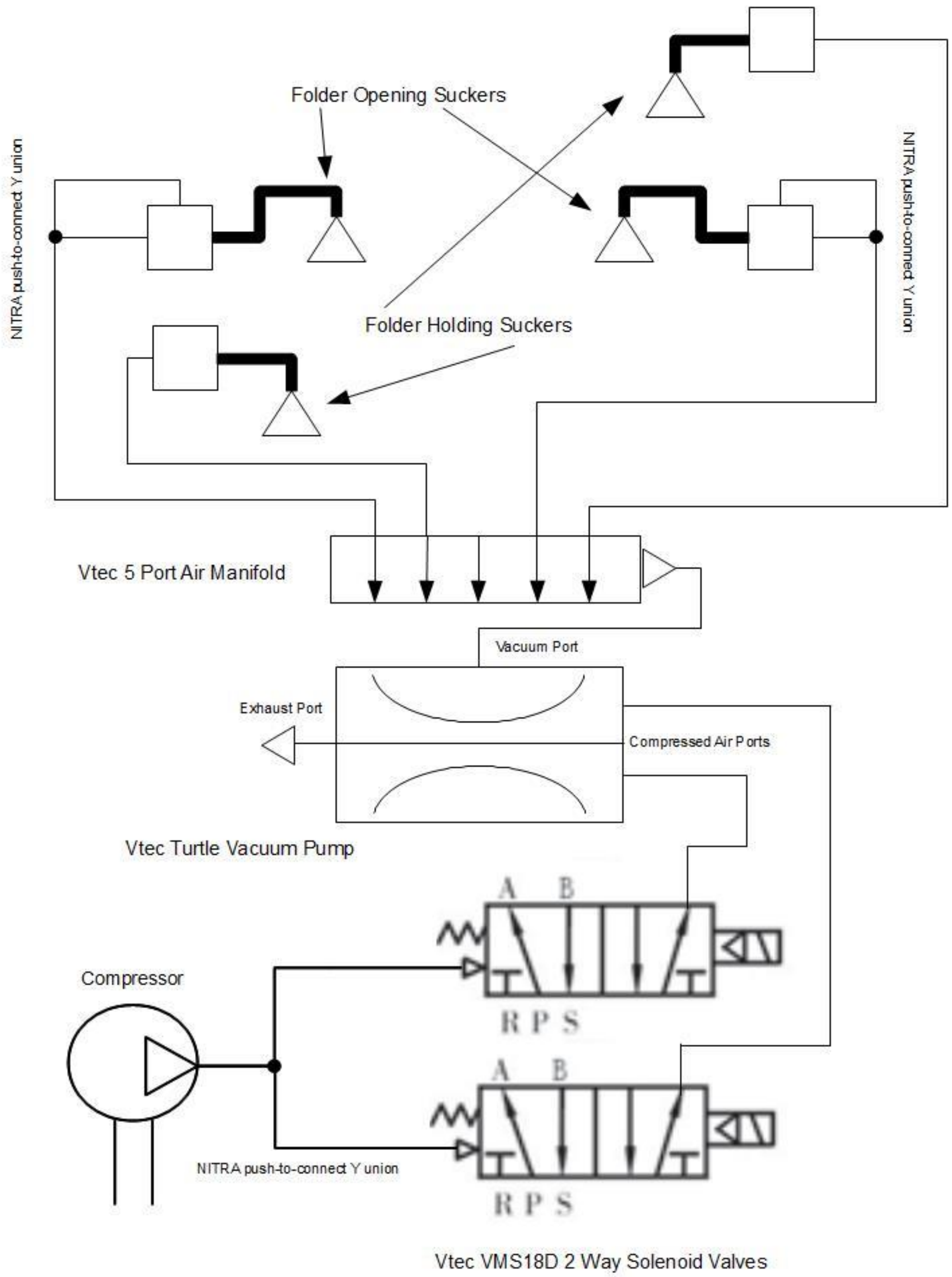


Figure 2.2.6: A schematic of the Slide Valet vacuum system shown with standard industry symbols

The Venturi pump purchased for the Slide Valet has five ports: two compressed air ports, two vacuum ports and an exhaust port. Each of the compressed air ports came with solenoid valves attached to the ports. One port is used as an air control valve and the other as the vacuum release valve. As show in Figure 2.2.6, compressed air is fed into the vacuum pump through both valves. As the air passes through the venturi cartridge chamber it creates a vacuum which is utilizes through the vacuum port. Only one of the vacuum ports on the pump was used. From this port, tubing connects the pump to a five-port manifold which acts as a splitter. From the manifold, the tubing branches out to each of the four sucker pieces. Air is sucked through these sucker pieces back down through the manifold and into the pump. On the pump, a silencer is attached to the exhaust port. The compressed air and the entrained air from the suckers are exhausted to atmosphere through this silencer.

Shutting the vacuum on and off is accomplished through the use of the air control valve. The operation of this valve is simple. The valve is normally closed so compressed air will not pass through it. Once a voltage is provided to the valve the solenoid moves and the valve is opened allowing the compressed air to move through and create the vacuum.

Leaving unused suckers open to atmosphere reduces the vacuum pressure of the system. Since the folder opening and folder holding system perform two separate functions they are never engaged on the folder at the same time. The way the vacuum system is set up the two systems work off the same vacuum supply at all times. With this setup the folder holding system will lose vacuum pressure in the system when the folder opening system is being used and vice versa. Through testing it was found that the vacuum system produced a maximum holding vacuum pressure of -30 kPa when only 2 of the 4 vacuum sucker pieces were engaged on the slide folder.

This is more than enough vacuum force to support the weight of the slide folder. Not having separate vacuum systems also provides the advantage of reducing the complexity of the system. From an electrical standpoint, this is beneficial because the circuit board and the machine programming are both less complicated as a result. Only a single control scheme needed to be made for the vacuum system rather than two.

The large oval-bellow sucker pieces were chosen for the holding system because they are rigid and have a large surface area (Figure 2.2.7). This helped create a larger holding force on the active folder and also allowed for a more stable hold on the folder to prevent it from wobbling as it was suspended. For the opening system, a smaller, more flexible sucker was chosen (Figure 2.2.8). Due to the rotational nature and design of the opening system the sucker piece had to account for some variability. The sucker piece chosen has a flexible bellow above the lip. When the lip is engaged on the folder cover the bellow allows for 45 degrees of variability in any direction around the piece. This sucker piece also weighs very little which makes the burden on the servo arm and motor easier and helps alleviate some of the frictional issues discussed earlier.

Figure 2.2.7: Oval Bellow Suction Cups are ideal for long, flat, rigid objects

Figure 2.2.8: Single Bellow Suction Cups with large lips are ideal for flat objects and flexible movement

2.3 SLIDE MOVEMENT SYSTEM

The design for the storage area was based on storing slides oriented vertically with the long axis up. This would allow a large number of slides to be stored in as small of an area as possible. This type of setup would also allow the robot to more easily manipulate the slides. Racks used to stain medical slides were the initial choice to create the storage area for the slides. These racks are shown in Figure 2.3.1. They are inexpensive and readily available and would

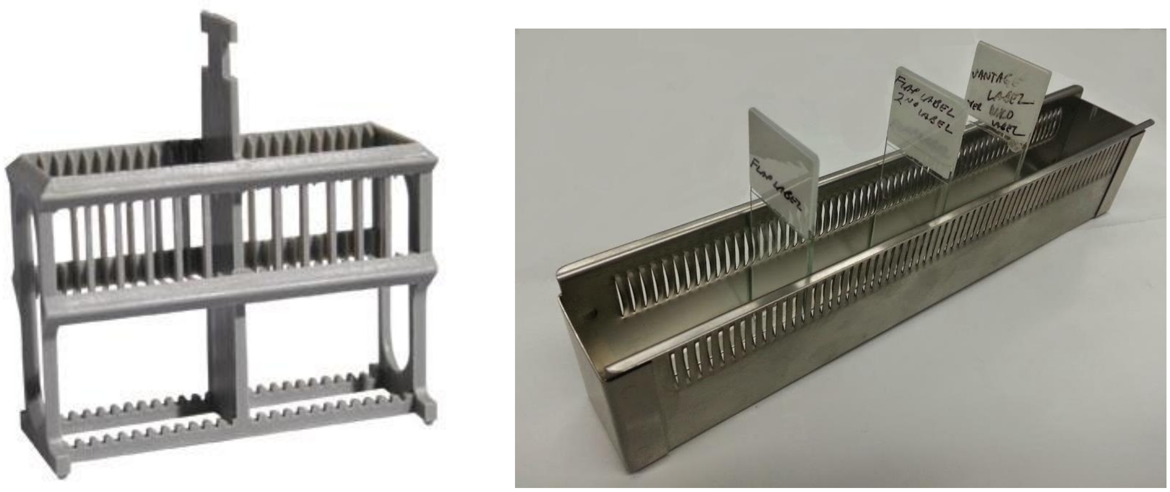


Figure 2.3.1: Standard slide staining racks

orient the slides vertically for easy robot manipulation. After testing though, it was clear that they were not a reliable solution. The major flaw with these rack designs is that the slots which the slides go into did not run the entire height of the rack. For this reason, if a slide was not dropped perfectly straight down it had a strong tendency of getting caught in one of the slot's gaps. This would prevent the slide from falling all the way down into the rack. Even when the slide did fall all the way down into the slot often times the bottom of the slide would be over in the neighboring slot. This would prevent the neighboring slot from falling all the way down into its slot. As reliability was a major design guideline for this project, a different solution was necessary.

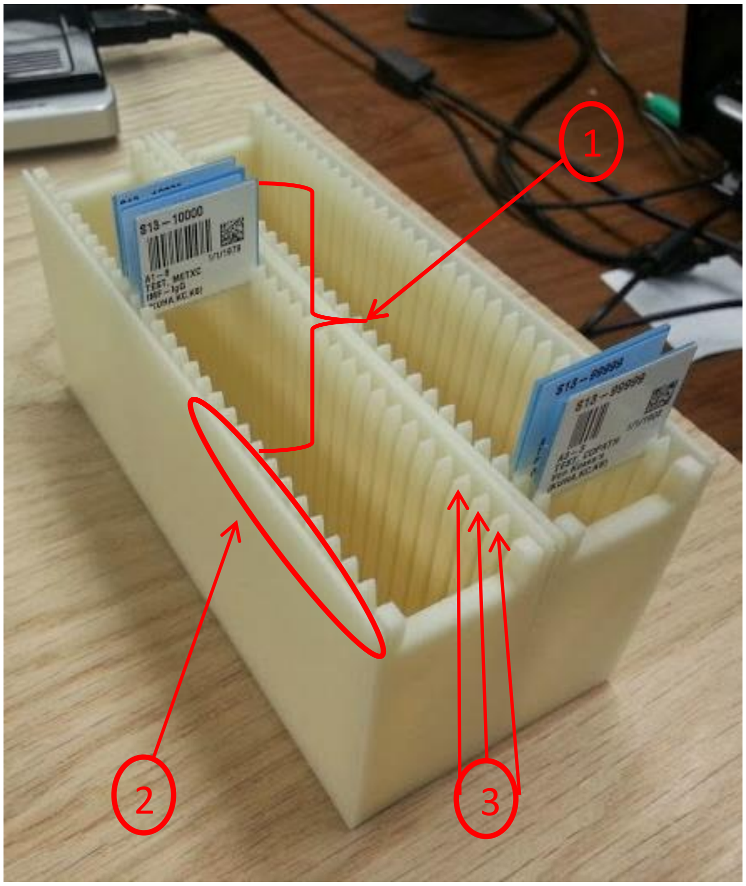


Figure 2.3.2: Slide holder with features

A slide holder was designed specifically to ensure the repeatability of moving slides in and out of the storage holder. It was designed to negate the flaws of the staining rack design. Figure 2.3.2 illustrates the features of this slide holder. The holder is fully enclosed. (1) Within the enclosure, each side of the slot runs the entire length of the slide and connects to the slot on the bottom as well. This means that each slot is connected on the inside of all three sides of the holder and there are no gaps in the slot. This ensures that the slide will not bind in the slot and not affect either neighboring slots. (2) The holder incorporates a channeling piece on the top which allows for some room for error in the slide's position side-to-side. A similar idea was used to design the median pieces that divide the sides and create the slots. (3) At the top of the holder, these pieces are sloped on both sides to ensure that the slide will still be funneled into its slot even if the slide is not lined up perfectly front-to-back. The current storage area uses two of these holder pieces mounted side by side. Each one has 29 slots so together they are capable of holding up to 58 slides. Due to the complexity in machining this part, it was manufactured using a Rapid Prototyping Machine and is made from plastic. Extensive testing was conducted to ensure that this design was reliable.

The station for scanning slides into inventory, shown in Figure 2.3.3, uses a similar

Figure 2.3.3: Slide scanning station including scanner

design to ensure reliability when dropping slides in to be scanned and picking them back out to be moved elsewhere. The scanning station only has two slots in its design and has an open face so that the barcode can be easily detected by the scanner in front of it. Because of the fact that the slide orientation is different between the storage area and the slide folders, it was necessary to have an intermediate place to change the robot’s grip on the slide. This scanning station serves this purpose as well. As soon as the slide is dropped into the station to be scanned the gripper moves to change its orientation and then grabs the slide and moves it to the next stage. This scanner station piece was also manufactured using the rapid prototype machine.

One of the most important aspects of the design was the method of gripping slides so that they could be moved around. The robot came with an end manipulator system already incorporated in its design which is shown in Figure 2.3.4 on the right. The robot manipulator had two simple pieces to create the gripper. These pieces had ball bearings press fit into them for rotation on one end and two threaded holes on the other end. A bolt was put onto one of the holes on each of the gripper pieces. These two bolts then worked together to do the actually gripping. The robot's manipulator system utilized a linear worm gear system to push a rod through a bushing. This rod then attaches to both gripper pieces. The gripper pieces are also connected to the end of the robot arm via the ball bearings. As the linear rod was pushed out the gripper pieces would swivel on the ball bearings and open up for gripping and as the rod was retracted the gripper pieces would close.

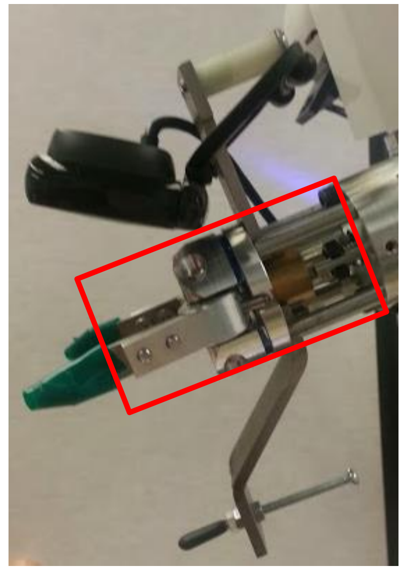


Figure 2.3.4: End Manipulator that came as part of robot

This manipulator system was not adequate for gripping medical slides. The radius on the gripper bolts was too small to grip slides reliably. The bolts would also shatter the glass when closed on a slide. Another minor issue was that the linear rod had no positional control so it was either out at its full stroke or fully retracted. This meant that the grippers could only be fully open or fully closed; there was no in between.

The slides are held in the folders, at a horizontal orientation with the specimen facing up, using recessed slots in the bottom of the folders. These slots are shown in Figure 2.3.5.

Figure 2.3.5: Close up of slide folder

When in these slots, the top of the slide is laid in flush with the bottom of the folder making it difficult to be picked up by the robot gripper. The gripper needed to incorporate a method to help remove the slides from these folder slots. The other challenge was that this same gripper must also grab slides from the storage area where the slides are held at a different orientation.

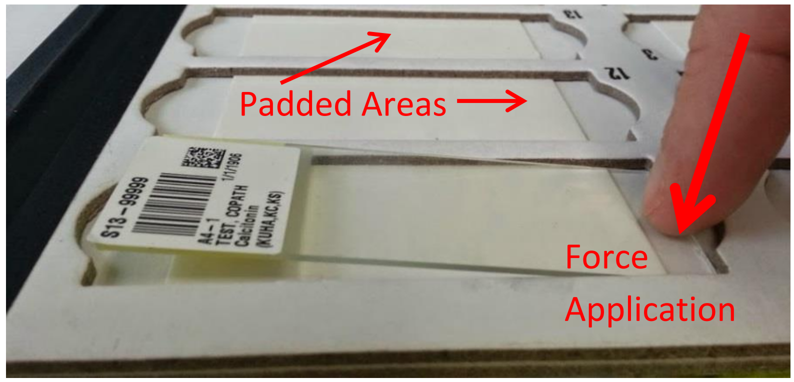


Figure 2.3.6: Applying force to one side allows easier slide pickup

As Figures 2.3.6 and 2.3.6 show, within each slot in the slide folder there is a padding piece that covers most of the bottom of the slot except for the ends. Figure 2.3.6 shows that when a force is applied to either end of the slot, the other side of the slide will pop up and out of the slot. That side of the slide is then much easier to grab with the robot.

Typical grippers use a single jaw, two finger design. The Slide Valet uses a single jaw, three finger design. The third finger is offset from the jaw by a

Part Identification:

1. Intermediate Pieces*
2. Gripper Jaw Pieces
3. Third Finger Bracket
4. Third Finger Bolt
5. Camera Bracket
6. Camera

*Included on purchased robot

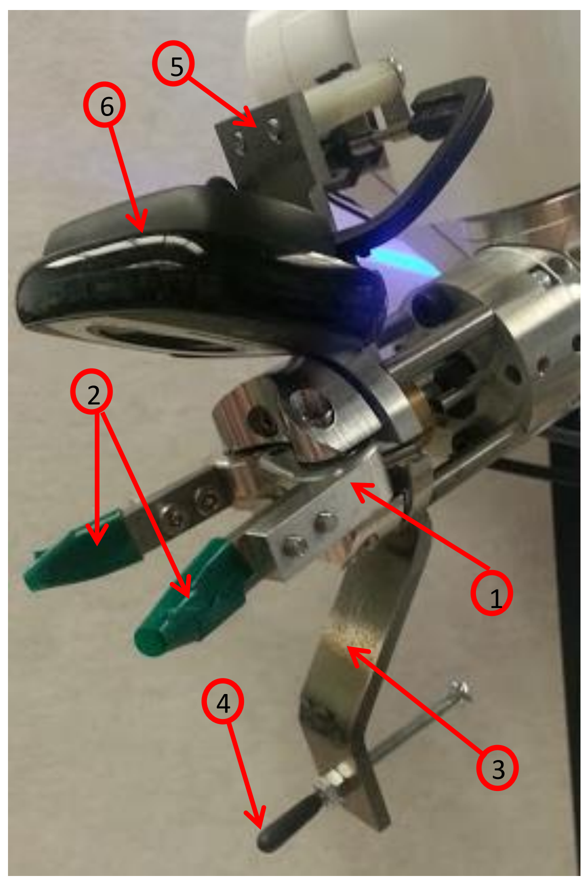


Figure 2.3.7: Overview of the Gripper System

slide's length. This third finger, shown in Figure 2.3.7, is used to apply the force to one end of the slide. The other end of the slide then pops up and the two-fingered jaw is able to easily close around it. The slide is then gripped and can be moved around by the robot. The third finger consists of two pieces. A bracket made from bent .125" steel serves as the mounting structure for the finger. The finger itself consists of a threaded bolt. The bolt is secured to the bracket by two locknuts and the length can be adjusted. The end of the bolt that contacts the slide is covered in Plasti Dip. Plasti Dip is a durable rubber coating that cushions the bolt when it makes contact with the glass slides.

The gripper pieces that make up the jaw were made out of .125" bent steel. When the gripper was fully closed, the pieces were designed to form a jaw slightly smaller than the width of a slide. This allowed for a comfortable grip on the slide without breaking it. The ends of these pieces were also tapered to allow for the gripper to pull individual slides out of the storage area and not interfere with the slides on either side of them. After initially testing with the steel gripper pieces, it was found that there was not enough friction between the steel pieces and the glass slides. When the robot moved the slides around, the slides would either shift around in the gripper or fall out of the gripper entirely. The first attempted solution was to add a layer of thin foam padding to the inside of the gripper pieces. This foam was held on by adhesive. This method worked well for the first couple of trials but the foam began to deform as more and more slides were picked up. Eventually the foam would rip entirely and have to be replaced. The second solution was to dip the gripper pieces in Plasti Dip to apply a thin layer of rubber to the gripper. The application method for this was very crude; a part is simply dipped in and out slowly and allowed to dry. With this method, the rubber layer between the two pieces was unequal; one piece would have more rubber on it than the other. This did not allow for consistent slide manipulation. Every time a slide was picked up it was at a slightly different orientation.

The third and final solution was to simply wrap the grippers in electrical tape. This solution eliminated the problems with the previous solutions. It provided a stable base layer that gripped the slides and prevented them from sliding around in the grippers. The electrical tape could be wrapped around each piece several times which created equal layers for both pieces. Also the electrical tape did not deform after a large number of trials.

2.4 ADDITIONAL SYSTEMS

2.4A Robot System

The robot chosen for this project is a six-axis robotic arm from the company ST Robotics. It came with a motor controller and utilizes stepper motors to control each joint. The robot uses a Pick and Pull programming method. This method is based on absolute coordinates of different significant designated points. Figure 2.4.1 shows an example of this method applied to the active folder (coordinates are not accurate). The slide in the lower left corner of the opened slide folder has an absolute coordinate based on the home position of the robot. This is also true of the storage and scanning areas and intermediate points that the robot will move to in order to avoid running into itself or other parts of the Slide Valet.

Figure 2.4.1: Absolute coordinates applied to active slide folder

2.4B Inventory System

To address the issue of lost slides and to keep a constant record of each slides location, an inventory program was written to interface with the user. This inventory keeps track of the status for each individual slide. Each slide will have a status of either “stored” or “checked out.” The interface is simple. When the user starts the program they have the option to store or retrieve slides. If they choose to retrieve slides then the program asks them to “create” folders. The user browses through the inventory and assigns up to 20 slides to each folder. After being pulled out of storage, each slide is passed through the scanning station before being put in a folder. As it is scanned, its status in the inventory changes. The most important aspect of this inventory is the correlation between the slide specimen’s identification information and its location within the storage area. As soon as the slide is scanned into inventory a storage location is correlated to that slide and it tells the robot where to go to retrieve that specific slide. If the slide is removed and scanned and it is the incorrect slide barcode then the user will be informed of this error. Depending on the number of slides needing to be retrieved a queue builds up and the program will continue to retrieve slides until all the folders are done and the queue is empty. To store slides the user only needs to place the folders in Bin 1 and tell the program to run the storage sequence. The program will then run until the bin is empty. As the slides are pulled from the folders they pass through the scanning station before going to storage so that their status will change in the inventory and their information can be correlated to a storage location for retrieval later.

2.4C Control System

The machine uses a closed loop control system that is based on sensor feedback. The bin actuator and stepper motor positions are both based on sensor feedback. Once the actuator has been told to extend, it will continue to extend until the ultrasonic distance sensor tells it to shut off. When it is told to retract it will continue to do so until the limit switch is triggered. The Folder Opening System is also dependent on this distance sensor. Once the folder stack reaches a milestone distance away from the stack, the Folder Opening servos rotate down and the vacuum system turns on to begin the process of opening the folder. Depending on which action is being done with the machine the stepper motor will move the bin system until the appropriate optical switch has been triggered.

3. CONCLUSIONS AND RECOMMENDATIONS

3.1 DESCRIPTION OF OPERATING PROCESS

Figure 3.1.1 shows the completed Slide Valet prototype. The storage process works as follows. The operator places the folders, containing slides to be stored, in bin 1 and then tells the Slide Valet to run the storage operation. The Folder Movement System takes over initially. The program moves the belt system so that bin 1 is above the actuator system. It then moves the actuator system up until the top folder is in the opening position. The Folder Opening system is then initiated to open the active folder. The Slide Movement System takes over and all slides are removed from the folder and scanned into the inventory system. As the slides are scanned they are moved into the storage area. After all the slides have been removed from the active folder, the folder must then be moved to the empty bin. The Folder Opening System first closes the active folder. The servo arms used for folder opening are then retracted and the Folder Holding

System is activated. As the folder is held the actuator system fully retracts and the belt system moves bin 2 over on top of the actuator. The actuator system then moves up again until the folder stack is underneath the active folder. The active folder is then dropped onto the bin and the actuator is retracted back down.

For retrieval the operator tells the system to begin the process. The operator logs into the

Figure 3.1.1: Finished Result for the Slide Valet

inventory and chooses what slides he/she wishes to remove. Up to twenty slides can be selected for each folder. The Folder Movement System takes over initially and moves Bin 2 into position over the actuator. An empty slide folder is moved up and then opened. The Slide Movement System then removes the appropriate slides from storage and places them in the empty slide folder.

3.2 RECOMMENDATIONS FOR FUTURE WORK

In its current state the Slide Valet cannot be depended upon as a reliable machine to perform fully automated storage and retrieval of slides. Each system functions well independently but combining them is when reliability becomes an issue. There are several recommendations that could fix this issue and help the project achieve the ultimate goal.

The Slide Valet currently operates using a pick and pull method for moving slides. This method is reliant on absolute coordinates that dictate locations for important points such as the storage area slots or active slide folder slots. This method is effective assuming that these positions do not move. If any of these positions were to move then the robot will not work as effectively and reliability will be compromised.

A camera system was designed as the source of robot control but was never fully implemented. The camera is a high definition webcam that is mounted on a bracket above the gripper. The camera system was designed to recognize defined edges to identify spatial relationships and then determine coordinates for the robot to move to. This is beneficial when it comes to any variability in the system. Using vision systems in manipulation robotics can be very useful for compensating for positioning errors in a system [21]. If any of the systems change slide positions, the robot would be able to account for these discrepancies and adjust the robot accordingly to preserve the machine's reliability. For instance if the slide folder was to move slightly out of position the camera system would be able to recognize this and adjust the gripper position so that it could still reliably grab the slide out of the folder.

A better solution needs to be determined for the material used on the gripper jaw pieces. This gripper is possibly the most important aspect of the project from a reliability aspect. If it is not reliable then many of the operations for the machine cannot take place. While the electric tape worked the best of the three methods that were attempted, it still ended up having reliability issues. As the robot was used more and more, the tape began to slide off the pieces. The main issue seems to be the adhesive on the tape. A simple solution would be to use a different type of tape. A seemingly viable option would be heat shrink tape. The tubing could be wrapped around the gripper pieces and then heated to form a tight fit around the piece and resistant to sliding off.

Integrating a refrigeration system would be a necessity as some samples are required to be stored in a refrigerated area in order to be preserved. This would be as simple as designing an encasement around the storage area and a door/conveying system to isolate this area. Another solution would be to just house the entire Slide Valet inside a refrigerated encasement and then extend the bin system's rail out farther. The bins could be loaded/unloaded outside of the refrigerated area and then conveyed along the rail, through a door/gate, and into the Slide Valet in the refrigerated portion.

Another suggestion would be to eliminate the scanning station in favor of an easier solution. The robots used in ARUP's AS/RS system have barcode readers integrated into their grippers so there is no need for an intermediate place to scan the barcode [6]. Using a similar setup for the Slide Valet would reduce the complexity of the system. The challenge with the

Slide Valet would be that the slide has to be reoriented in the gripper regardless, to transfer from the storage to the folder or vice versa. So a new method that worked for gripping the slides for both the folders and the storage area would have to be developed or the storage area would have to be redesigned to accommodate the slide orientation that occurs based on the slide folders.

REFERENCES

[1] Brooks, Jerry, and Leigh Brooks. "Automation in the medical field." *Engineering in Medicine and Biology Magazine, IEEE* 17.4 (1998): 76.

[2] Boyd, James. "Robotic laboratory automation." *Science* 295.5554 (2002): 517-518.

[3] Kaur, Satwant. "How Medical Robots are going to Affect Our Lives." *IETE Technical Review* 29.3 (2012).

[4] Alwan, Majd, and Mingjun Zhang. *Systems Engineering Approach to Medical Automation*. Artech House, 2008.

[5] Cowan, Daniel F., ed. *Informatics for the clinical laboratory*. Springer, 2002.

[6] McMahon, Jim. "Making the switch from manual to automated specimen handling." Scientist Live. Setform Limited, n.d. Web. 17 Apr. 2014. <http://www.scientistlive.com/content/25129>.

[7] "Automated Storage and Retrieval System." ARUP Laboratories. ARUP Laboratories, n.d. Web. 17 Apr. 2014. <https://www.aruplab.com/LaboratoryExpertise/AutomationInitiative/as_rs.jsp>.

[8] Boyd, J. C., R. A. Felder, and J. Savory. "Robotics and the changing face of the clinical laboratory." Clinical chemistry 42.12 (1996): 1901-1910.

[9] Orsulak, Paul J. "Stand-alone automated solutions can enhance laboratory operations." *Clinical chemistry* 46.5 (2000): 778-783.

[10] Lam, Choong Weng, and Edward Jacob. "Implementing a Laboratory Automation System Experience of a Large Clinical Laboratory." *Journal of laboratory automation* 17.1 (2012): 16-23.

[11] Gwynne, Peter, and Gary Heebner. "Laboratory Technology Trends: Lab Automation and Robotics." Science Magazine. American Association for the Advancement of Science, 18 Jan. 2014. Web. 17 Apr. 2014. <http://www.sciencemag.org/site/products/robotfinal.xhtml>.

[12] Hawker, Charles D., and Marc R. Schlank. "Development of standards for laboratory automation." Clinical chemistry 46.5 (2000): 746-750.

[13] Markin, Rodney S., and Scott A. Whalen. "Laboratory automation: trajectory, technology, and tactics." Clinical chemistry 46.5 (2000): 764-771.

[14] Ball, Stuart. "Exploring optical and magnetic sensors." Embedded. UBM Tech, 17 June 2003. Web. 17 Apr. 2014. <http://www.embedded.com/design/prototyping-and-development/4024586/Exploring-optical-and-magnetic-sensors>.

[15] "How to Decide Between Pneumatic and Electric Actuators." Automation World. Summit Media Group, Inc., 16 Aug. 2012. Web. 17 Apr. 2014. <http://www.automationworld.com/control/how-decide-between-pneumatic-and-electric-actuators>.

[16] "Linear Actuators: Choosing Pneumatic or Electric Control." Design News. UBM Canon, 27 July 2007. Web. 17 Apr. 2014. <http://www.designnews.com/document.asp?doc_id=221771>.

[17] Ali, Hazem I., et al. "A review of pneumatic actuators (modeling and control)."Australian Journal of Basic and Applied Sciences 3.2 (2009): 440-454.

[18] Granet, Irving. "Fluid Dynamics." Fluid Mechanics.4th ed. Englewood Cliffs, New Jersey: Prentice Hall, Inc., 1996. . Print.

[19] Pascoe, Daniel. "Pump or Venturi?." Fluid Power Journal. Innovative Designs & Publishing, 29 Aug. 2013. Web. 16 Apr. 2014. <http://fluidpowerjournal.com/2013/08/pump-or-venturi/>.

[20] "Why Use a Venturi Vacuum Pump?." iQ Valves. iQ Valves Co., n.d. Web. 16 Apr. 2014. <http://www.iqvalves.com/WhyUseAVenturiVacuumPump.aspx>.

[21] Espiau, Bernard, François Chaumette, and Patrick Rives. "A new approach to visual servoing in robotics." Robotics and Automation, IEEE Transactions on8.3 (1992): 313-326.

APPENDIX A: DRAWINGS FOR FOLDER MOVEMENT SYSTEM

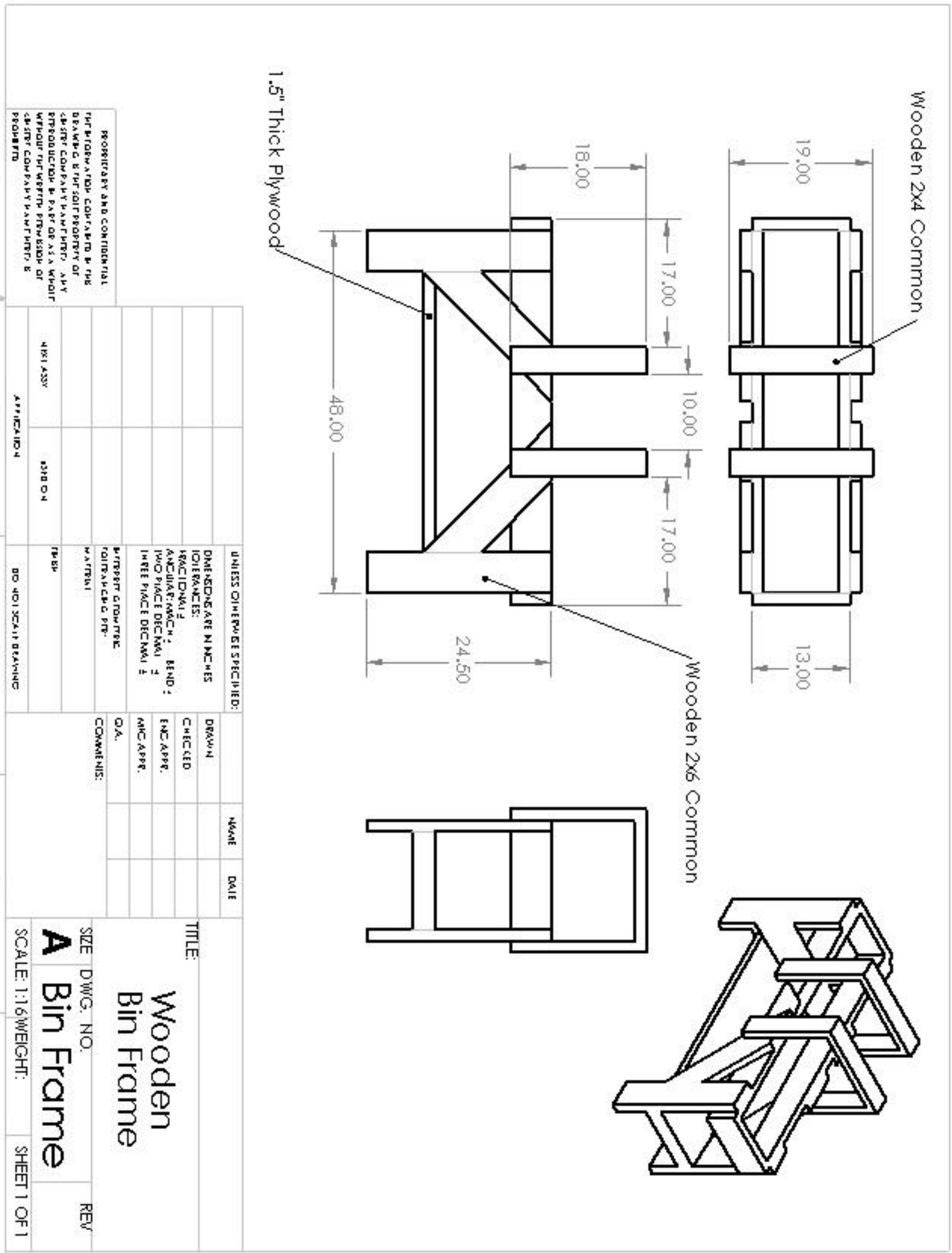


Figure A.1: Wooden Bin Frame that supports the bin and actuator systems

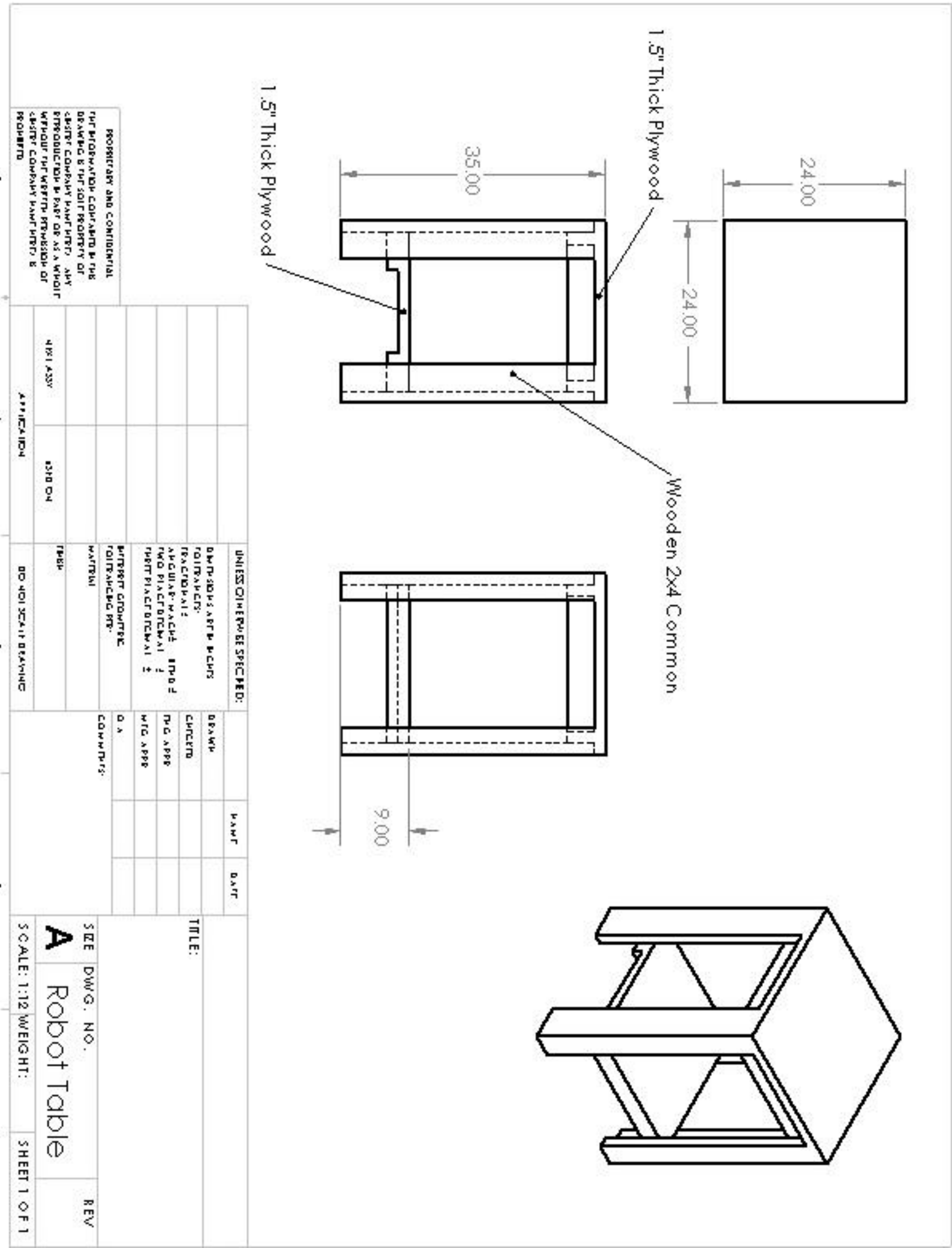


Figure A.2: Robot Table that supports the robotic arm, its controller and the slide storage and scanning areas

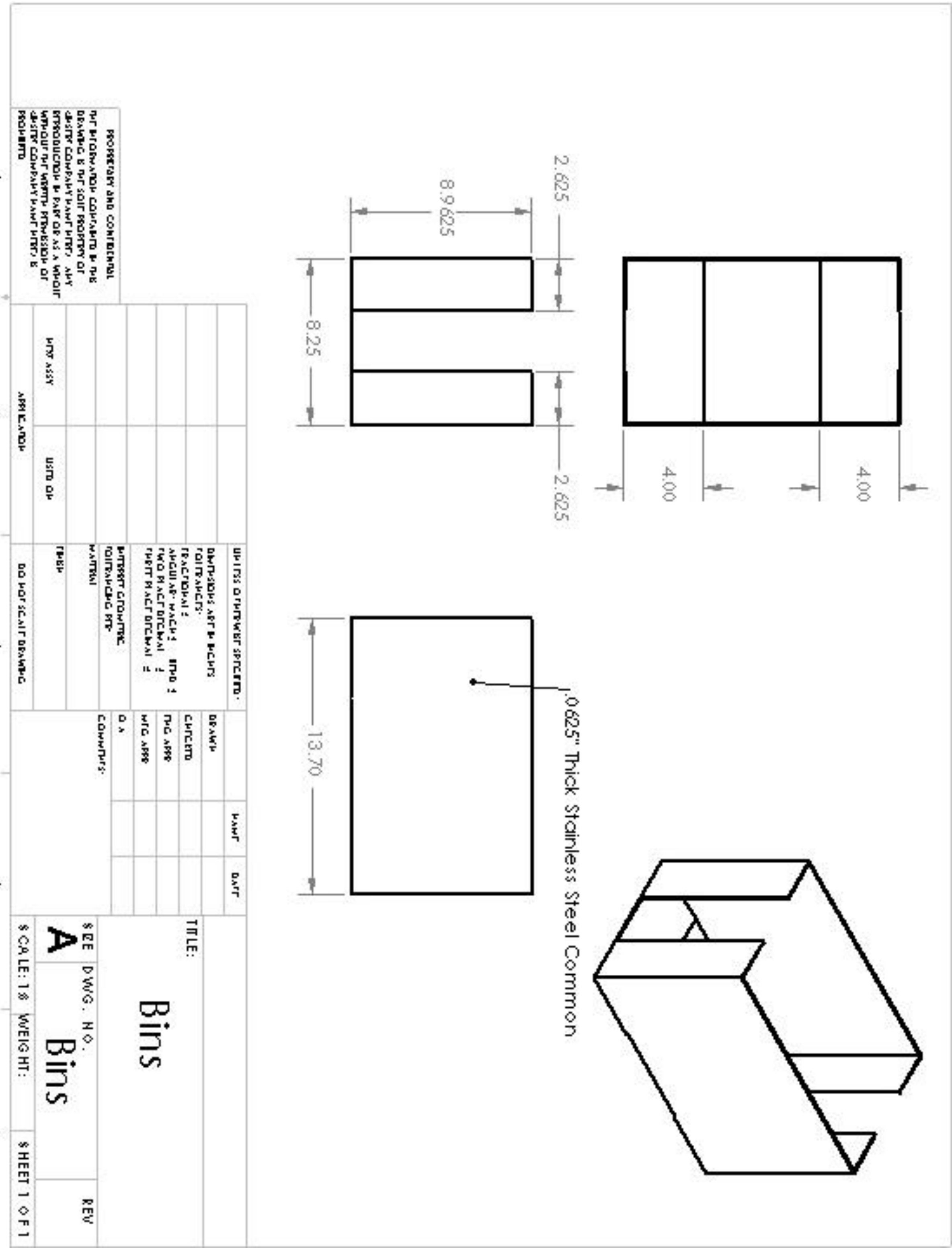


Figure A.3: Bins that hold the slide folders

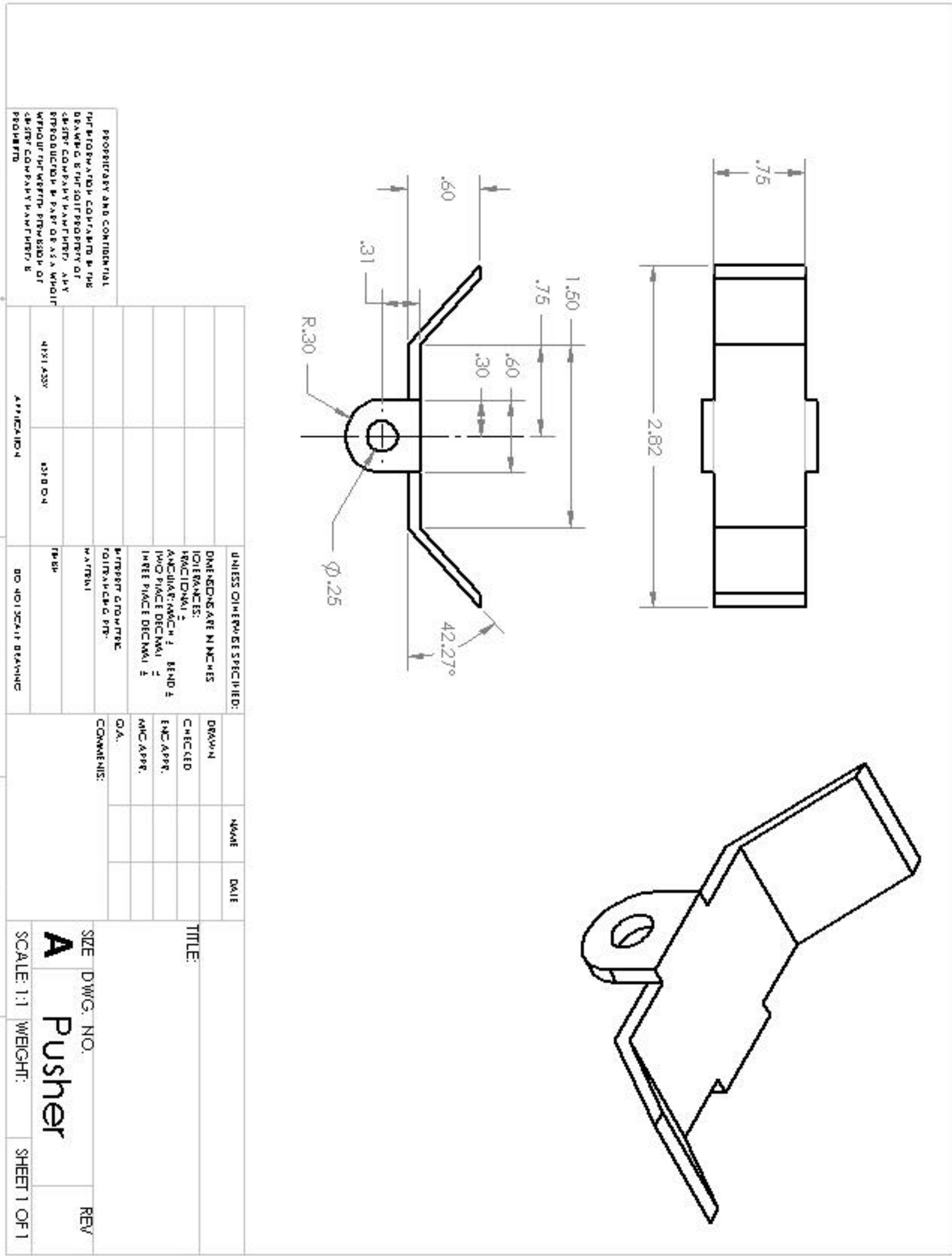


Figure A.4: Main Pusher Piece which connects the pusher assembly to the actuator rod

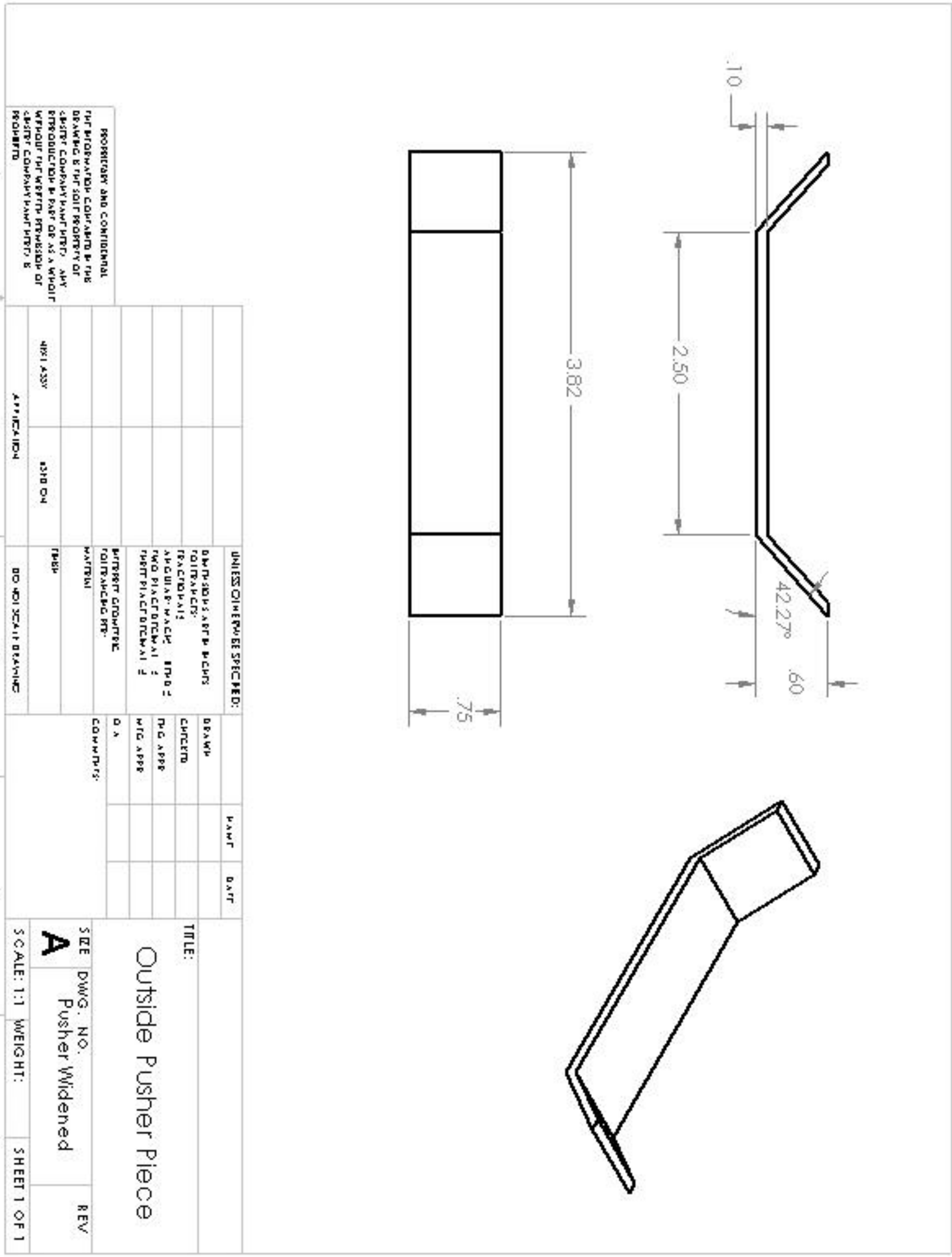


Figure A.5: Outside Pusher Piece to distribute the actuator upward force evenly across the bottom of the slide folder stack

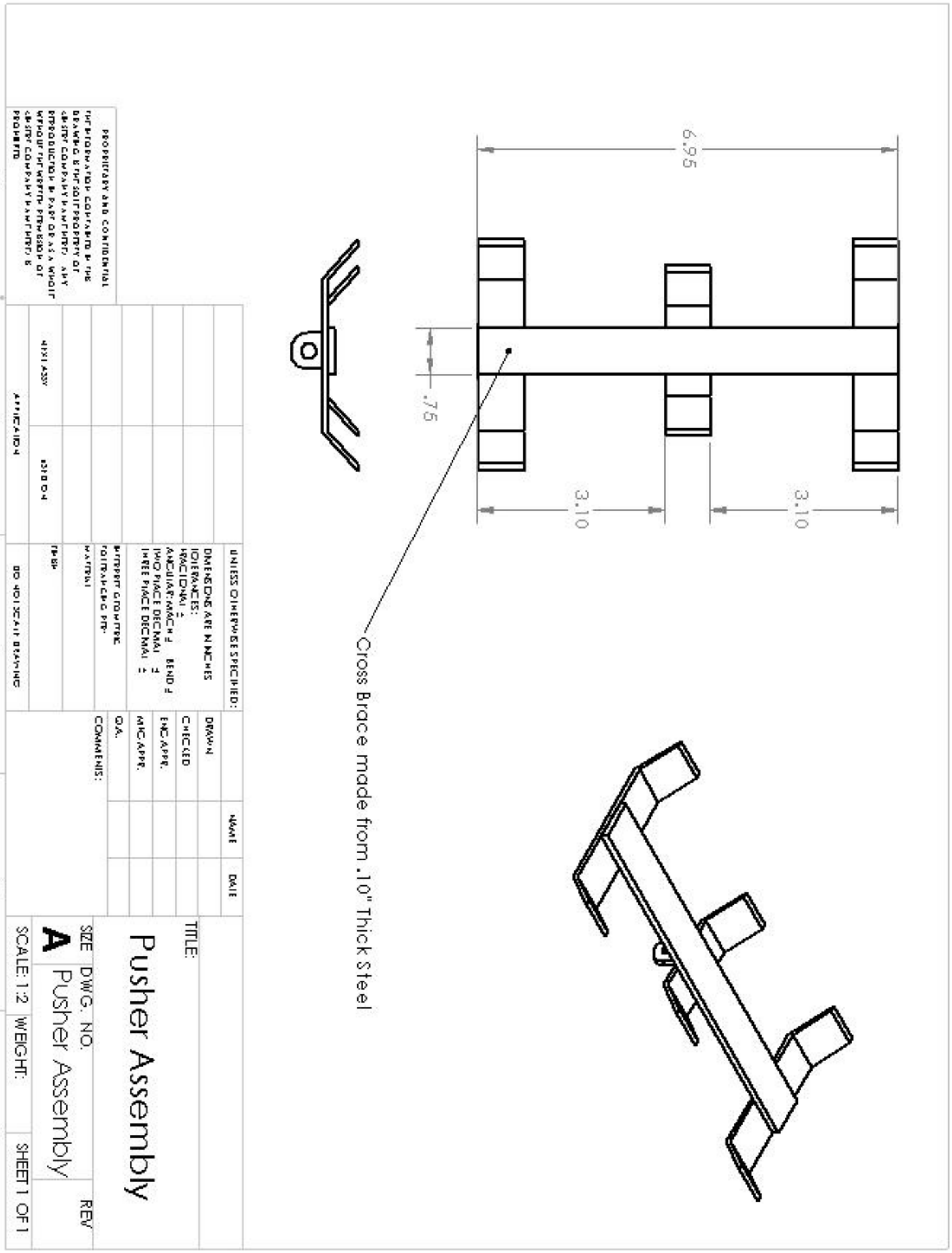


Figure A.6: Complete assembly of the pusher connected to the actuator system

APPENDIX B: DRAWINGS FOR FOLDER OPENING/HOLDING SYSTEM

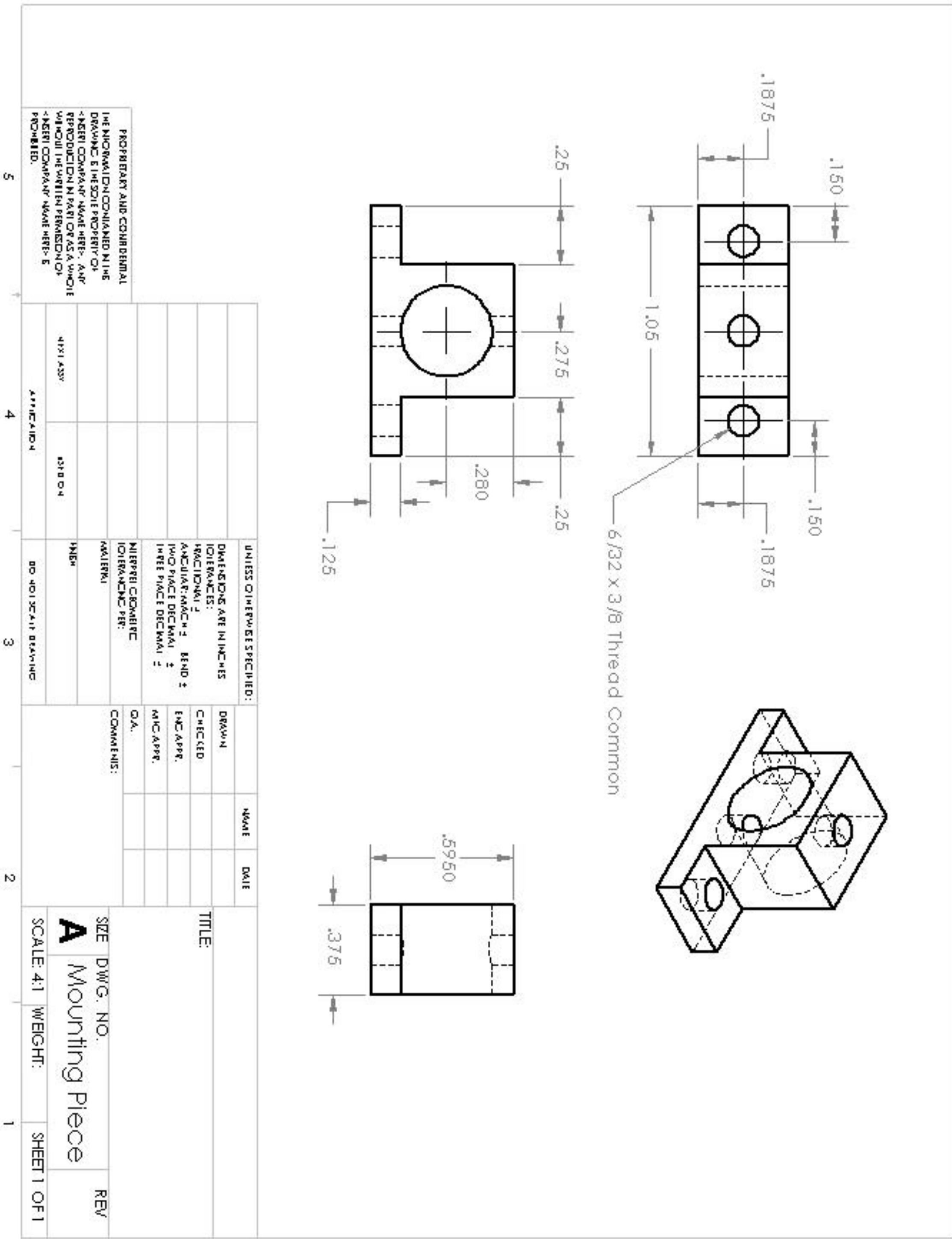


Figure B.1: Mounting Piece which connects the sucker assembly to the servo arm. This piece is nearly identical between the Holding and Opening Systems. The Opening System simply has a larger servo arm hole.

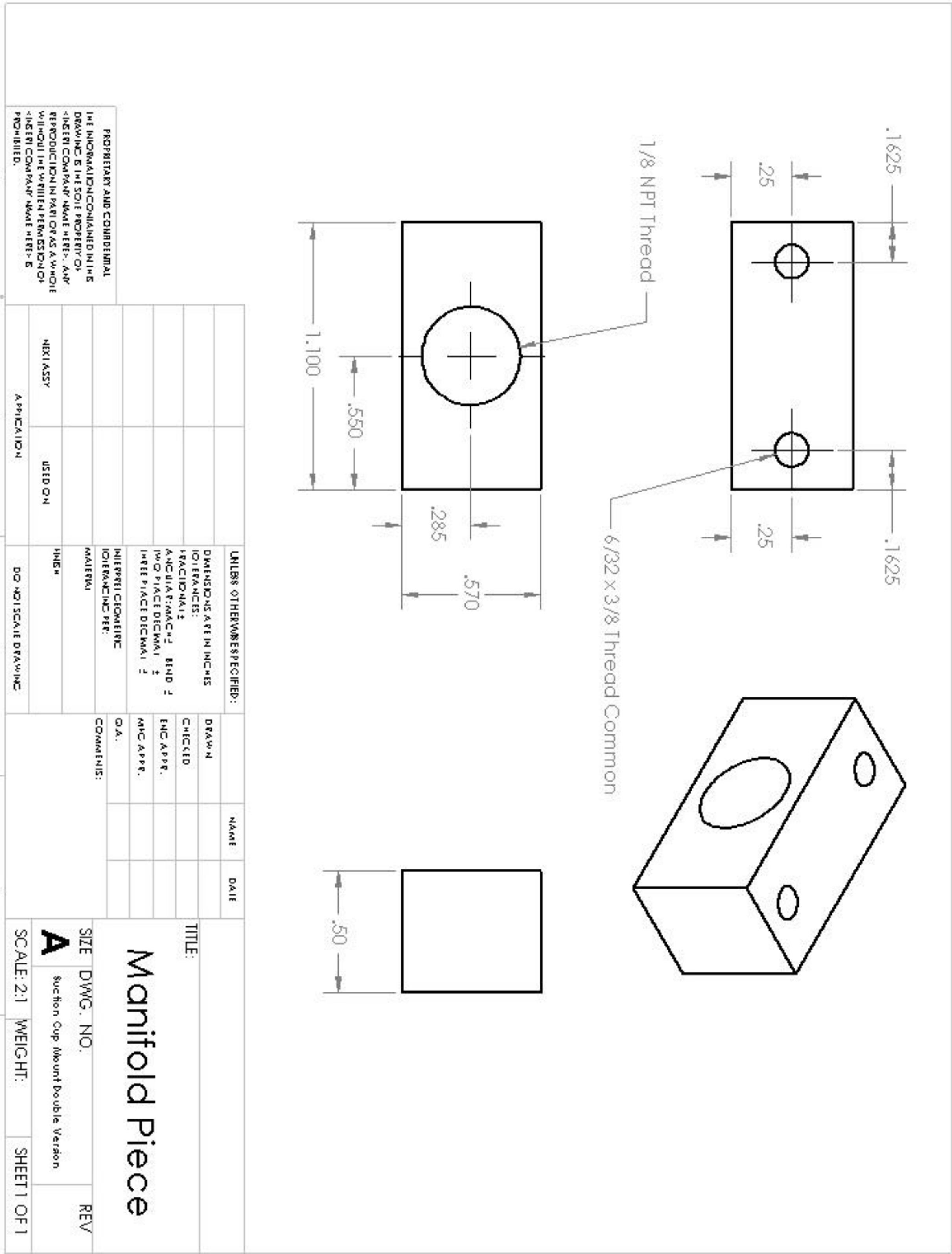


Figure B.2: Manifold Piece which connects the sucker fitting to the mounting piece for the Folder Opening System which uses two servo arm assemblies

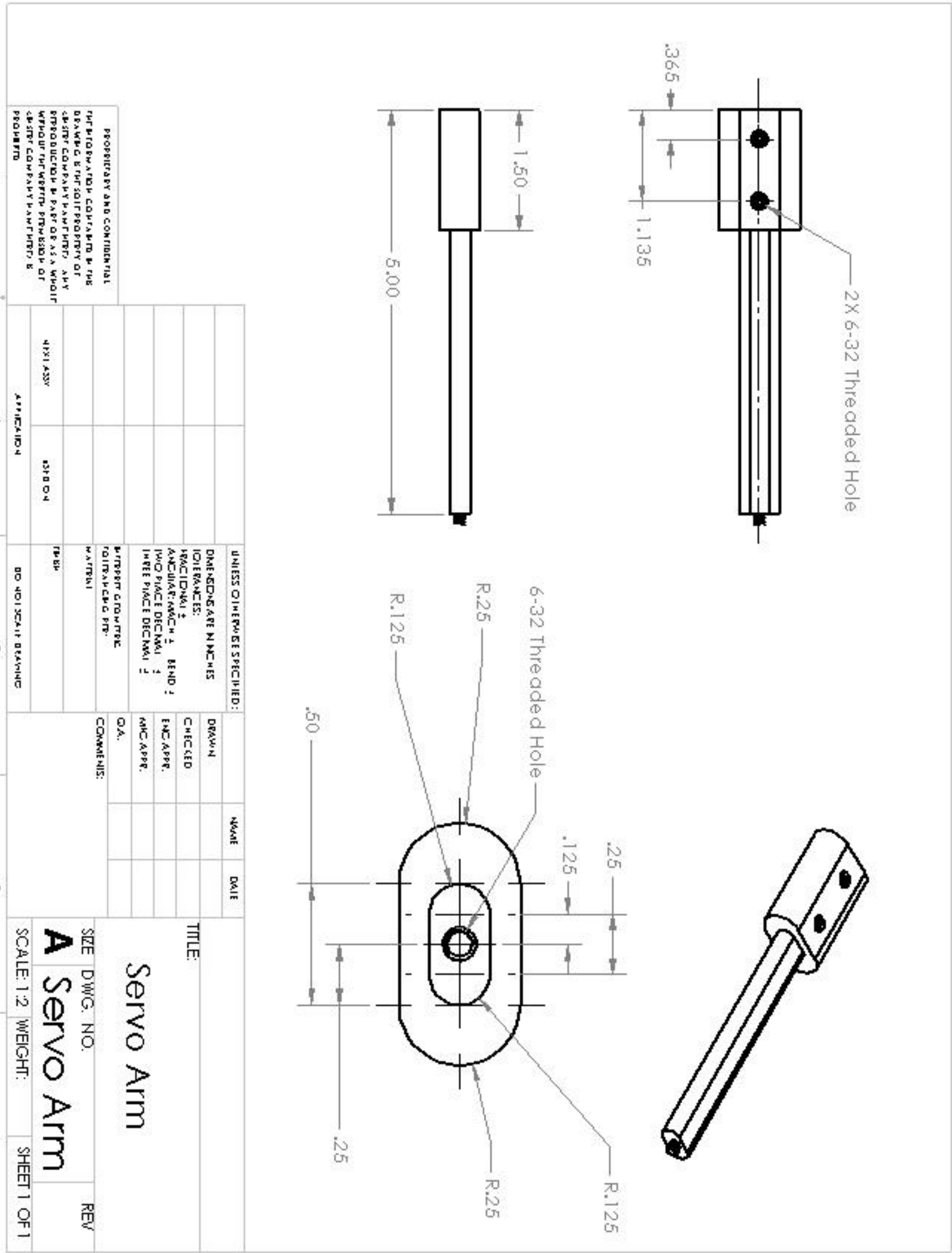


Figure B.3: Servo Arm used to connect the sucker pieces to the servo motors and allow for the folder opening action. This piece is identical for both the Opening and Holding Systems.

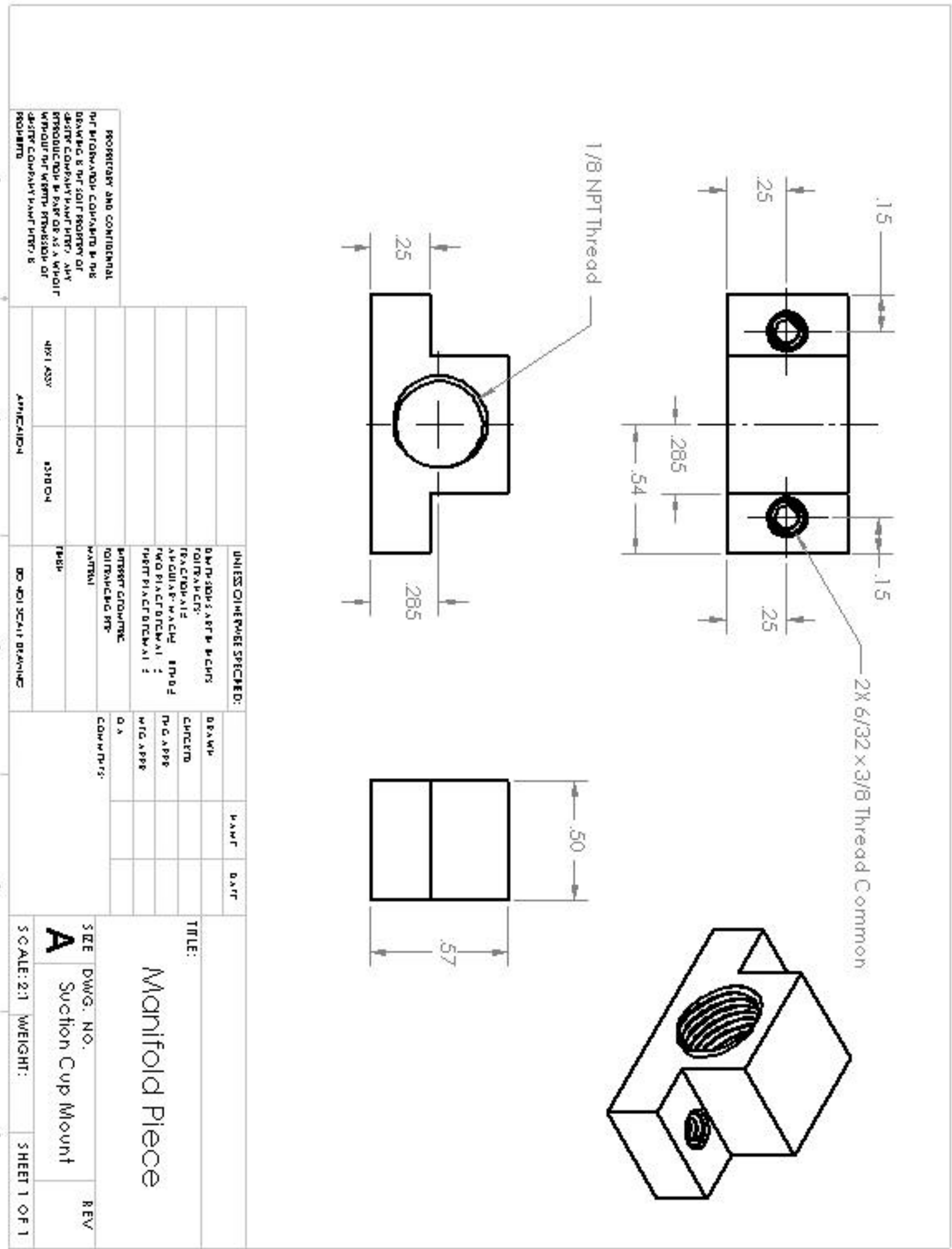


Figure B.4: Manifold Piece which connects the sucker fitting to the mounting piece for the Folder Holding System which only uses one servo arm assembly.

APPENDIX C: DRAWINGS FOR THE SLIDE MOVEMENT SYSTEM

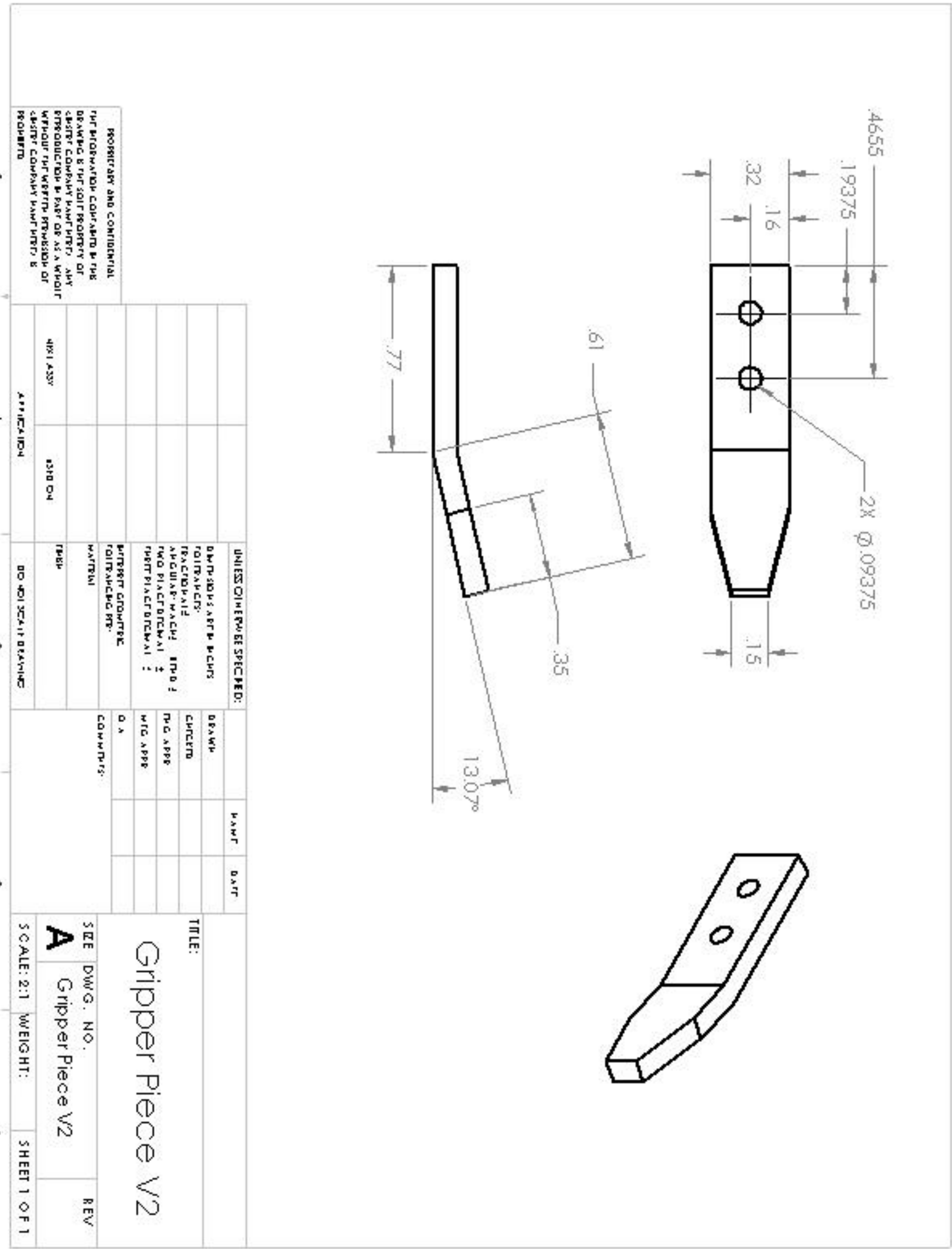


Figure C.1: Gripper Pieces used to create the jaw for the gripper assembly.

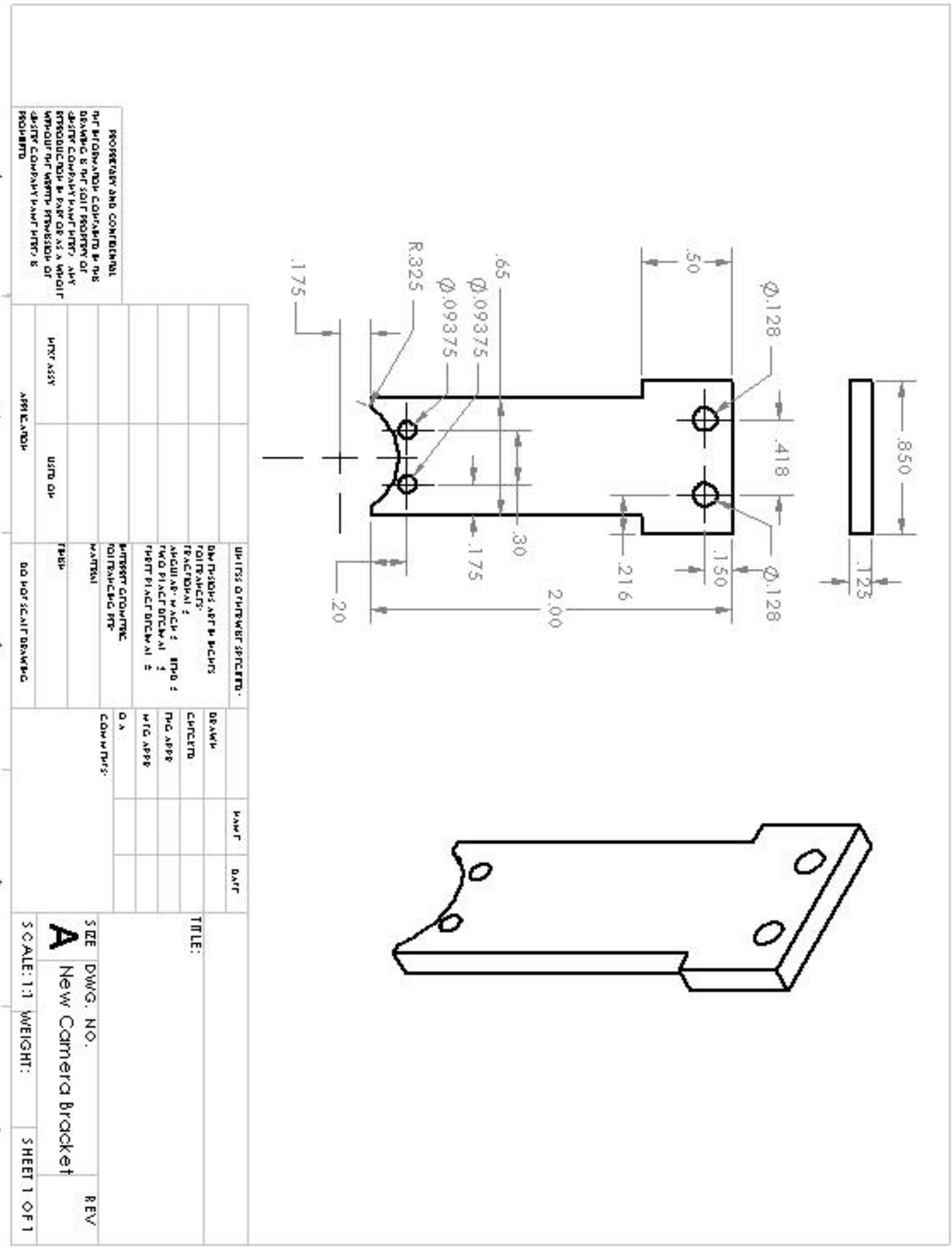


Figure C.2: Camera Bracket used to mount the camera on the gripper assembly

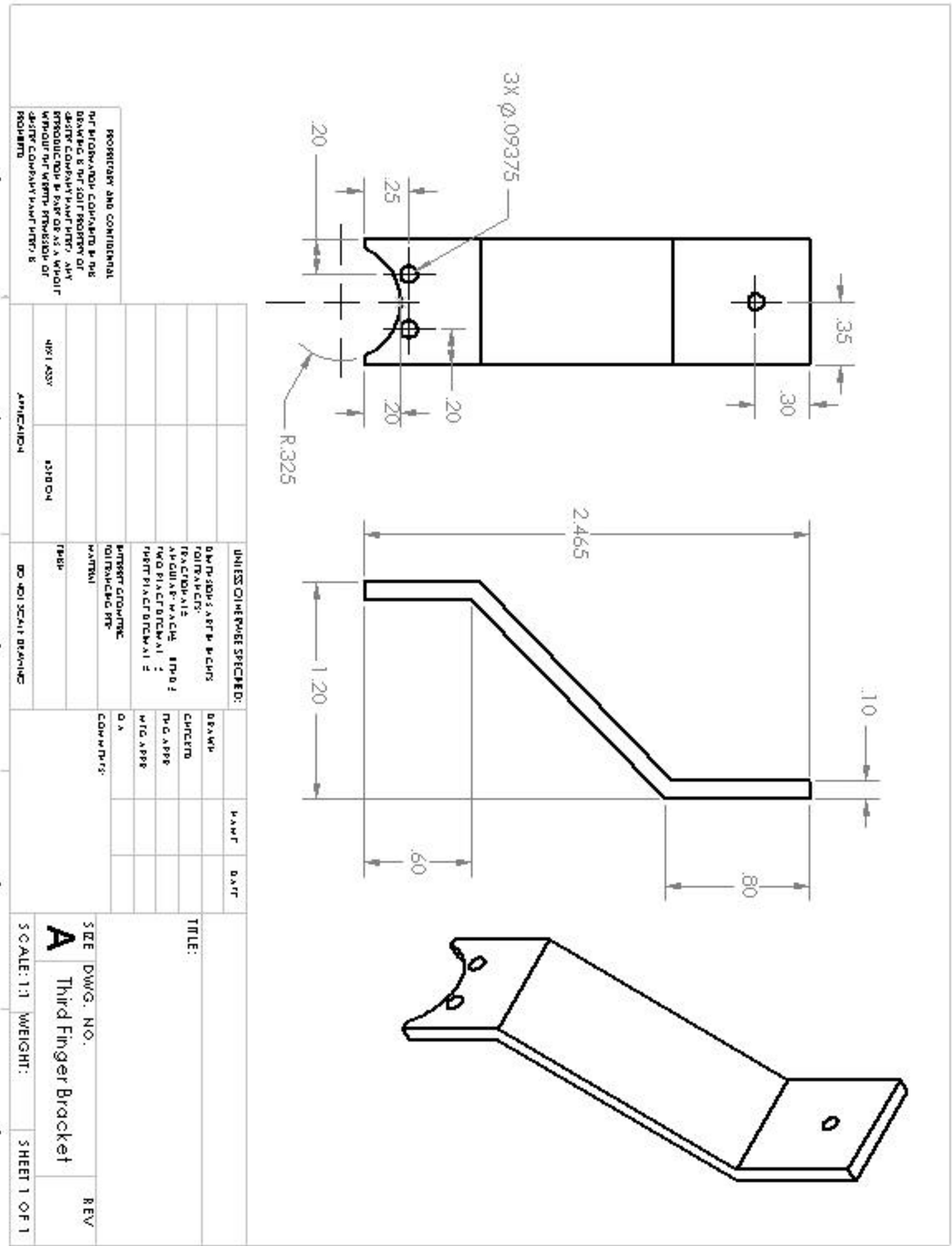


Figure C.3: Third Finger Bracket used to create a three finger gripper to lift slides out of the slide folder slots

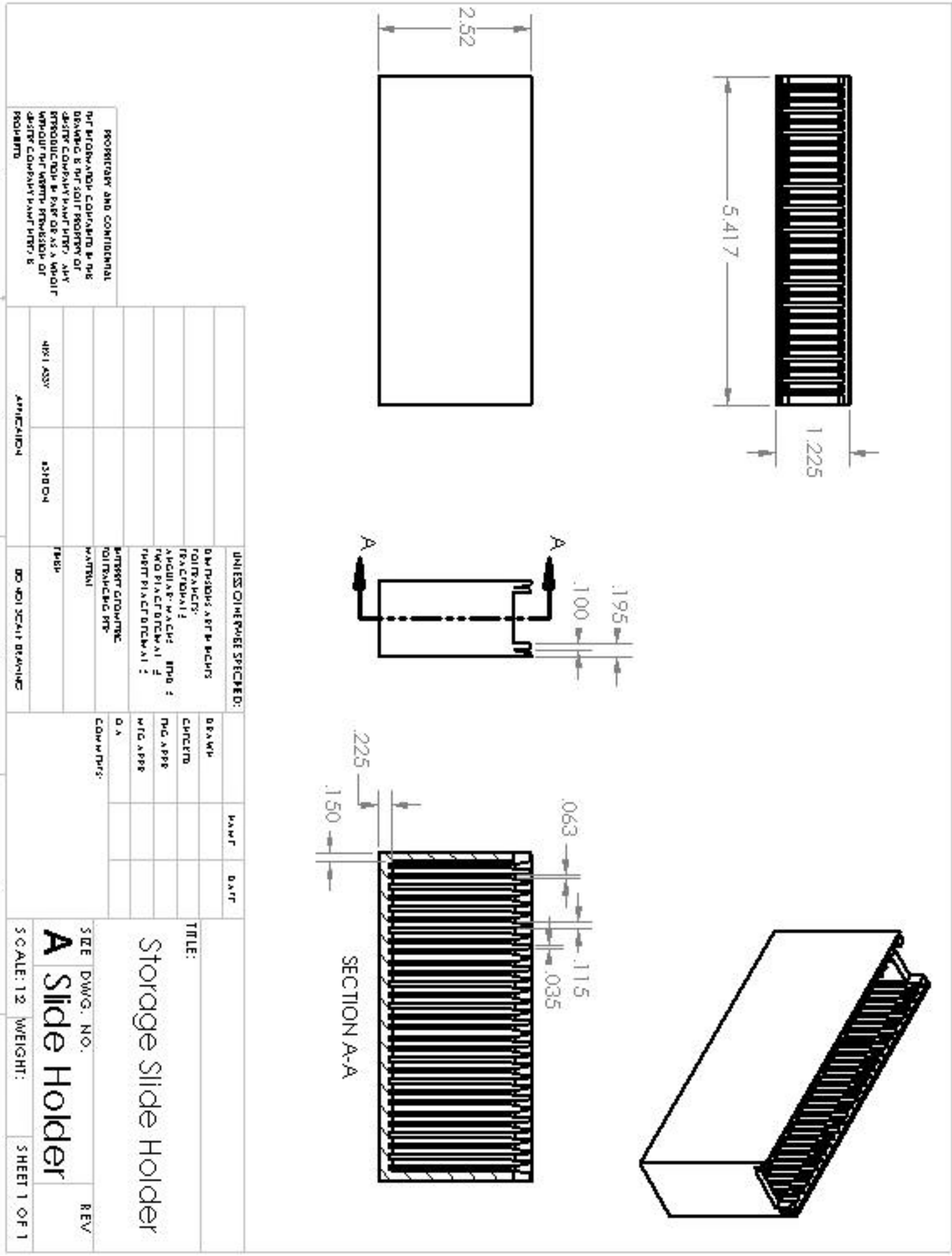


Figure C.4: Slide Holder used to store medical slide specimens

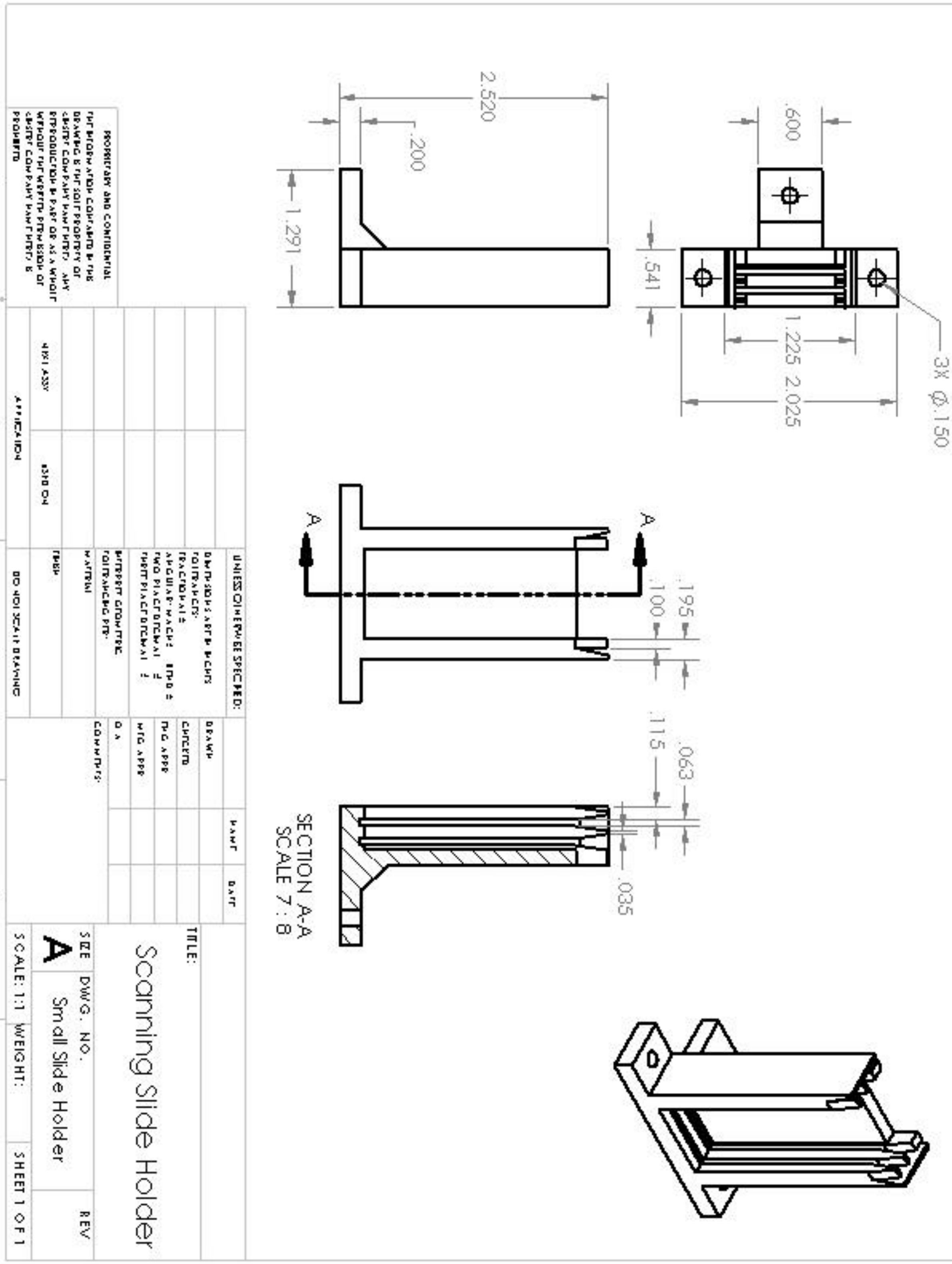


Figure C.5: Smaller Slide Holder used to hold slides being scanned into or out of storage and to help the gripper reorient it's gripping position on the active slide