Design and Development of a Placement Mechanism for an Automated Packaging Machine

By

Steven Ratner

B.S. Mechanical Engineering
Boston University, 2015

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING IN ADVANCED MANUFACTURING AND DESIGN
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

September 2019

Signature of Author: Signature redacted

Steven Ratner
Department of Mechanical Engineering
August 9, 2019

Certified by: Signature redacted

David Hardt
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by: Signature redacted

Nicolas Hadjiconstantinou
Professor of Mechanical Engineering
Chairman, Committee for Graduate Students

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Abstract

This thesis describes the development of an automated packaging machine capable of transitioning bulk vials into containers of 100 nested vials. Specifically, this thesis focuses on the design of an automated placement mechanism that is used in the packaging machine to feed groups of 10 vials into a tray for shipment. The placement mechanism is composed of a rake into which the vials are funneled, allowing the rake to push a line of 10 vials forward, dropping below into a tray. Creation of the placement mechanism aids the packaging machine automate the loading of vials, decreasing labor, increasing throughput, reducing packaging components, and implementing a layer of robustness to the process through automatic inspection and recording. An explanation of antecedent packaging procedure along with industry priorities are reported along with the methodology behind the mechanical design that went into creating the mechanism. The constructed packaging machine is theoretically capable of packing 30 packages per hour.

Thesis Supervisor: David E. Hardt
Title: Professor of Mechanical Engineering

Acknowledgments

Thank you, Valentina.

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Chapter 1

Introduction

This chapter outlines the background and motivation behind Waters' request for an automated packaging machine to be designed and constructed. Furthermore, the project's objectives, scope, and work distribution are reviewed to provide the reader with a proper understanding of the program's purview.

1.1 Background and Motivation

The analytical laboratory instrument manufacturing company, Waters, produces a comprehensive range of system solutions for the life sciences industry. Liquid chromatography and mass spectrometry machines are the center of Waters' product offering. As a holistic supplier of its services, Waters provides auxiliary goods to support its laboratory instruments.

One such auxiliary product, QuanRecovery, was introduced to the market in Q2, 2019. QuanRecovery minimizes the effect of sample loss due to non-specific binding and ionic interactions through a proprietary treatment. This treatment is applied to the interior surface of 1ml vials, shown in Figure 1-1, that are sold to laboratories globally. Through a successful marketing campaign, propelled by the addition of free chemistry socks with every order, a well-known favorite amongst scientists and procurers alike, Waters' obtained excellent early adoption after considerable initial interest as a result of marketing efforts and product quality. Figure 1-2 displays an advertisement of the QuanRecovery vials along with the aforementioned chemistry socks.

Figure 1-1: Side view of a 350µl QuanRecovery vial. Vial measures 12mm in diameter at the base by 32mm in height.

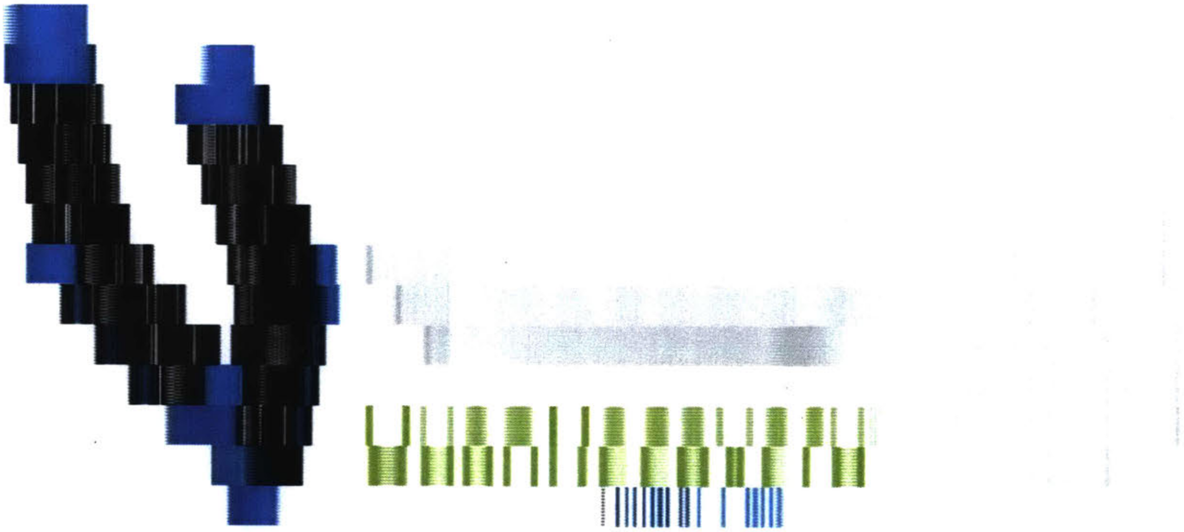


Figure 1-2: An advertisement for QuanRecovery vials and plates with the inclusion of chemistry socks [1]. Note: Chemistry socks and vials are not drawn to scale. This figure represents the advertisement Water's used to allure customers to buy QuanRecovery vials.

Waters sells the 350µl vials in packs of 100, as shown in figure 1-3. Experimentation indicates a human takes 2 minutes to package 100 vials by hand. With an estimated labor rate of

15 dollars per hour, close to 0.5 dollars per pack could be eliminated with an automated system. Additionally, hand packaging is disadvantaged in the precision of vial placement and the containment of external particulate. The human packagers have been known to input 99 vials instead of 100 vials, leading to an increased probability of breakage during transit. Due to the uncertainty of vial count, Waters is forced to label similar products packages as having 'approximately 100' vials instead of '100' vials. With the introduction of this automated system into the first QuanRecovery production line, Waters will be able to label the packages as '100'.

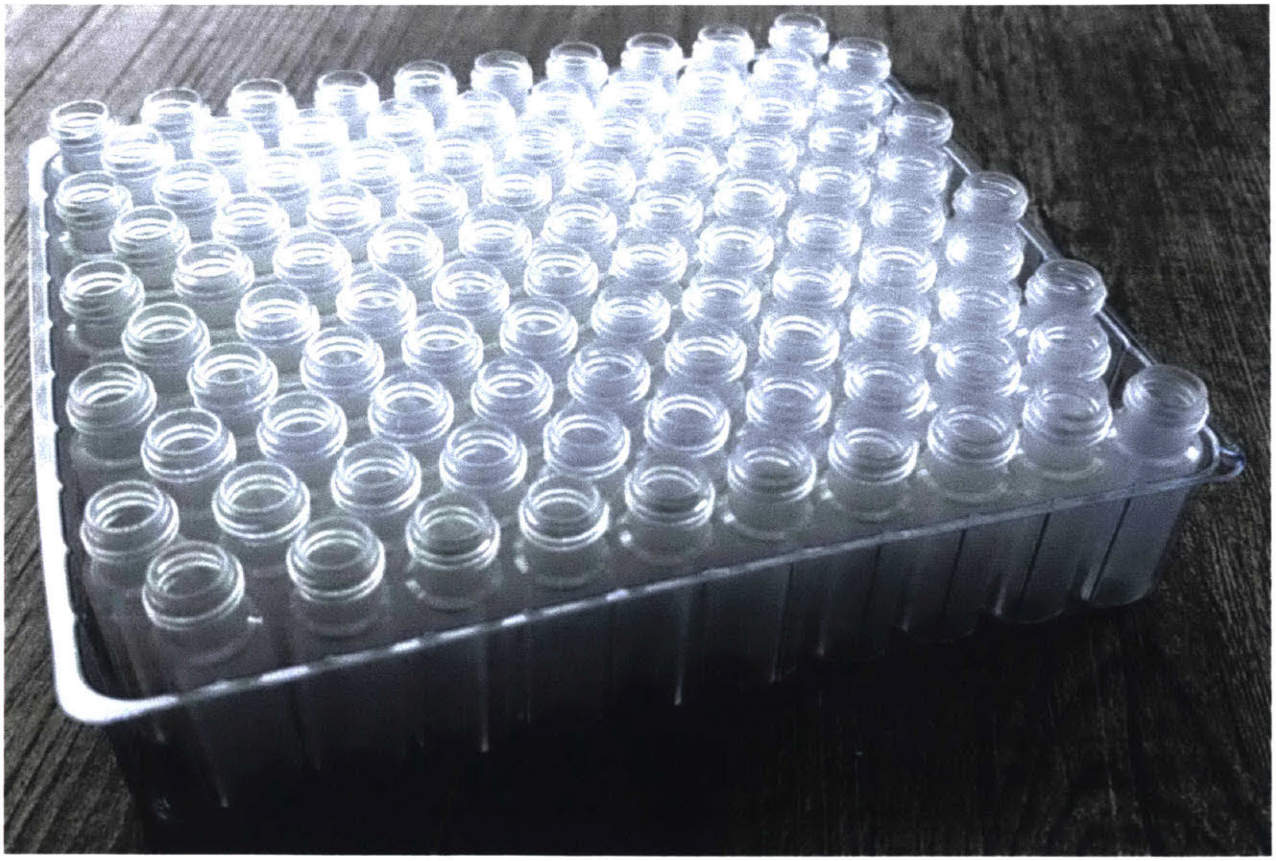


Figure 1-3: A package containing 100 350μl vials with QuanRecovery treatment. Note: Vials in the package are positioned in a 10 by 10 matrix with every other row being staggered to nest in as tight packed of a position as possible. All vials are facing 'upward' with their opening situated at the top of the container.

The downsides of Water's current packaging methods prompted the company to enlist help from the 2019 MIT MEng cohort to develop an automated solution that would robustly place 100 vials into each container. This thesis describes the solution that was created to replace Waters' human packaging system.

1.2 Objectives

The project proposed to design an automated system that would take a pile of vials and correctly place them facing upwards in groups of 10 by 10 to fill a 100-vial container in a repeatable manner. The key objectives were as follows:

- Receive a bulk pile of unoriented vials and place them in a 10 by 10 matrix facing upwards in a vial package.
- Package a minimum of 100 vials per 2 minutes.
- Minimize external particulates from accumulating within the vials.
- Validate that 100 vials are placed into each package.
- Keep development and production costs under $10,000.

1.3 Scope

The project scope was contained to developing and building a functional prototype, displayed in Figure 1-4 below, that could be used to demonstrate the potential for the proposed automated machine. Once the prototype was complete and working, engineering drawings of each custom component were made along with an assembly and user manual. This way, Waters could manufacture and operate future iterations of the machine as production levels deemed necessary.

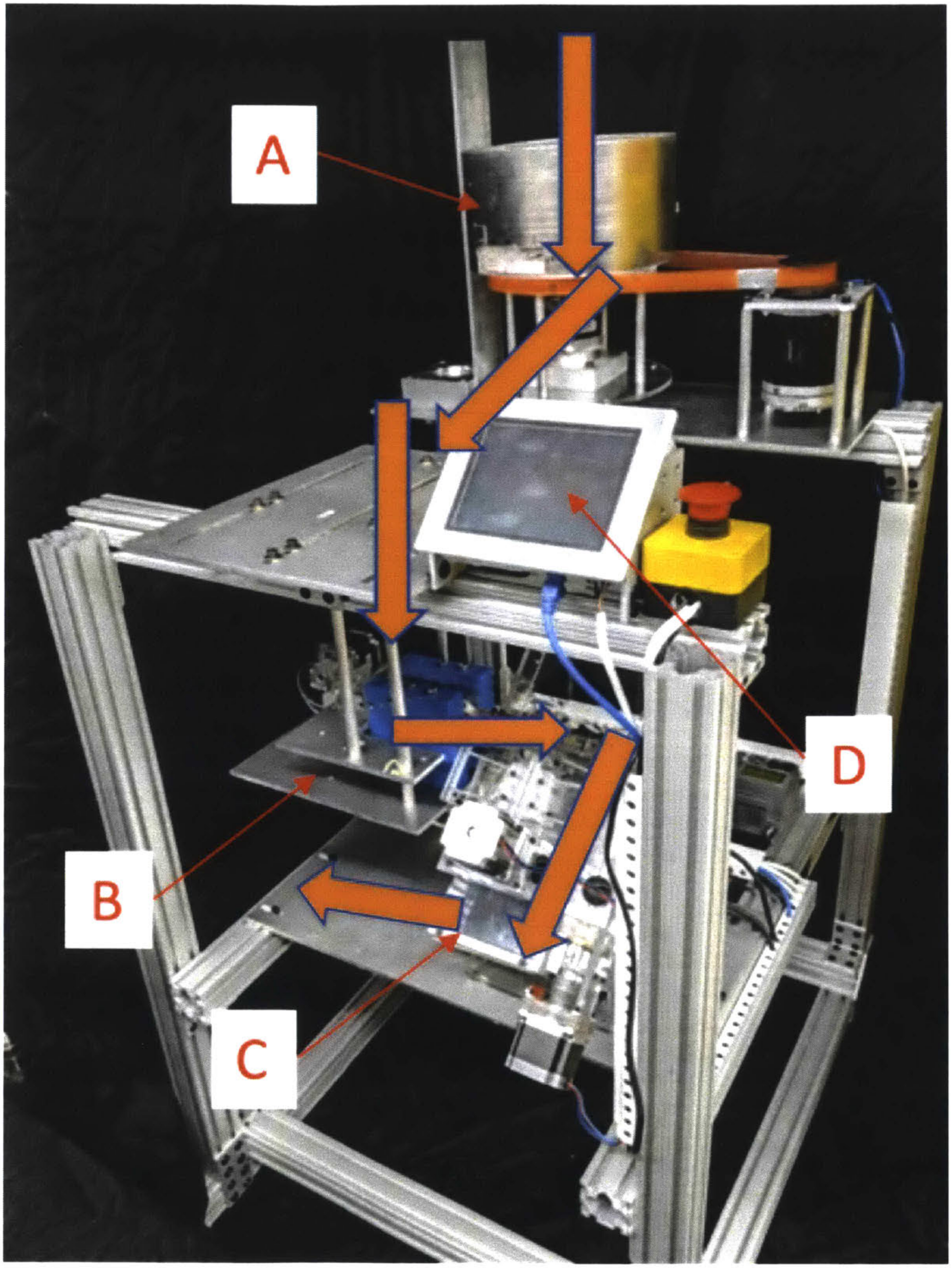


Figure 1-4: Functional automated packaging machine prototype. A) Vial acceptor and orienter. B) Transfer line feeder. C) Vial placement mechanism. D) Control panel. Note: Orange

arrows represent the path vials flow as they make their way through the machine. Loose vials are placed in the vial acceptor and orienter, moved through the transfer line feeder, then stacked in the vial placement mechanism.

1.4 Work Distribution

The system was split into five main tasks as listed below:

(1) Orienting the vials from a bulk unorganized state.

(2) Feeding the oriented vials into the placement mechanism through a transfer line.

(3) Packaging the vials into trays.

(4) Validating the packaged vials to ensure they are correctly placed.

(5) Motor selection and control.

Initially, all of the group members worked on each of the tasks together. However, after the inceptive brainstorming stage was complete, the five tasks were split between each of the teammates for the sake of efficiency. The owners of each task are as follows: (1) Zhengyang Zhang [2], (2) Efstratos Moskofidis [3], (3) Steven Ratner, (4) Siyang Liu [4], (5) Diarny Fernandes [5].

Chapter 2

Automation

This chapter presents a definition for automation; one that will be used as the premise for why the packaging machine creation is relevant in the 21st century. Furthermore, the societal impact of automation is briefly explored.

2.1 Defining Automation

In the history of the manufacturing industry, the transition from hand-made to automated work has taken many forms over the last quarter-century. Current buzzwords such as machine learning, data analytics, artificial intelligence and the Internet of Things (IoT) are redefining what popular belief would have once suggested was the face of automation: robotics. Even over the last five years, many questions have been raised about what truly defines automation and where it is going. In the workplace there are concerns over the ethics of replacing the human being with a machine. In the home there is concern over data collection and privacy, where both logical and physical machines are recording what we say, tracking products and services we prefer, and tailoring the media we consume to our analyzed behaviors. It is easy to get lost in the many thousands of online articles warning of the impending danger of becoming a more mechanized civilization. However, from the perspective of an engineer, we must see the state of the art for what it is in order to extract from the hysteria the truly plausible implications of increasing automation.

For the purposes of this thesis, automation will be defined as the use of a computer-guided mechatronic system to perform a physical task with little to no human intervention. The system may also collect data on its environment and respond to stimuli in that environment. However, it is not necessary for the system to do so in order to abide by this crude definition of automation. In this thesis we will focus specifically on what the human being relies on the machine to do and what types of mechanical intervention can be considered automation by this definition. We will explore the motivations for implementing physical automated systems on the factory floor and not software-only solutions such as data analytics and machine learning. These are for another technical discussion that is out of the scope of this particular thesis. For more detailed work on Industry 4.0 integration for this project, refer to Siyang Liu's thesis: Design and development of an automated inspection system for vials [4].

2.2 Reasons for Automation Implementation

Increasing throughput, reducing injury from repetitive motion or boredom, and making manufacturing less costly may immediately come to mind as the main motivations for the manufacturing industry to implement automation. With a computer-controlled machine the benefits are nearly immediate to understand: the company no longer has to pay an employee's hourly wage, insurance or other benefits just so he or she can continuously perform a single task or flow of tasks. The employee may then seek more engaging, personally fulfilling or challenging work.

Chapter 3

System Overview

This chapter provides a synopsis of the vial packaging system's features, layout, and operation. Specifically, the system is broken down and detailed through its five principal components. Figure 3-1 below displays the final layout of the prototype machine.

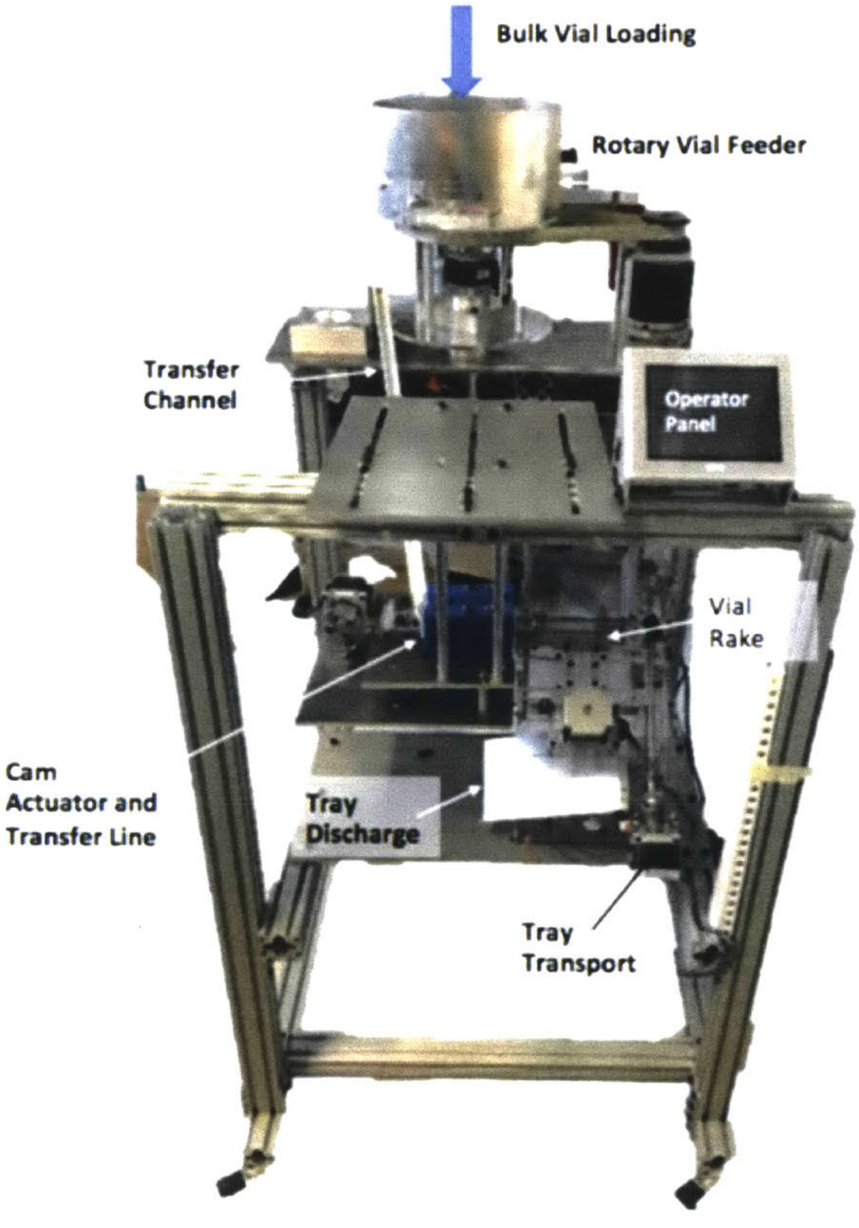


Figure 3-1: Annotated layout of the protype machine [5].

3.1 Vial Accepter and Orienter

The vial sorting system is the first stage of the automated machine. It accepts loose vials in bulk and outputs singulated vials, all with the same final orientation. Figure 3-2, 3-3, and 3-4 below displays the setup of the vial sorting system, resembling a bowl feeder.

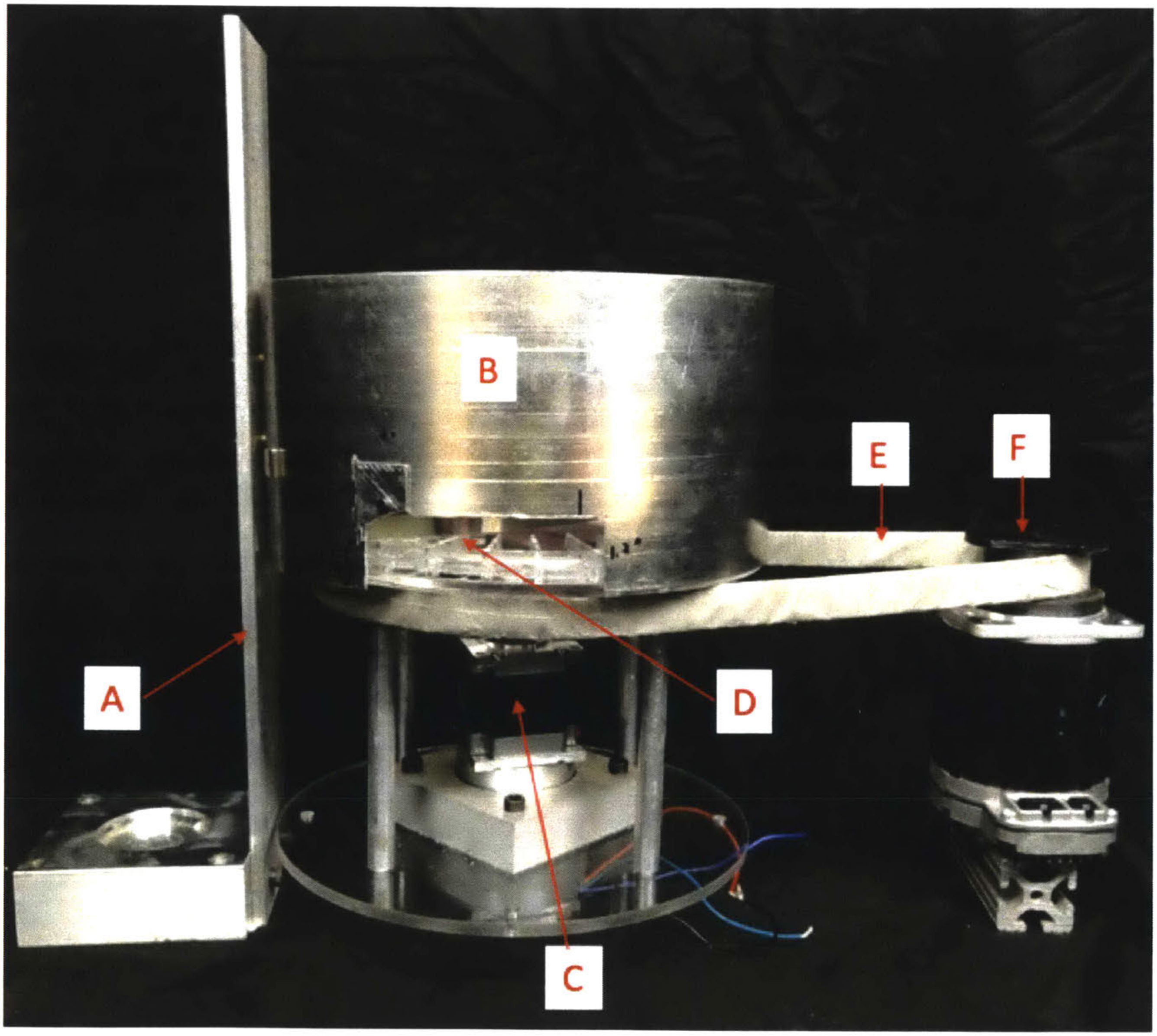


Figure 3-2: First stage of the automated packaging machine, vial accepter and orienter. A) Vial orienter bowl stand. B) Vial orienter bowl. C) Internal vial orienter bowl motor. D) Oriented vial exit point. E) Drive belt. F) External vial orienter bowl motor.

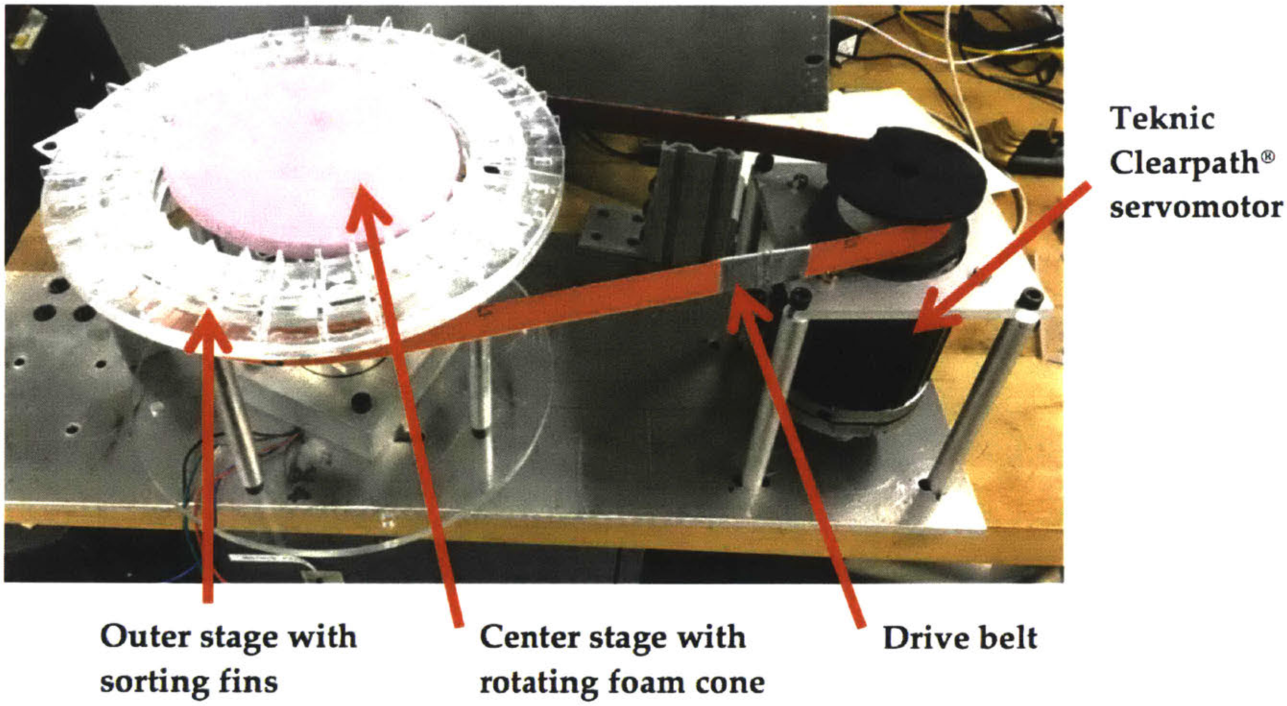


Figure 3-3: First stage of the automated packaging machine with the outer shell of the vial orienter bowl removed to reveal sorting acrylic sorting fins along the outer shell of the feeder [5].

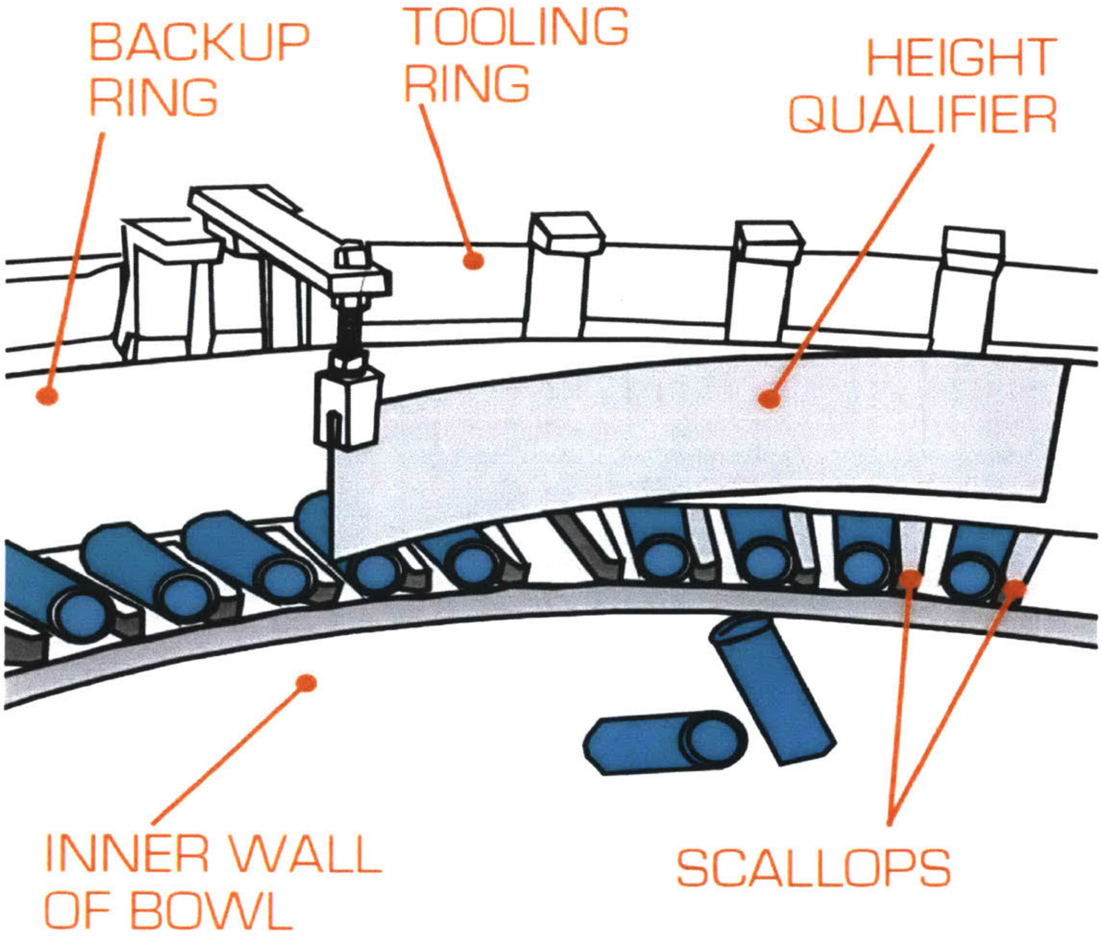


Figure 3-4: Drawing of the inner segment of the vial orienter displaying the 'height qualifier' pushing unoriented vials out of the 'scallops' while leaving oriented vials to pass through the system [5].

The sorting system contains by three primary components: a center disk that accepts loose vials and transports them, a bowl with scallops that singulates vials, and viarious selectors that retain vials facing the desired orientation while rejecting non-oriented vials. The inclined center disc rotates, applies centrifugal force on vials, and propels them onto the scallop pockets. The bowl also rotates continuously and moves the vials past series of passive mechanical selectors which reject vials that are not properly nested within the scallops and not facing the right orientation. The rejected vials are returned to the center of the bowl and recirculated; the retained vials are pushed out of the bowl and move on to transfer line.

For a more detailed overview on the design, development, and performance of the vial sorting mechanism, refer to Zhengyang Zhang's master's thesis: Design and development of an automated sorting and orienting machine for vials [2].

3.2 Transfer Line Feeder

The transfer line feeder is the second stage of the automated machine. It receives sorted vials from the vial accepter and orienter and transfers them to the vial packaging mechanism at the proper cadence and alignment. Figures 3-5, 3-6, 3-7, and 3-8 below displays the transfer line feeder.

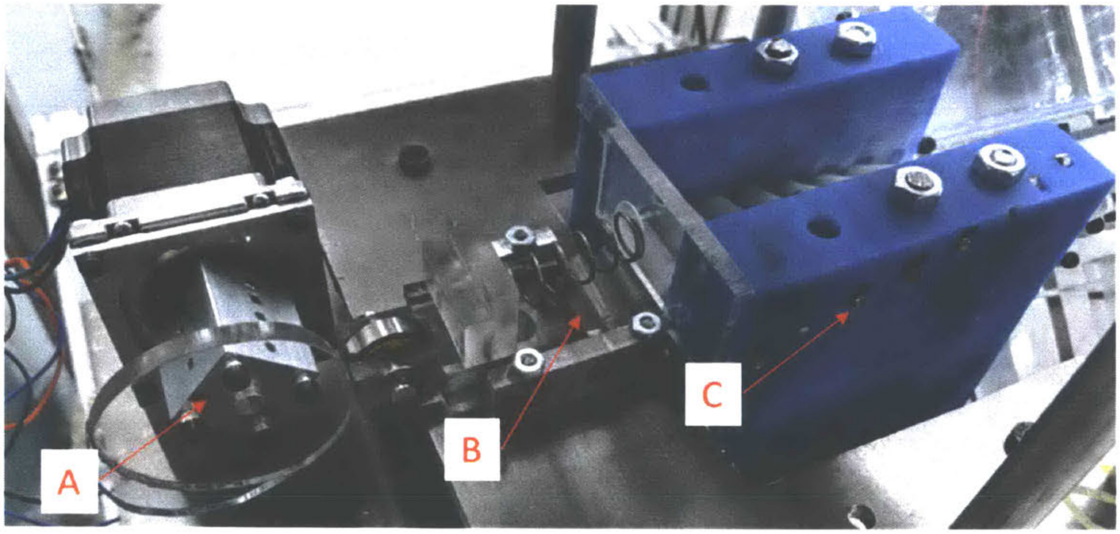


Figure 3-5: Second stage of the automated packaging machine, transfer line feeder. A) Cam mechanism. B) Vial pusher. C) Vial turner.

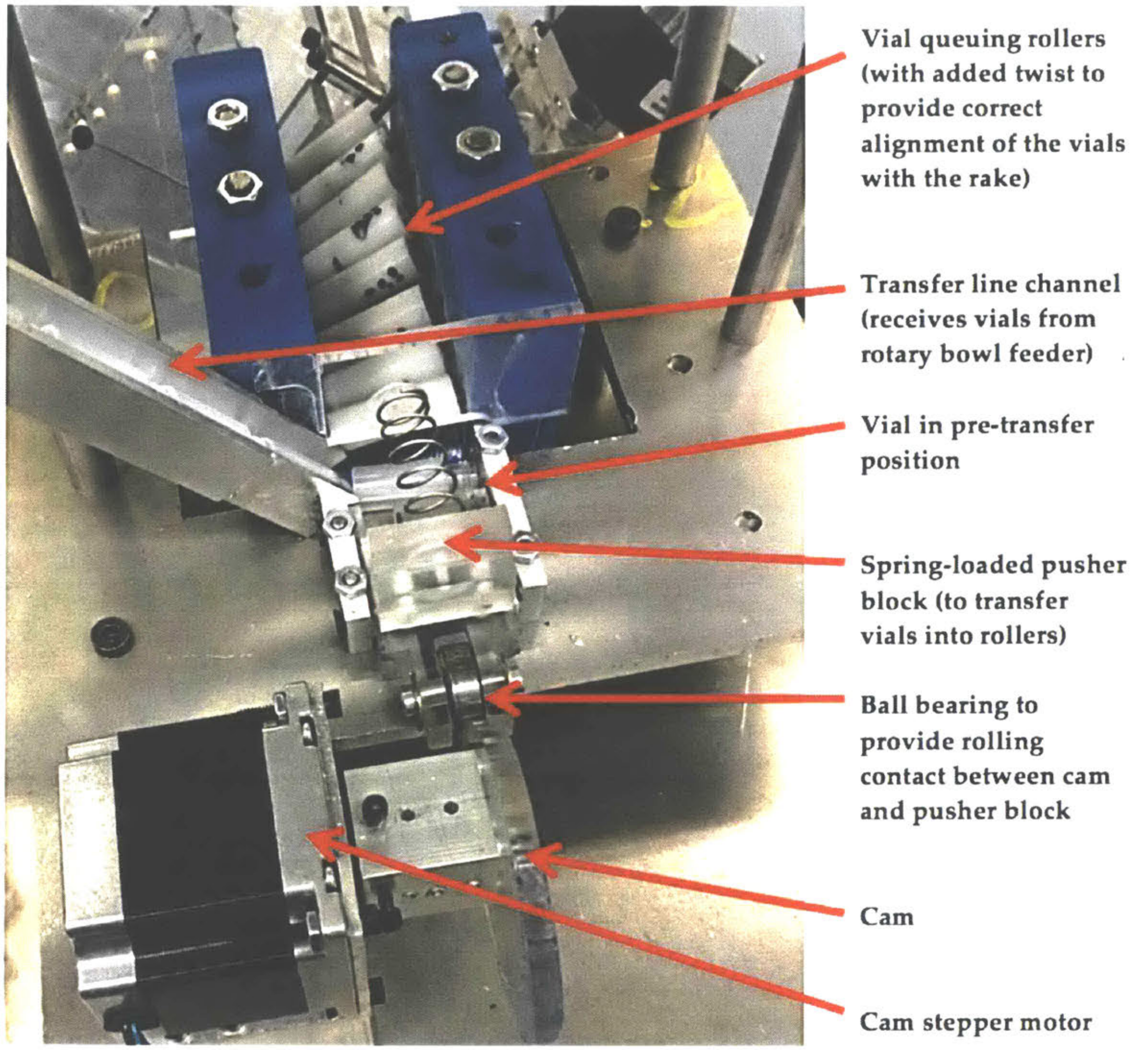


Figure 3-6: Picture of the vial transfer line system indication the position of major components [5].

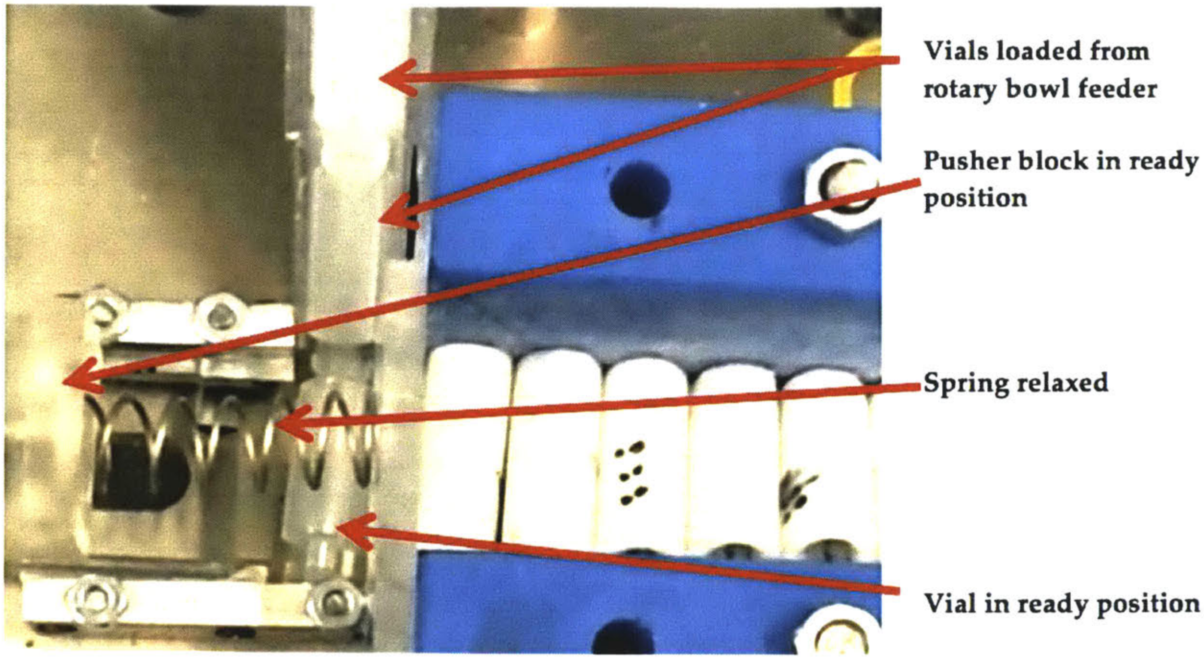


Figure 3-7: Picture of the transfer line feeder in the initial state as vials are being loaded into the queue position [5].

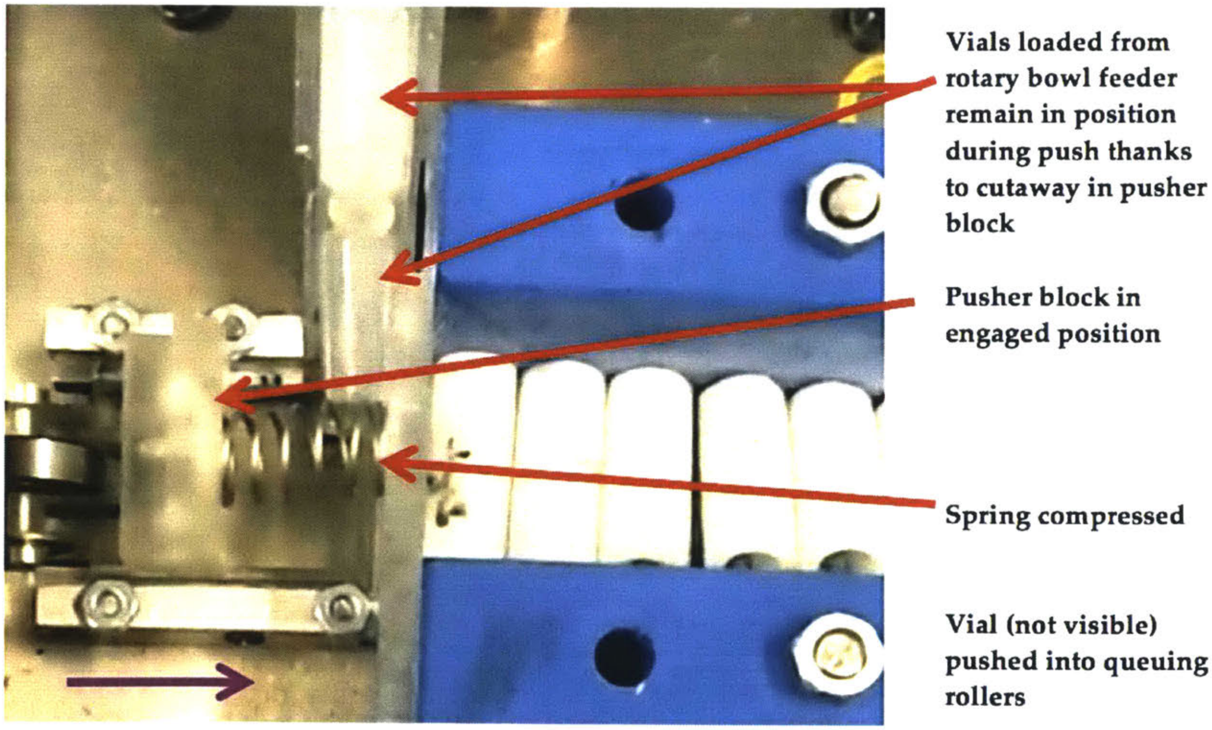


Figure 3-8: Picture of the transfer line feeder in the final state as a loaded vial is being pushed into the orienting system [5]

The transfer line feeder contains three subsystems: a channel acting as a queue accepting vials from the sorting and orinenting system, a vial pushing mechanism that propels vials through a turner, and a turner that orients vials at the correct inclination to match with the placement mechanism's angle.

For a more detailed overview on the design, development, and performance of the transfer line feeder, refer to Efstratios Moskofidis' master's thesis: Design and development of a transfer system for an automated vial packaging machine [3].

3.3 Vial Placement Mechanism

The vial placement mechanism performs two primary tasks: loading the oriented vials into a tray and queueing empty trays to be loaded with vials. Figures 3-9 and 3-10 below displays a diagram of the placement mechanism with the major components labeled.

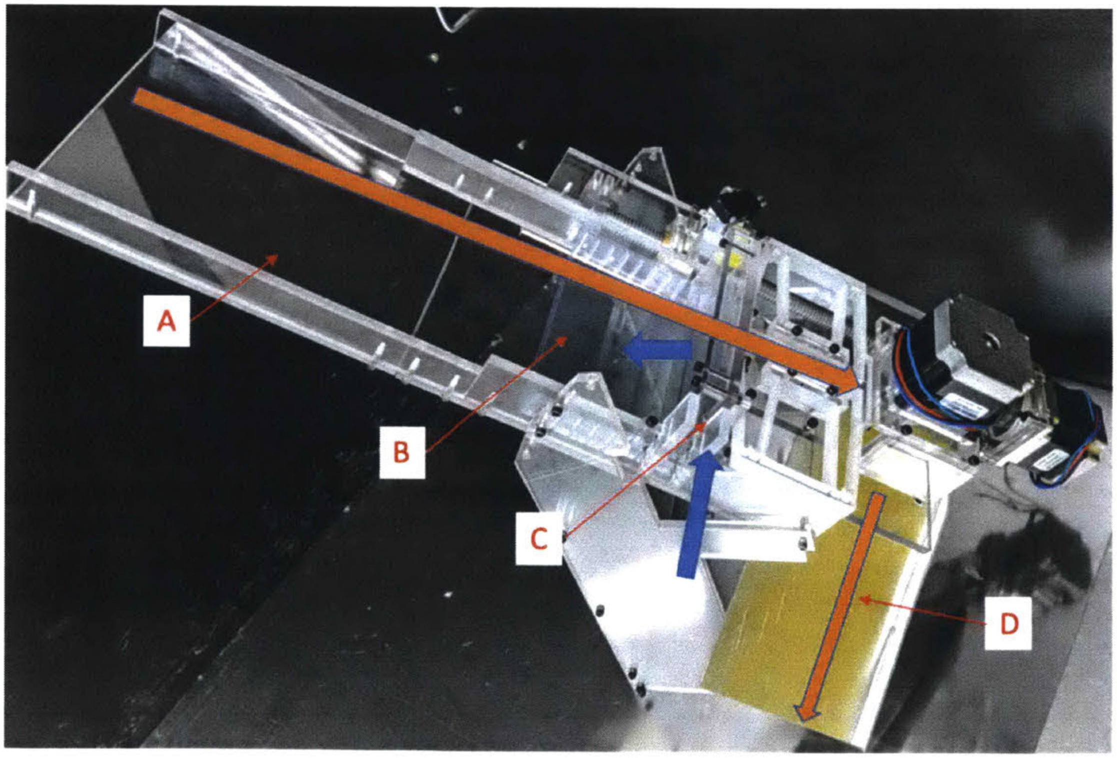


Figure 3-9: Third stage of the automated packaging machine, vial placement mechanism. A) Empty tray entrance. B) Tray loading section. C) Oriented vial entrance. D) Packaged tray

exit. Note: Orange arrows represent the movement of the trays through the packaging mechanism. Blue arrows represent the movement of vials through the packaging mechanism.

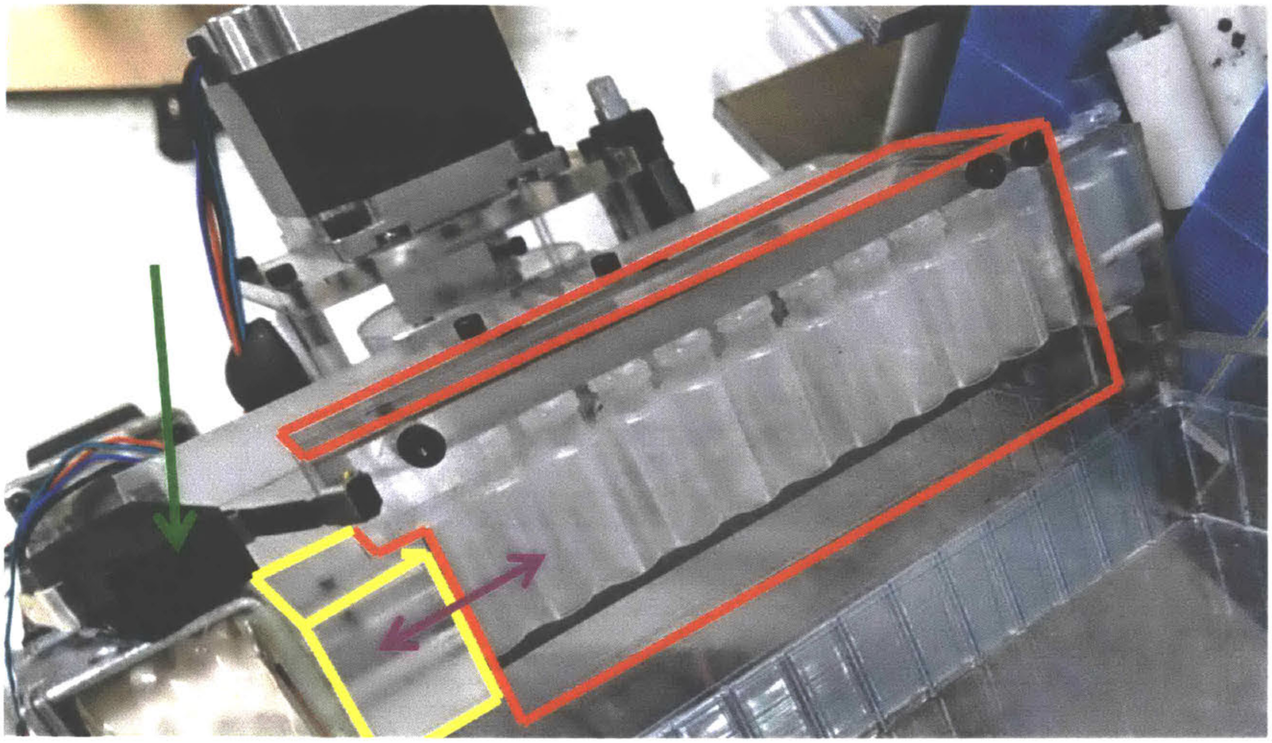


Figure 3-10: Front side view of the rake holding 10 vials with the biasing block extended. The rake is highlighted in red and the biasing block is highlighted in yellow. Be purple arrow represents the direction in which the biasing block actuates and the green arrow is pointing to a microswitch that senses the extension of the rake [5].

Positioned after the transfer line feeder, the placement mechanism funnels a line of 10 vials into the rake. The cam applies force through the flexure, acting as a linear slide, to the rake. This force propels the rake forward, positioning it over the tray, allowing vials to drop into their final placement. After each stroke of the rake, the tray slider steps down to the next empty row, allowing the process to repeat.

When a tray is loaded with 100 vials, the tray slider moves down to the offboard ramp, where the full tray is able to slide out towards the vision system. After the full tray has been discharged, the tray slider moves back up; permitting the next empty tray to fall into place on the tray slider.

For a more detailed overview on the design, development, and performance of the vial placement mechanism, refer to chapters four through six in this thesis.

3.4 Motor Selection & Programming

The machine utilizes several motion axes to achieve reliable vial packaging. The following list describes all motors and actuators used on the machine:

Vial rake – 24 VDC stepper motor (operating a cam)

Tray lead screw – 24VDC stepper motor (direct drive)

Vial-biasing block – 120VAC linear solenoid

Transfer line feeder – 24 VDC stepper motor (operating a cam)

Rotary bowl feeder (center stage and sorting ring) – Teknic ® ClearPath TM servomotor with integrated motor controller

Sensors are placed throughout the machine layout to provide feedback on the machine's performance:

Transfer line sensor: standard 24VDC optical sensor

Vial counter: standard 24VDC optical sensor

Rake actuation counter: 24VDC microswitch, wired normally open

For a detailed overview of the motor selection and programming of the machine, please refer to Diarny Fernandes' master's thesis: Design and development of a precision packing stage and master control system for an automated vial packaging machine [5].

3.5 Vision System and Industry 4.0 Connectivity

The last stage of the packaging machine is automated inspection and data transfer. The machine needs to produce exactly 100 vials packaged in a plastic tray in a robust fashion. Therefore, an automated inspection system is developed to confirm the correct number of vials in a package. In addition, Waters needs to keep track of the manufacturing data of the packaging machine since the packaging process happens at a remote offsite location. As such, a data delivery system is also developed to post operational data in a server so that Waters can monitor the machine performance in real time. Figure 3-11 below displays a picture of representing the machine vision algorithm's output when counting 100 vials.

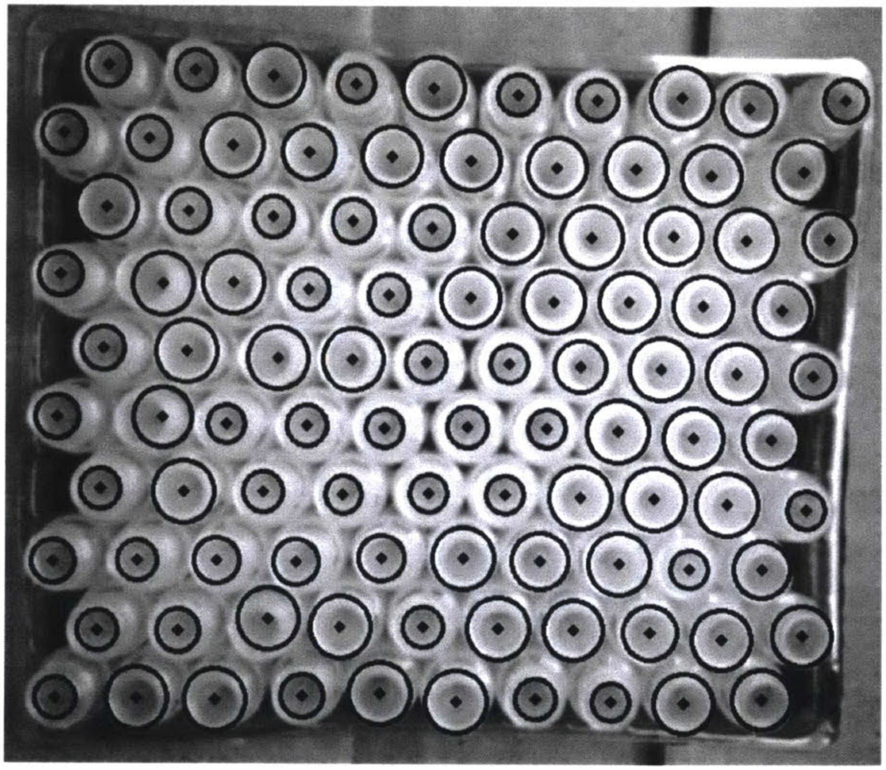


Figure 3-11: Machine vision algorithm's output when counting 100 vials. The image is positioned with a camera pointing down towards the top of the vials. Each circle and diamond represents one counted vial as captured by the vision system. The picture is converted to black and white [5].

The automated inspection system is enabled by a Raspberry Pi 3 Model B+ and a Raspberry Pi NoIR Camera module with infrared capability. As a completed package of vials exits the packaging stage, it enters a black box with the camera installed on the ceiling. The black box is selected in order to create a controlled lighting environment for the camera to deliver a robust performance. Both white LEDs and Infrared LEDs are selected to provide adequate lighting inside the black box so that the camera can capture all the features in the package. The Raspberry Pi is set up with Python 3 and OpenCV to run feature recognition algorithms.

Once the image recognition algorithm finishes running. The output data is stored in the SD card with Raspberry Pi, which will be keeping track of the machine uptime and total number of properly packed packages that have been produced. Along with some other crucial operational data such as machine throughput rate and machine uptime, the data will be sent through ethernet to the Waters server for storage and inspection.

For a detailed view of the automated inspection and connectivity of the machine, please refer to Siyang Liu's master's thesis: Design and development of an automated inspection system for vials. Master's thesis [4].

Chapter 4

Placement System Design

This chapter describes the design methodologies behind each progression of the prototype that culminated in the final delineation of the placement system.

The placement system was designed to operate freely without input from the other modules to increase the ease of prototyping and lead to overall modularity of the machine. During prototyping, correctly oriented vials were hand loaded into the rake. For final assembly, collaboration between the placement system and transfer line feeder took place to ensure optimal mating of both subsystems.

As previously stated, the placement system encompasses oriented vial loading into a tray in a 10 x 10 matrix. Additionally, the placement system contains a queue for empty trays and passes loaded trays onto the vision system.

4.1 Design Methodology

A total of 4 prototypes were built before resting on the final design. Each prototype was created to test a specific set of functions within the placement mechanism. As iterations progressed, the machine was able to leverage insight from previous prototypes to reach an optimized delivery point. This section describes the fundamentals behind each of the models with lessons learned and positive points highlighted for final comparison.

Background Research 4.1.1

Initially, background research occurred to find an existing solution to the presented problem. Investigation included patent searching, YouTube video viewing, and internet searching for any automated machine that packaged vials or a similar shaped object. Many videos and companies were found that created machines to orient and linearize a pile of objects. For example, numerous bowl feeders exist to orient larger bottles. However, none, of the stock mechanisms nested cylindrical objects in a 10 by 10 matrix within a tray exactly as needed.

Inspiration was drawn from two specific YouTube videos; one displaying the nesting technique used for bottle packaging by the company Arpac [6], the other showing the insertion of Crayola crayons into their packages [7]. Figure 4-1 below shows a snapshot of a conveyor mechanism mated to a linear slide that pushes a line of 8 bottles into rows. The translation of linear motion in an orthogonal direction by a 'pusher' spurred the development of the rake attachment used in the final product. Although the bottles in Arpac's machine are not placed inside of a four-walled tray, their arrangement presented a unique view into a plausible possibility to leverage on the final prototype.

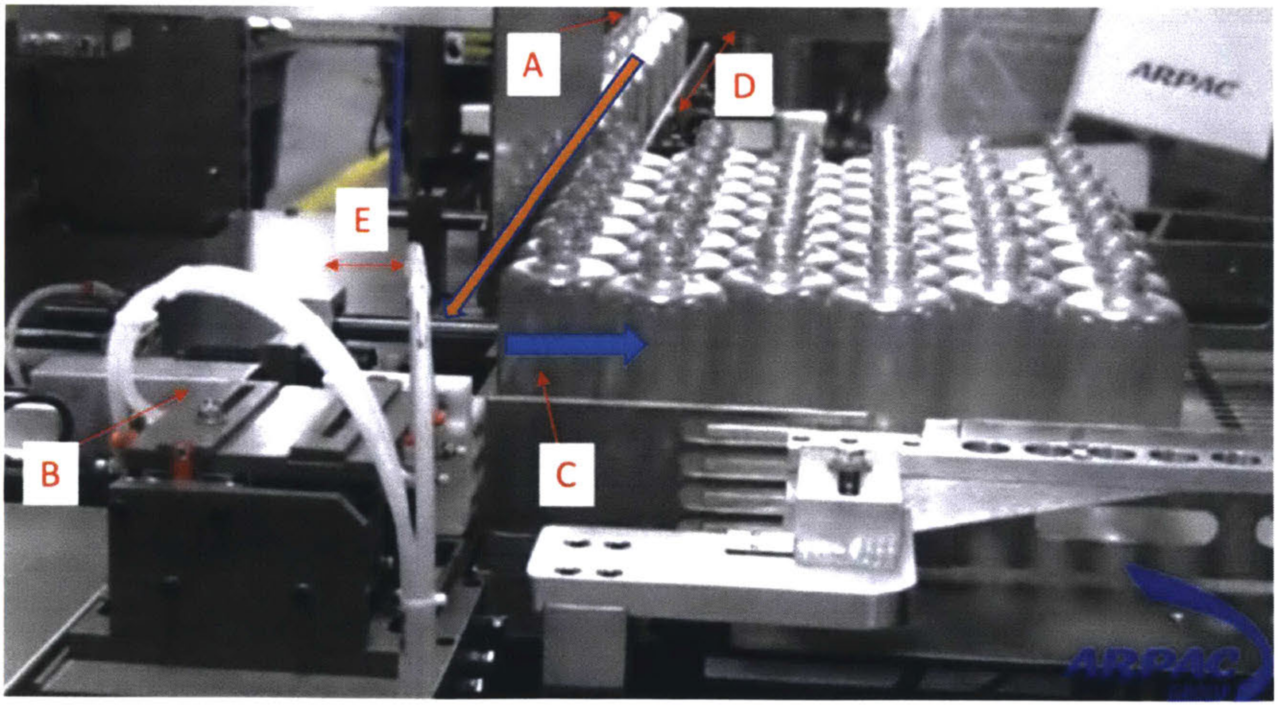


Figure 4-1: Picture of Arpac's automated bottle stacking mechanism leveraging a solenoid to push a line of bottles into an 8 by 8 matrix [6]. A) Input line of bottles. B) Bottle pushing solenoid. C) Nested stack of bottles. D) Direction of input bottle travel. E) Direction of solenoid

pusher & nested bottle travel. Note: The orange arrow represents the direction of travel of newly inserted vials while the blue arrow represents the direction of one stroke length of the solenoid pushing bottles forward into their nested position.

Crayola's technique for inserting arrayed cylinders (crayons) into packages involved a similar setup as Arpac's pusher. The main difference was Crayola's use of gravity to feed oriented vials into the pushing device. Figure 4-2 below displays the crayons lined up and oriented in a specific direction before they drop into the pushing device. This use of gravity assisted crayon alignment was mimicked in the vial placement systems technique that allowed vials to freely fall under the rake mechanism into the tray below.

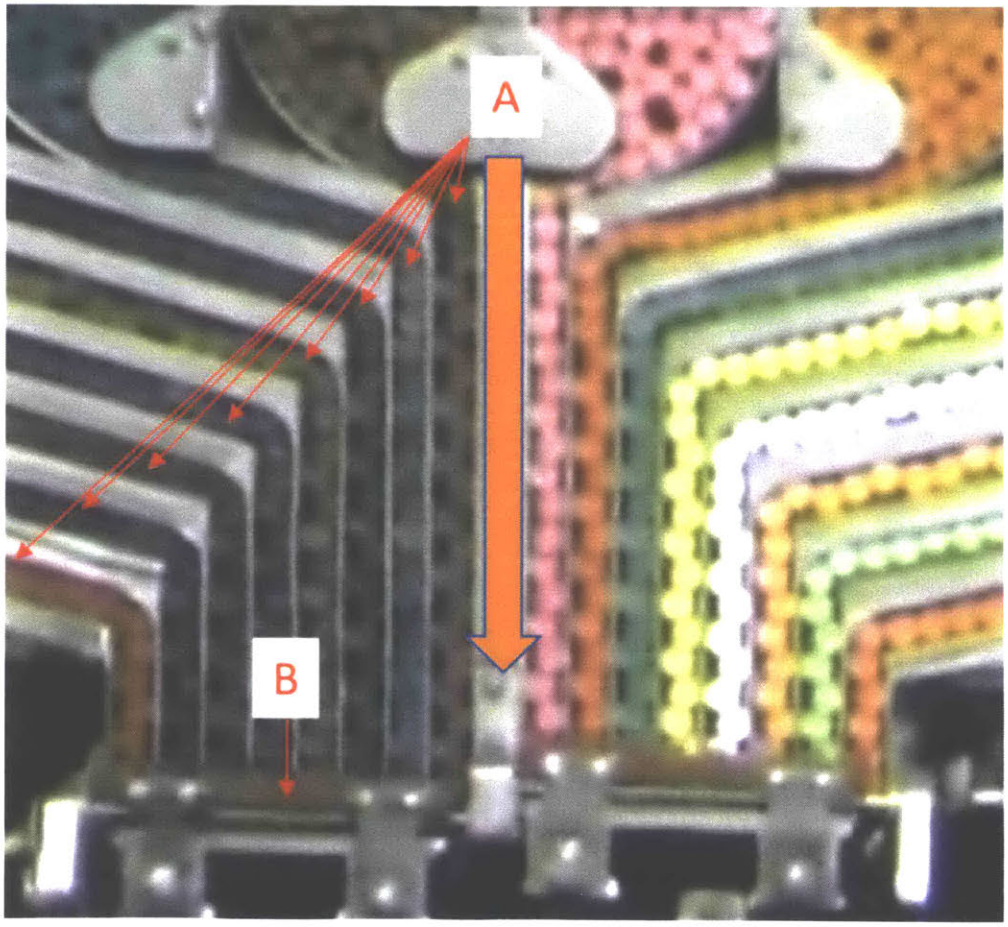


Figure 4-2: Picture of Crayola's crayon packaging mechanism with gravity fed crayon pusher mechanism [7]. A) Rows of Crayola crayons. B) Pusher mechanism. Note: Orange arrow

represents the directional force that gravity is placing on the crayons, and thus the direction that the crayons travel. As stated in the text above, this figure pays tribute to the Crayola packaging video that lay the foundation of gravity feeding into the packaging machine's design.

Initial Sketches 4.1.2

The first month of design ideation consisted of background research, discussed above, and brainstorming sketches. The initial concept of loading 10 vials above the tray is highlighted in Figures 4-3, 4-4, and 4-5. This abstraction presents an opening door concept in which the 10 vials are aligned above the pallet onto which they will be loaded. A door swings open from the bottom of the vials, and they are able to fall in place onto the tray. Although the opening door mechanism was not pursued in the physical prototypes, the structural make-up of these first three sketches acted as a base-point for the following ideas.

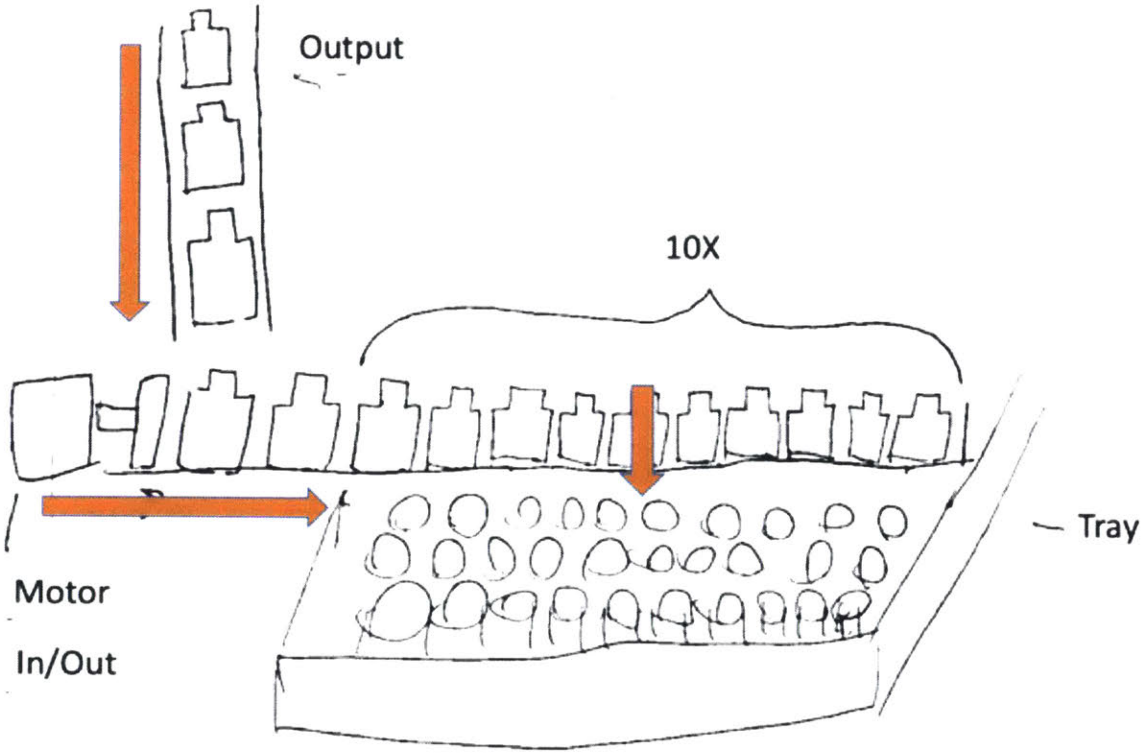


Figure 4-3: Sketch of the pallet loading mechanism initial brainstorming idea. Output tube from top bowl feeder shown on the upper left side of the sketch. Solenoid motor pushing vials into line

shown on the middle left side of the sketch. 10x vials lined up above tray shown in the middle of the sketch. Note: This is a modified image of the initial drawing created during the first month of prototyping. Although the outline of the sketch remains the same, the orange arrows have been inserted to represent the vial's direction of travel. Furthermore, typeface has been placed on top of traditional handwriting for the sake of legibility.

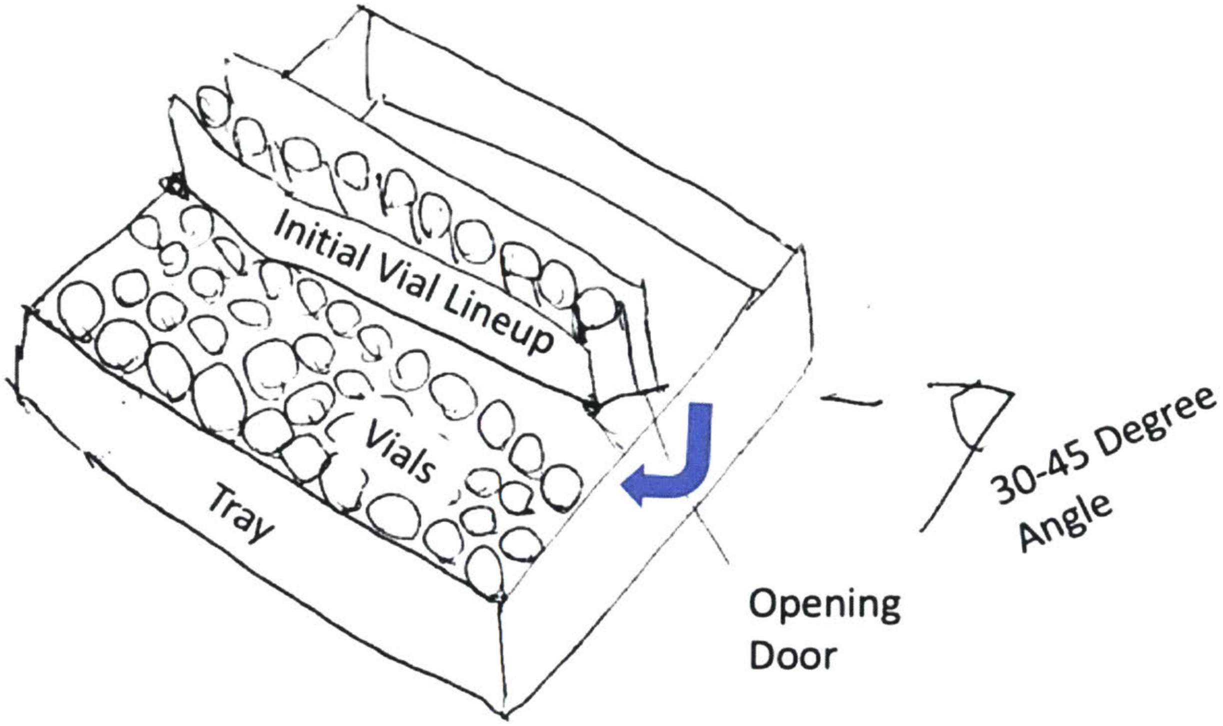


Figure 4-4: Isometric sketch of the pallet loading mechanism initial brainstorming idea. Aligned vials sitting above a partially full tray displayed in the sketch. 30 to 45 degree angle indication for the slope at which the tray will sit. Opening door sitting beneath aligned vials. Note: This is a modified image of the initial drawing created during the first month of prototyping. Although the outline of the sketch remains the same, the blue arrow has been inserted to represent the motion that an opening door would follow. Furthermore, typeface has been placed on top of traditional handwriting for the sake of legibility

The second three sets of sketches in Figures 4-5, 4-6, and 4-7 introduced the ‘rake’ or ‘pushing’ mechanism that would later be carried through in the physical prototypes. These two sketches display a solenoid pushing aligned vials off of a platform, forcing them to fall into a tray. The idea of aligned vials feeding parallel to the surface of the pusher creates stability between the vial contact surfaces and compactness within the entire machine. The solenoid motor was selected as an easy-to-program, short-travel, inexpensive mechanism to provide the actuation of the pushing plate. Here, the mechanism is expected to be angled to keep vials resting on the pusher.

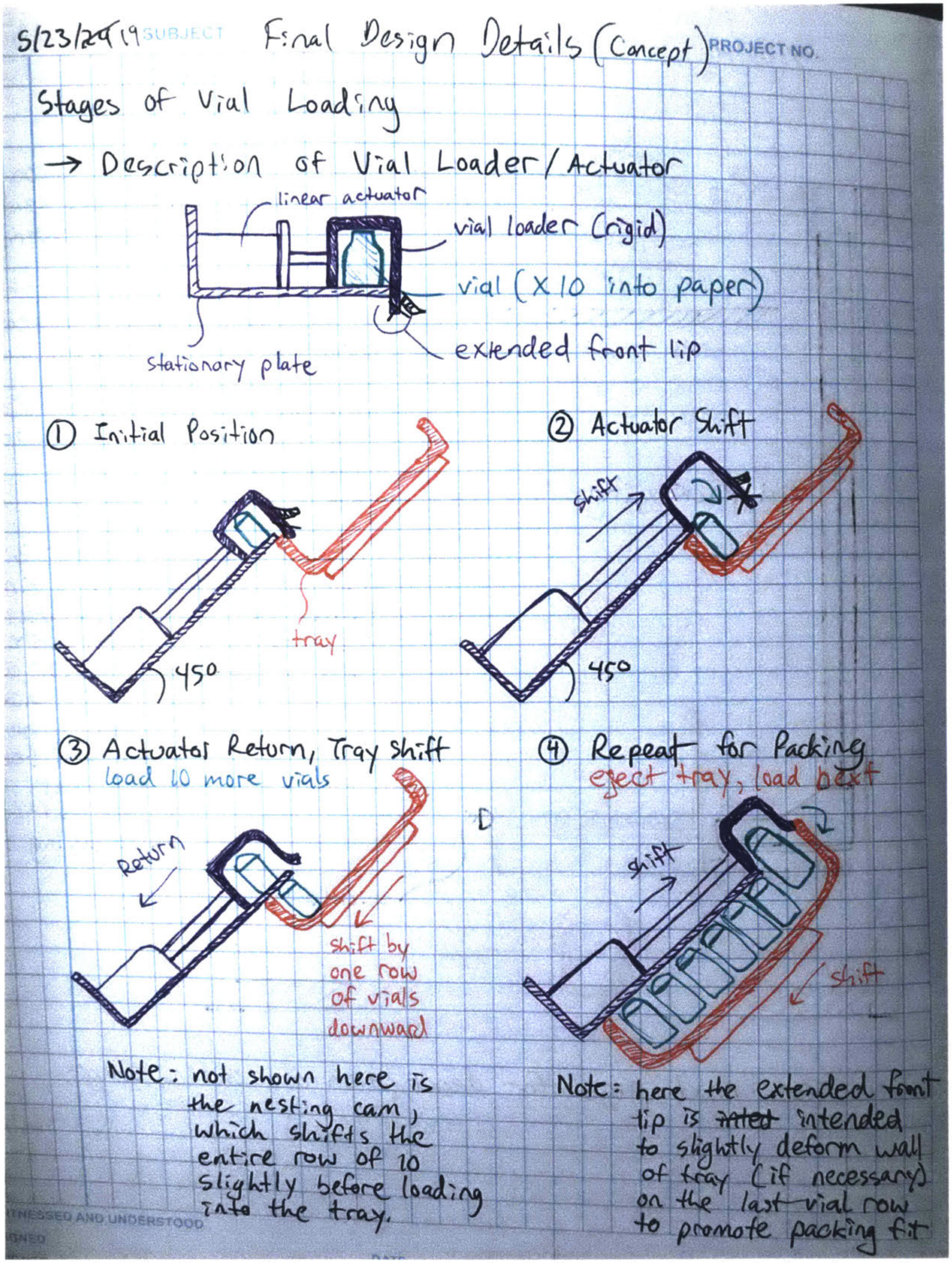


Figure 4-5: Side view preliminary concept sketch of rake mechanism displaying the motion of the rake moving over the vials as drawn by Diarny Fernandes [5].

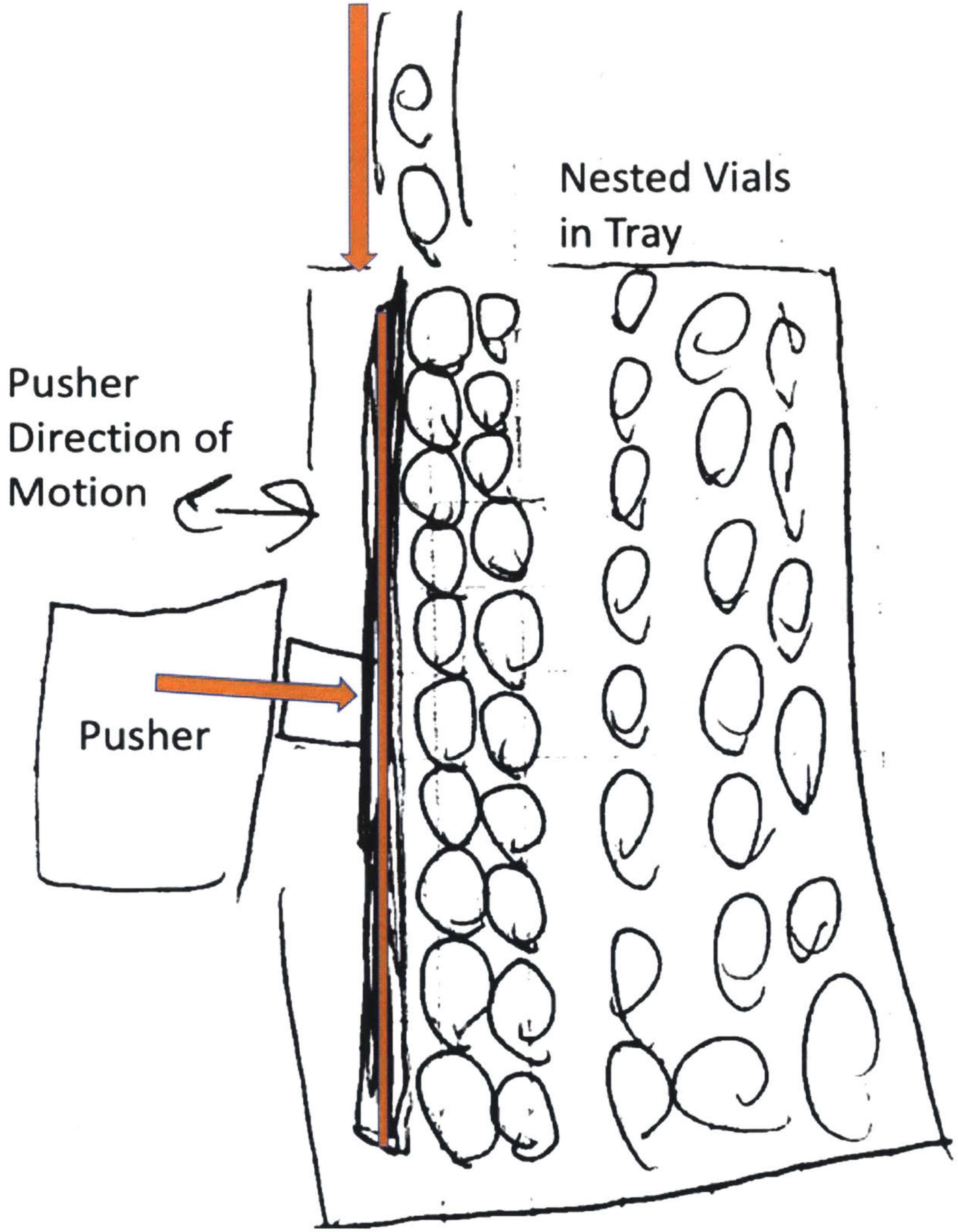


Figure 4-6: Top-down view of pushing mechanism (solid black bar) connected to a solenoid (square with directional) feeding aligned vials into tray below. Note: This is a modified image of

the initial drawing created during the first month of prototyping. Although the outline of the sketch remains the same, the orange arrows have been inserted to represent the direction that vials would move to get in front of the pusher and the direction of motion that a pusher would move the vials into the tray. An orange bar has been placed over the solid black rectangle to represent the pusher. Furthermore, typeface has been inserted for further clarification of parts.

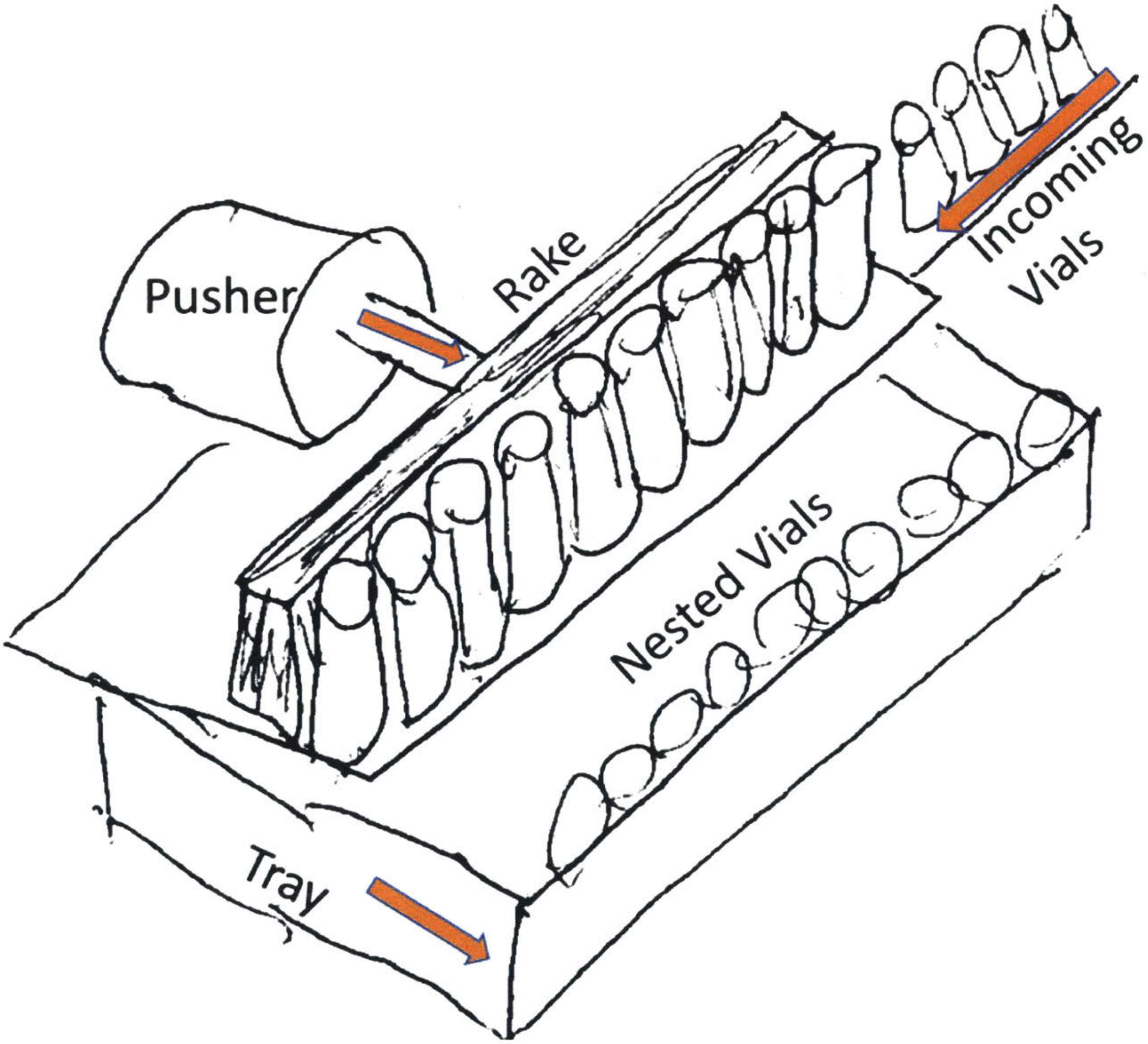


Figure 4-7: Isometric view of pushing mechanism concept displaying aligned vials sitting in front of pusher on top of a tray with one row of loaded vials. Note: This is a modified image of the initial drawing created during the first month of prototyping. Although the outline of the

sketch remains the same, the orange arrows have been inserted to represent the direction that vials would move to get in front of the pusher, the direction of motion that a pusher would move the vials into the tray, and the trays direction of motion. Furthermore, typeface has been inserted for further clarification of parts.

Lastly, the three-sided shape of the 'slide' or 'pusher' mechanism was conceived during the last stage of design sketches. Figures 4-8 and 4-9 display the slider encompassing the top and both sides of aligned vials. With this setup, when the slide moves forward past the edge of the floor, the vials have only one direction to fall. The three-sided setup prevents the vials from tumbling forward when falling. As shown in the drawings, a rail abutment holds a track on which the slide is supposed to move, preventing any motion other than linear travel in one axis. However, the physical prototypes neglected to feature this setup due to complexity and presumed stiction between the slide and track.

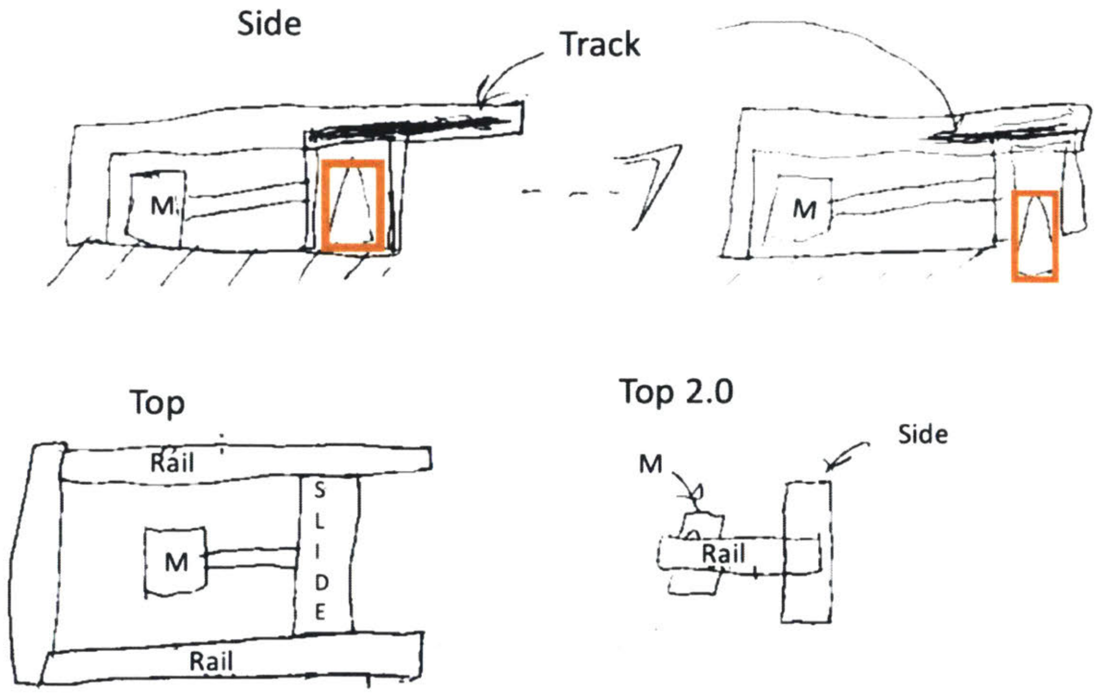


Figure 4-8: Sketches of the three-sided slider mechanism connected to a track on which the slider can move in one axis when actuated by a solenoid. The solenoid is indicated by the letter 'M' for

motor in this picture. Note: This is a modified image of the initial drawing created during the first month of prototyping. Although the outline of the sketch remains the same, an orange box has been inserted to represent a vial in traditional rectangular form. Furthermore, typeface has been placed on top of traditional handwriting for the sake of legibility

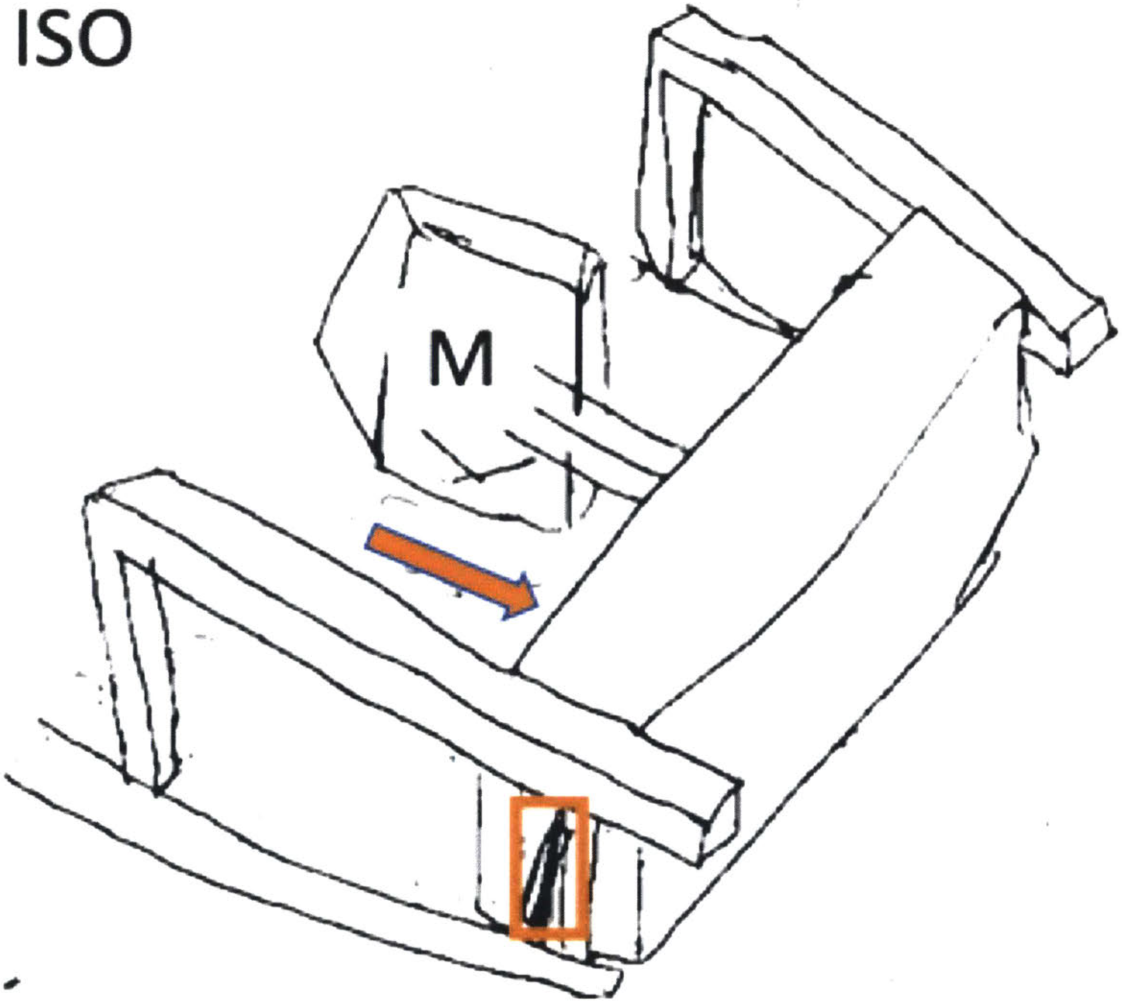


Figure 4-9: Isometric sketch of the three-sided slider connected to the track system with the solenoid, lettered ‘M’, sitting behind the slide. Note: This is a modified image of the initial drawing created during the first month of prototyping. Although the outline of the sketch remains the same, an orange box has been inserted to represent a vial in traditional rectangular form. The

orange arrow represents the direction of travel of the slide. Furthermore, typeface has been placed on top of traditional handwriting for the sake of legibility

Prototype I 4.1.3

The first physical prototype was created to test the dynamics of aligned vials falling into place over the vial package. As shown in Figures 4-10 and 4-11, the prototype contained two pieces, an aluminum U-shaped channel with a piece of duct tape on the end representing the slider and an aluminum L-bracket with a piece of aluminum bolted onto the top representing the tray guide. An empty vial tray was able to be placed on the bottom of the L-bracket while aligned vials could be slid into the slider from the side. When the slider was pushed forward, the vials could drop into the tray. The entire mechanism was operated by hand, usually requiring a total of three hands, or two people. The prototype was tilted to different angles, providing the basic intuition for how different angles related to controlled falls of the vials. In the end, this simple prototype validated the assumption that the vials could be dropped into their tray with a U-shaped slider mechanism and provided the groundwork for the slider mechanism and holder in future prototypes.

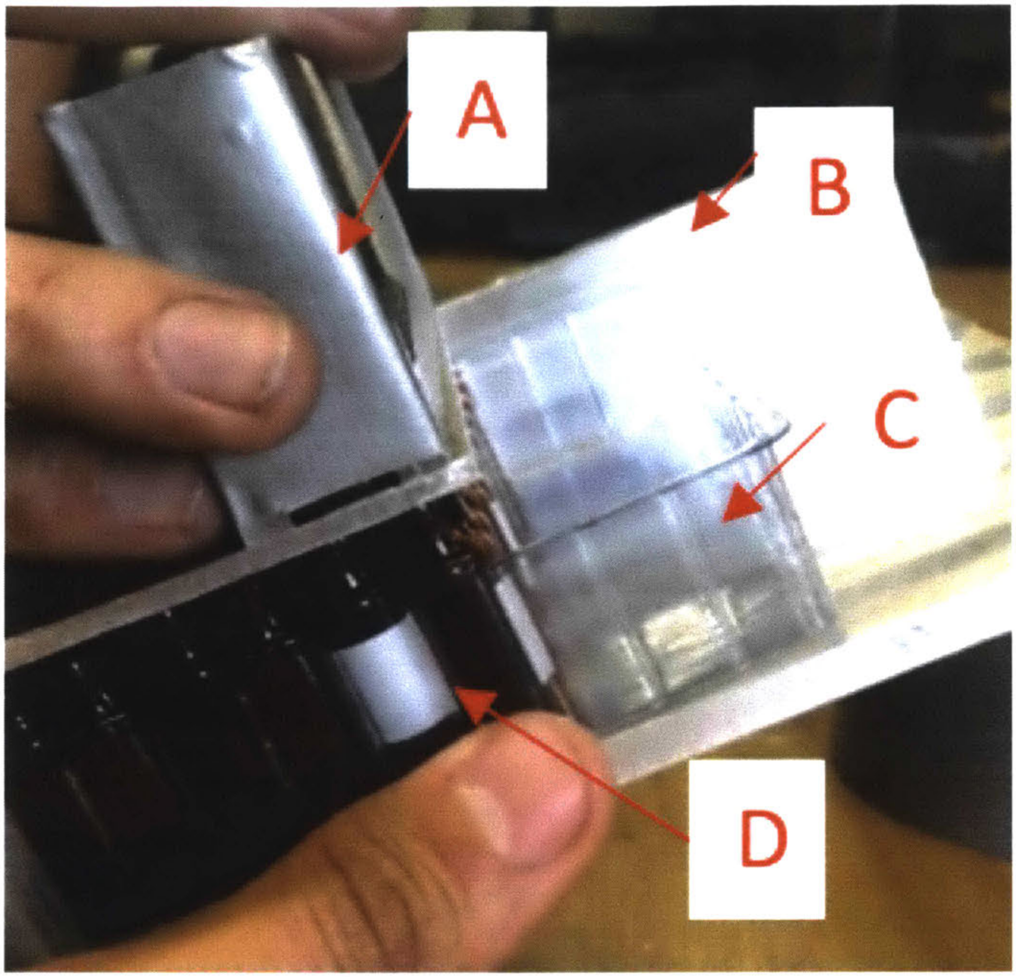


Figure 4-10: Side view of prototype I including: A) U-shaped slider containing vials with duct tape on side. B) L-bracket. C) Tray. D) Vials. Prototype verified the ability for vials to be nested inside of the tray through free fall after being pushed into position by a slider. Note: The vials in this picture are glass yet have the same dimensions as the plastic vials.

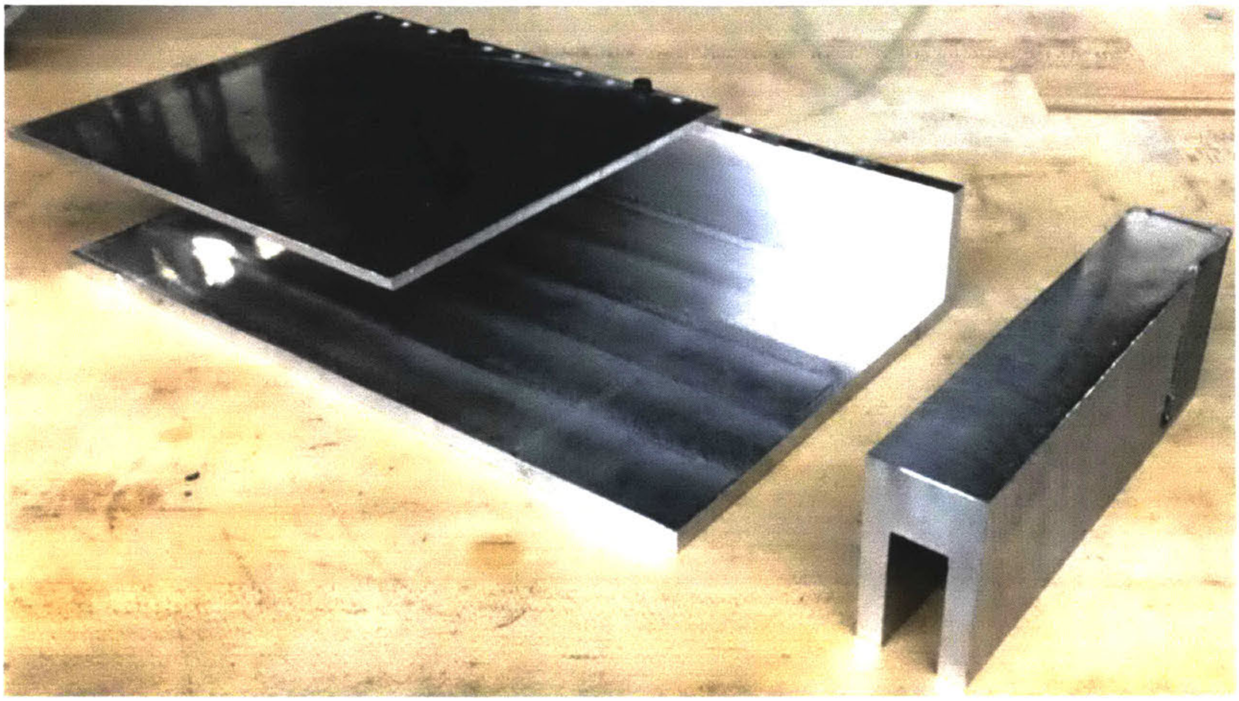


Figure 4-11: Isometric view of L-bracket on the left with U-shaped channel on the right. Refer to Figure 4-10 above for a general outline of sizing in comparison to the vials.

Prototype II 4.1.4

The second prototype introduced two new concepts: use of a flexure to act as a linear slide for the rake and a notch in the rake to allow for biasing of the vials. Figures 4-12 and 4-13 display a top view and a side view of the entire prototype. The prototype contains 3 main parts: an acrylic flexure acting as the linear slide, an acrylic support structure holding the flexure and rake, and a Formlabs clear resin 3D printed rake.

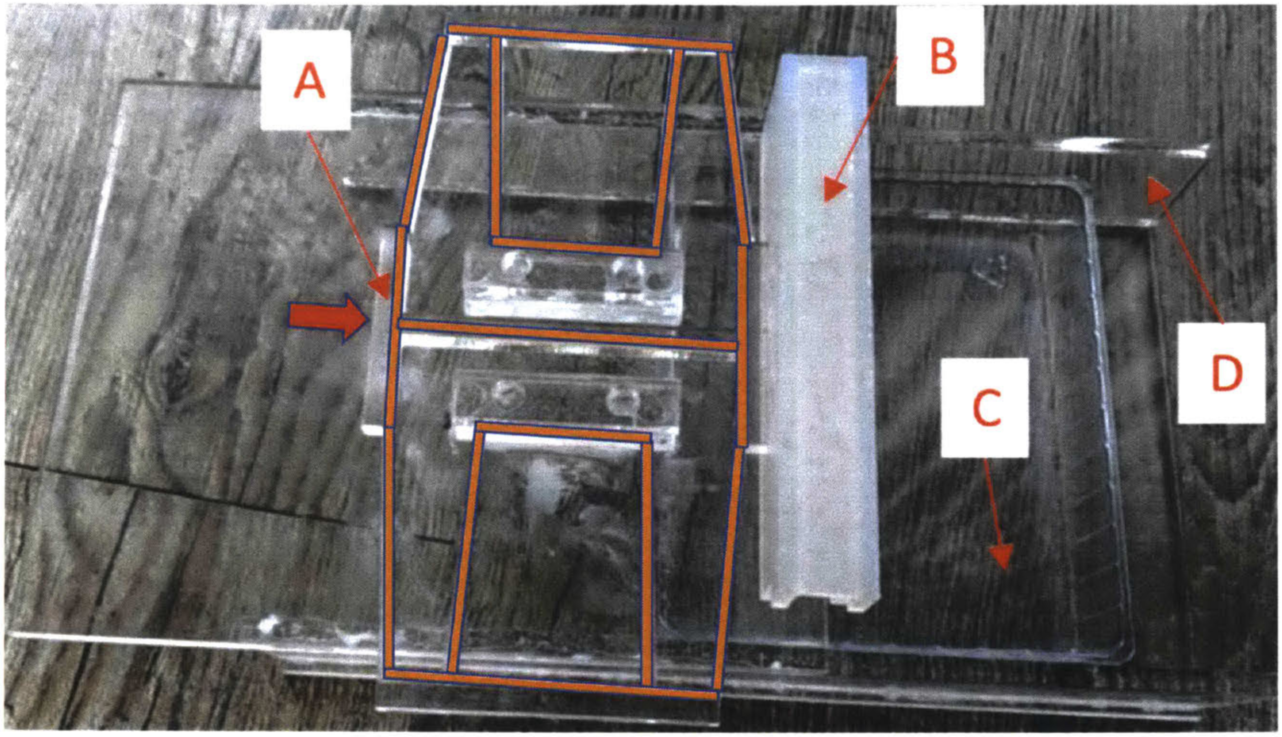


Figure 4-12: Top view of prototype II. A) Flexure. B) Rake. C) Tray. D) Tray and slider chassis. Note: Orange outline highlights the shape of the flexure. The large red arrow indicates the position where force is applied to move the flexure forward and slide the rake.

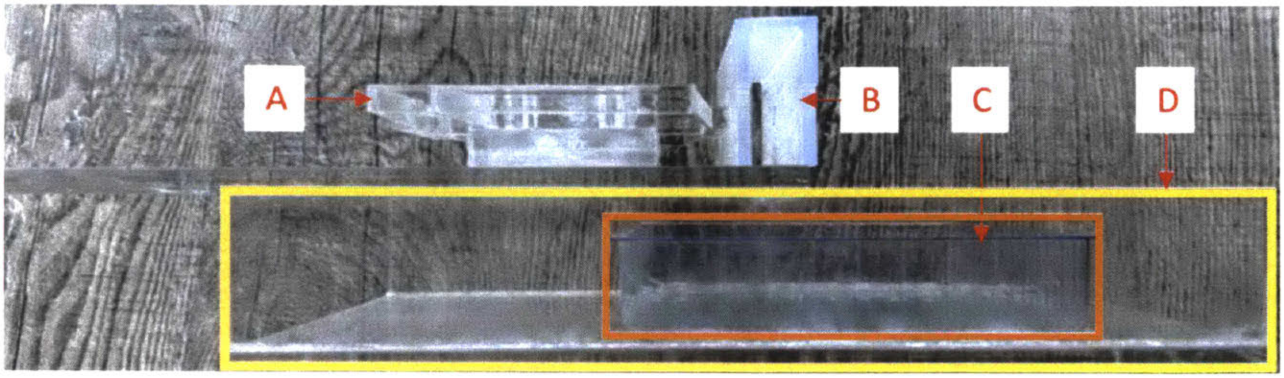


Figure 4-13: Side view of prototype II. A) Flexure. B) Rake. C) Tray. D) Tray and slider chassis. Note: The yellow box outlines the tray slider chassis body and the orange box outlines an empty tray.

The idea for using a flexure to act as a linear slide came from a combination of Professor Slocum's class Fundamentals of Precision Machine Design in which the benefits of flexures are discussed and the 2.72 class Elements of Mechanical Design where a flexure is created to act as a linear slide on a micro lathe. As shown in Figure 4-14, the flexure created for this prototype is based off of the geometry of the flexure used in 2.72. The benefit of using a flexure instead of the rail mechanism's displayed in Figures 4-8 and 4-9 is the flexure's ability to restrict motion in all but one axis in a simple, clean, easy to manufacture, and maintenance-free manner. The flexure used in this prototype was made out of acrylic due to ease of fabricating through laser cutting. However, acrylic is inherently brittle. Therefore, future iterations of the flexure would cycle through other materials to optimize the flexure's lifespan.

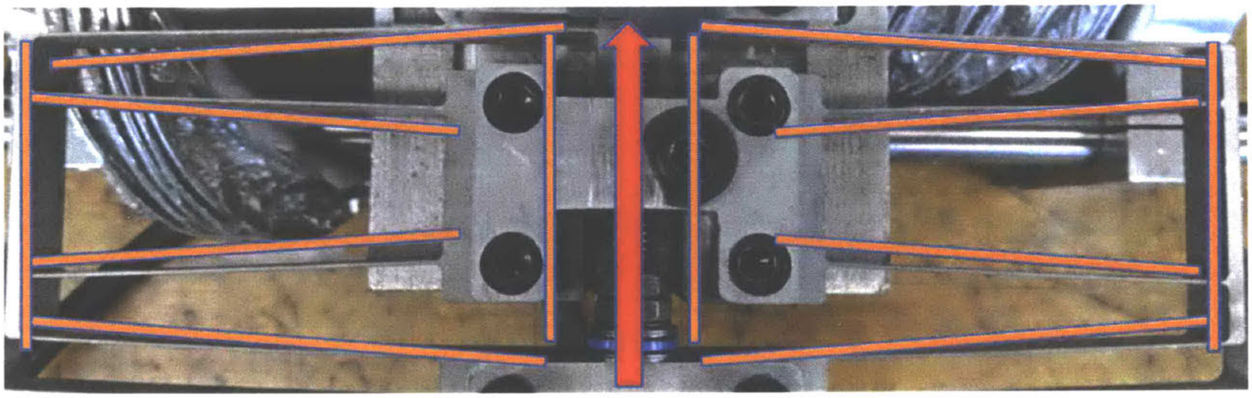


Figure 4-14: Top view of flexure acting as a linear slide on one of the lathes from 2.72. Note: The orange bars have been inserted on top of the flexure to better reflect the general shape of a flexure acting as a linear slide. The red arrow represents unconstrained direction of motion the linear slide flexure can travel.

The second iteration of the rake features a 0.2" notch on the side in which a block can slide into to assist biasing the vials. The idea of using a block attached to a solenoid to bias the vials was conceived when meeting with DAPR, an engineering design consultancy group based in Nashua, NH. Figure 4-15 displays the sketch drawn up during the meeting with DAPR. Figure 4-16 displays the physical rake prototype with the side cut. The block, which can move in and out, allows the vials to drop in 2 distinct locations, shifting towards the right side or left side of the package after every other row. This enables the vials to nest in the zig-zag position as shown in Figure 1-2 above.

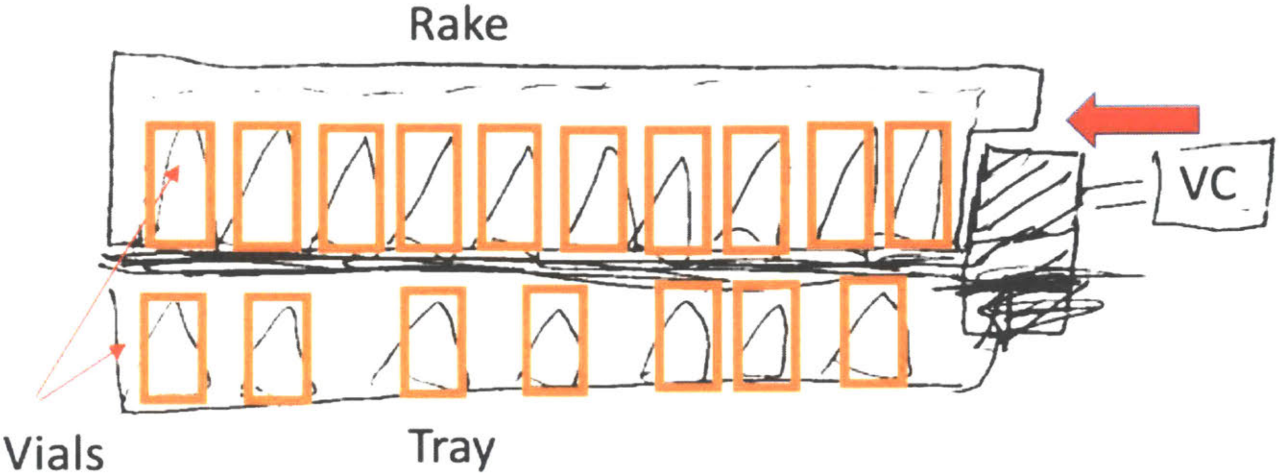


Figure 4-15: Front view sketch of a rake holding vials sitting above a tray holding vials. The back square on the right side represents a pushing block connected to a voice coil. Note: This is a modified image of the initial drawing created during the first month of prototyping. Although the outline of the sketch remains the same, an orange box has been inserted to represent a vial in traditional rectangular form. The red arrow represents the direction of travel of the biasing block. Furthermore, typeface has been placed on top of traditional handwriting for the sake of legibility

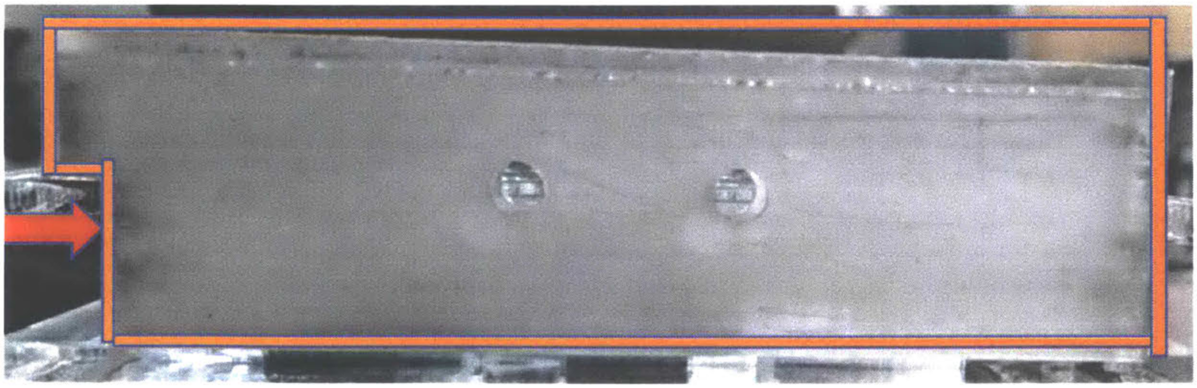


Figure 4-16: Front view of a 3D printed rake with notch for biasing block cut out on the left side. Note: The orange bars have been inserted on top of the rake to better outline the general shape of

the front of the rake. The red arrow represents the position in the notch where the biasing block will enter.

Both of these design elements, notched-rake and flexure, are carried through to further iterations of prototypes. When testing the 2nd prototype by hand, vials were able to drop into the package in a biased manner by pushing on the back of the flexure to move the rake forward. However, given the imprecision of human interaction to act as actuators for this prototype, a consistent level of vial dropping and nesting could not be achieved. Therefore, the decision to size and order motors for the next prototype was made in order to increase the level of precision in part movement.

As indicated above, laser cutting and 3D printing were the primary methods used to manufacture this prototype. Their relatively high rate of production with minimal operator input allowed this prototype to be constructed and tested within one week. The laser cutter was ideal for constructing 2D parts out of 1/8" and 1/4" acrylic, while the 3D printer could create more complex geometries. Yet, even given 3D printing's benefits, the choice was made to move away from this manufacturing method on future prototypes. 3D printing could not be used on the range of materials we wanted to use in a clean room environment. Furthermore, 3D printing did not produce a high enough level of precision to create threading strong enough to hold up to the structural constraints needed in the final prototype. Lastly, the need to produce a design that could easily be replicated within Water's manufacturing floor bared 3D printing on a Formlabs printer.

Prototype III 4.1.5

The third iteration of the prototype focused on the areas of design for manufacturing and motor selection with integration. The prototype was constructed out of laser cut acrylic and milled polycarbonate joined by 8-32 machine screws leading to ease of manufacturing and assembly.

Three motors were selected, two solenoids and an encoder for pushing the rake, biasing block, and driving the tray slider. In this prototype, the rake, flexure, tray slider, and chassis were integrated in their in their penultimate form.

Figures 4-17, 4-18, and 4-19 display the prototype resting on its test platform. As shown, the rake, flexure assembly, tray slider, and chassis are all novel and made to be assembled with little more than a hex key and machine screws. The ingenuity put into the layout of this design not only allowed rapid prototyping but permitted agile reconfiguration of the assembly as complications arose. As such, parts from prototype III were interchangeable with parts in prototype IV, decreasing the total amount of fabrication time and material waste needed during the project.

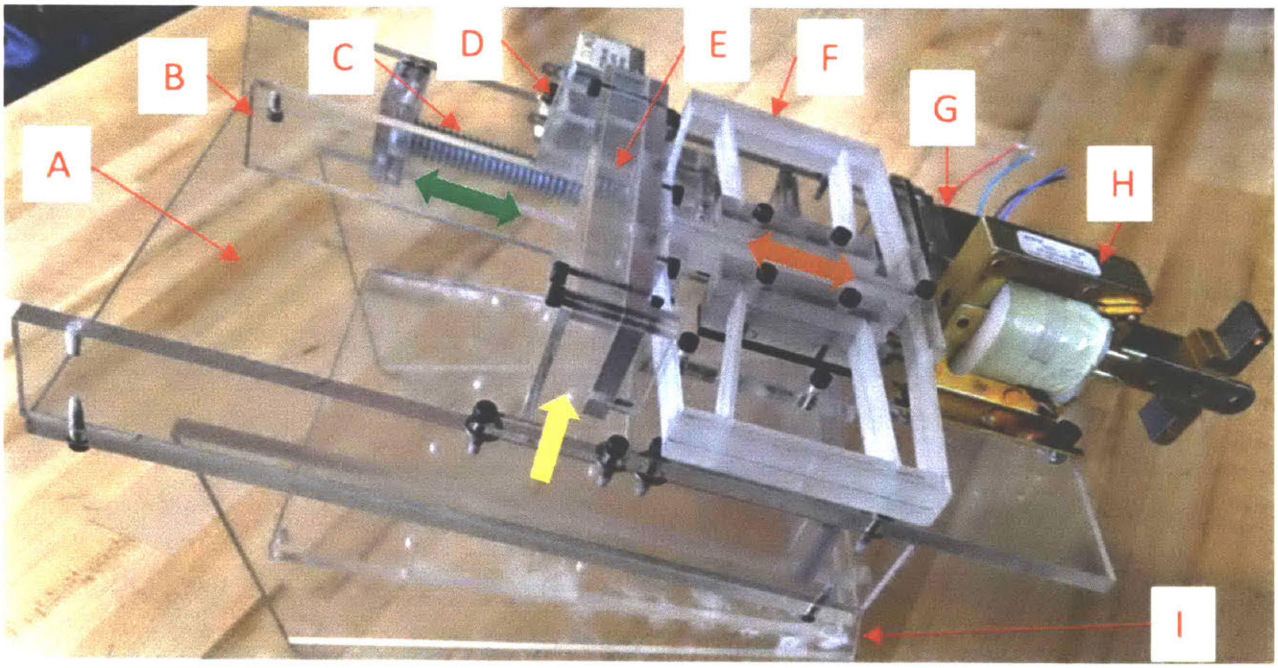


Figure 4-17: Left side view of prototype III. A) Chassis. B) Tray slider. C) Tray slider lead screw. D) Biasing motor. E) Rake. F) Flexure. G) Lead screw motor. H) Rake-actuating motor. I) Test platform. Note: The yellow arrow points to the vial entrance hole in the rake. The orange arrow indicates the direction of motion of the flexure. The green arrow indicates the direction of motion of the tray slider.

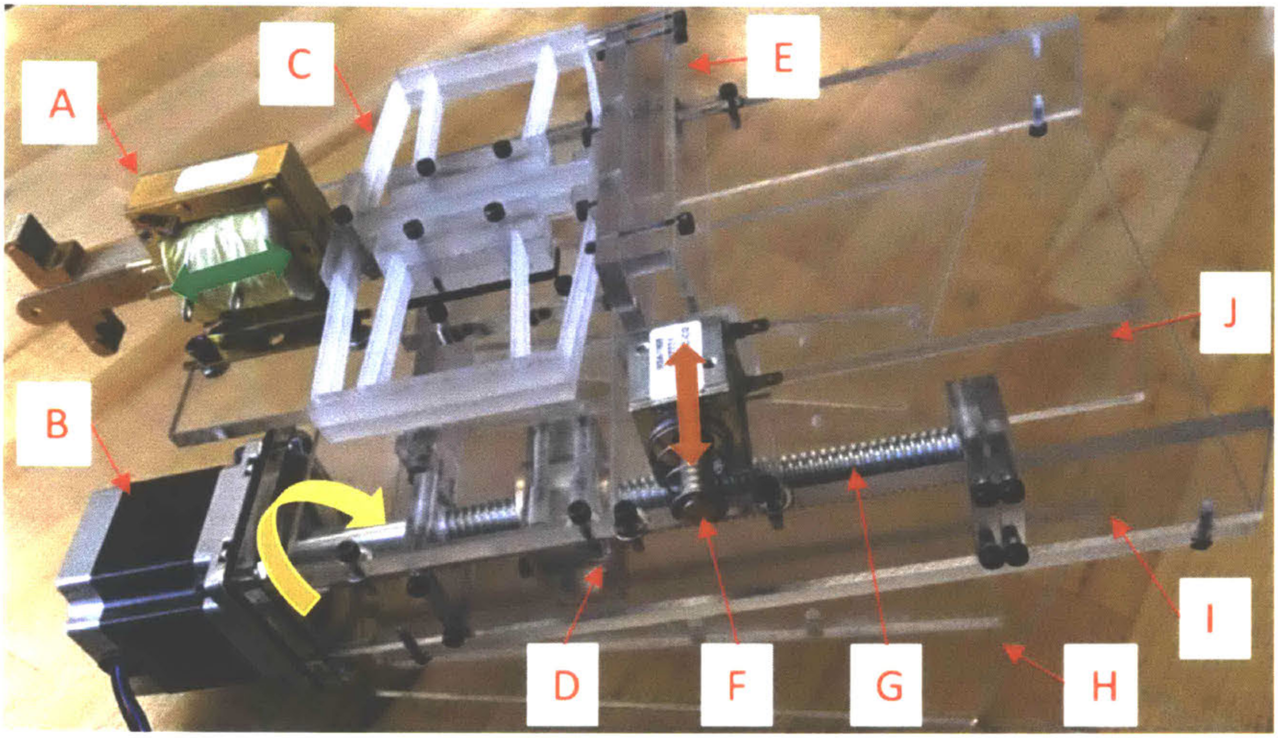


Figure 4-18: Right side view of prototype III. A) Rake-actuating motor. B) Lead screw motor. C) Flexure. D) Tray slider lead screw bearing block. E) Rake. F) Biasing motor. G) Tray slider lead screw. H) Test platform. I) Chassis. J) Tray slider. Note: The green arrow represents the direction of motion of the rake-actuating motor. The orange arrow represents the direction of motion of the biasing motor. The yellow arrow represents the direction of twist of the lead screw motor.

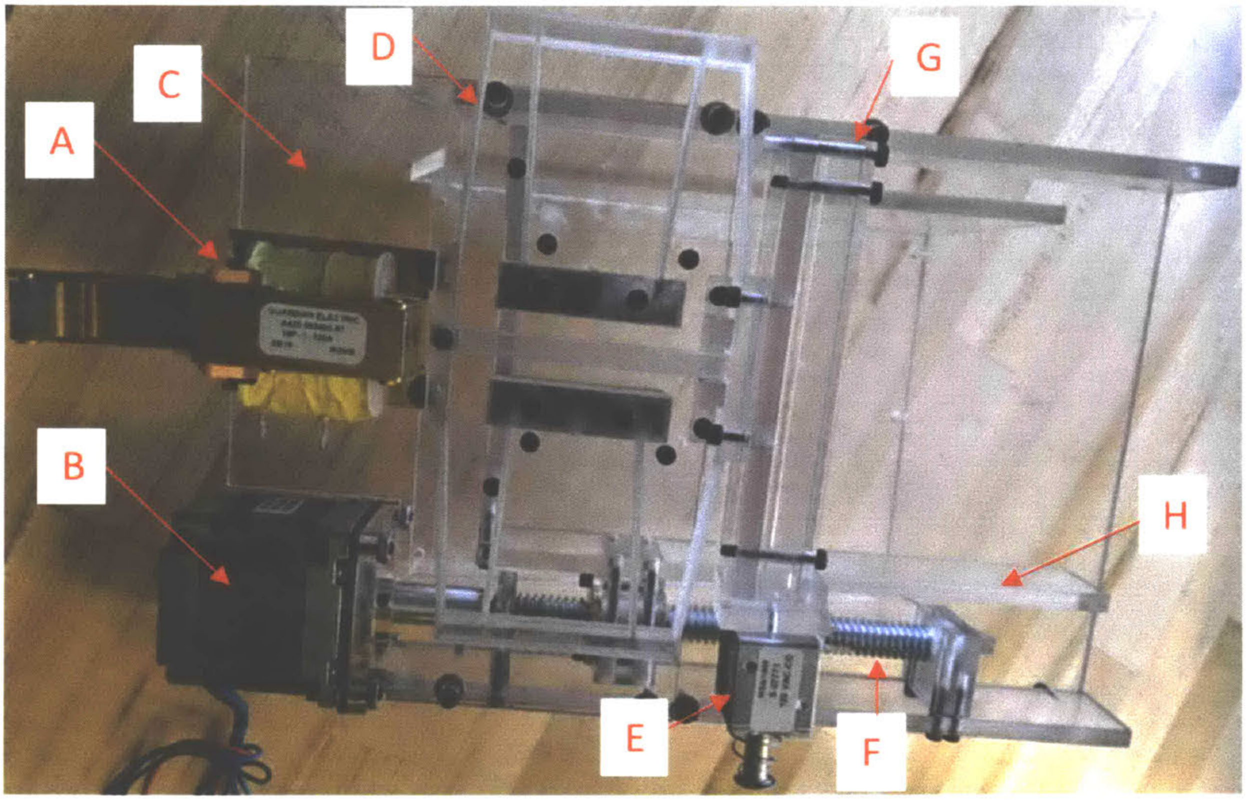


Figure 4-19: Top side view of prototype III. A) Rake- actuating motor. B) Lead screw motor. C) Chassis. D) Flexure. E) Biasing motor. F) Tray slider lead screw. G) Rake. H) Tray slider.

Prototype III proved useful in validating motor compliance with the mechanical structures. The first motor to be tested was the flexure-actuating solenoid. The solenoid, rated to output a force of 144 oz at full extension, was much too violent to be used on the machine. When activated, the solenoid's rod moved forward at such a great acceleration that the vials within the rake were jostled. Furthermore, when fully extended in contact with the flexure, the solenoid's rod would aggressively vibrate at a rate of 60 Hz. The vibration caused the vials to shake while exiting the rake, preventing their ability fall smoothly into the tray. Therefore, the discovery that a solenoid would not be able to be used to push the flexure was realized. Using this finding, Diarny Fernandes deduced the elegant solution of a cam attached to a stepper motor used in prototype IV to push the flexure.

The second motor to be tested was the vial-biasing solenoid. Given this was a much smaller motor, providing only 3 oz of force at full extension, the violence experienced in the flexure-actioning solenoid. The motor was able to provide enough force to hold the vials in place while it induced an offset. The one unknown was how the motor would perform when interacting with the transfer line feeding into the rake. However, it was assumed that given the correct calibration, the transfer line would be able to link well with the rake and biasing mechanism.

The last motor to be tested was the tray-sliding stepper motor. The motor accurately moved the tray slider up and down throughout the leadscrew's length. Furthermore, the motor provided enough torque to move the weight of a tray loaded with vials; indication that the motor would be able to bear the force of multiple queued up trays pushing on the slider.

Finally, minor issues with the fit and finish of the overall assembly were found that needed to be fixed for the final iteration. As shown in the pictures above, washers were placed between the sides of the frame and top panel to increase the amount of space needed for the tray slider to move. More washers were placed under the flexure's mounting assembly to provide the proper amount of height needed to position the vials within the rake. Furthermore, given that the lead screw bearing was acting the only point of contact for the tray slider to the frame, the tray slider was able to wiggle back and forth. All of these snags were able to be identified and corrected for the final prototype.

Prototype IV 4.1.6

The final prototype adjusted imperfect parts and connections from prototype III as well as included new sections vital to the system. Parts that were added or adjusted include: a new cam actuation setup for flexure movement, an offramp for trays to exit, a queue section for trays to enter, a guide for the tray carriage to follow, mounting brackets with variable angle selection, a backstop to assist with the first row of vial loading, and a gate apparatus to guide vials into the rake. The new parts integrated in prototype IV can be seen in Figures 4-20 and 4-21 below. These changes gave the final prototype the ability to accept vials, queue trays, and offload completed trays as required by Waters.

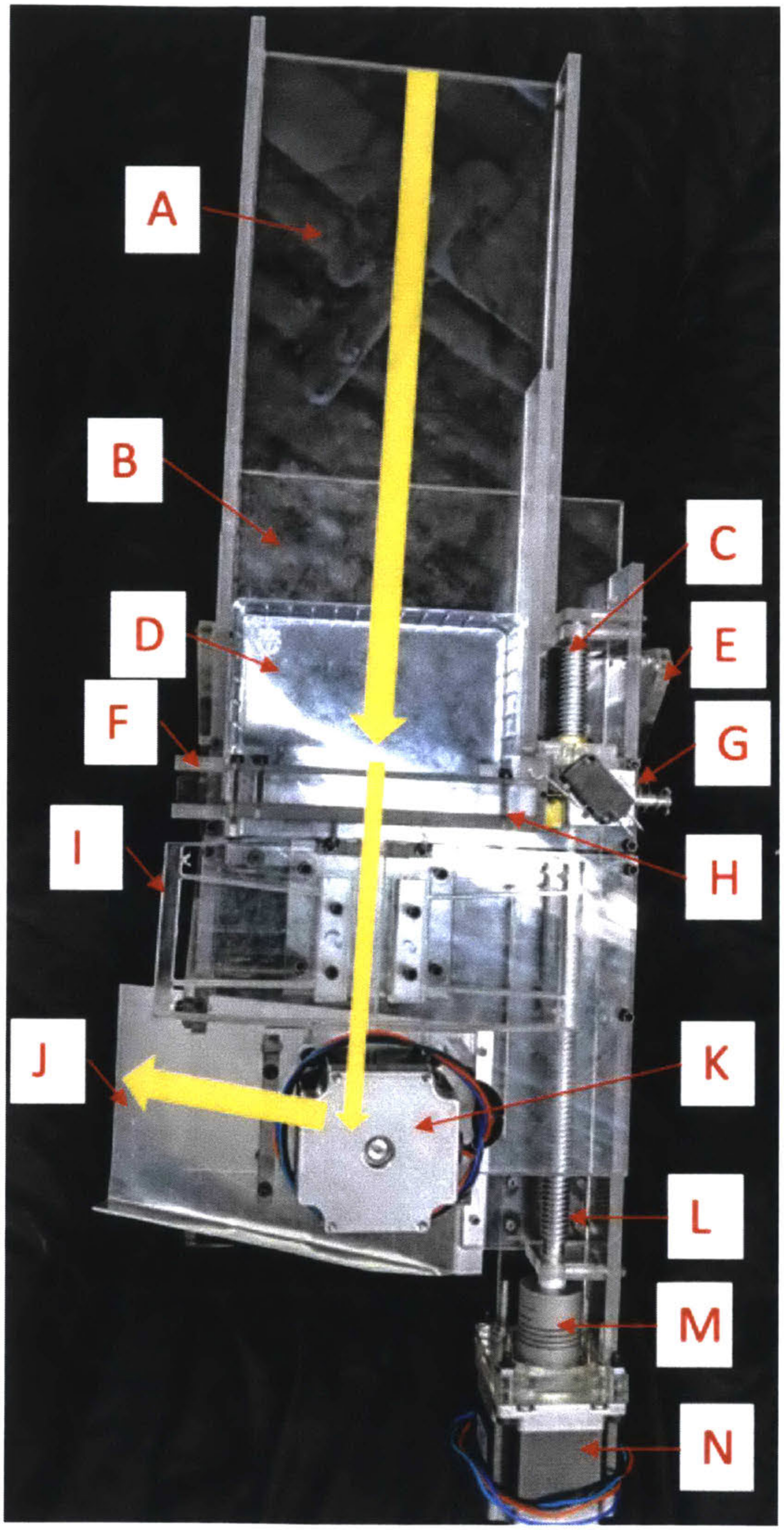


Figure 4-20: Top side isometric view of prototype IV. A) Tray queue. B) Chassis. C) Lead screw front. D) Tray. E) Angle bracket mount. F) Vial entrance gate. G) Biasing

mechanism. H) Rake. I) Flexure. J) Tray exit ramp. K) Cam stepper motor. L) Lead screw back. M) Flexible coupling. N) Lead screw motor. Note: The yellow arrows indicate the tray's direction of travel within the placement mechanism.

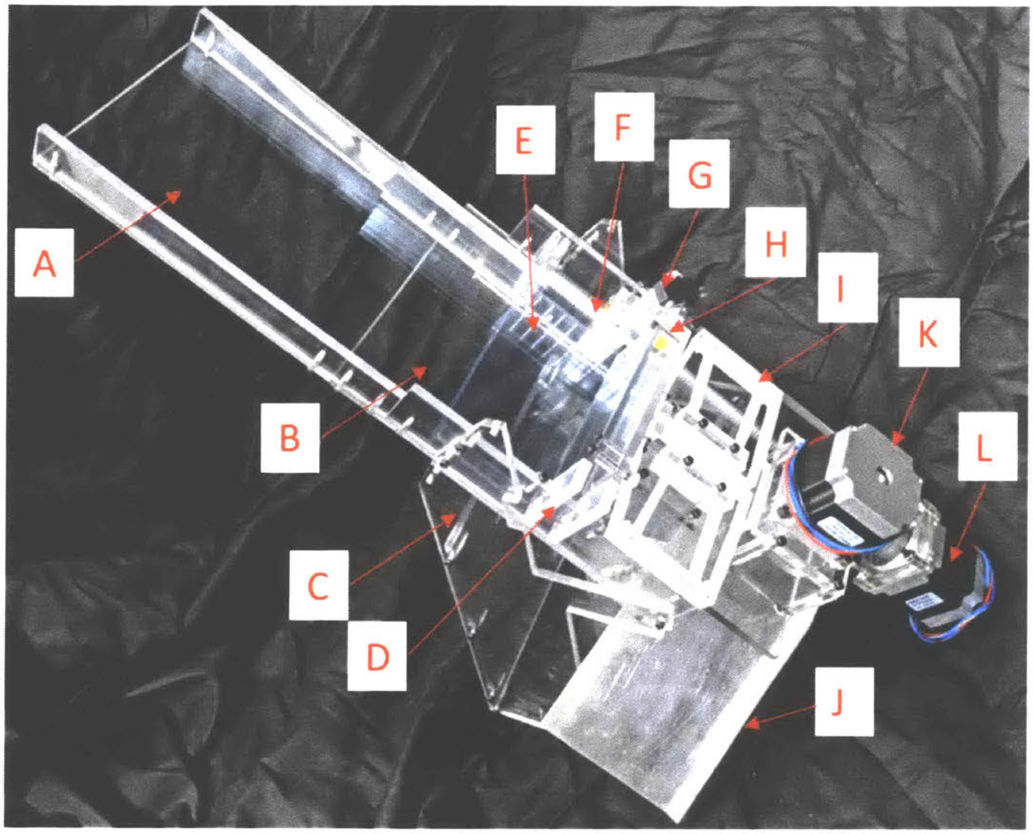


Figure 4-21: Left side isometric view of prototype IV. A) Tray queue. B) Chassis. C) Angle bracket mount. D) Vial entrance gate. E) Tray. F) Tray slider lead screw. G) Biasing mechanism. H) Rake. I) Flexure. J) Tray exit ramp. K) Cam mechanism. L) Tray slider lead screw stepper motor.

The first system to be redesigned was actuator required to push the flexure forward. As learned from prototype III, solenoids do not provide the smooth transfer of force necessary to drop the vials into the tray accurately. Therefore, another type of motor would need to be used that could provide enough force with smooth motion. Watching the stepper motor rotate the lead screw on the previous design provided Diarny Fernandes a thought of brilliance; invert the stepper motor perpendicular to the flexure and insert a cam to the end of the stepper motor to push the flexure. As shown in Figure 4-22 below, the stepper motor with the cam attached was integrated into the final system. The stepper motor provides enough torque to be transferred into force pushing the flexure. Furthermore, the cam designs could be infinitely tuned to dial in on the precise flexure motion needed to drop the vials into the tray robustly.

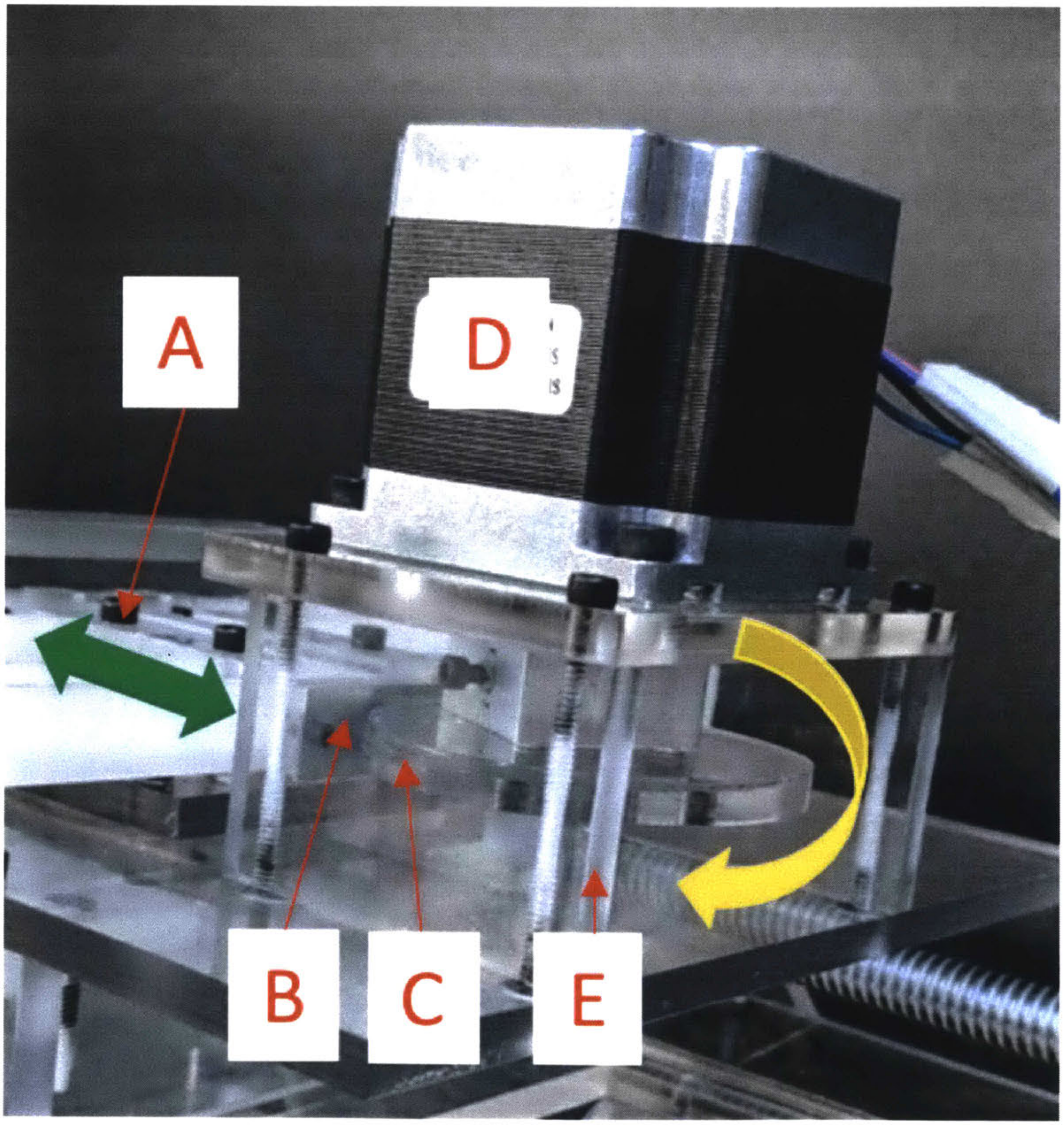


Figure 4-22: Isometric view of cam mechanism. A) Flexure. B) Metal contact surface on flexure. C) Cam. D) Stepper motor. E) Cam mechanism mounting structure. Note: The yellow

arrow indicates the cam's direction of twist leading to the actuation of the flexure represented by the green arrow.

The second system to be added was the offramp on which full trays could exit. This tray was a constructed of 1/10" sheet of steel with a 20-degree slope. The ramp was specifically designed to be simple while remaining effective at removing trays from the system. Figure 4-23 below displays the ramp attached to the back end of the system.

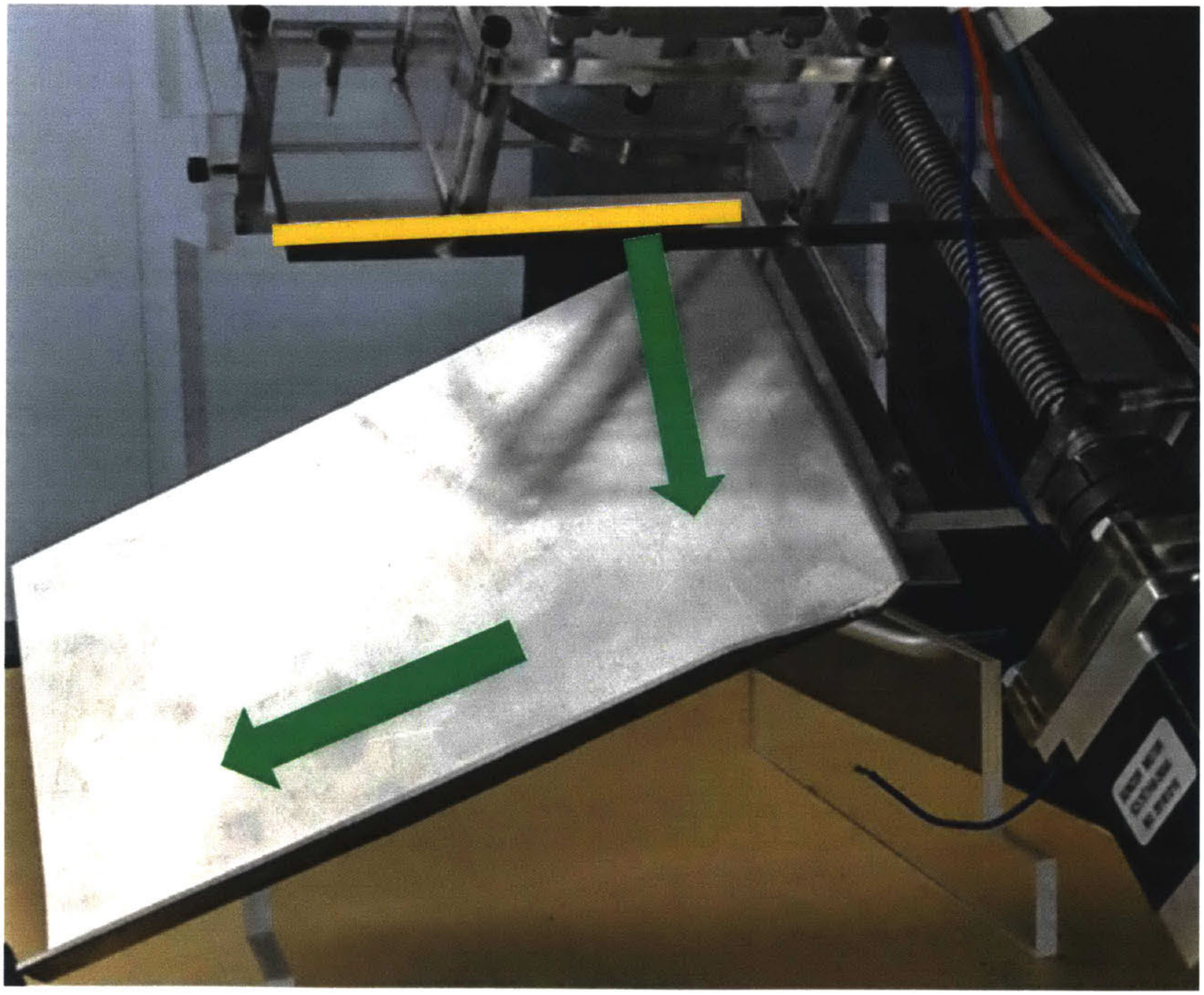


Figure 4-23: Offload ramp attached to back of chassis. Note: The green arrows indicate the tray's direction of travel out of the back of the chassis to the offloading ramp. As shown, the

tray exits perpendicular to its original direction of loading motion. The yellow line indicates the end point of the chassis before the offload ramp begins.

The third system to be added was the tray queueing assembly on which multiple empty trays could be loaded. Another simple design, the tray queue extends outward past the main body of the placement system, providing extra space for the trays to be loaded. This design was made to hold four empty trays. Yet, the ability to bolt on different lengths of surface allows the tray queue to be modified once handed off to waters to hold as many trays as they find necessary. Figure 4-24 below shows the tray queue attached to the front end of the system. Note the placement of the right wall of the tray system, extending back close to the leadscrew. This placement was intended to shield empty trays from a moving leadscrew while the tray carriage was near the end of its stroke offloading a vial.

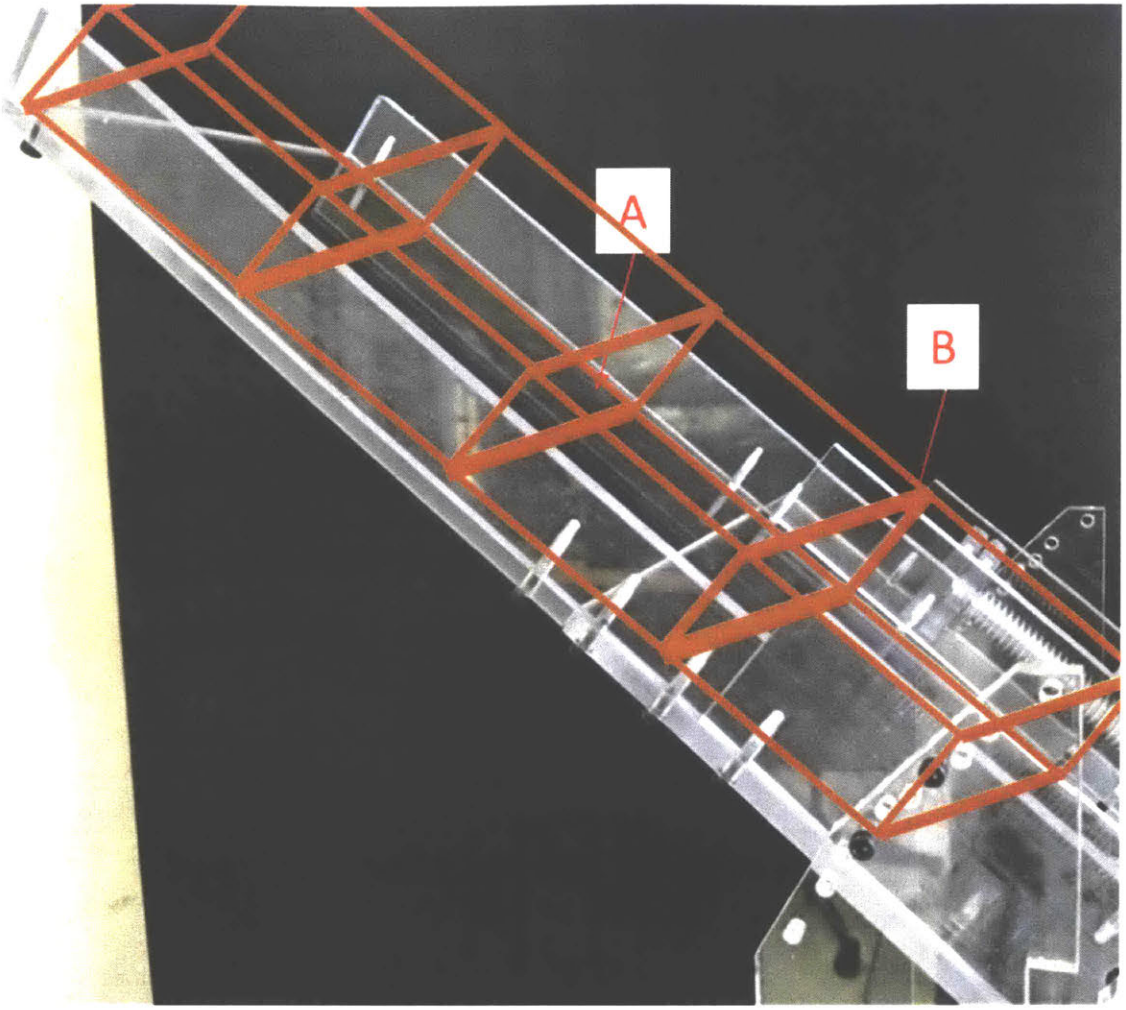


Figure 4-24: Tray queue attached to front of chassis. A) Tray queue. B) Chassis. Note: The orange boxes represent the placement of four trays within the tray queue.

The fourth system to be added was a guide for the tray carriage to follow. Prototype III proved that the tray carriage was plagued with inherent wobbling. This is because the carriage was using the lead screw bearing both as a positioning figure as well as a movement mechanism. As pointed out by Professor David Hardt, this one point of contact design is considered 'bad engineering.' Therefore, a groove was cut into the bottom surface of the system where a set screw connected to the bottom of the tray carriage could rest. Figure 4-25 below shows how the edge of the groove provides latteral constraint for the lead screw

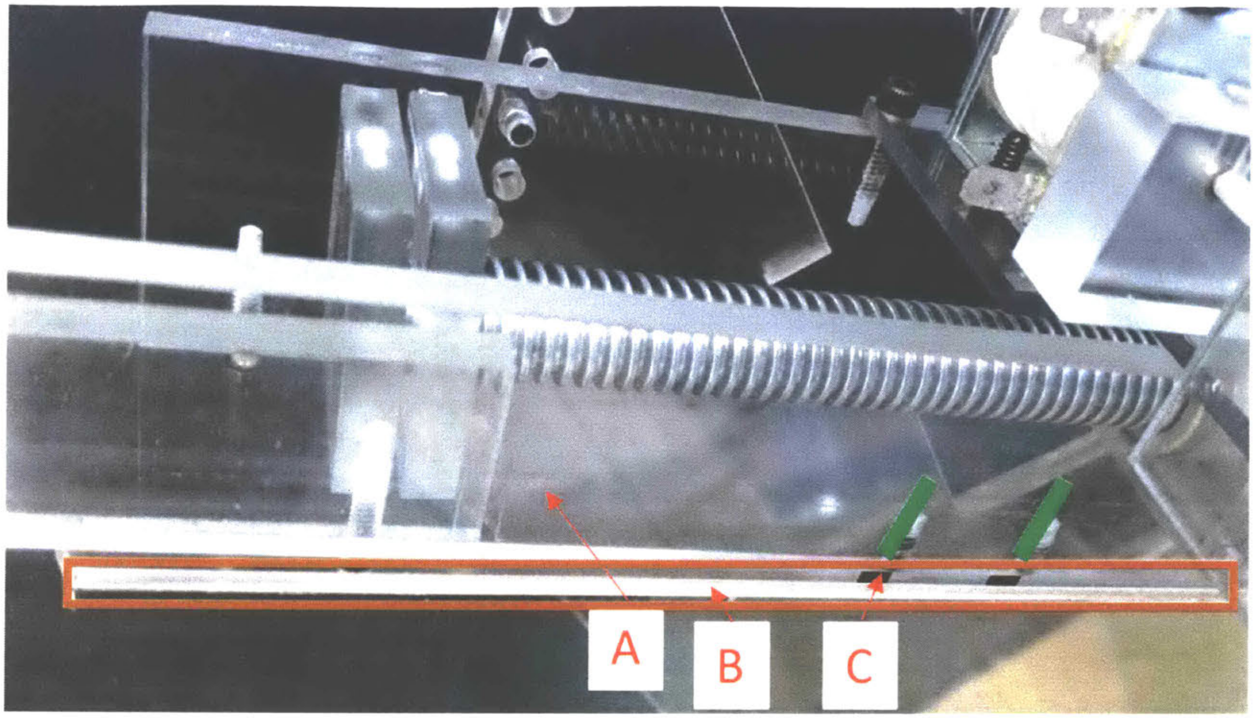


Figure 4-25: Tray slider sitting on top of guide grooves. A) Tray slider. B) Guide groove C) Tray slider set screw. Note: The orange box overlays the groove guide and the green squares denote the location of the tray slider set screws.

The fifth mechanism to be added were mounting brackets with variable angle selection. The system mount, shown in Figure 4-26 below, featured a modest three bolt connection on which the outer two bolts could pivot around a central bolt. The mount can angle the placement mechanism anywhere between 30-degrees to 50-degrees from the ground at 5-degree increments. Variable angling provides the benefit of selecting the most robust configuration for vial delivery into the tray.

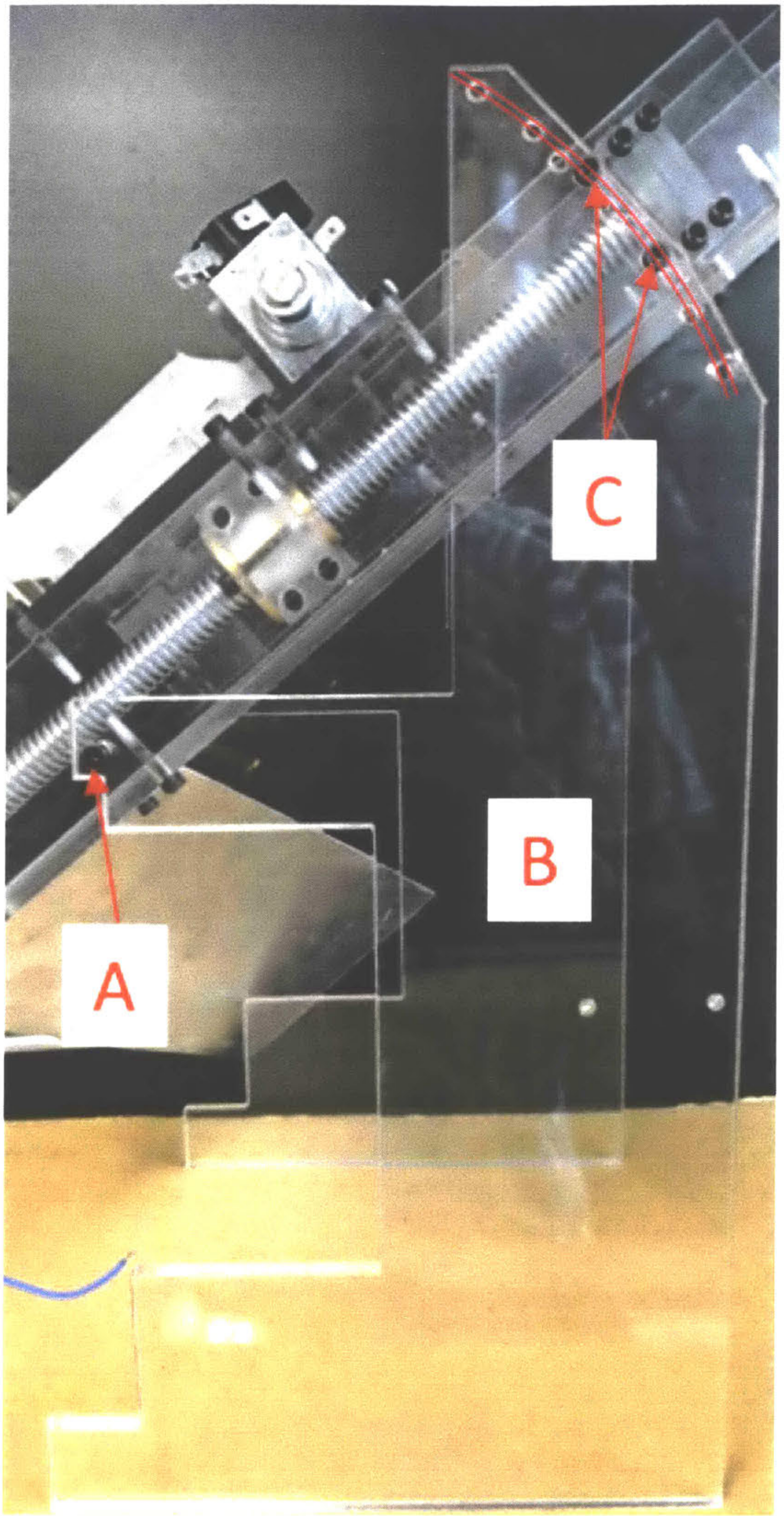


Figure 4-26: Mounting brackets with variable angle holes. Path of mounting holes outlined in red. A) Rear pivot mounting hole. B) Mounting bracket. C) Dual front mounting hole.

The penultimate system to be modified was the lip assisting the first row of vials entering the tray. As noted in prototype III, the first row of trays would not remain biased to the left or the right once settled on the tray. This is because there was nothing preventing the vials from wiggling back or forth. All rows after the first are constrained by the edges of the vials before them, but the first row does not experience this situation. Therefore, as shown in Figure 4-27 below edge of the lip protrudes out an extra quarter of the inch on the right-hand side to allow the vials to rest against once in the tray. The right side was chosen for biasing first versus the left side because trays exit on the left. Keeping the protrusion on the right side allows the trays to exit steadily without being disturbed by the material.

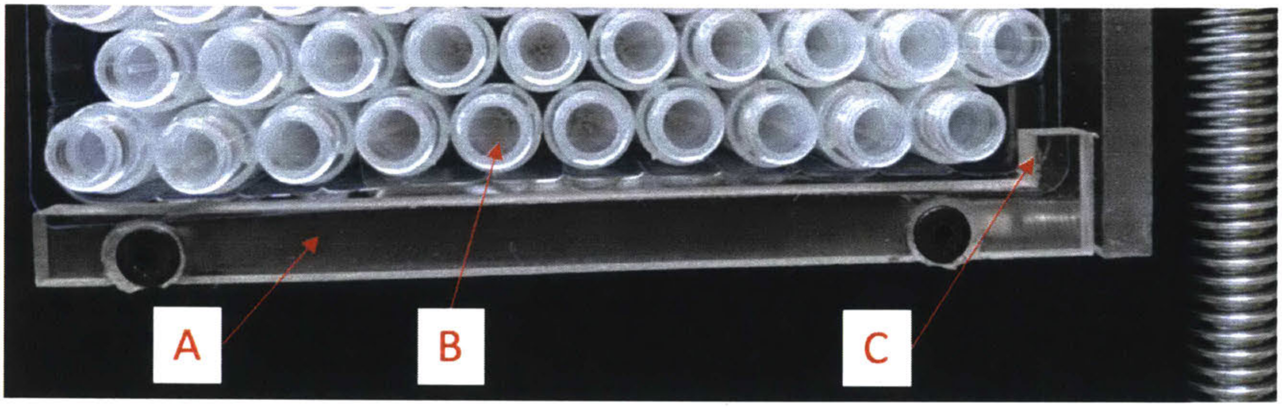


Figure 4-27: First row assistance edge on back wall of tray slider. A) Tray slider first row edge. B) First row of vials. C) First row biasing feature on first row edge.

The final system to be added was a gate to guide new vials into the rake. The gate provides a connection point to the transfer mechanism in which output vials can be accepted. Furthermore, the gate, remaining stationary, is able to act as a wall on which the 11th vial in a system can leverage off of when pushed out of the rake. Figure 4-28 below displays the gate positioned next to the rake.

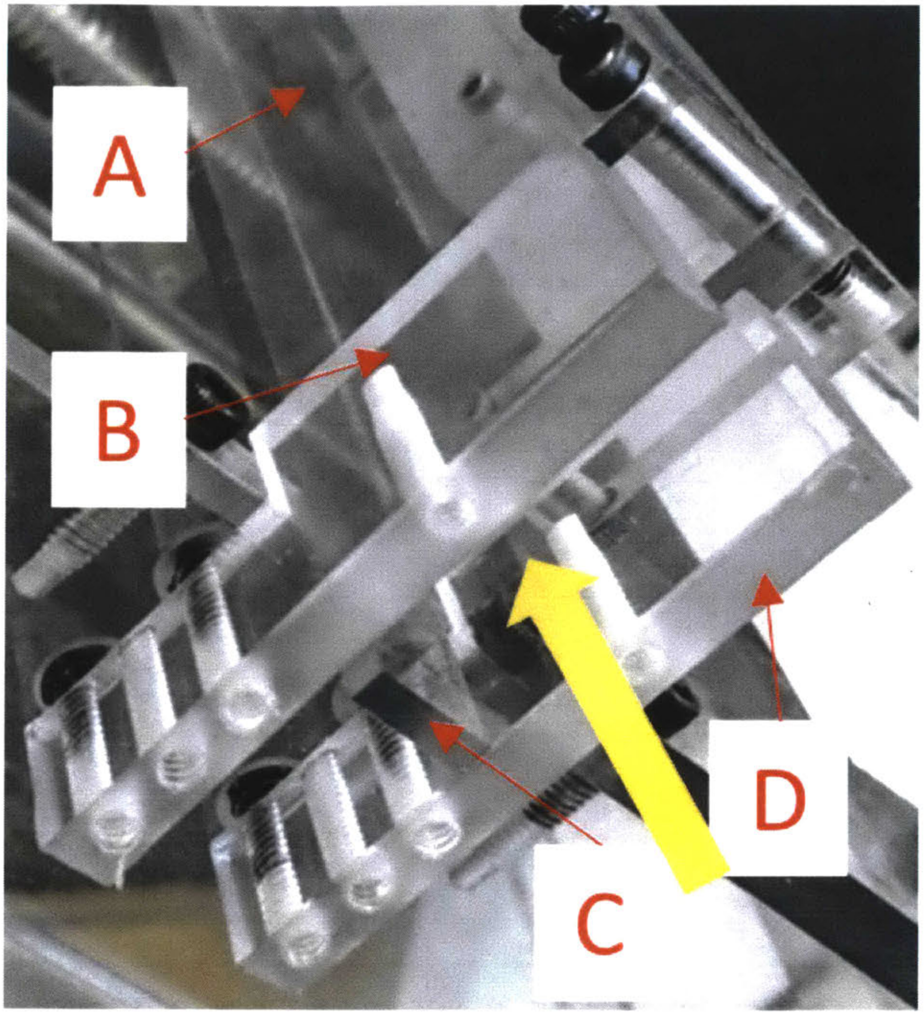


Figure 4-28: Gate funneling incoming vials into rake. A) Rake. B) Front side vial gate. C) Bottom surface on which incoming vials slide. D) Back side vial gate. Note: The yellow arrow points to the direction of vial insertion.

Lastly main body of the placement mechanism was lengthened to account for the addition of the tray queue and exit ramp. This meant the prototype gained utilized a foot-long lead screw and longer sidewalls. All height dimensions remained the same as in the previous prototype.

4.2 System Overview

The as previously stated, the vial placement mechanism performs two primary tasks: loading the oriented vials into a tray and queueing empty trays to be loaded with vials. five critical components ensure the two tasks are executed properly: flexure, rake, tray transport system, cam mechanism, and chassis. Two stepper motors and one solenoid actuate these components. Refer to Figure 4-29 below to see these components and actuators as they are situated in the placement system.

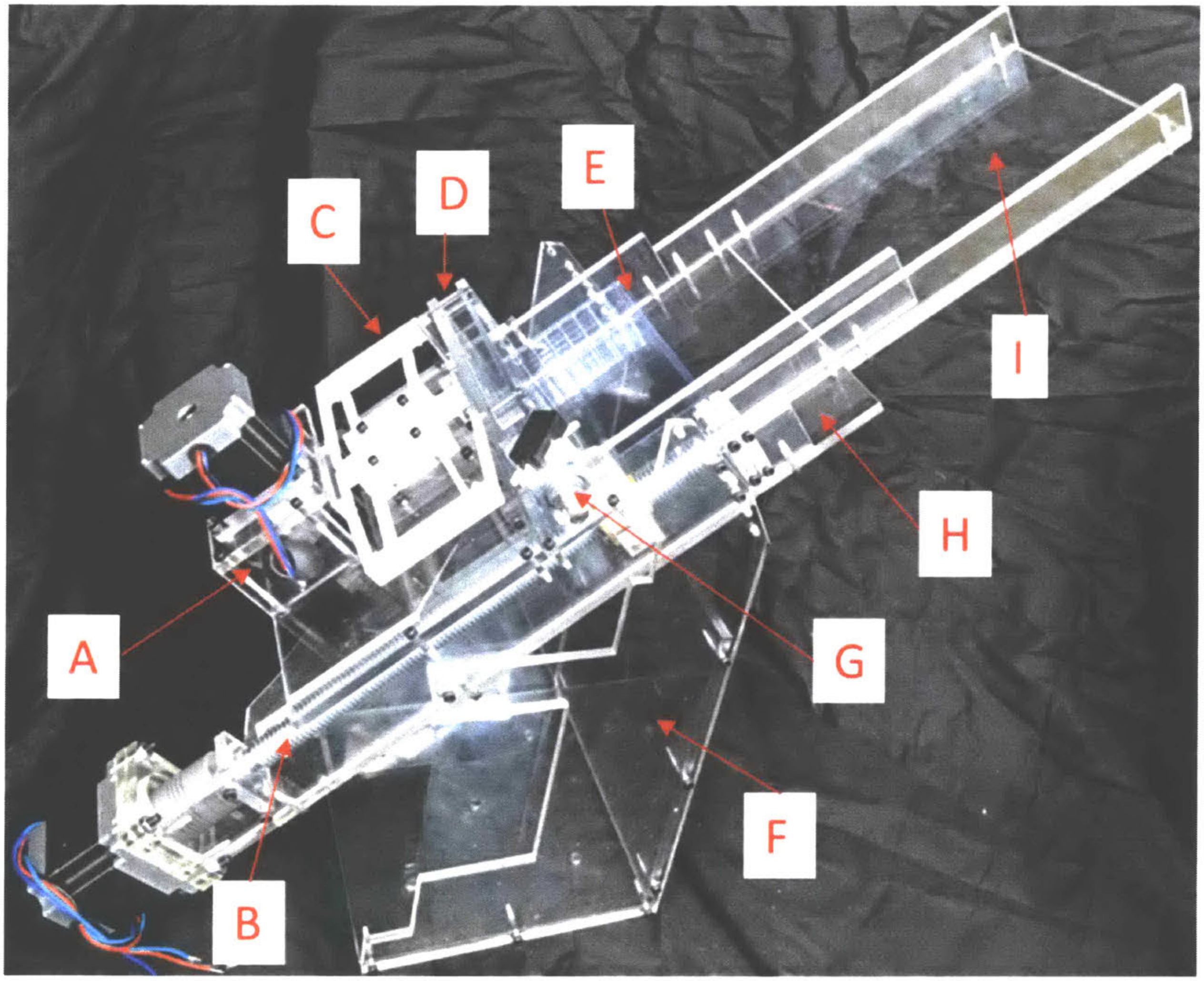


Figure 4-29: Final vial placement mechanism. A) Cam mechanism. B) Tray slide lead screw. C) Flexure. D) Rake. E) Tray. F) Angle bracket mount. G) Biasing mechanism. H) Chassis. I) Tray queue.

Sections 4.3 through 4.9 provide a detailed overview of the design, selection, testing, and implementation of each of the various components and actuators.

4.3 Flexure

The polycarbonate flexure acts as a linear slide constraining motion in all but one axis. As previously articulated, a flexure was selected to translate motion from the actuator to the rake for the sake of reliability, part reduction, lack of maintenance, and tunability. Furthermore, the flexure offers boundless possibilities for calibrating lateral stiffness depending on the part's geometric layout.

Design of the flexure's geometry was primarily performed in Solidworks with static force simulations. As shown in Figure 4-30 below, iterations of flexure layout were tested with different loads to determine the optimal wall thickness of the flexure's components. Tradeoffs were weighed between walls that were too thin and prone to fracture over walls that were too thick requiring excessive force to fully move the flexure. Ultimately, a finite range of flexure shapes were chosen for physical validation within the placement mechanism. The final geometric layout of the flexure is shown in Figure 4-31 below.

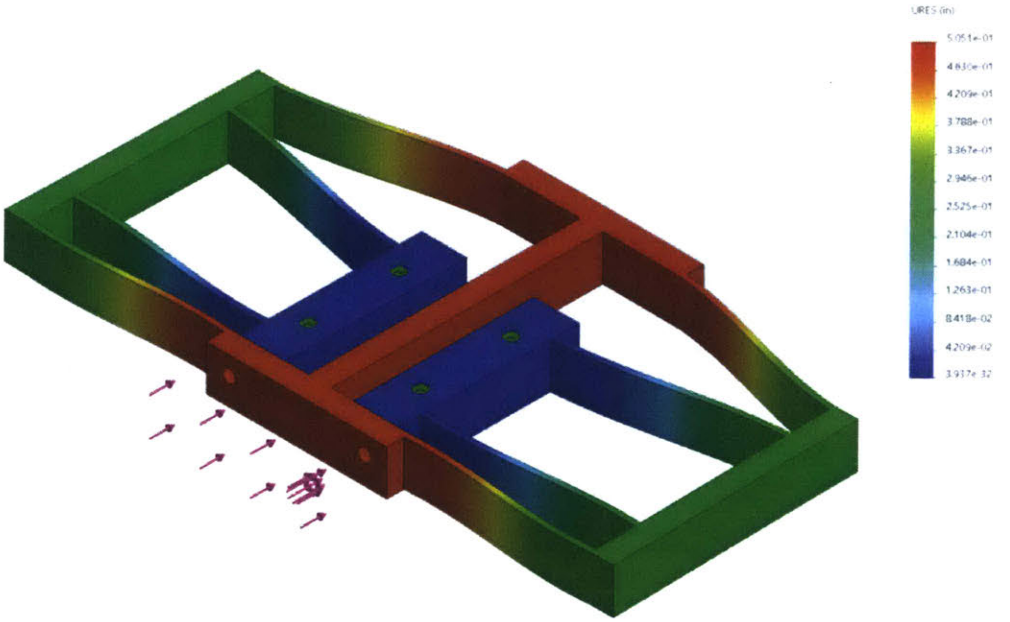


Figure 4-30: Solidworks static force simulation on flexure.

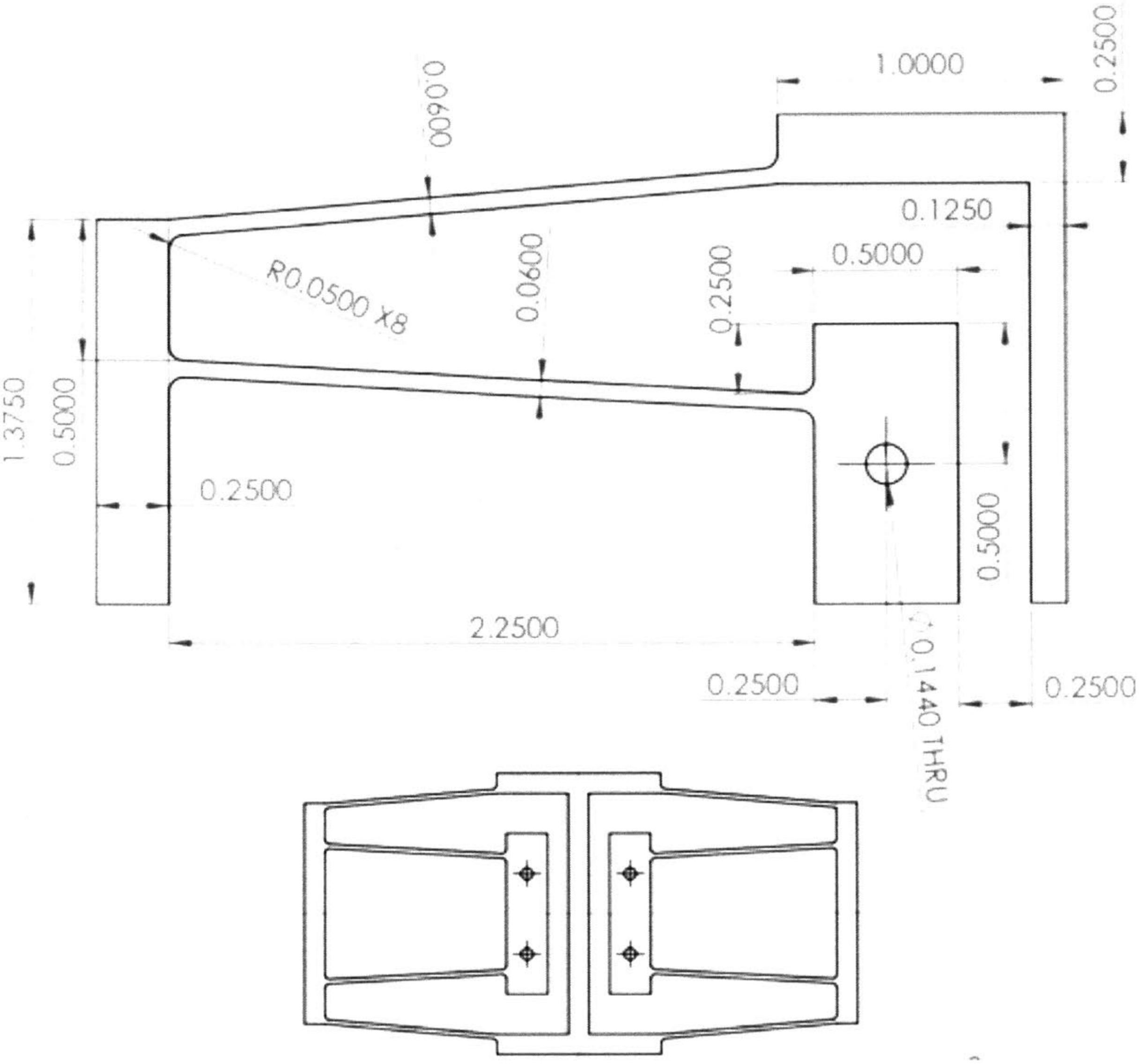


Figure 4-31: Technical drawing of flexure geometry.

Material selection for the flexure was first narrowed down between plastics and metals. Plastics were chosen due to their superior ductility and ability to resist work hardening over multiple cycles. When looking within the collection of plastics available, five contenders were considered: acrylic, high density polyethylene, polymethyl methacrylate, polypropylene, and polycarbonate. Ultimately, polycarbonate was selected because of its high impact resistance, ductility, chemical inertness in a cleanroom setting, and ability to withstand cycle fatigue.

4.4 Rake

The rake was created to accept a line of 10 incoming vials, bias vial offset, and control the vial descent during their fall into the tray. The rake contains four notable features: a channel for vials to accumulate, a cutout for the biasing mechanism to enter, an elongated front panel to assist with vial falling, and a tailstock to assist with incoming vial retention during the movement phase.

The channel for vials to accumulate is 5% wider than the diameter of each vial. This width difference removes the possibility for vials to bind when entering the channel. Furthermore, the gate in the injection molding process is placed on the side of each vial. This creates a miniature protrusion rendering the diameter larger than 12mm in that location. The is long enough to hold 10.35 vials. The extra third of a vial is used when vials are biased towards the right-hand side of the tray. Because the eleventh vial enters the tray a distance less than half of its diameter, it is able to be squeezed out by the vial entrance gates shown previously in Figure 4-28.

Once the eleventh vial is squeezed out of the channel, pressure is still exerted on the vial trying to move it into the void where the channel used to be. The tailstock, shown below in Figure 4-32 acts as a barrier to the eleventh vial. It is only activated when the rake moves forward in the vial dumping stroke.

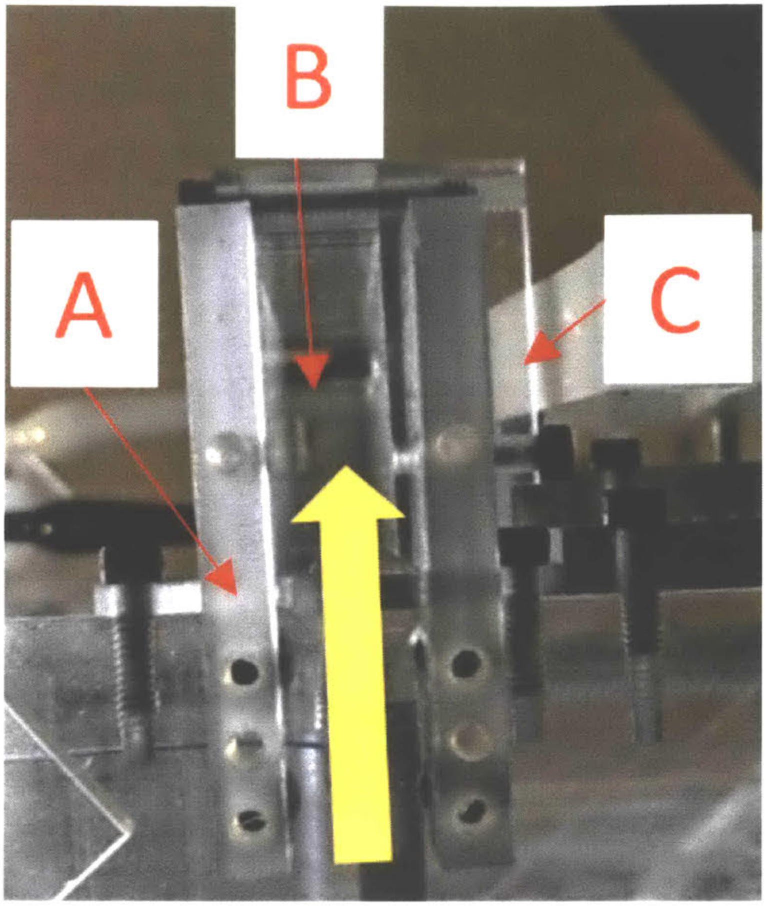


Figure 4-32: Left side view of rake depicting: A) Vial entrance gate. B) Chute leading to interior of rake. C) Tail stock. Note: The yellow arrow indicates the direction the vials flow as they enter the vial entrance gate.

A cutout on the side of the rake makes room for the vial biasing block to enter from the vial biasing mechanism. Figure 4-33 below displays the vial biasing block in its extended position inserted into the rake. When the biaser is extended, the tray length decreases to hold ten vials.

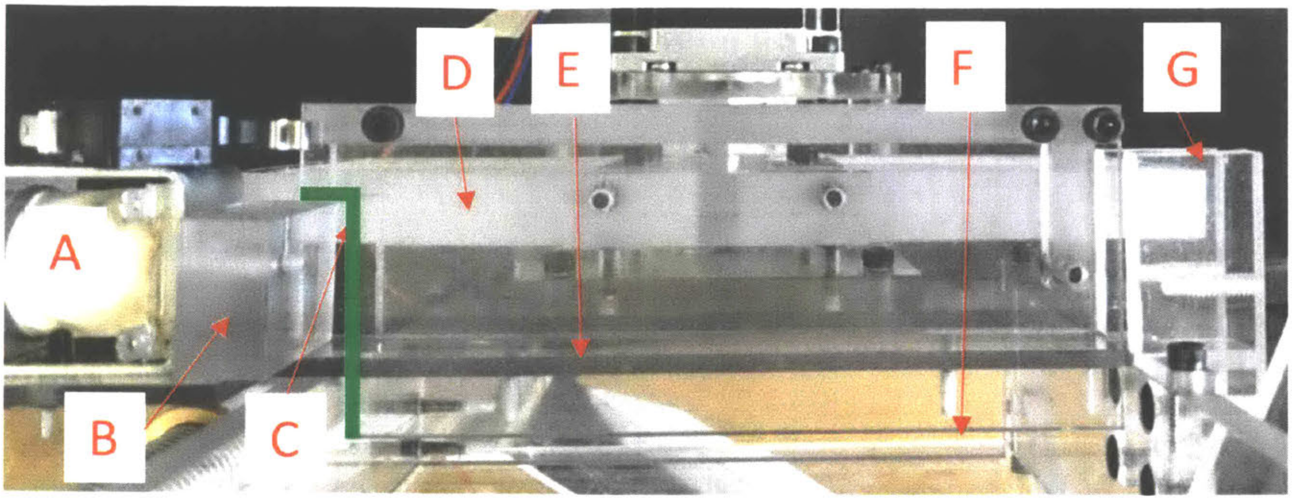


Figure 4-33: Front side view of rake depicting: A) Vial biasing solenoid. B) Vial biasing block. C) Cutout in rake for vial biasing block. D) Flexure. E) Bottom surface on which incoming vials rest. F) Bottom of rake's front surface. G) Incoming vial gate. Note: Green outline highlighting the notched edge of the rake where the vial biasing block fits.

The front of the rake extends downwards past the surface that the accumulated vials sit on, stopping just short of the tray's upper lip. The extended surface provides more surface to guide the vials when falling. Because the top of the vials extends past the bottom of this surface when sitting in a tray, the tray cannot be pushed backwards once a row of vials is loaded.

4.5 Tray Transport System

The tray transport system moves trays from a queue, through the main body of the placement mechanism, out to an exit ramp. A tray slider carries the trays through the entire system and provides finite adjustments to accurately position each tray under the rake for vial loading. The slider is directed forward and backward through a leadscrew attached to a stepper motor. Figure 4-34 below displays a bottom view of the transport system.

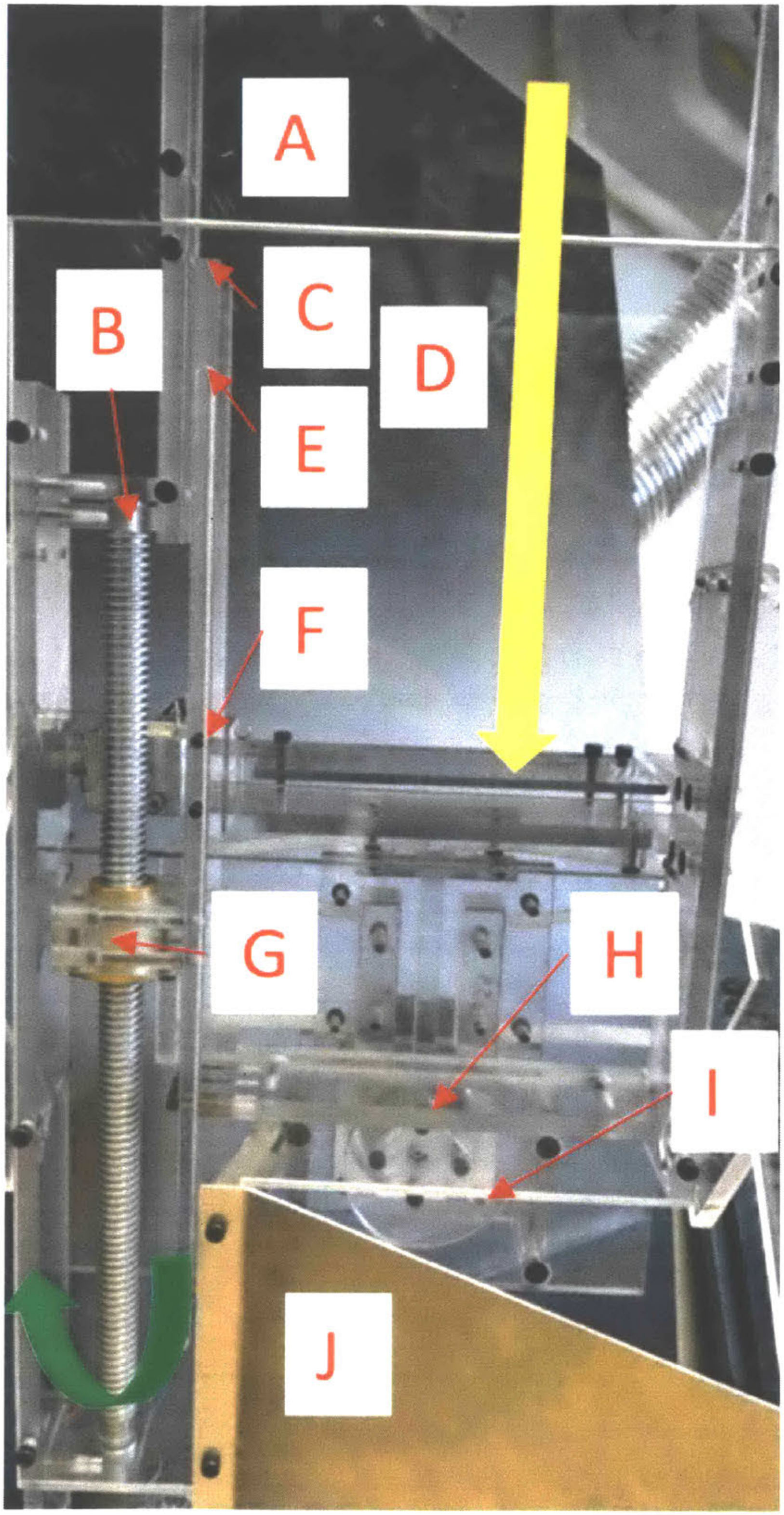


Figure 4-34: Bottom side view of tray transport system. A) Tray queue section. B) Front of lead screw. C) Front tip of tray slider. D) Start of chassis section. E) Front end of guide

groove. F) Tray slider guide set screw. G) Tray slider bearing block. H) Back wall of tray slider. I) Back edge of chassis. J) Exit ramp. Note: The yellow arrow indicates the tray's direction of movement through the transport system and the green arrow represents the lead screw's direction of twist.

As previously discussed, empty trays enter the system through a tray queue. The current tray queue can hold four trays but is designed to be swapped out with tray queue sections of different lengths. The first tray to be placed in the queue drops onto the front surface of the slider by the force of gravity. Once positioned on the tray slider, a lead screw moves the slider down under the rake. After the first line of vials are loaded onto the tray, the stepper motor rotates the leadscrew 5 revolutions to move the tray slider down one vial length. This repeats another eight times until the tray is full. Lastly, the tray slider moves over the exit ramp to discharge the packaged tray.

The tray slider mechanism is composed of four pieces of polycarbonate and that act as control surfaces for the tray, falling vials, and leadscrew bearing. Additionally, two setscrews jut out of the bottom of the guide arm. Figure 4-35 below displays the key components of the slider mechanism.

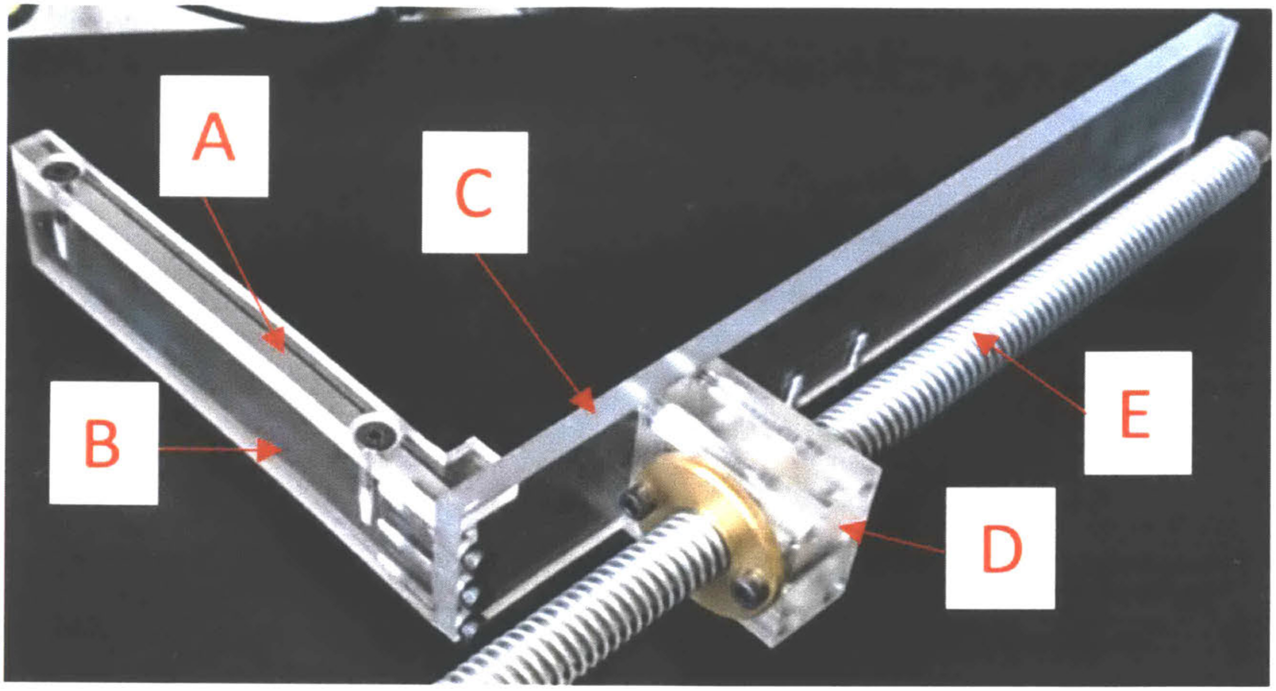


Figure 4-35: Isometric view of tray slider mechanism. A) First row biasing lip. B) Back panel. C) Side panel. D) Lead screw bearing block. E) Lead screw.

The back panel of the tray slider mechanism acts as a surface to hold the tray. The side panel constrains lateral motion, wedging the tray between itself and the left wall of the chassis. On top of the back panel, a first-row guide protrudes over the upper lip of the tray to more accurately guide the first row of vial into the tray. A bearing block is attached to the side panel to move the entire tray. Two set screws sit within a groove on the bottom surface of the chassis to constrain lateral motion of the tray slider mechanism.

4.6 Cam Mechanism

The cam mechanism converts rotary motion to linear motion, providing smooth power transfer from a stepper motor to the flexure. As previously mentioned, the cam mechanism was developed after inherent flaws of solenoids were discovered during creation prototype III's testing. Use of a cam allows a range of designs regarding geometric layout to push the flexure forward at different rates. Figure 4-36 below displays the cam mechanism while Figure 4-37 displays the geometric layout of the cam.

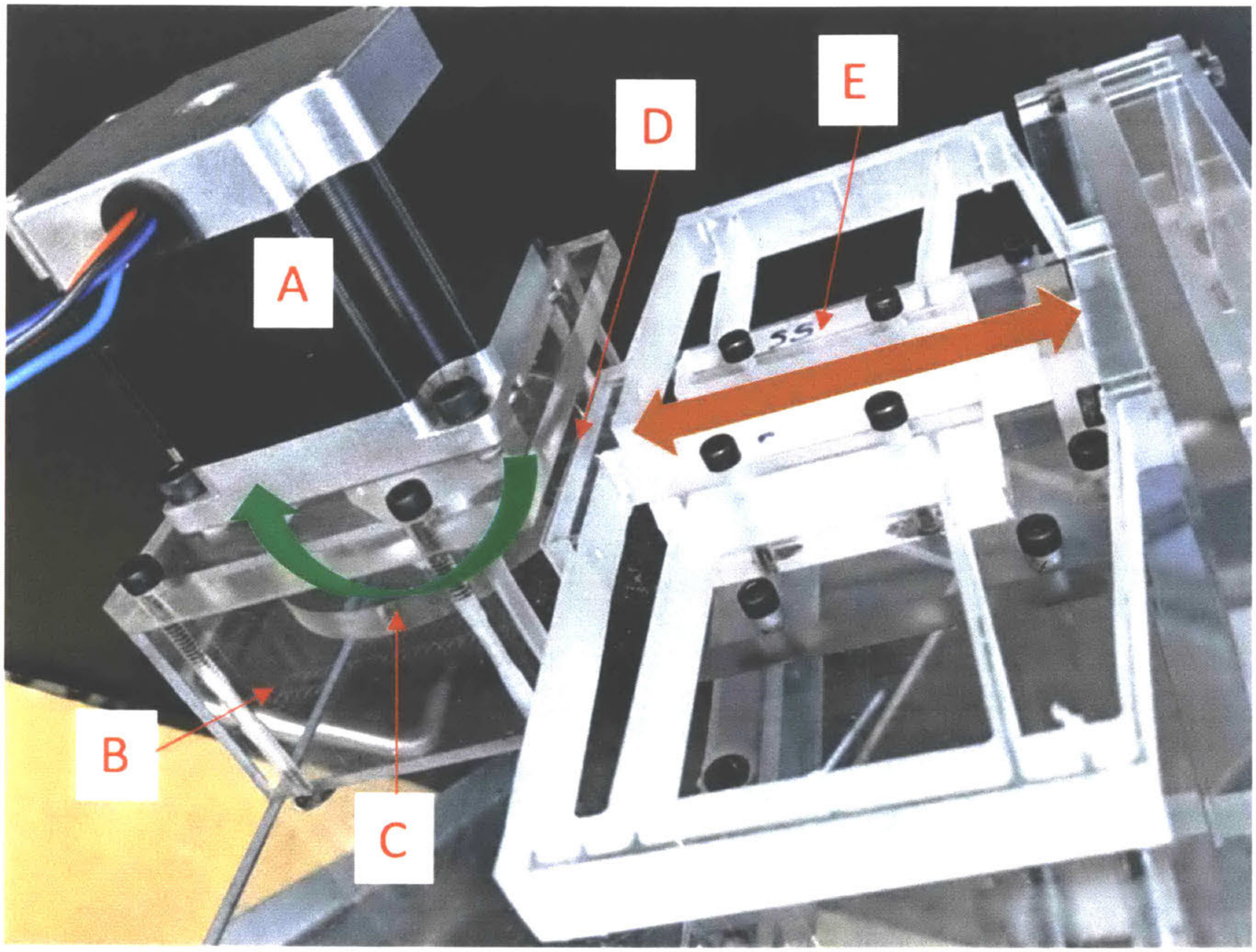


Figure 4-36: Cam mechanism connecting to the flexure. A) Cam actuating stepper motor. B) Cam mechanism mounting structure. C) Cam. D) Cam to flexure contact point. E) Flexure. Note: The green arrow represents the cam's direction of twist and the orange arrow indicates the flexure's corresponding direction of motion.

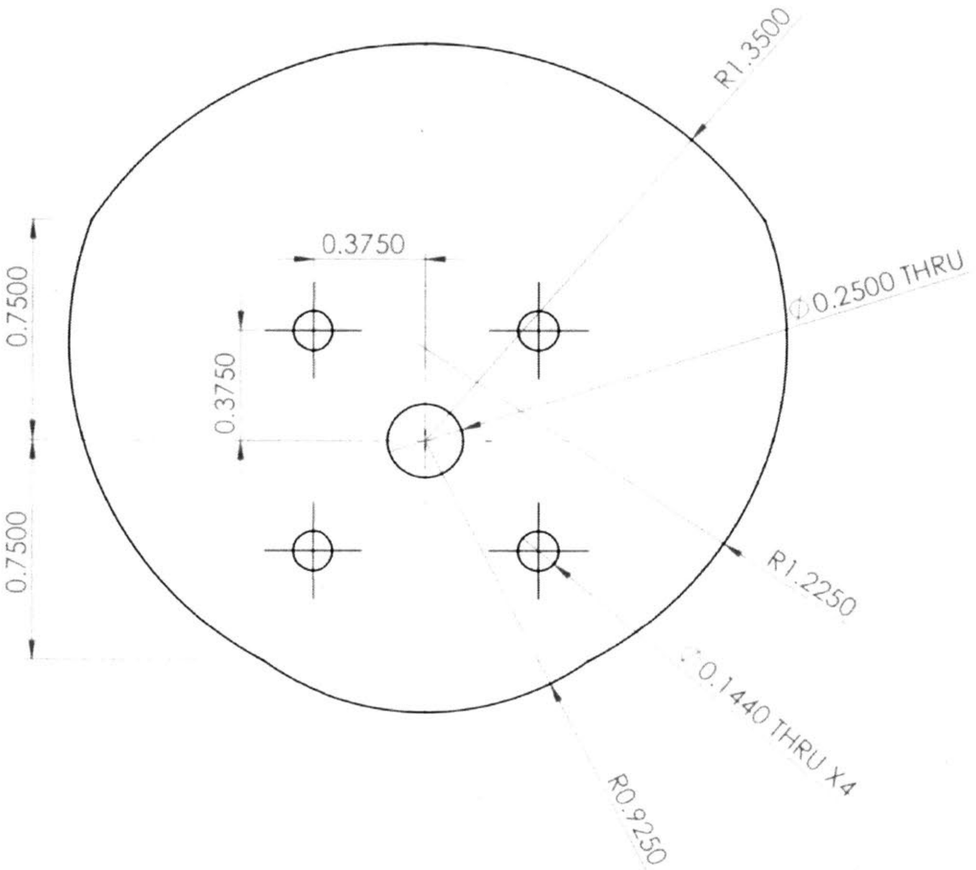


Figure 4-37: Technical drawing of cam geometry.

An aluminum plate was attached to the back of the flexure where the cam makes contact to provide a dissimilar material for the cam to rub. Additionally, the cam was constructed out of acrylic instead of polycarbonate like the rest of the components. This is because acrylic provides a more wear resistant surface when exposed to prolonged friction. Additionally, acrylic can be easily laser cut, an important manufacturing method to leverage on such a complex geometry.

4.7 Chassis

One quarter thick sheets of polycarbonate were used to create every piece of the chassis. As previously discussed, this created an engaging design space where pieces were created in a two-dimensional fashion and bolted together by 6-32 machine screws to create a three-dimensional structure. Akin to Ikea's design philosophy, this construction method led to ease of assembly.

Furthermore, chassis holds the ability to be constructed out of any rigid material that can be cut from a quarter inch sheet. This grants Water's the ability to change materials for any reason at some time in the future if they find the need to do so. Moreover, being constructed out of polycarbonate adds the benefit of being transparent. This attribute played well when building and troubleshooting system dynamics.

The main body of the chassis is a rectangular cavity that holds the cam, flexure, rake, and biaser on top while positioning the tray transport system below. The queuing section sits in front of the chassis while the exit ramp rests in the back. Mounting brackets are placed to either side of the chassis and position the structure at the chosen angle. Therefore, the angled chassis imparts the inherent angle to every mechanism bolted onto its surface.

Beyond providing structural support and angle to every mechanism in the system, the four sections of the chassis, labeled in Figure 4-38 below, allocate orientation for all mechanisms. The top section aligns the cam mechanism to the flexure-rake combination and the rake to the biaser. The right section aligns the lead screw to the stepper motor, inherently translating to the tray slider placement. The left section aligns the vial accepter gates to the side of the rake. The bottom section guides the tray slider and positions the left and right sections to align the top section components over the bottom section. Therefore, precision manufacturing of these sections was crucial to ensure all components fit together properly.

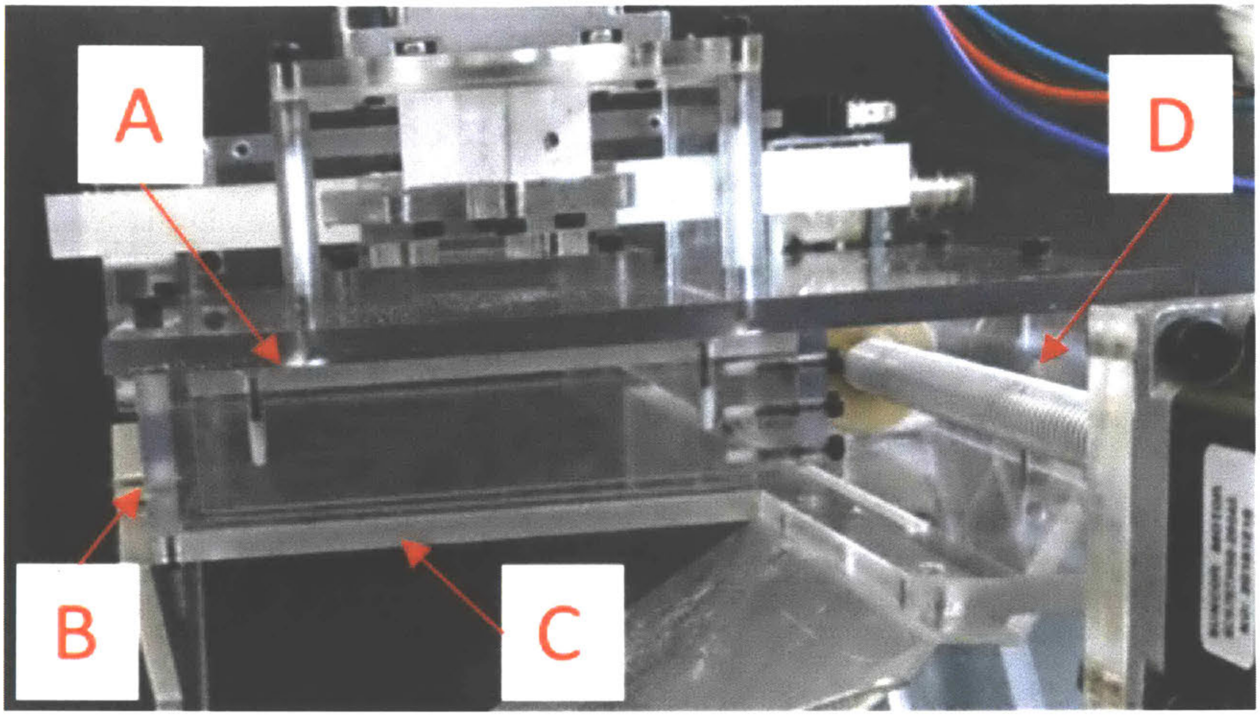


Figure 4-38: Isometric view of chassis displaying four main sections. A) Chassis top section. B) Chassis left section. C) Chassis bottom section. D) Chassis right section.

4.8 Actuators

Three actuators provide necessary movement to the placement system: two stepper motors and one solenoid. The first stepper motor provides rotary force to the leadscrew to linearly move the tray slider through the system. The second stepper motor provides rotary force to a cam, which actuates the flexure that pushes the rake forward. The solenoid provides linear force to the biasing block. All actuators are tethered to a control system that provides power and commands.

The two stepper motors were selected for their ability to provide adequate torque to actuate the cam and leadscrew under load. Furthermore, the motors fit within the designated budget and were properly sized to attach onto the placement mechanism. The solenoid was selected for similar reasons, replacing torque with linear force.

For more information on motor selection and control, refer to Diarny Fernandes' 2019 thesis.

Chapter 5

Placement System Performance

This chapter describes the methods that were used to evaluate the placement mechanism's performance. Results of the evaluations are noted and analyzed to predict how the system will perform in operation.

5.1 Evaluation Methods

Two tests were conducted to determine the how different attributes of the placement mechanism managed under prolonged use. The experiments performed included: an accelerated life failure test of the flexure, and a vial placement robustness test.

It is important to note that, barring notation, all of the trails were performed on the placement mechanism isolated from the overall packaging machine. Vials were hand packed into the vial acceptor gates instead of fed through the transfer line feeder. This procedure owes itself to the fact that the upstream processes were not complete at the time when testing occurred. Therefore, evaluation results must be explored with an undertone of suspect.

The accelerated life failure test on the flexure transpired first. Once the final material and form of the flexure was determined and manufactured, a continuous cycle test of one flexure actuation per second by the cam happened. The flexure lasted for 39,000 cycles before fracturing. Additionally, a thin black residue built up on the back edge of the flexure where the cam contacted the metallic plate. Discrepancies between test and standard loading conditions include the following: the standard flexure actuation rate is 10 times slower at once every 10 seconds, and the flexure is normally full of vials when actuated whereas it was empty in the test. Given the standard actuation rate allows more heat to dissipate from the cam contact surface and within the stressed flexure material, it is theorized real life conditions would increase the flexure's life span. Furthermore, given the excess force from vials loaded in the rake are negligible compared to the amount of force required to move the unloaded rake, the second discrepancy is not factored into the performance analysis.

The vial placement robustness test was carried out to find the ratio of correct placements versus incorrect placements the mechanism could perform. Because there are 10 rows in each tray, 10 placements transpire per full packaging. For the test, approximately 400 placements were conducted. Each row that correctly landed inside of the tray was counted as a viable placement. Conversely, rows that did not land correctly were counted as failures. Any time a failure occurred, the row was emptied and repeated. The ratio of viable to failure placements was 33:1. In the field, incorrect vial placement events may not result in removal and retrying of the failed row. The full systems control, and sensor setup was not complete at the time of the test resulting in the strategy for responding to this scenario not being established. Lastly, over half of all failed placements occurred during when stacking the first row. As previously stated, the lack of vials acting as backing for the first row creates a climate of excess instability where vials are more prone to falling. Proposals on correcting this error can be found in section 6.2.

5.2 Performance

From the two tests performed, the following conclusions are drawn on the performance of this machine: the machine is able to robustly fill 3 trays on average without error over a month's period of time. After each month, the flexure, in its current design, should be replaced to prevent failure. Furthermore, daily cleaning of the cam to flexure contact surface is advised to reduce particulate buildup.

The number of consecutive correctly filled trays was calculated by dividing the ratio of viable to failure placements and by the number of rows per tray and rounding down to the nearest whole number. Similarly, the flexure replacement cadence was determined by dividing the number of working minutes per month by the number of flexure actuations before failure and rounding down to the nearest whole number. Lastly, the recommendation for daily cleaning of the flexure was estimated by the perceived rate of accumulation of residue during the flexure failure test.

Evaluation of the placement mechanism yielded further recommendations to extend flexure life, decrease particulate accumulation, and increase placement robustness. The proposals can be found in section 6.2.

Chapter 6

Conclusions, Recommendations, and Future Work

This chapter outlines the conclusions that are drawn from the design, development, manufacturing, and testing of the placement mechanism. Recommendations for improvement are explored along with a framework for future work.

6.1 Conclusions

This thesis embodied aspects relevant to machine design. From receiving a customer's problem statement, characterizing it into its requisite objectives and constraints, researching existing methods, brainstorming potential solutions, designing – fabricating – testing repeatedly, the team was able to successfully meet the goals laid out in the beginning of the project. Furthermore, each individual was pressed to work diligently under a strict deadline, with efficient resource utilization such as budgeting, time management, external consultant leveraging, and teammate specialties. Undoubtably, these attributes molded the graduate students into more capable engineers who have proven they can tackle consequential industry problems in a professional setting.

Personally, I most enjoyed learning the principals necessary to create a functional three-dimensional machine using a predominantly two-dimensional framework of sheets bolted together. As discussed in section 4, this design style drew inspiration from Ikea furniture design. An increase in prototyping efficiency was enjoyed from leveraging the sundry of manufacturing methods to create each piece. Furthermore, the ease of assembly and rapid part replacement validated this design philosophy.

Not only were the aspects of machine design explored, but the traits necessary for leadership were imbued through completion of the project. I learned to coherently communicate project status, needs, and barriers to the customer. I perfected my ability to coordinate schedules, plans, and designs between teammates, laboratory technicians, vendors, and the customer. Lastly, I recognized the necessity for mutual respect between all parties involved in this project.

The acquirements discussed above led to the assembly of a prototype that theoretically has the capability of accepting bulk unoriented vials and outputting inspected trays full of 100 vials. Although the prototype does not match the recommended form for integration into the customer's factory, it validates that the provided mechanical drawings, when manufactured and assembled to specification, will perform as needed to fulfil the customer's requirements.

Specifically, the placement mechanism reached its final shape, operation, and performance to the point where it could be implemented directly within the customer's manufacturing environment. However, recommendations on alternatives for craftsmanship and placement mechanism construction before amalgamation with the customer's factory are discussed below.

6.2 Recommendations and Future Work

The placement mechanism succeeded in meeting the functional requirements prescribed by the team and customer. Yet, in the pursuit of perfection, the following steps are recommended to optimize the performance of the machine.

First, the bulk material in which the machine was created can be changed from polycarbonate to aluminum. As mentioned above, polycarbonate was selected as the material of choice because it was strong, resilient, and most importantly transparent. The transparency aided in troubleshooting the machines dynamics yet are no longer needed now that the layout of the machine is solidified. The only part that needs to be kept polycarbonate is the flexure due to the material's mechanical properties that were leveraged in the creation of the device. Aluminum is recommended as the material of choice because it is a stiffer material than polycarbonate and can aid in the rigidity of the overall structure. Furthermore, aluminum is relatively inexpensive and easy to machine compared to other materials.

Second, a rolling contact surface should be designed and implemented in the flexure-cam interface. This change will lead to both particle reduction and prolonged flexure life. A roller bearing could be attached on to the back of the flexure as the contact surface to the cam. The bearing would greatly decrease friction at the interface, which would decrease wear of the cam and aluminum back plate.

Third, the entrance ramp and exit ramp could be further designed to accept stacked trays and output packaged trays in a more robust fashion. New trays enter the factory in stacks and must be removed one by one to be placed on the tray queue by an operator. Developing a mechanism to automate this step would allow the machine to run continuously without human intervention for a longer period of time. If the machine is running for a longer period of time without human intervention, trays will begin to stack up at the end. A more robust exit ramp could funnel the trays down to a longer queue as they await shipment to the customer.

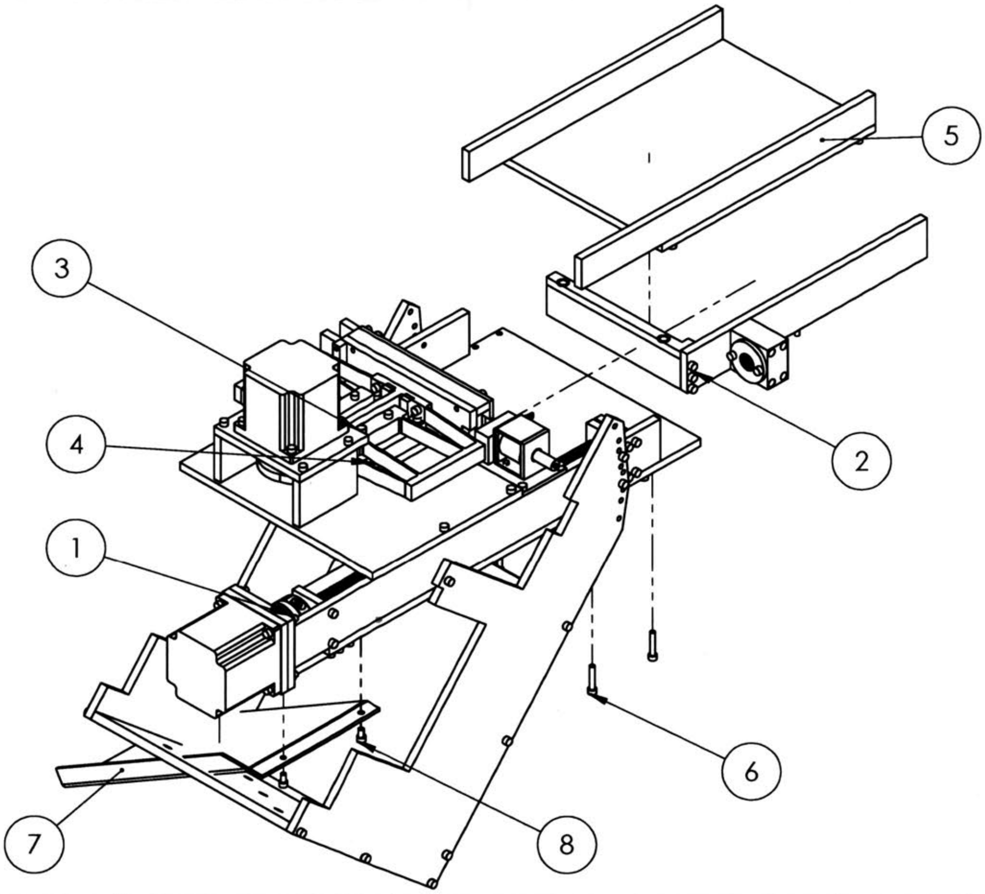
Fourth, the first tray carriage's first row lip should be optimized to robustly accept the first row of vials. Grooves representing the shape of a previous row of vials could be drilled into the lip, providing a similar level of stability that the other rows of vials enjoy.

Beyond the recommendations specific to the current iteration of the placement mechanism, future work could occur in relation to other products that Waters already packages by hand. For example, the company currently sells glass vials of the same exterior dimensions. Assuming the glass vials dynamics are similar to that of the plastic vials, they could be packaged by the same machine to further automate Waters manufacturing operations.

Appendix A

Engineering Drawings

A complete catalogue of engineering drawings used to construct the final prototype of the placement mechanism is displayed in this section.



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1	Shell	Shell Assembly	1
2	Tray_Carriage	Tray Carriage Assembly	1
3	Flexure_Mount_Rake	Flexure Mount Assembly	1
4	6_32_1-2	1/2" 6-32 Machine Screw	4
5	Tray_Queue_Assy	Tray Queue Assembly	1
6	6_32_3-4	3-4" 6-32 Machine Screw	4
7	Exit Ramp	1/10" Aluminum	1
8	6_32_1-4	1/4" 6-32 Machine Screw	2

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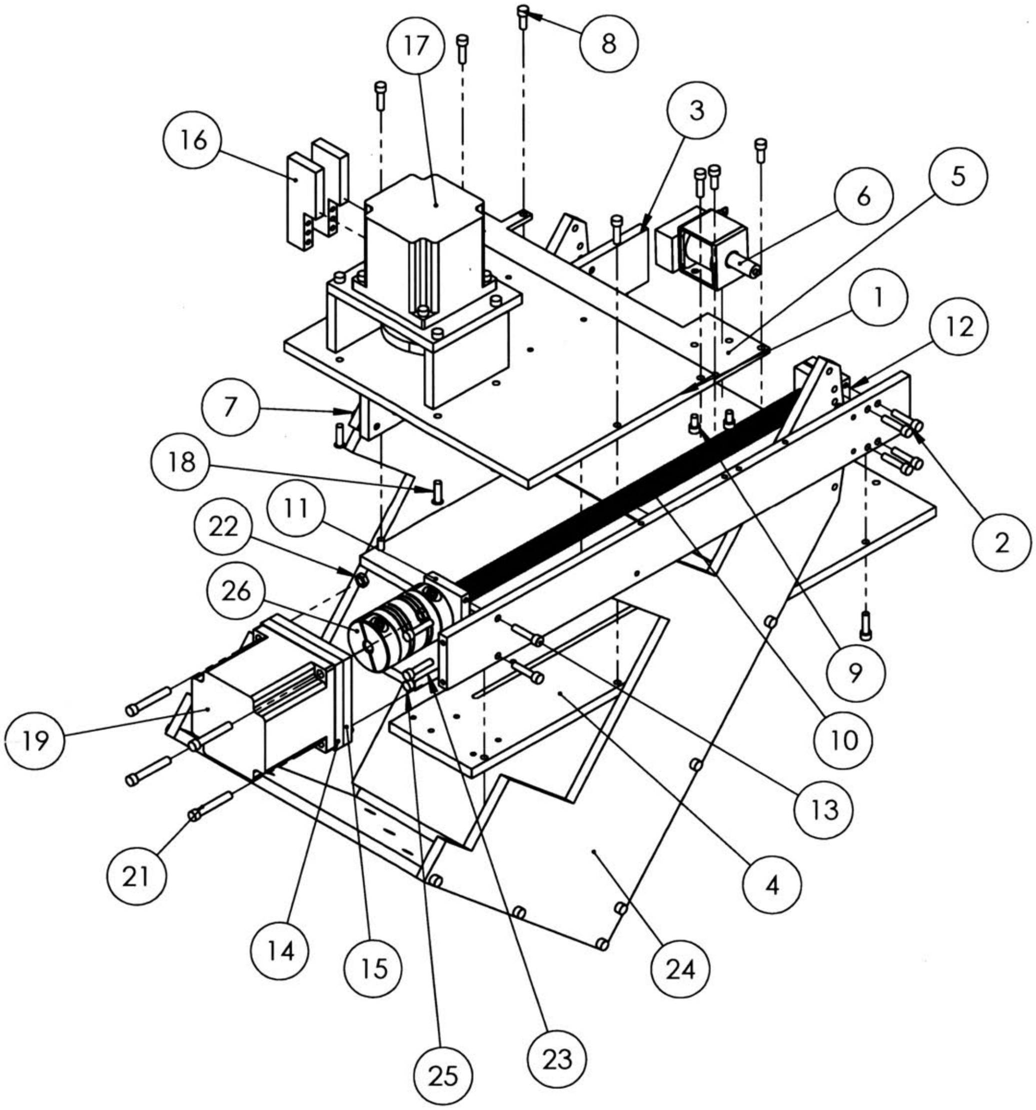

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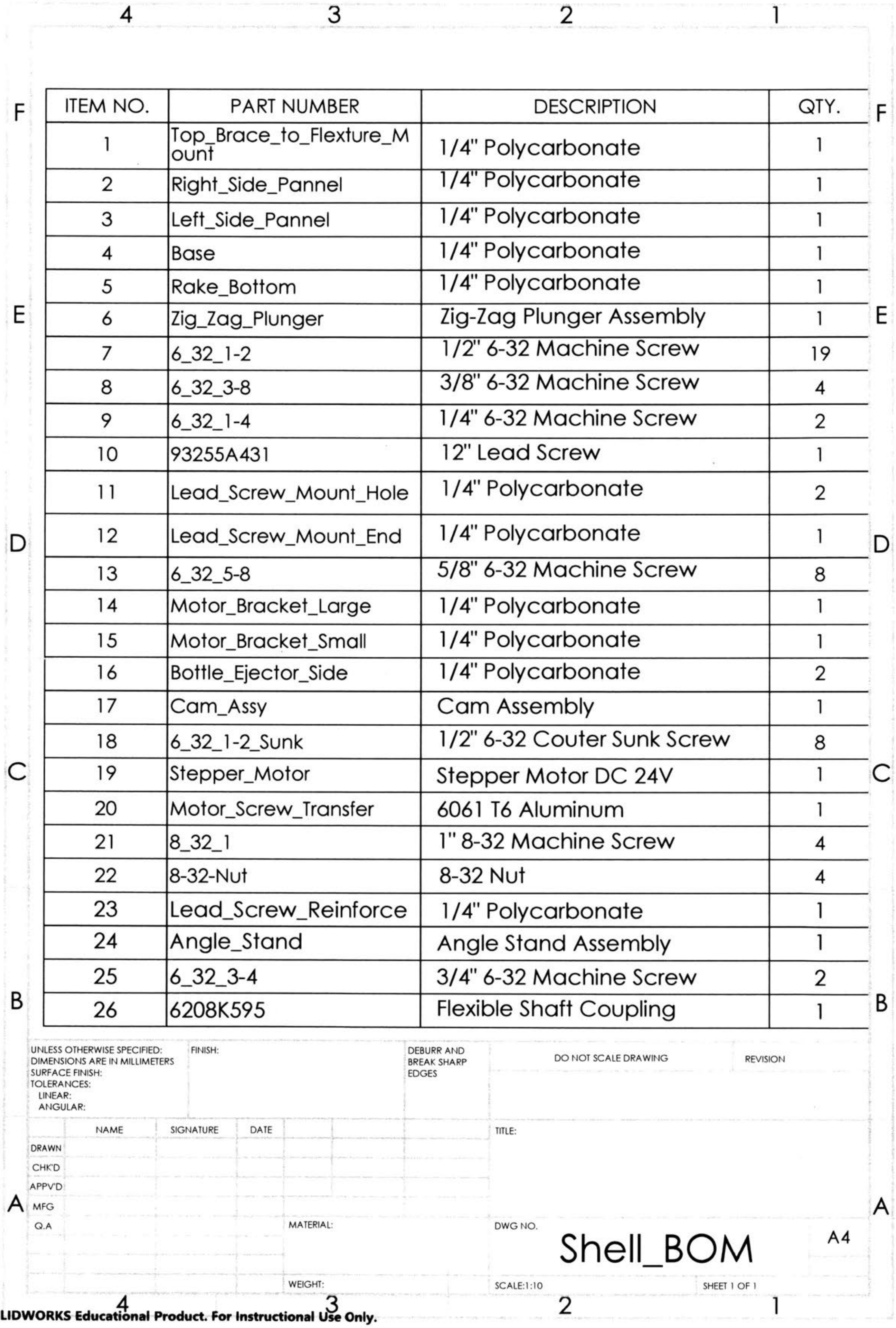

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2	Right_Side_Pannel	1/4" Polycarbonate	1
3	Left_Side_Pannel	1/4" Polycarbonate	1
4	Base	1/4" Polycarbonate	1
5	Rake_Bottom	1/4" Polycarbonate	1
6	Zig_Zag_Plunger	Zig-Zag Plunger Assembly	1
7	6_32_1-2	1/2" 6-32 Machine Screw	19
8	6_32_3-8	3/8" 6-32 Machine Screw	4
9	6_32_1-4	1/4" 6-32 Machine Screw	2
10	93255A431	12" Lead Screw	1
11	Lead_Screw_Mount_Hole	1/4" Polycarbonate	2
12	Lead_Screw_Mount_End	1/4" Polycarbonate	1
13	6_32_5-8	5/8" 6-32 Machine Screw	8
14	Motor_Bracket_Large	1/4" Polycarbonate	1
15	Motor_Bracket_Small	1/4" Polycarbonate	1
16	Bottle_Ejector_Side	1/4" Polycarbonate	2
17	Cam_Assy	Cam Assembly	1
18	6_32_1-2_Sunk	1/2" 6-32 Couter Sunk Screw	8
19	Stepper_Motor	Stepper Motor DC 24V	1
20	Motor_Screw_Transfer	6061 T6 Aluminum	1
21	8_32_1	1" 8-32 Machine Screw	4
22	8-32-Nut	8-32 Nut	4
23	Lead_Screw_Reinforce	1/4" Polycarbonate	1
24	Angle_Stand	Angle Stand Assembly	1
25	6_32_3-4	3/4" 6-32 Machine Screw	2
26	6208K595	Flexible Shaft Coupling	1

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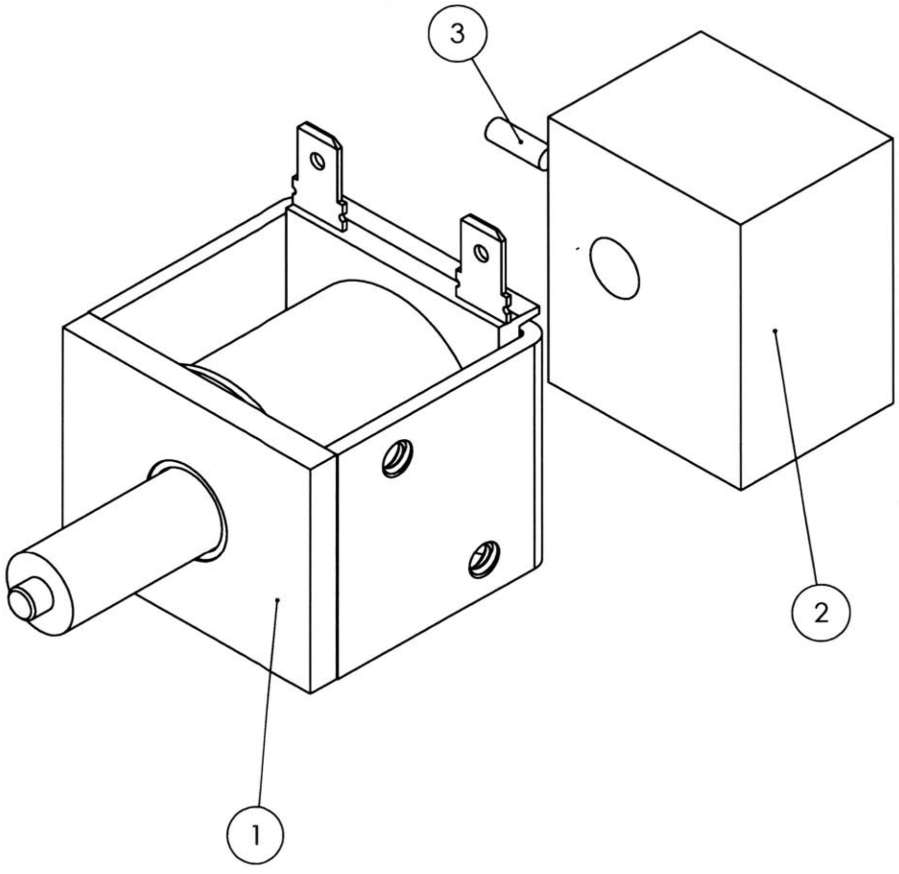
SOLIDWORKS Educational Product. For Instructional Use Only.



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1	70155K661	Linear Solenoid	1
2	Plunger_Block	3/4" Polycarbonate	1
3	2_56_1-4_Set	1/4" 2-56 Set Screw	1

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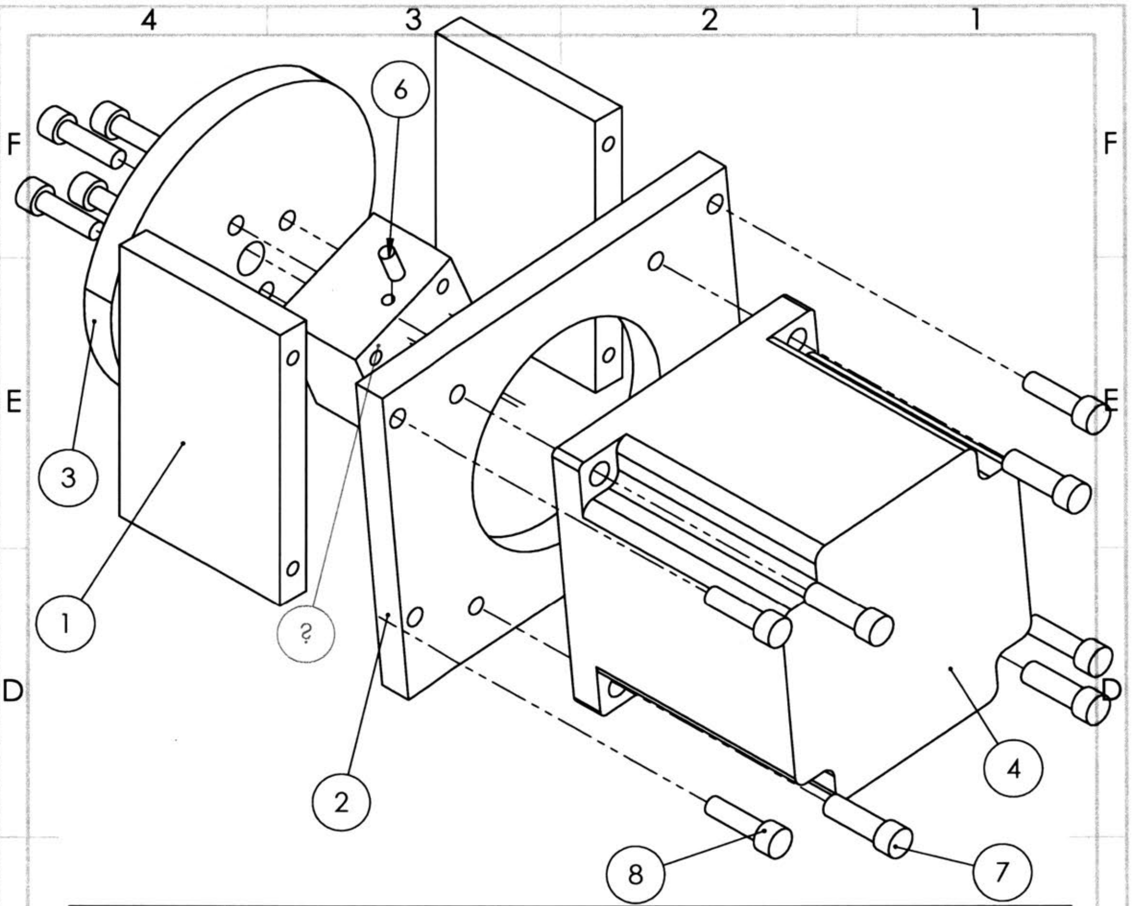

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2	Motor_Bracket_Cam	1/4" Polycarbonate	1
3	Cam	1/4" Polycarbonate	1
4	Stepper_Motor	Stepper Motor DC 24V	1
5	Cam_Motor_Transfer	6061 T6 Aluminum	1
6	4_40_1-4_Set	1/4" 4-40 Set Screw	1
7	8_32_1-2	1/2" 8-32 Machine Screw	4
8	6_32_1-2	1/2" 6-32 Machine Screw	8

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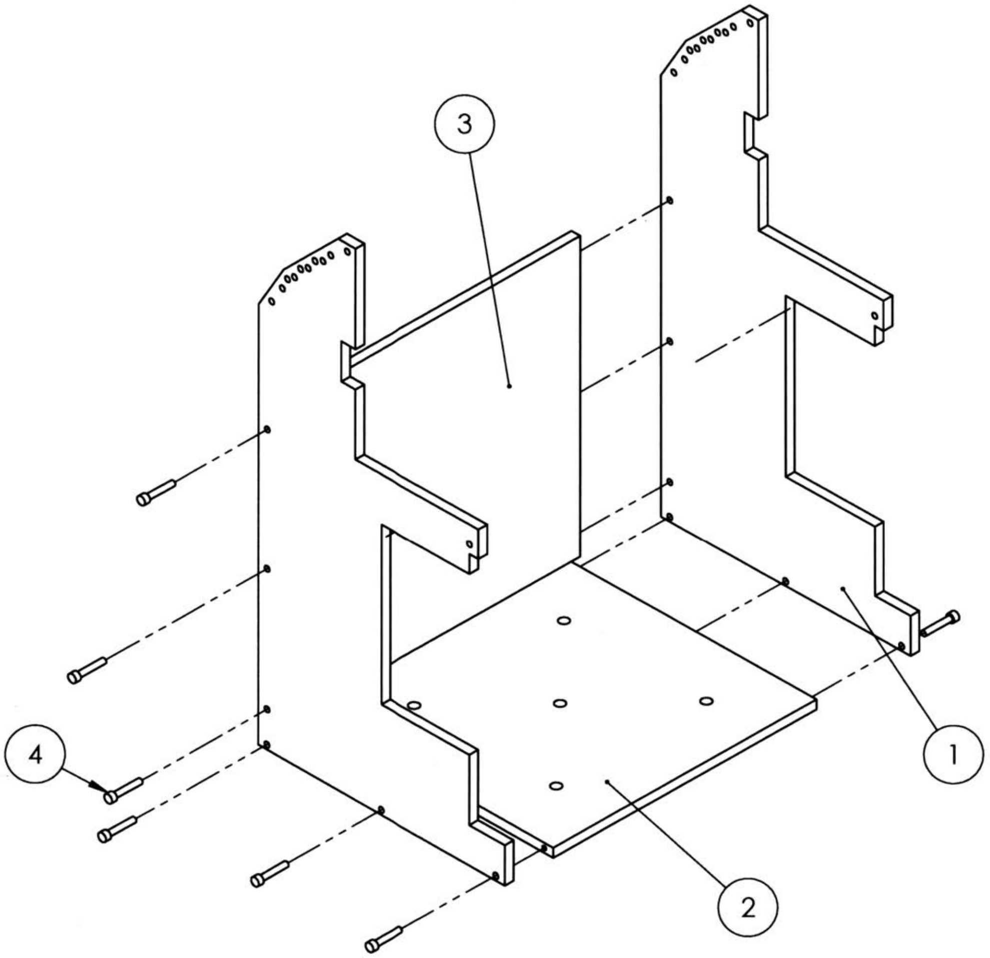

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
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2	Bottom Brace	1/4" Polycarbonate	1
3	Back Brace	1/4" Polycarbonate	1
4	6_32_3-4	3/4" 6-32 Machine Screw	12

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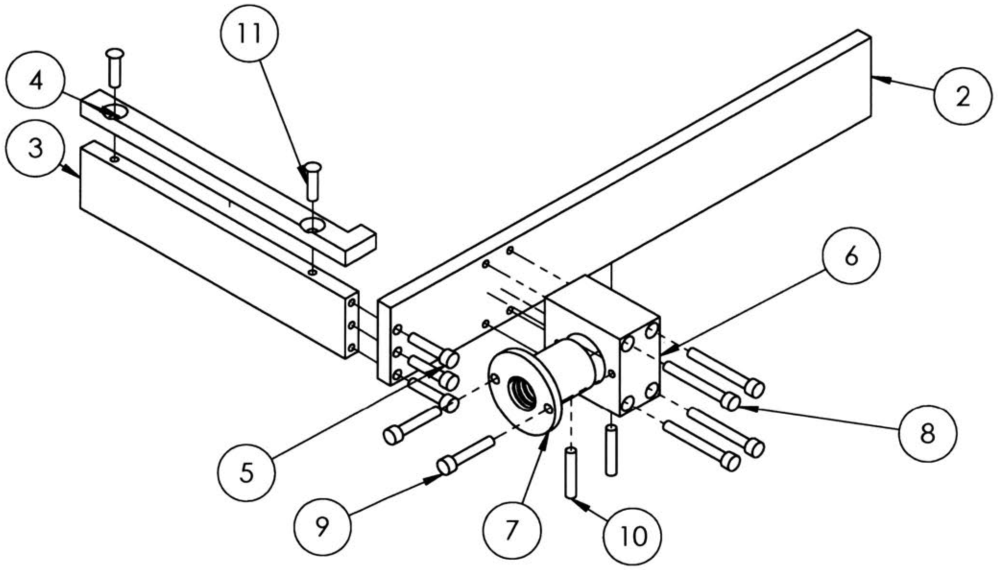

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3	Tray_Slider_Bottom	1/4" Polycarbonate	1
4	Tray_Slider_First_Row	1/4" Polycarbonate	1
5	6_32_5-8	5/8" 6-32 Machine Screw	3
6	Drive_Bearing_Block	3/4" Polycarbonate	1
7	95120A111	932 Bearing Bronze Flange Nut	1
8	6_32_1--1-8	1 1/8" 6-32 Machine Screw	4
9	6_32_3-4	4/3" 6-32 Machine Screw	2
10	6_32_3-4_Set	3/4" 6-32 Set Screw	2
11	6_32_1-2_Sunk	1/2" 6-32 Countersunk Screw	2

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MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

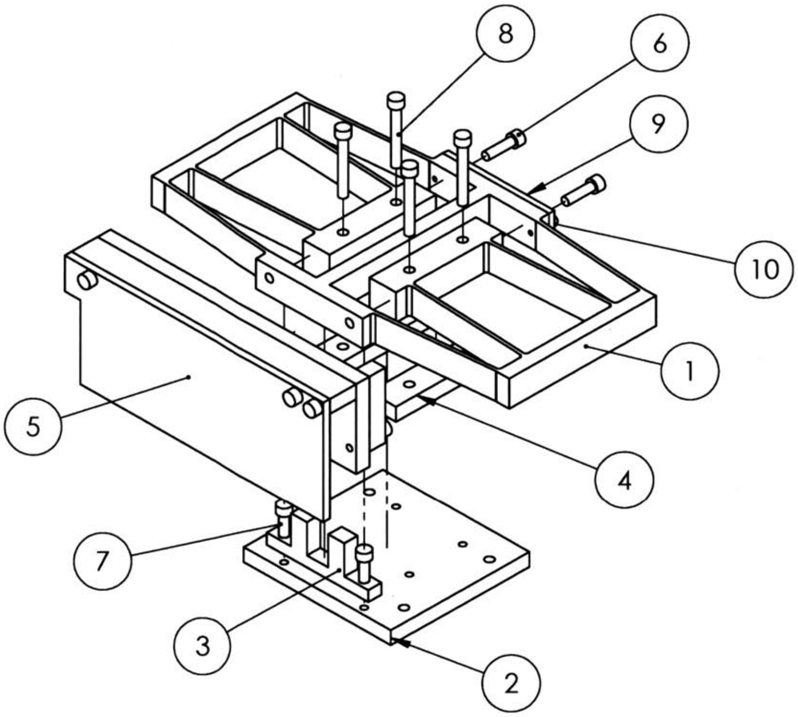
DWG NO.

Tray_Carriage

A4

SCALE:1:5

SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Flexure_0.6_V3	1/2" Polycarbonate	1
2	Flexure_Mount	1/4" Polycarbonate	1
3	Preload_Mount	1/4" Polycarbonate	1
4	Flexure_Shim	1/4" Polycarbonate	2
5	Rake	Rake Assembly	1
6	6_32_1-2	1/2" 6-32 Machine Screw	2
7	6_32_3-8	3/8" 6-32 Machine Screw	2
8	6_32_1	1" 6-32 Machine Screw	4
9	Flexure_Metal	0.1" Aluminum	1
10	2_56_1-4	1/4" 2-56 Machine Screw	2

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

WEIGHT:

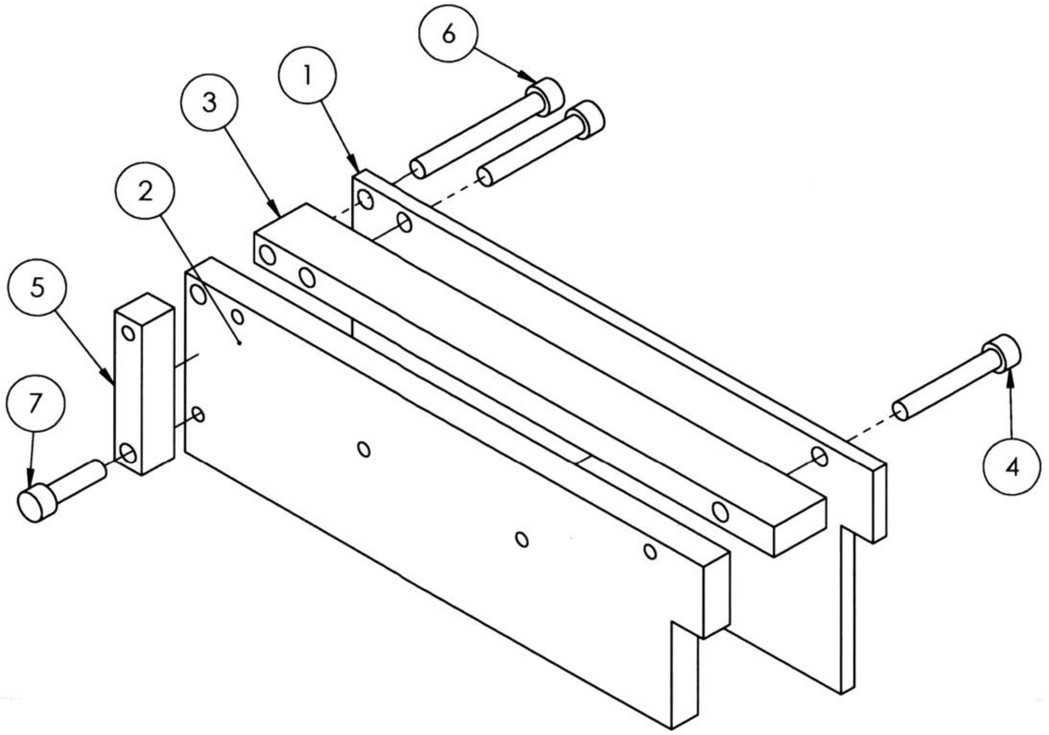
DWG NO.

Flexure_Mount_Rake

A4

SCALE:1:5

SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Rake_Front_Flat	1/8" Polycarbonate	1
2	Rake_Back_Holes	1/4" Polycarbonate	1
3	Rake_Top_Flat	1/4" Polycarbonate	1
4	6_32_7-8	7/8" Machine Screw	2
5	Rake_Tail	1/4" Polycarbonate	1
6	6_32_1--1-8	1 1/8" 6-32 Machine Screw	1
7	6_32_1-2	1/2" 6-32 Machine Screw	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

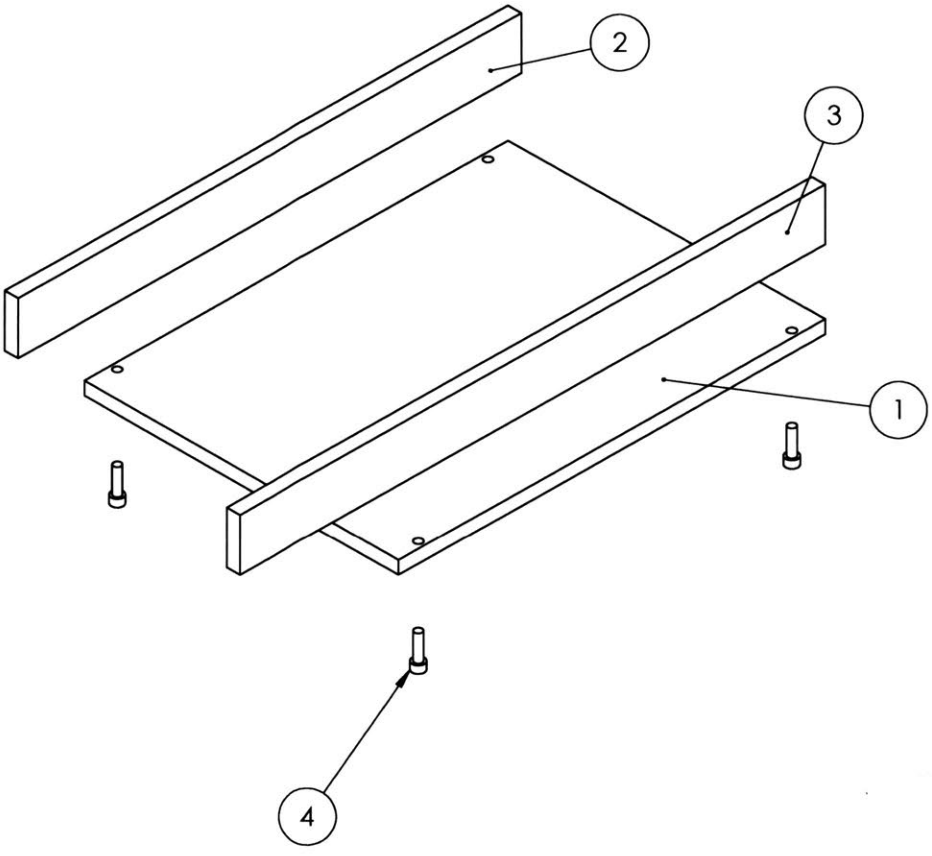
Rake

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Queue Base	1/4" Polycarbonate	1
2	Queue_Left_Wall	1/4" Polycarbonate	1
3	Queue_Right_Wall	1/4" Polycarbonate	1
4	6_32_1-2	1/2" 6-32 Machine Screw	4

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

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DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

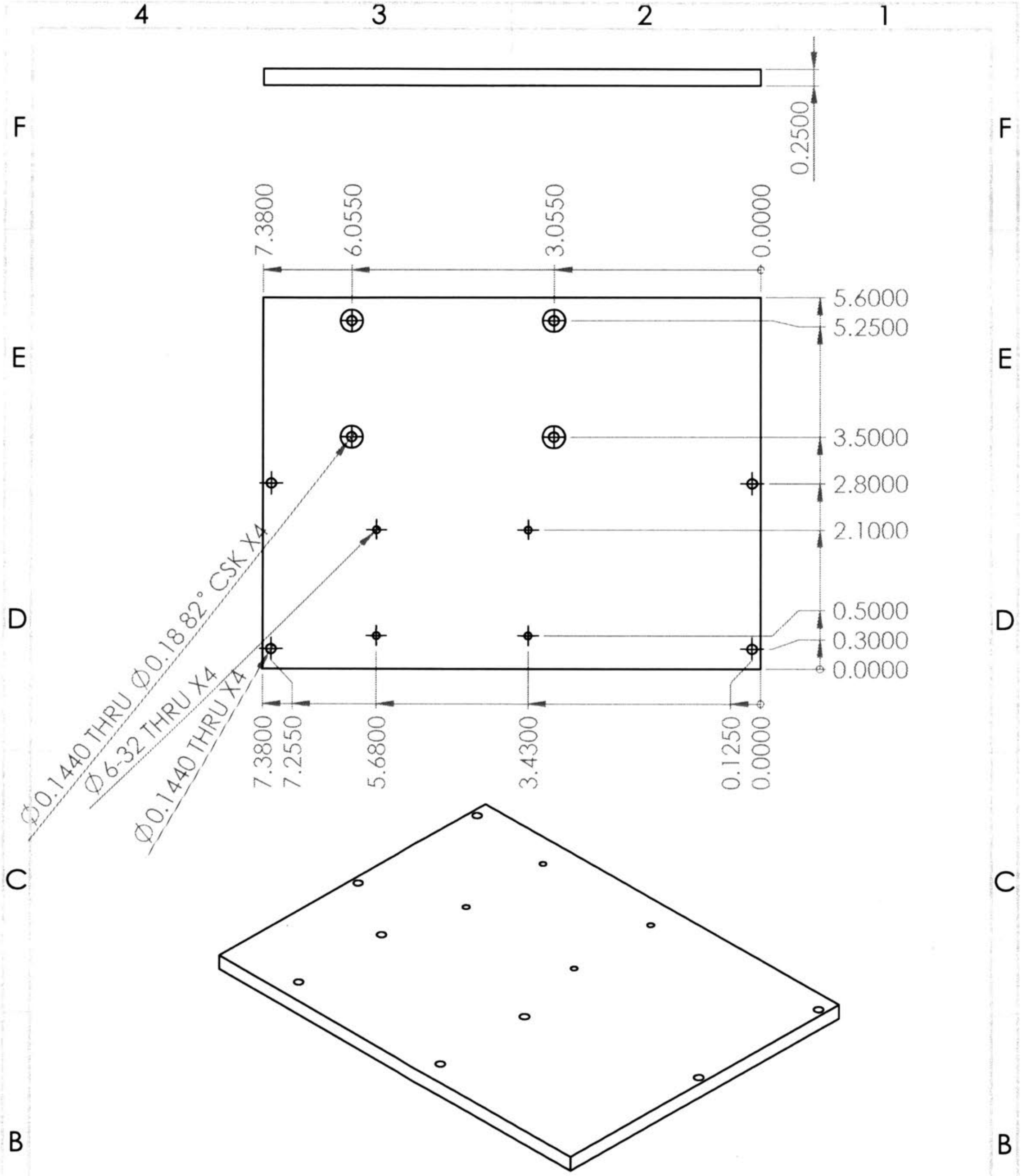
Tray_Queue_Assy

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

DWG NO.
Top_Brace_to_Flexture_Mour

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1

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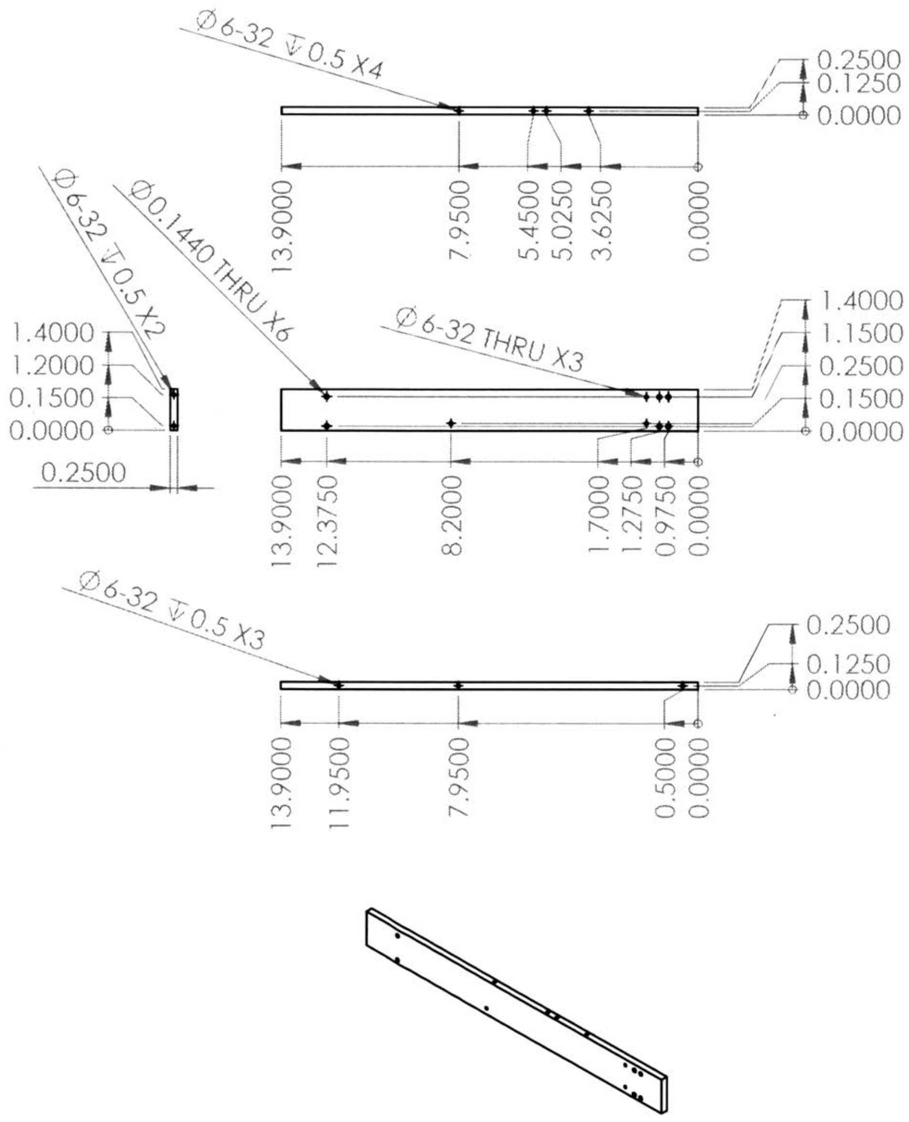

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TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

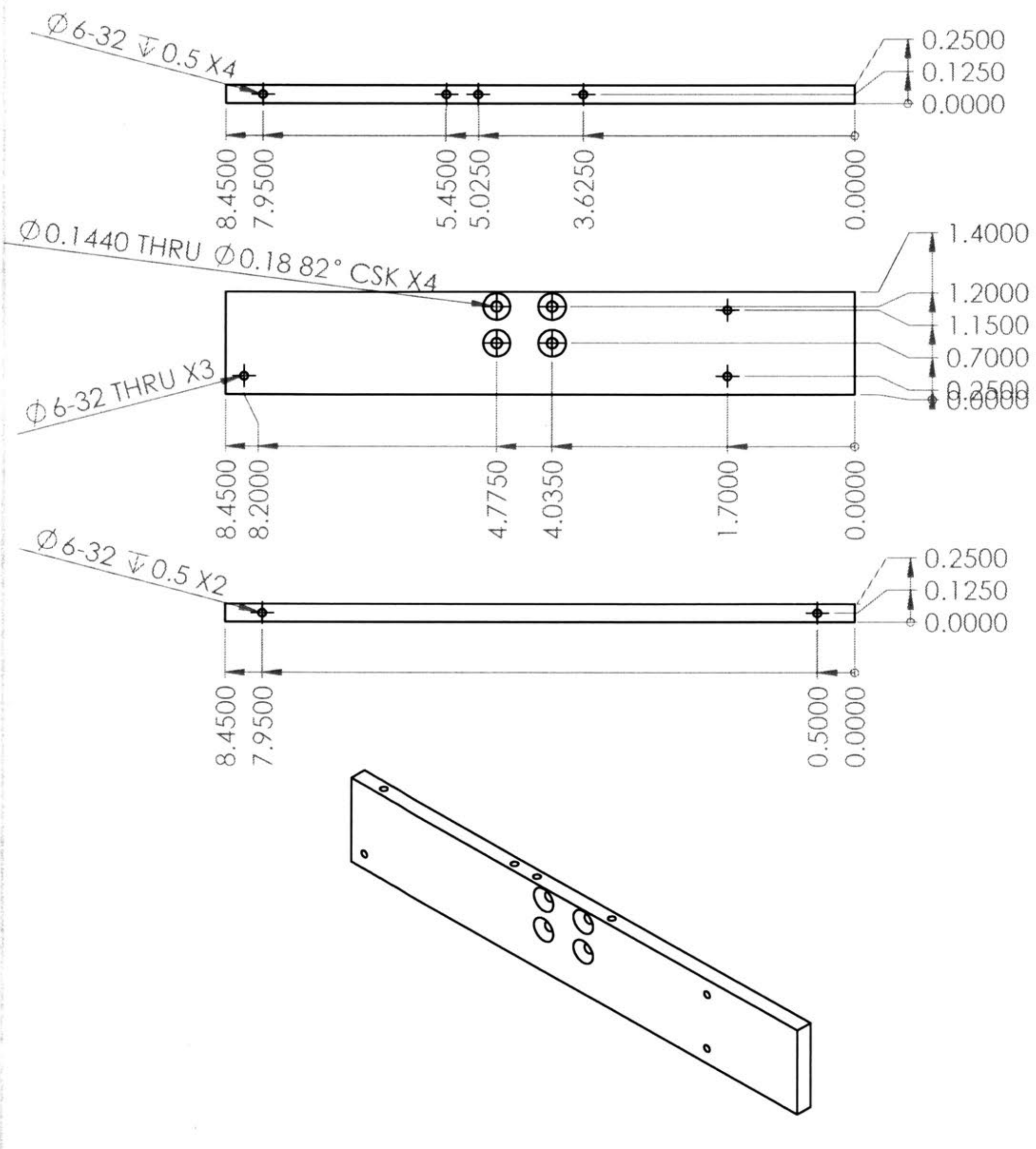
Right_Side_Pannel

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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			REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

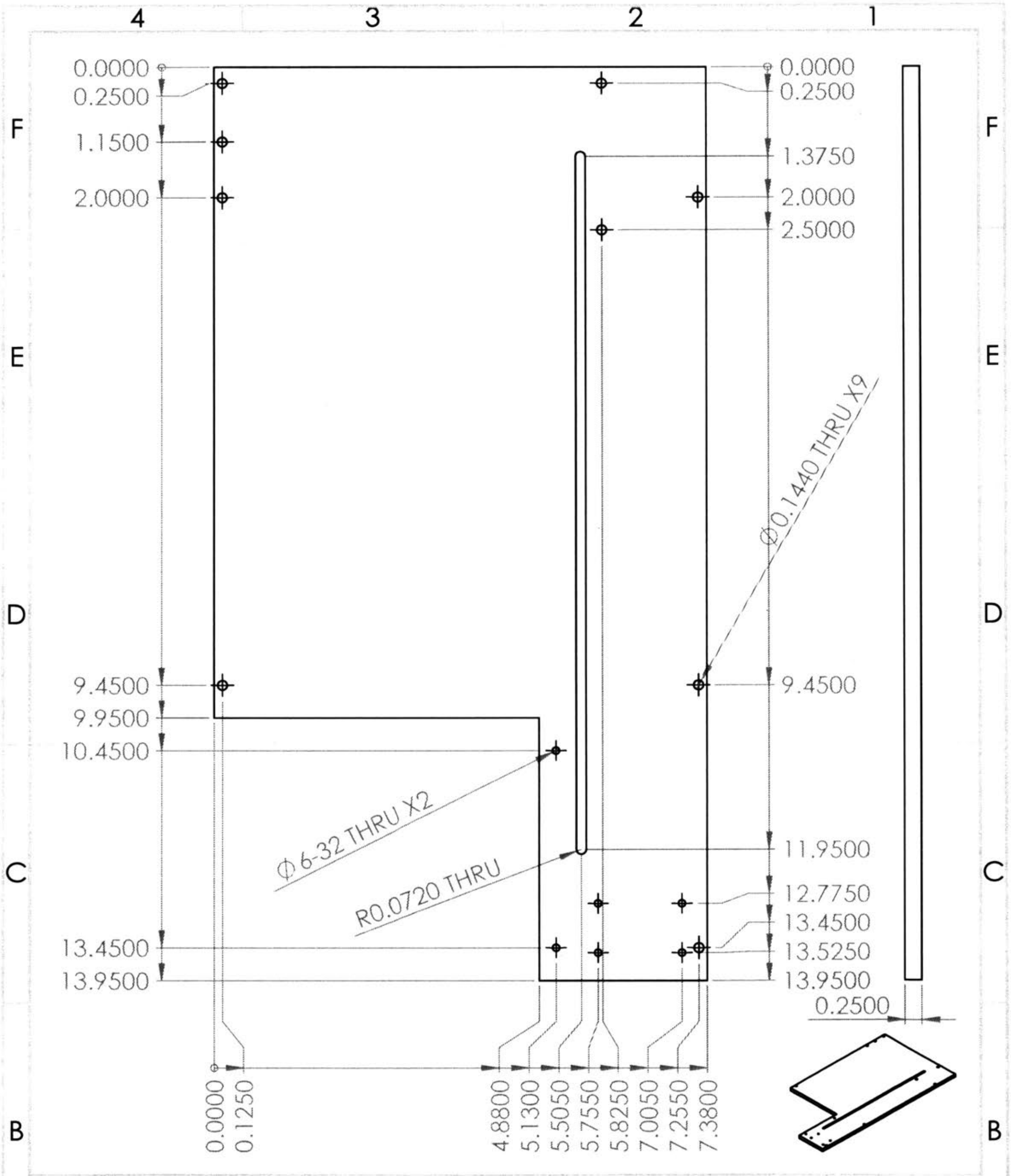
MATERIAL:
Polycarbonate

DWG NO.
Left_Side_Pannel A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



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DIMENSIONS ARE IN MILLIMETERS
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TOLERANCES:
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ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

Base

A4

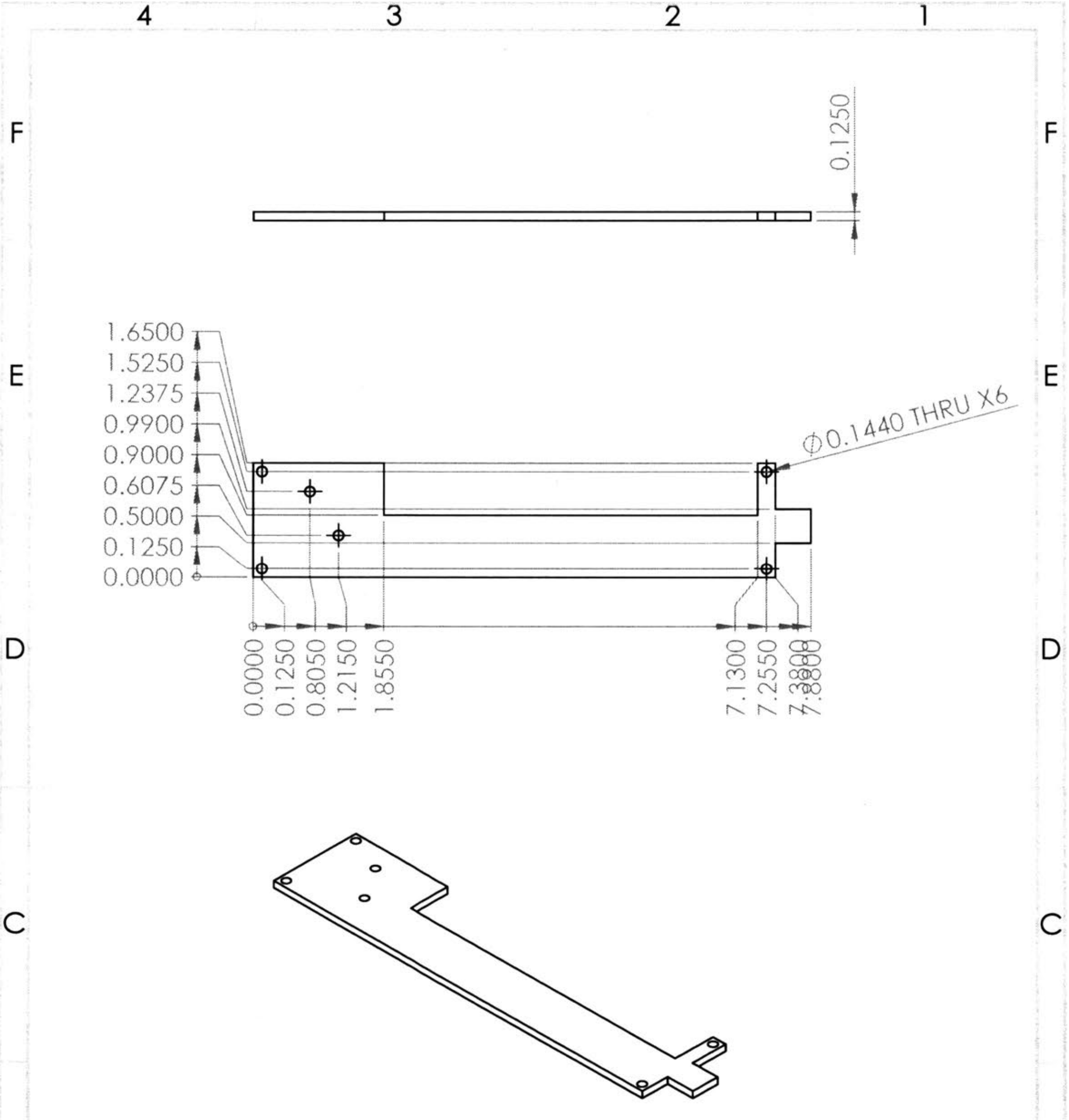
WEIGHT:

SCALE:1:5

SHEET 1 OF 1

4 3 2 1

A A



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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

WEIGHT:

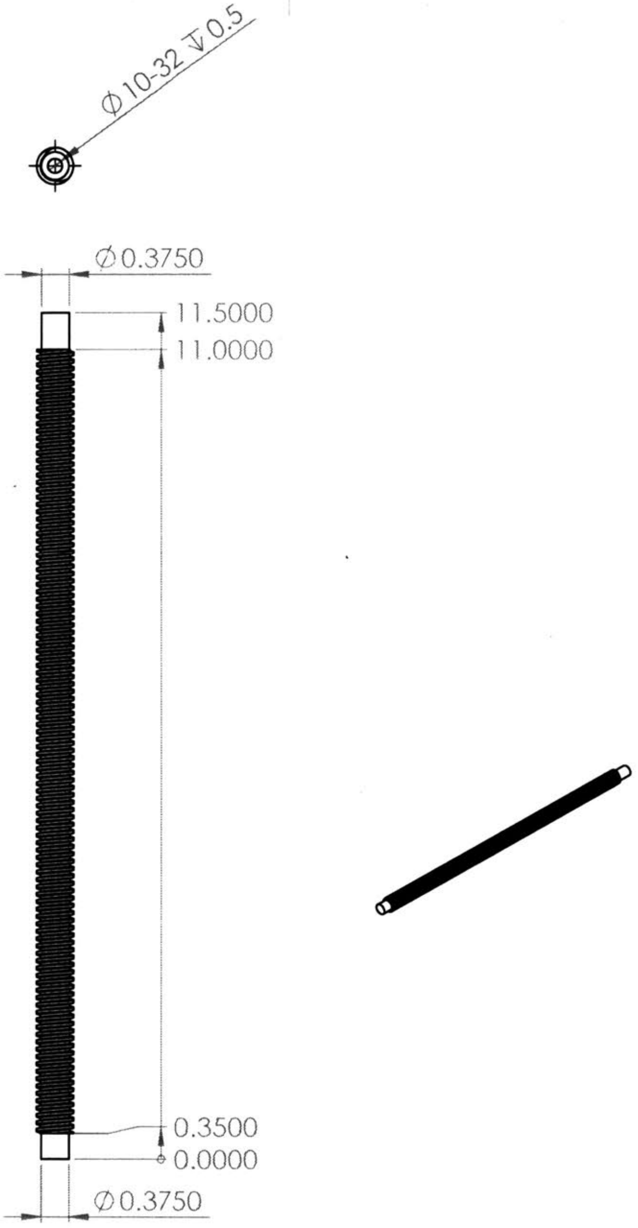
DWG NO.

Rake_Bottom

A4

SCALE:1:5

SHEET 1 OF 1



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	NAME	SIGNATURE	DATE	
DRAWN				
CHK'D				
APPV'D				
MFG				
Q.A				

TITLE:

MATERIAL:

DWG NO.

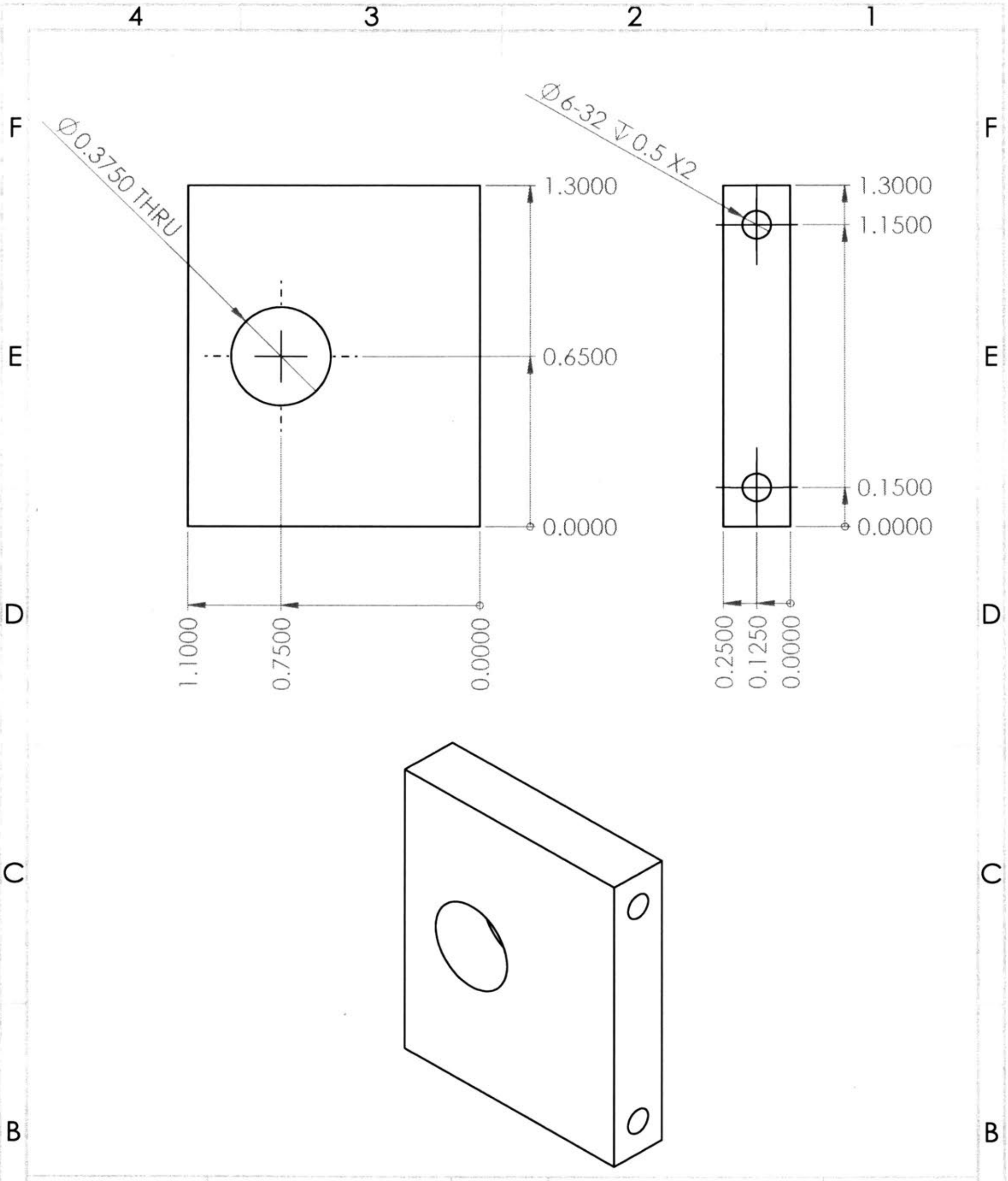
93255A431_ACME LEAD SCRE

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

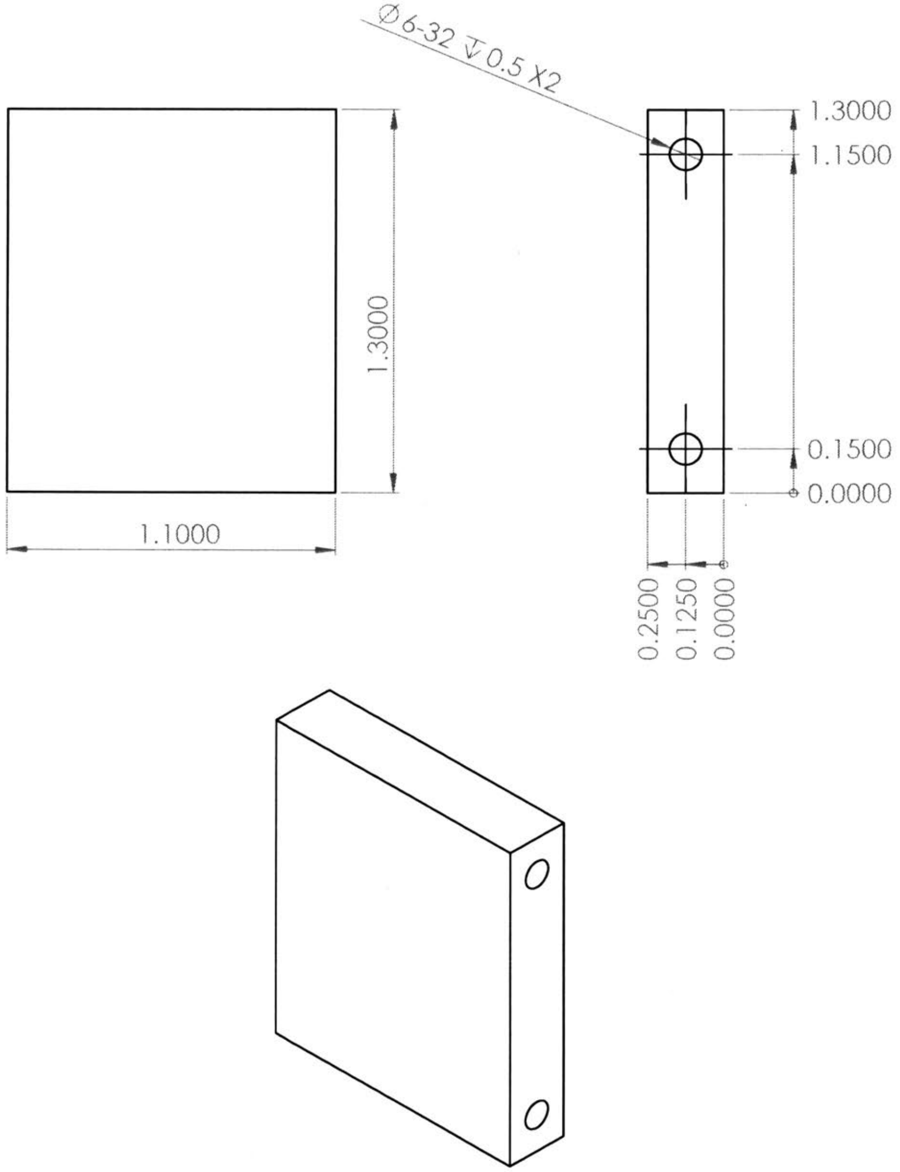
DWG NO.
Lead_Screw_Mount_Hole

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

DWG NO.
Lead_Screw_Mount_End

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1

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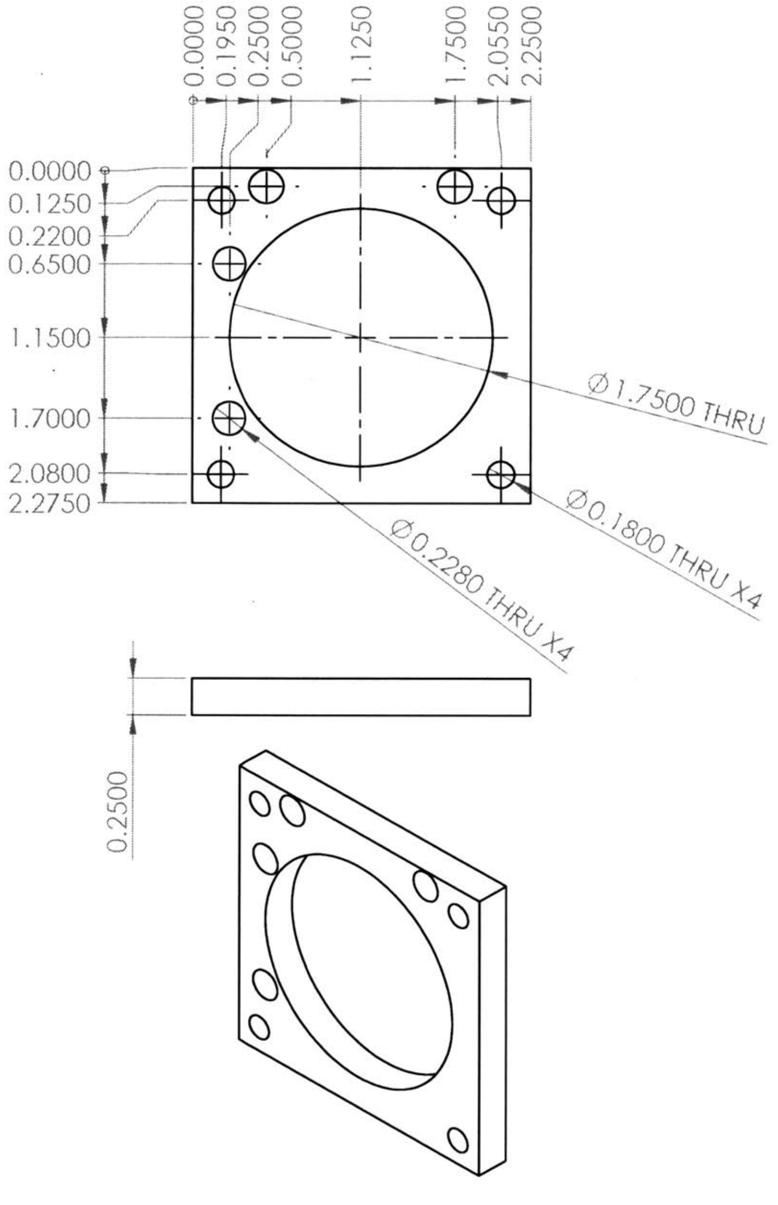

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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

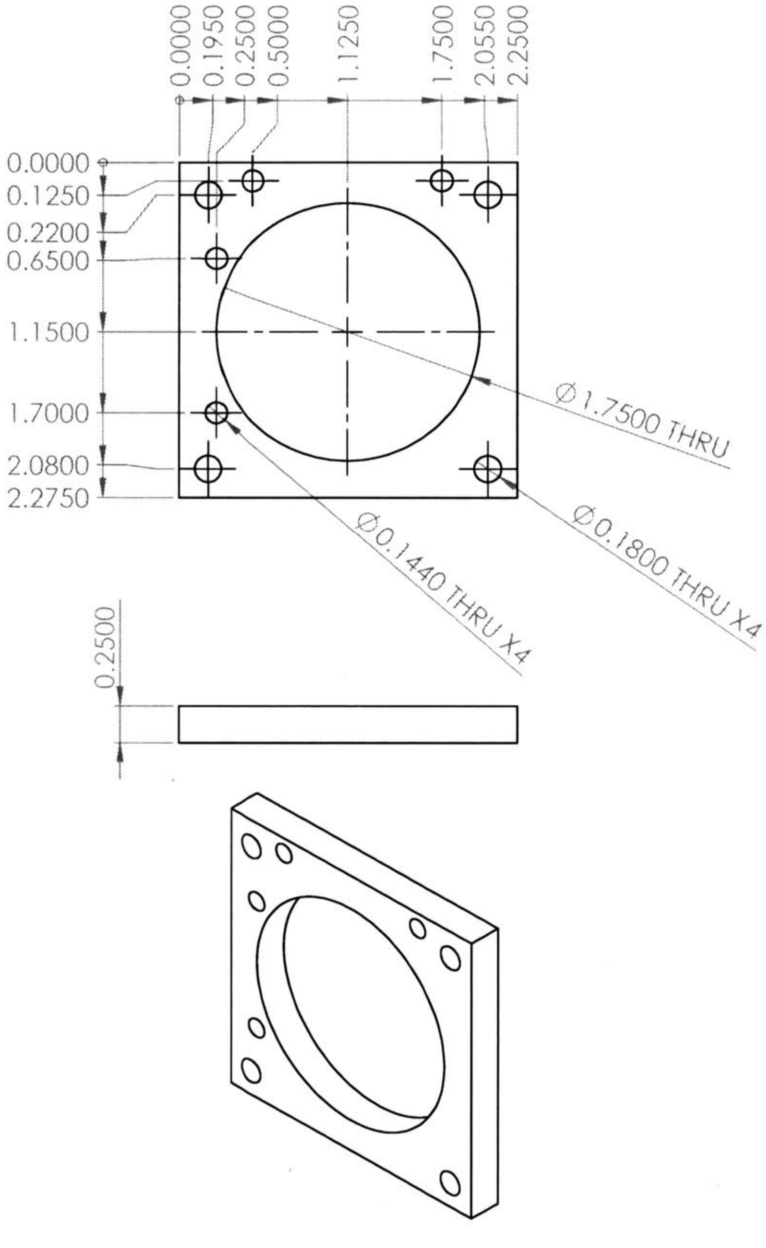
DWG NO.
Motor_Bracket_Large

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL: **Polycarbonate**

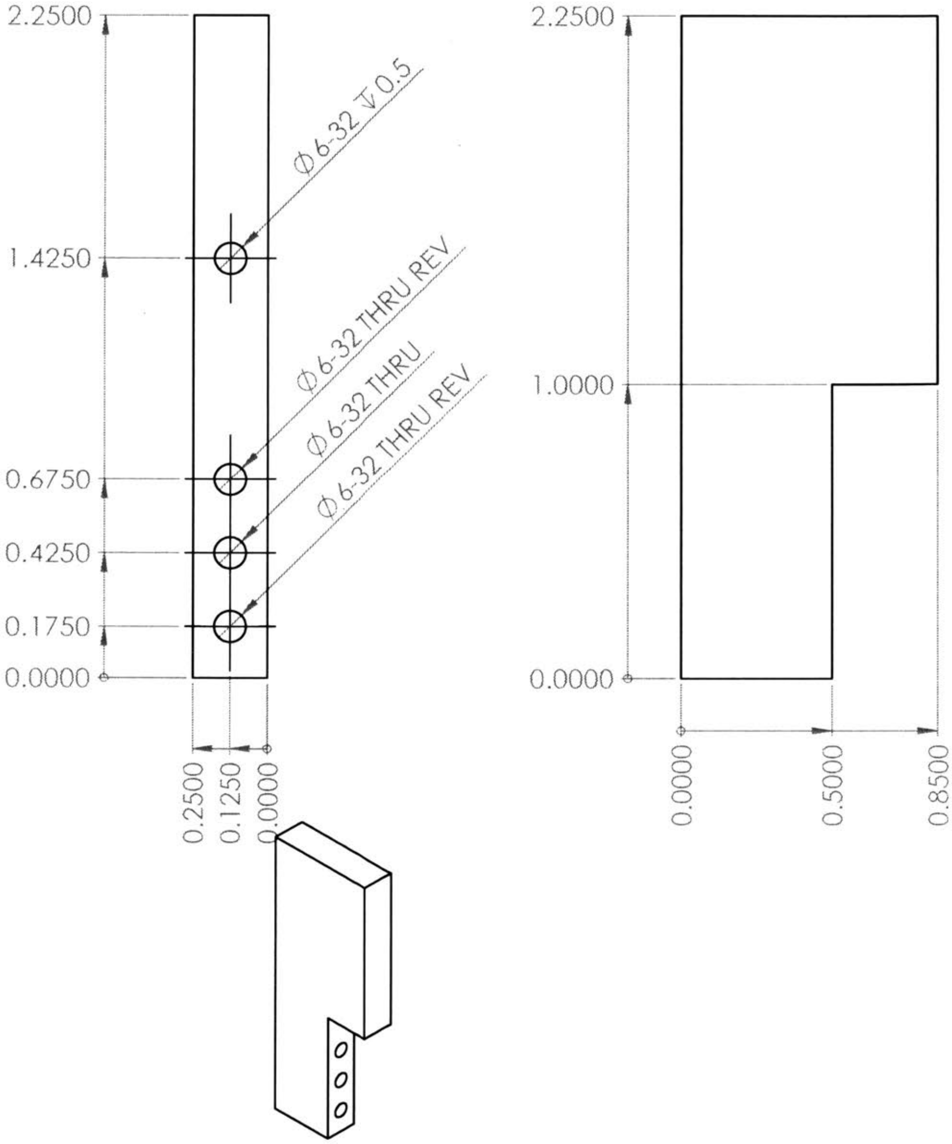
DWG NO. Motor_Bracket_Small

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

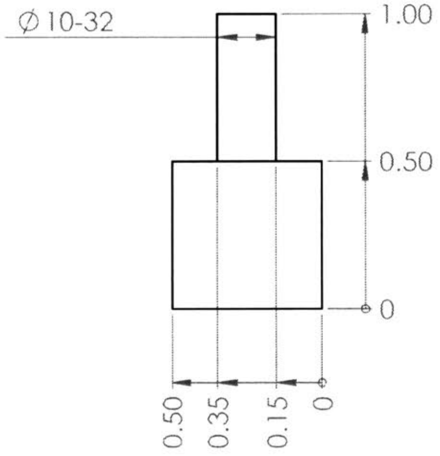
Bottle_Ejector_Side

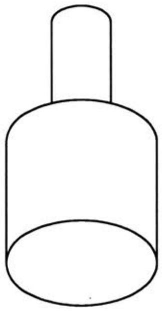
A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1





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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
6061 T6 Aluminum

DWG NO.
Motor_Screw_Transfer

A4

WEIGHT:

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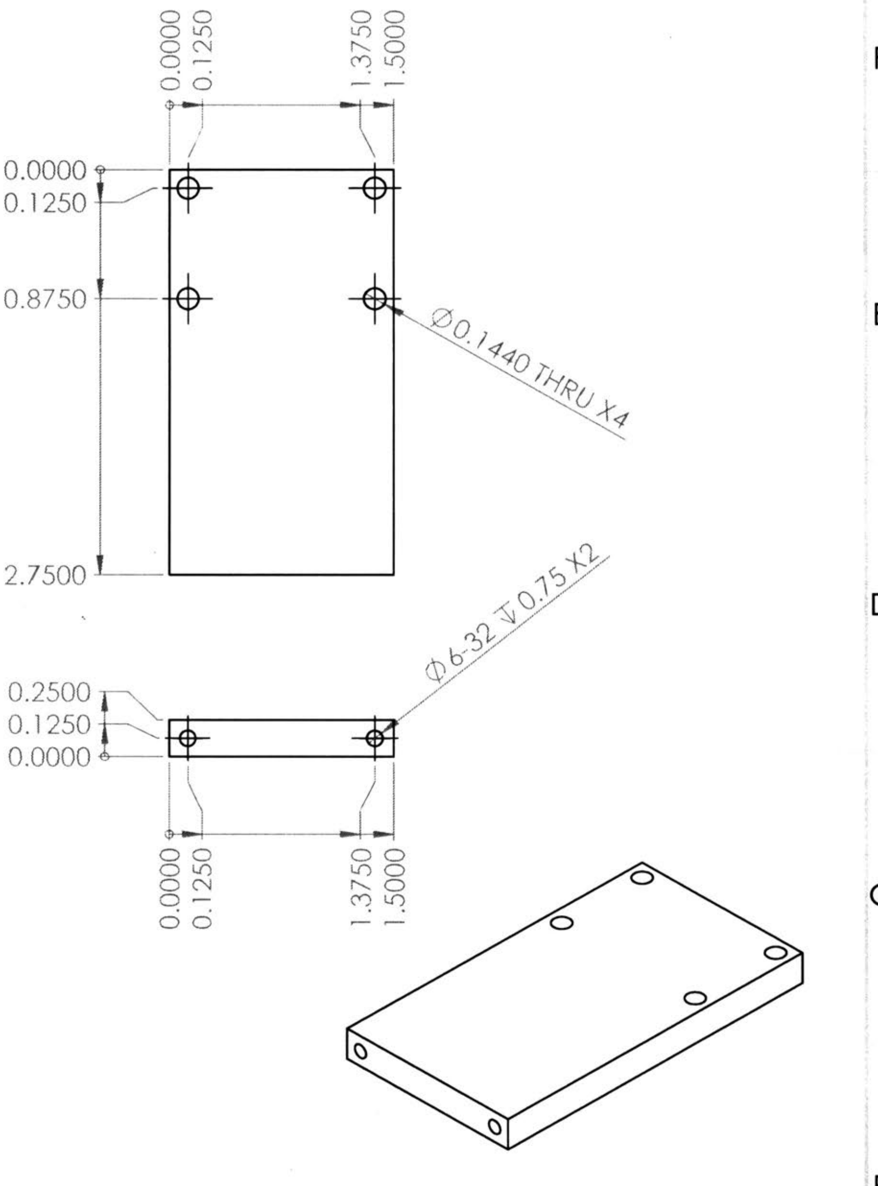
SHEET 1 OF 1

SOLIDWORKS Educational Product. For Instructional Use Only.



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ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

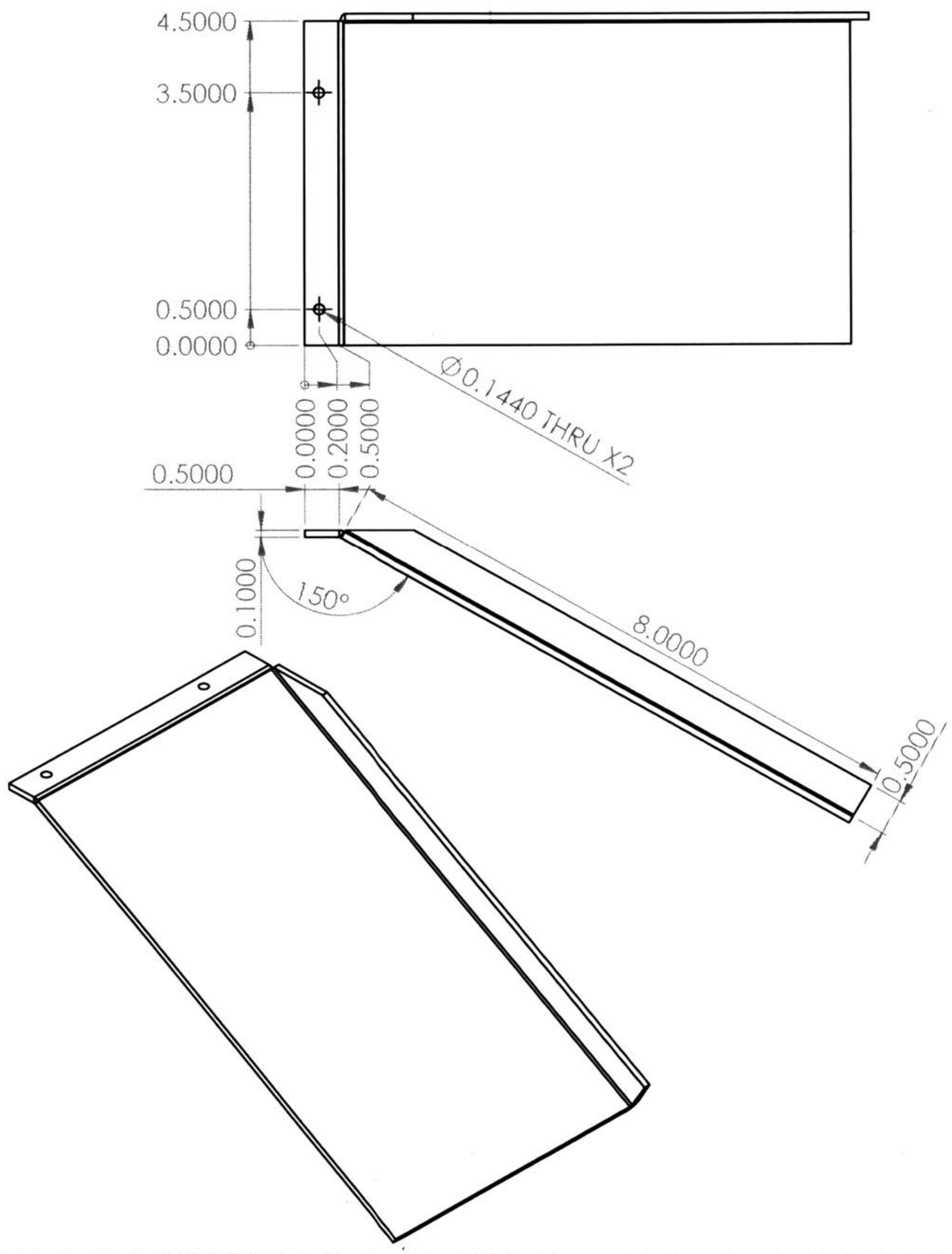
Lead_Screw_Reinforce

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
6061 T6 Aluminum

DWG NO.

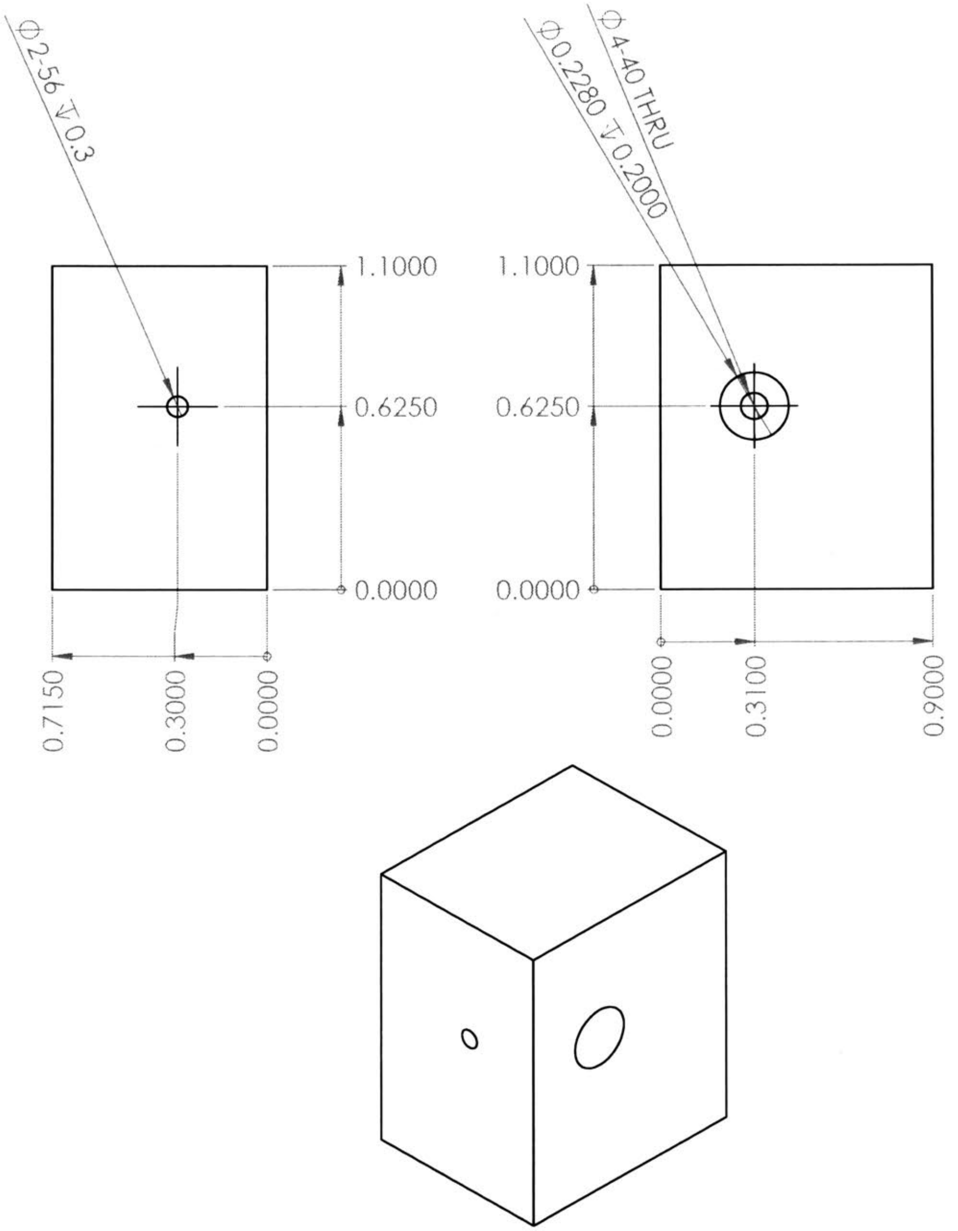
Exit Ramp

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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TOLERANCES:
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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

DWG NO.
Plunger_Block

A4

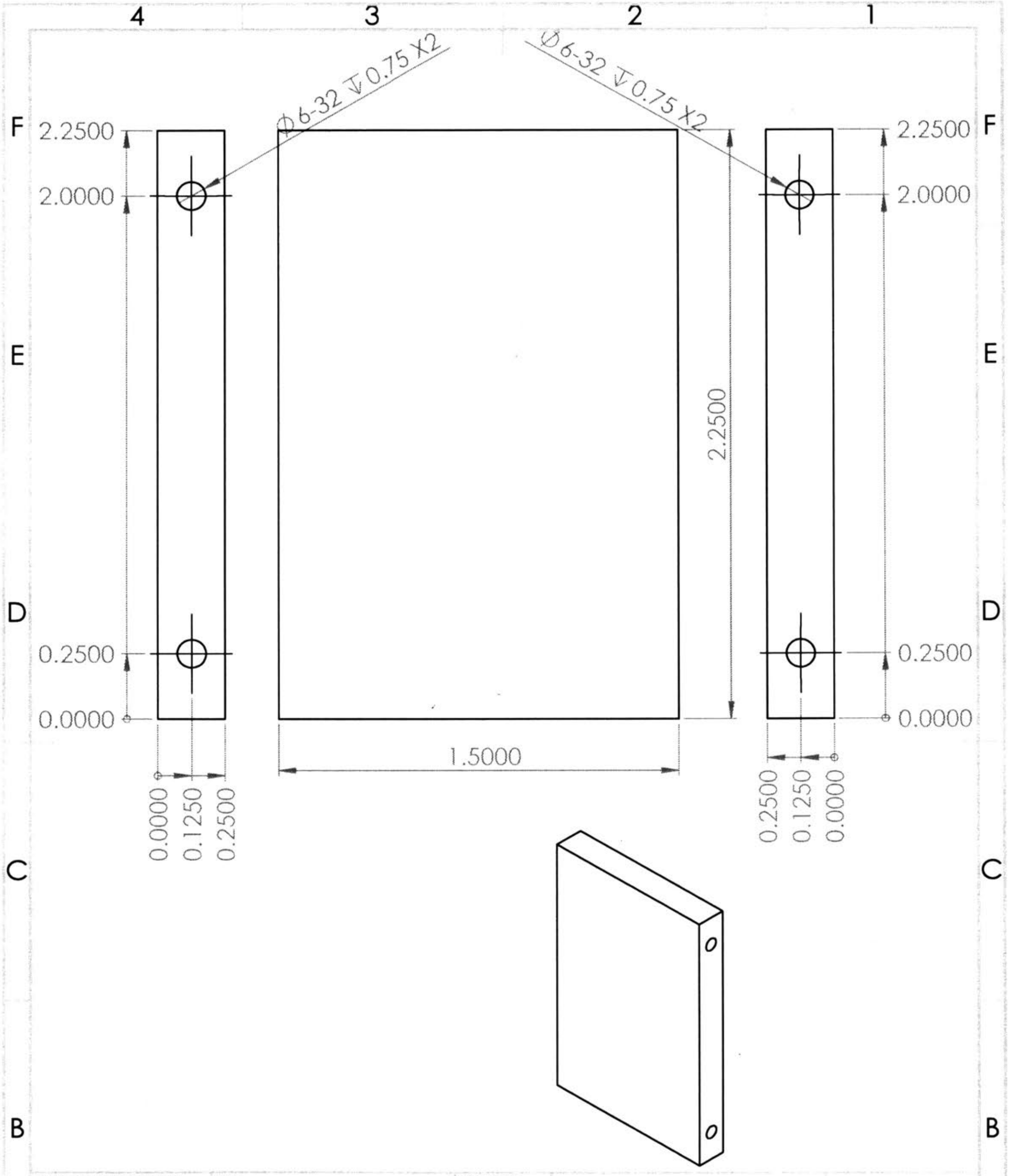
WEIGHT:

SCALE:2:1

SHEET 1 OF 1

A

4 3 2 1



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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
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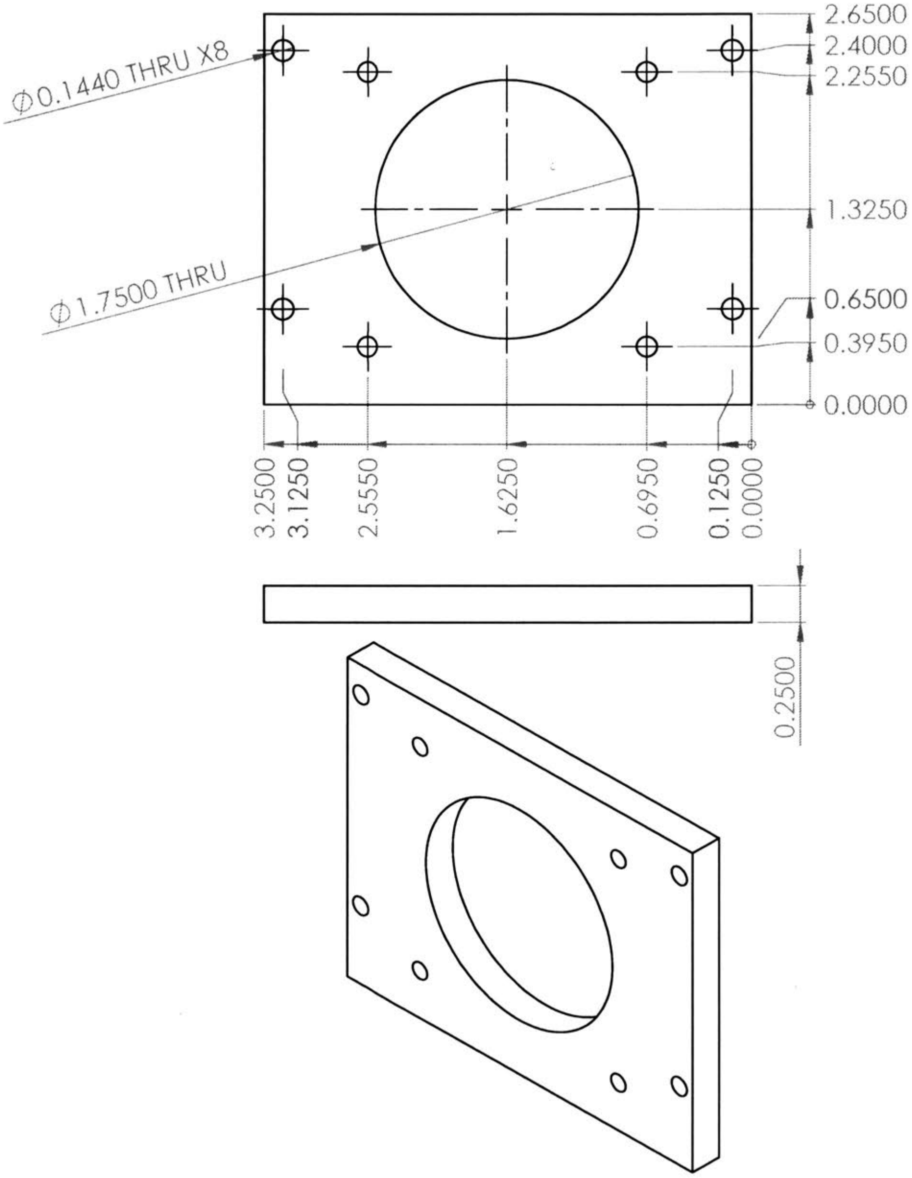
DWG NO.
Motor_Bracket_Side

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

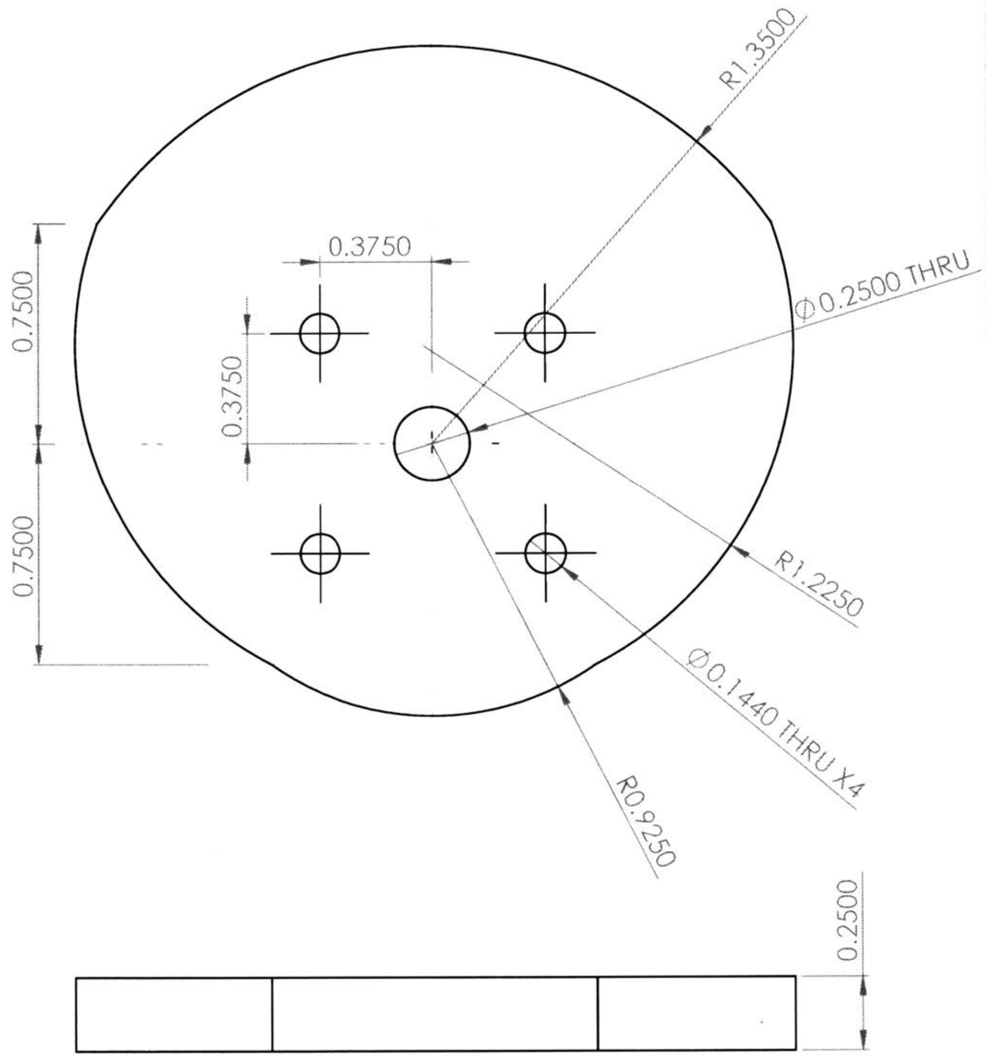
DWG NO.
Motor_Bracket_Cam

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Aluminium

DWG NO.
Cam.2

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1

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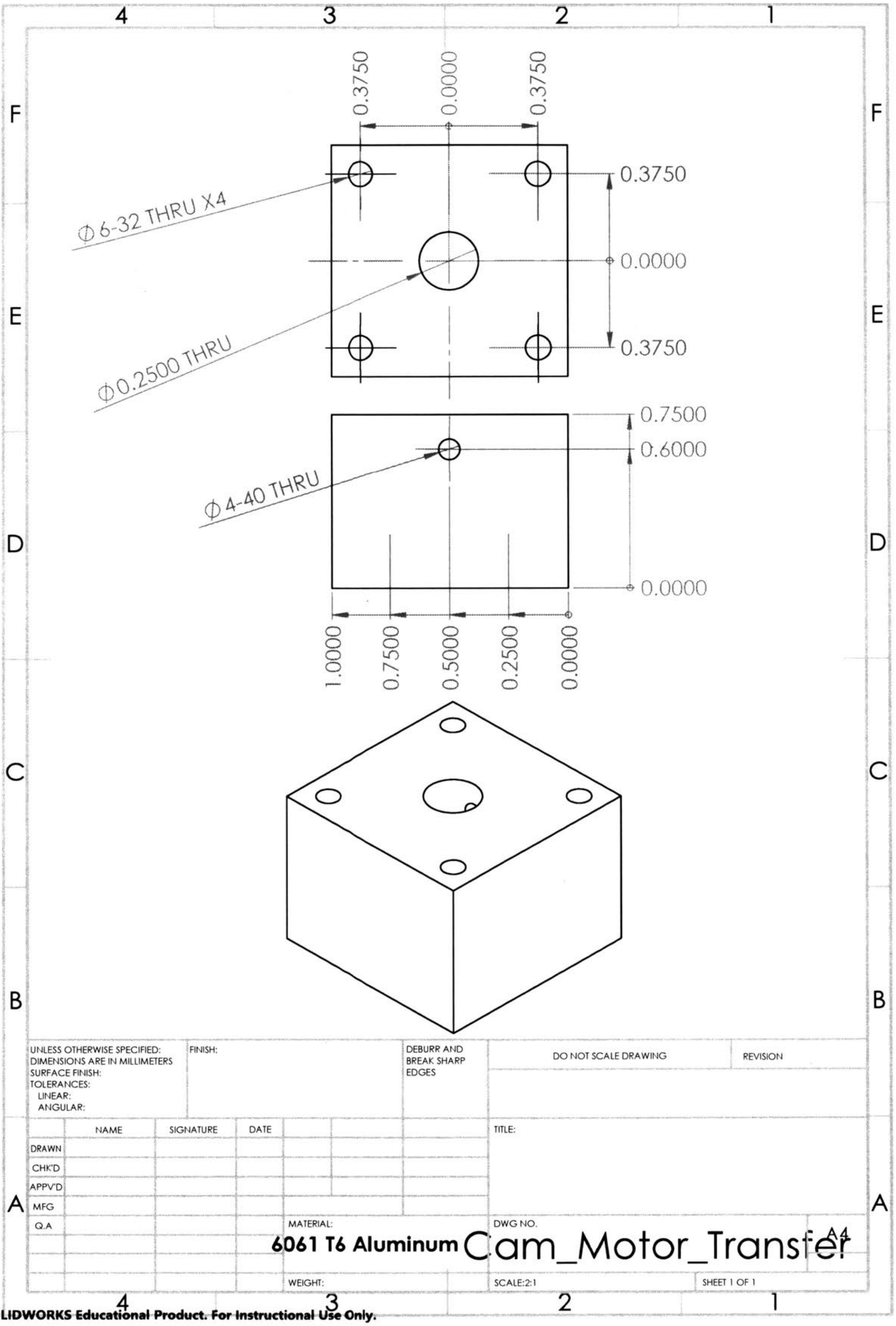

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LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
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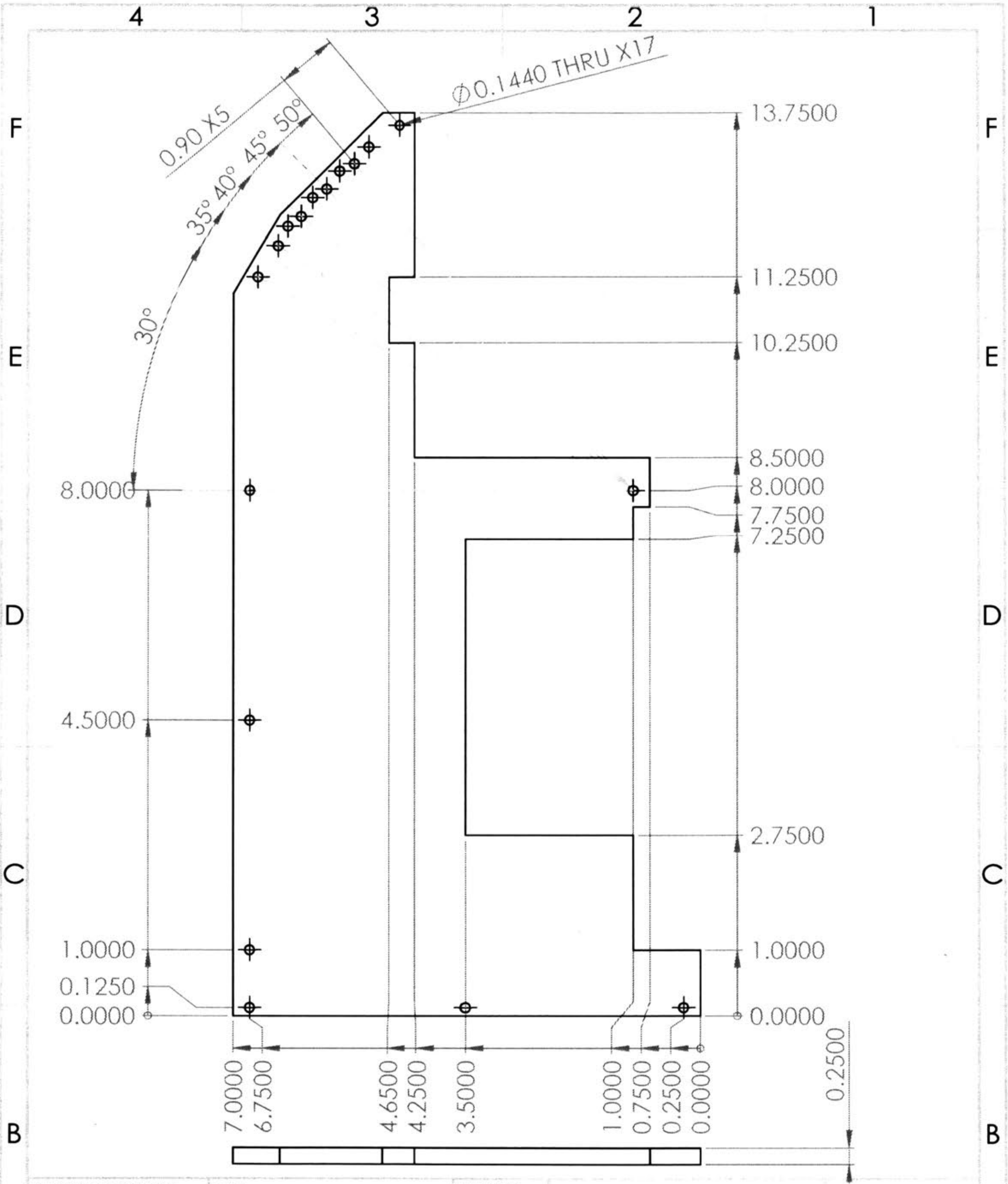
DWG NO.
Cam_Motor_Transfer

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
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TITLE:

MATERIAL:
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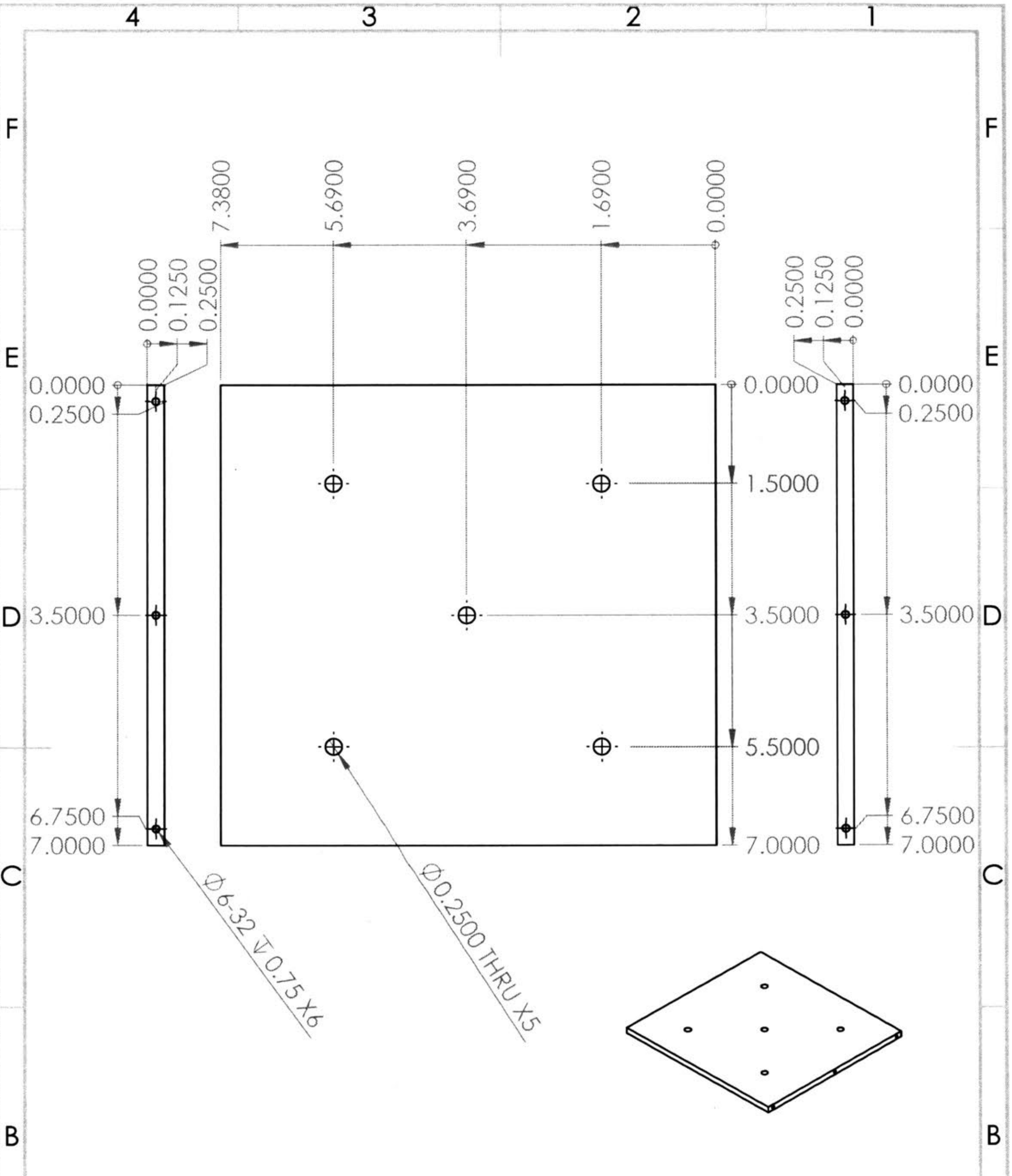
WEIGHT:

DWG NO.
Angle Bracket

A4

SCALE:1:5

SHEET 1 OF 1



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DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

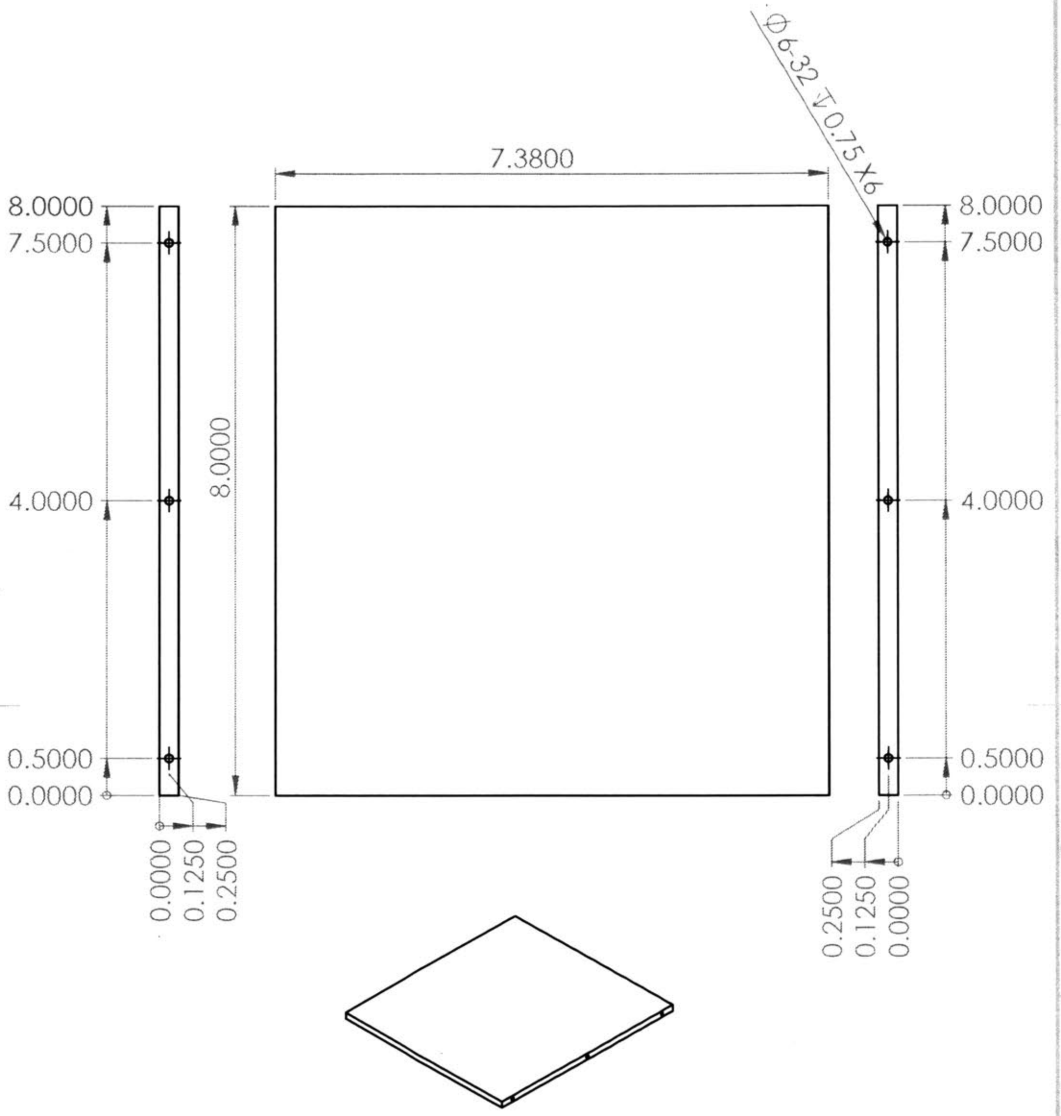
DWG NO.
Bottom Brace

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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SURFACE FINISH:
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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

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DWG NO.

Back Brace

A4

WEIGHT:

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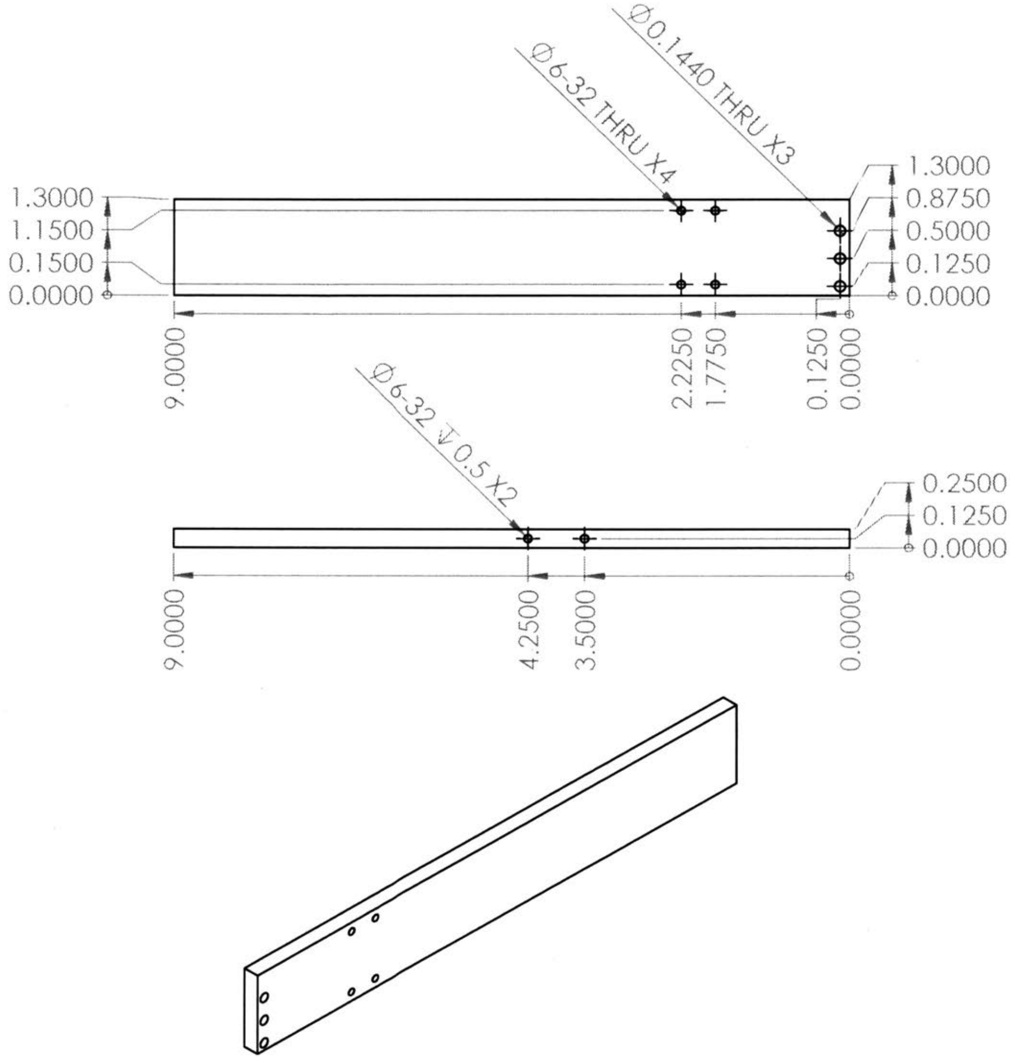
SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

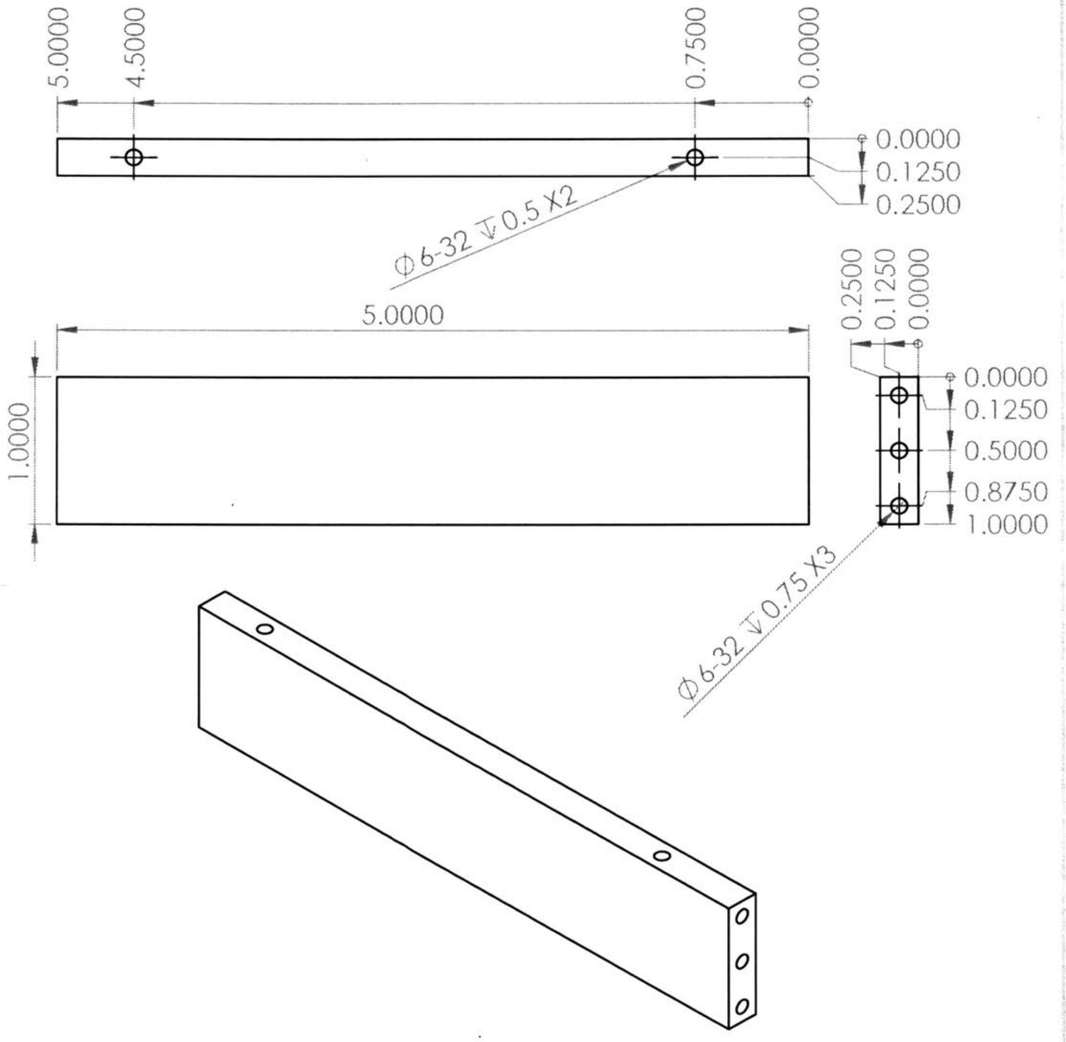
Tray_Slider_Side

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

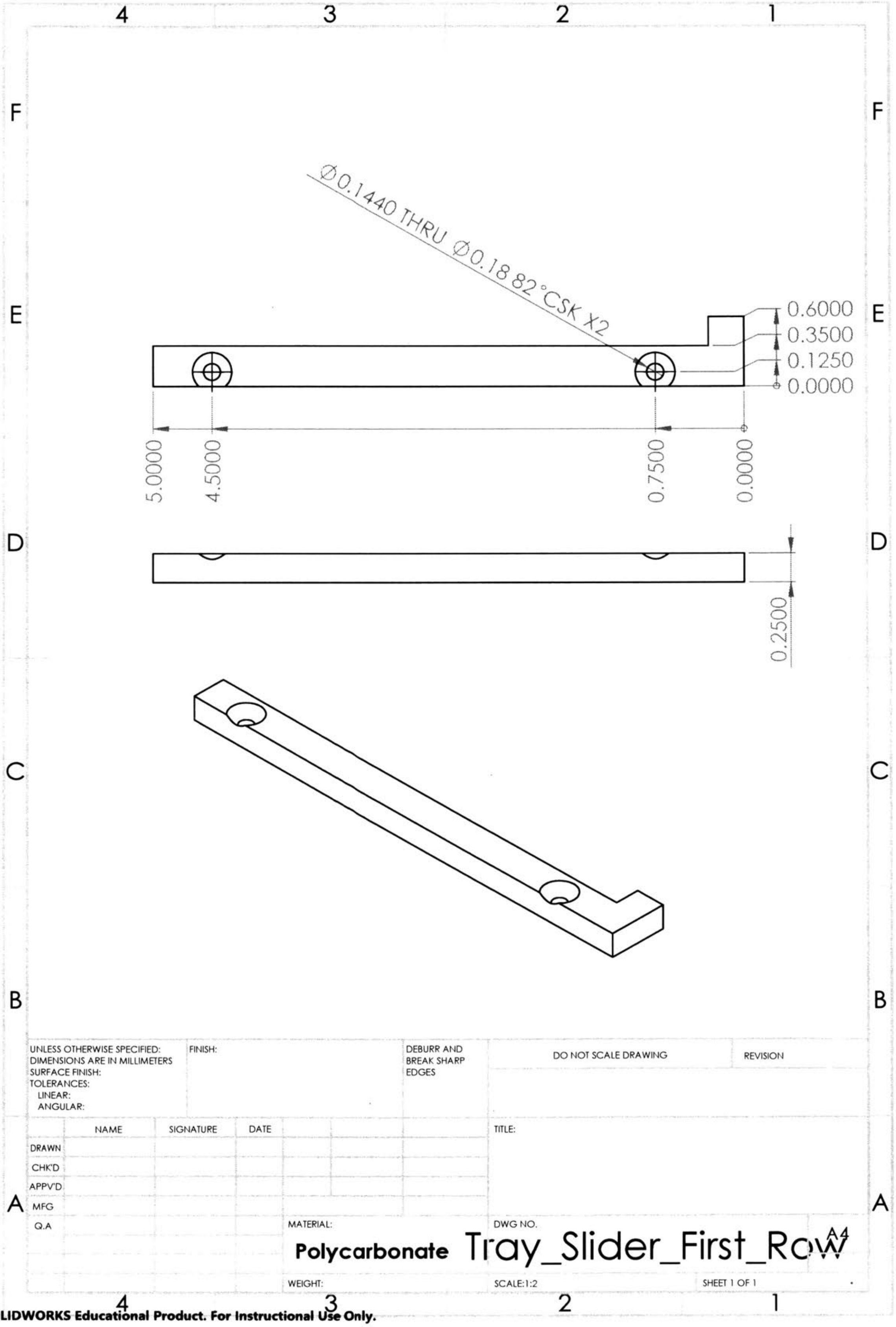
DWG NO.
Tray_Slider_Bottom

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



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ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

Tray_Slider_First_Row

A4

WEIGHT:

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SHEET 1 OF 1

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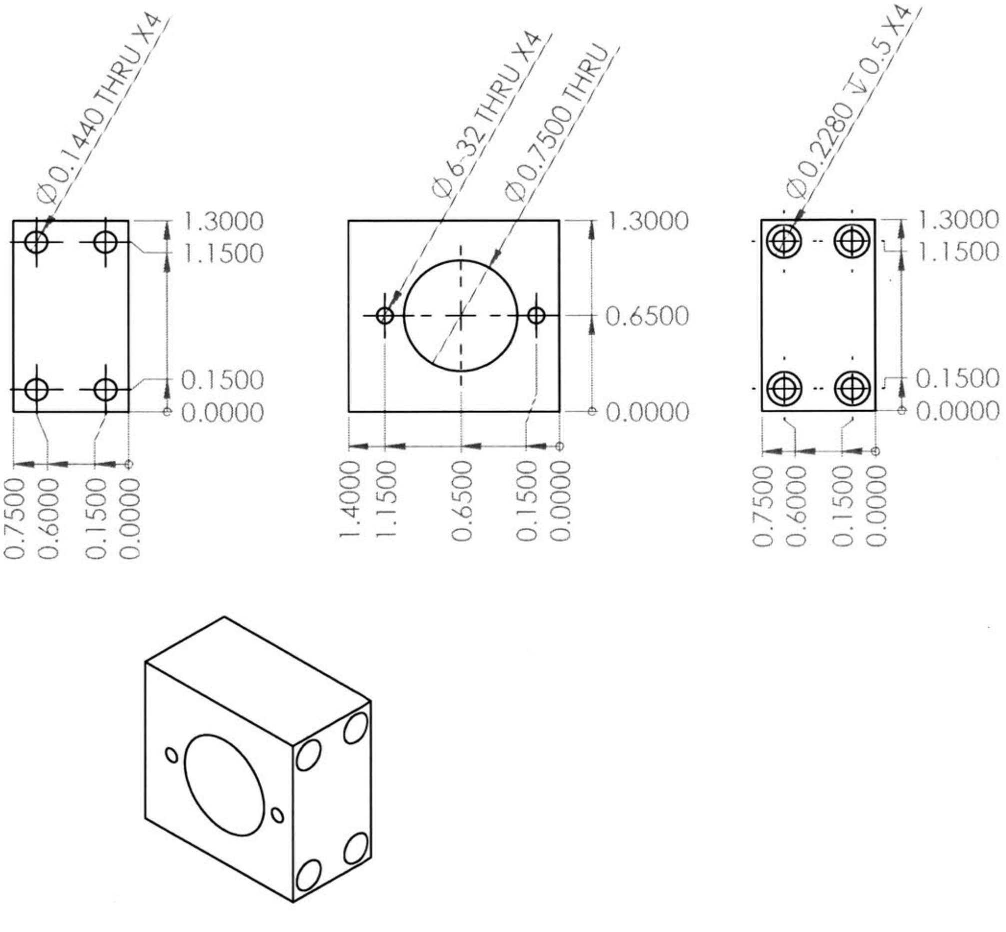

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DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

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DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
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A4

WEIGHT:

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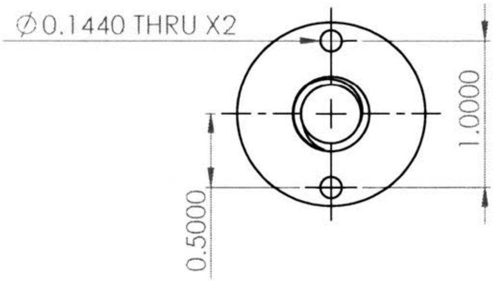
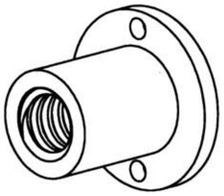
SHEET 1 OF 1

4 3 2 1

F E D C B A





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	NAME	SIGNATURE	DATE
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APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

95120A111_BRONZE GENERAL PURPOSE ACI

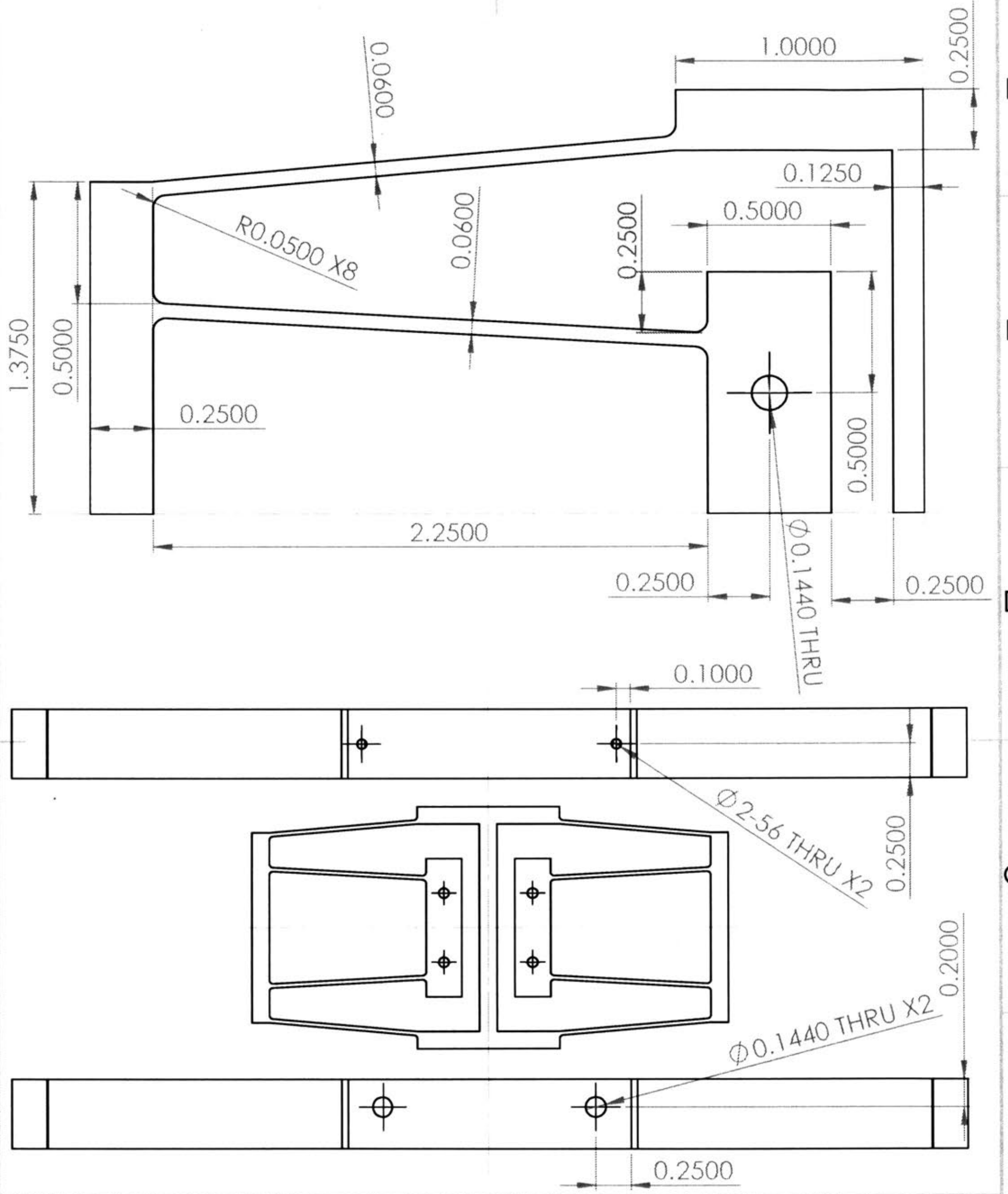
A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1

4 3 2 1



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ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
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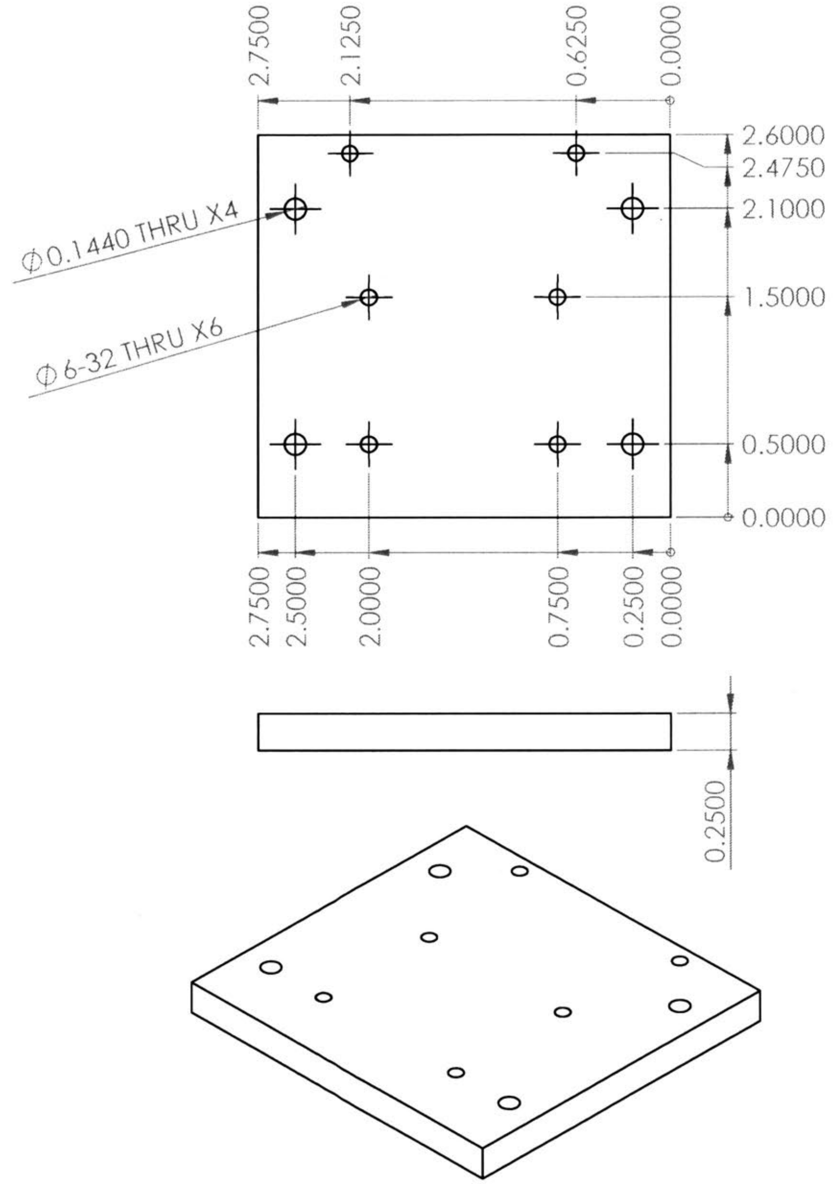
DWG NO.
Flexure_0.6_V3

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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ANGULAR:

FINISH:

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BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

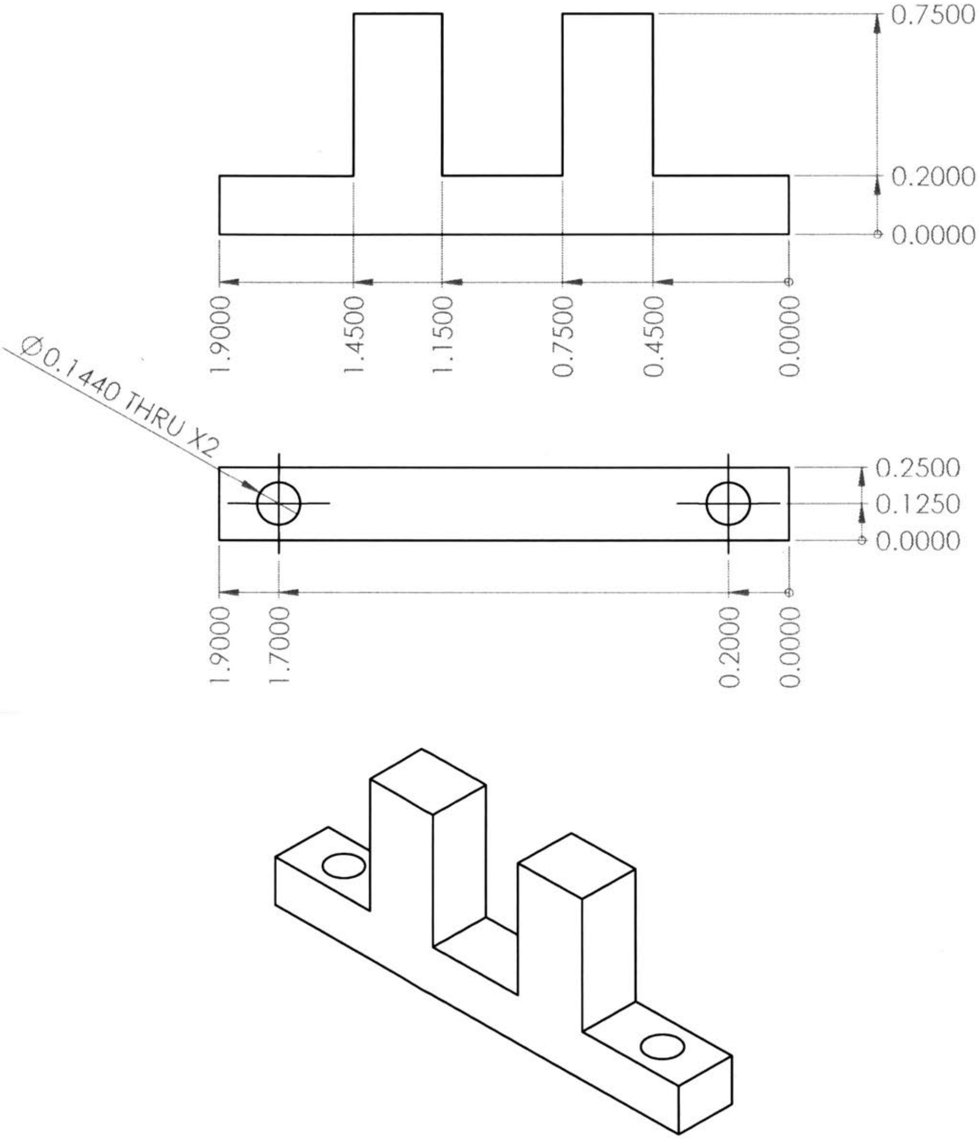
DWG NO.
Flexure_Mount

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



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LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
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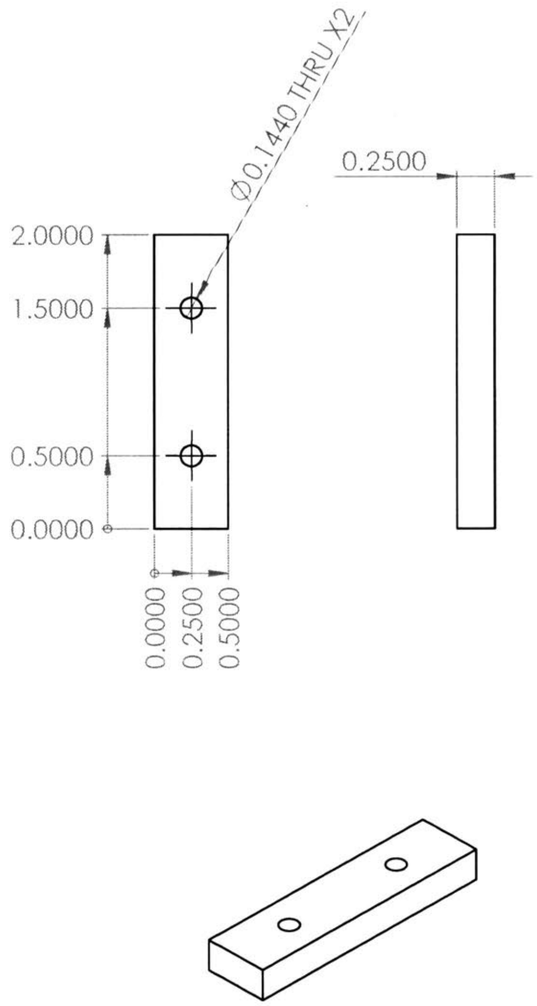
DWG NO.
Preload_Mount

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

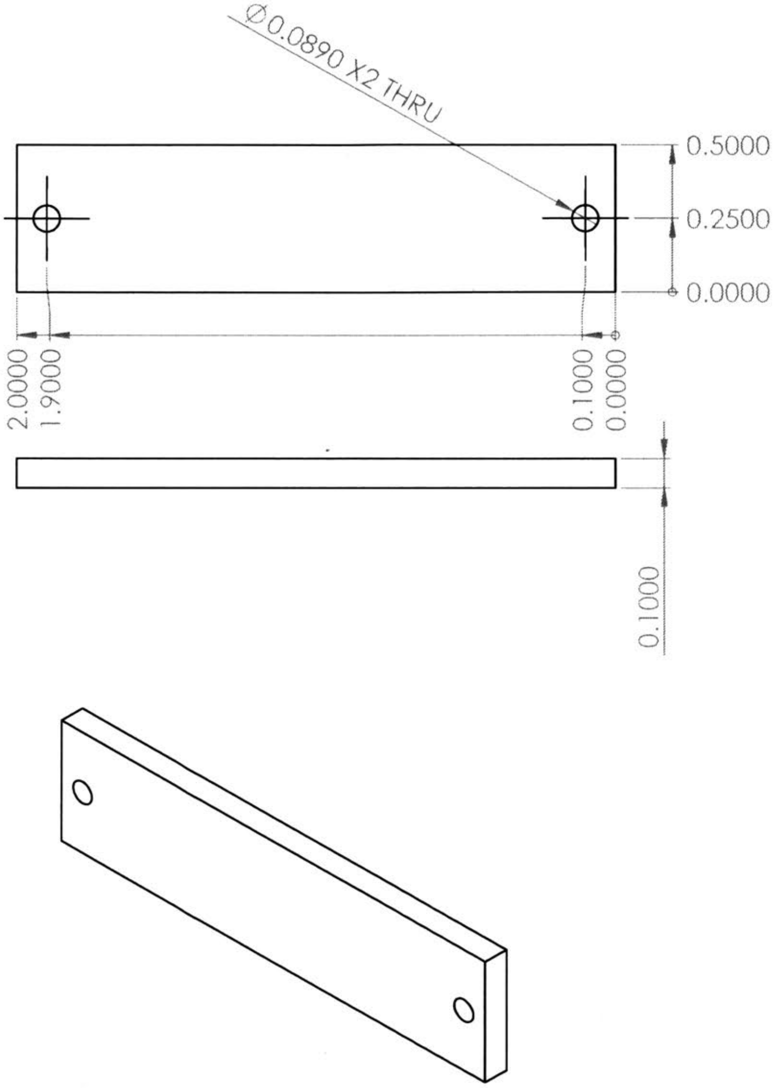
DWG NO.
Flexure_Shim

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



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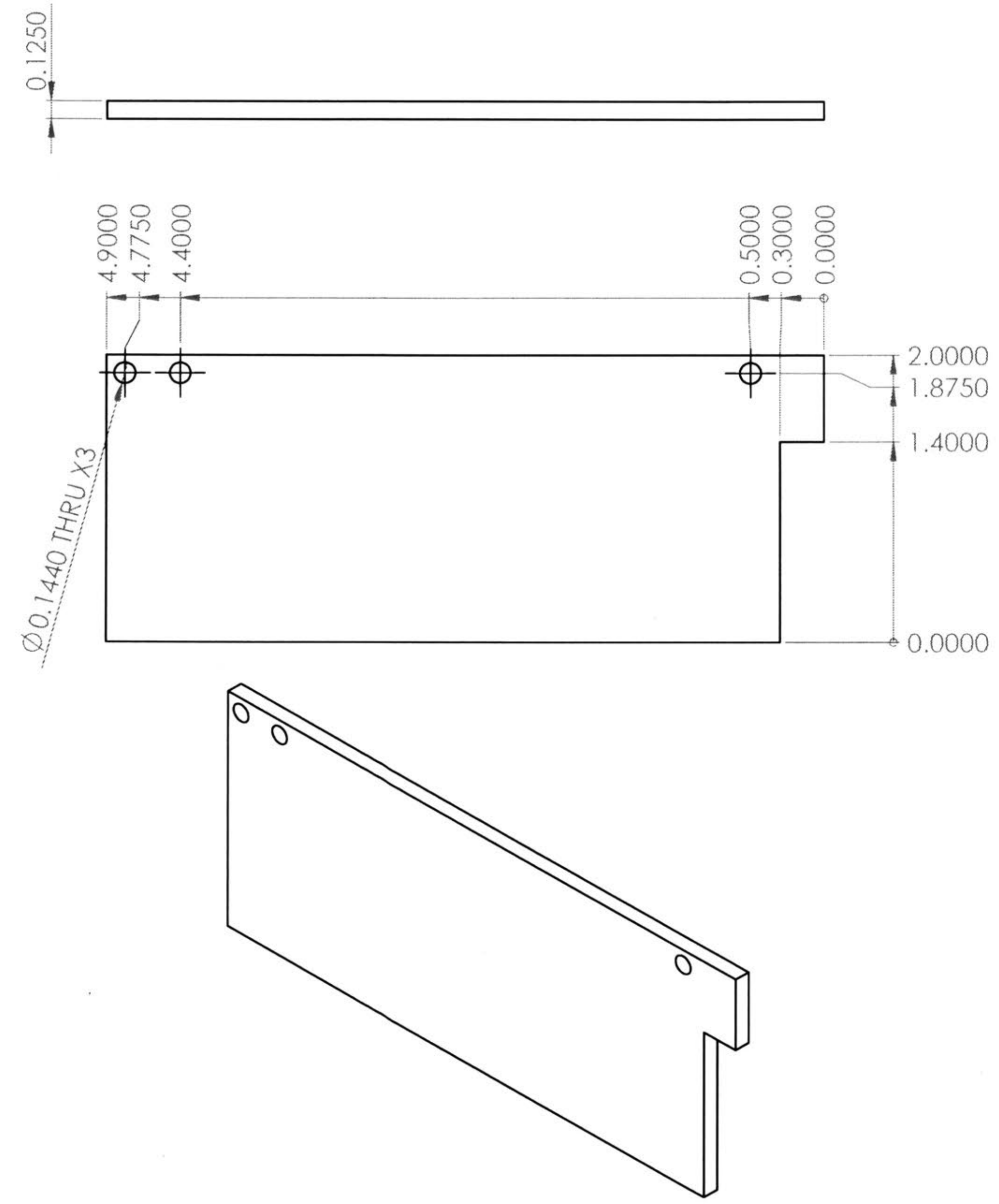
	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:		
MATERIAL: **6061 T6 Aluminum**	DWG NO. Flexure_Metal	A4
WEIGHT:	SCALE:2:1	SHEET 1 OF 1



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ANGULAR:

FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

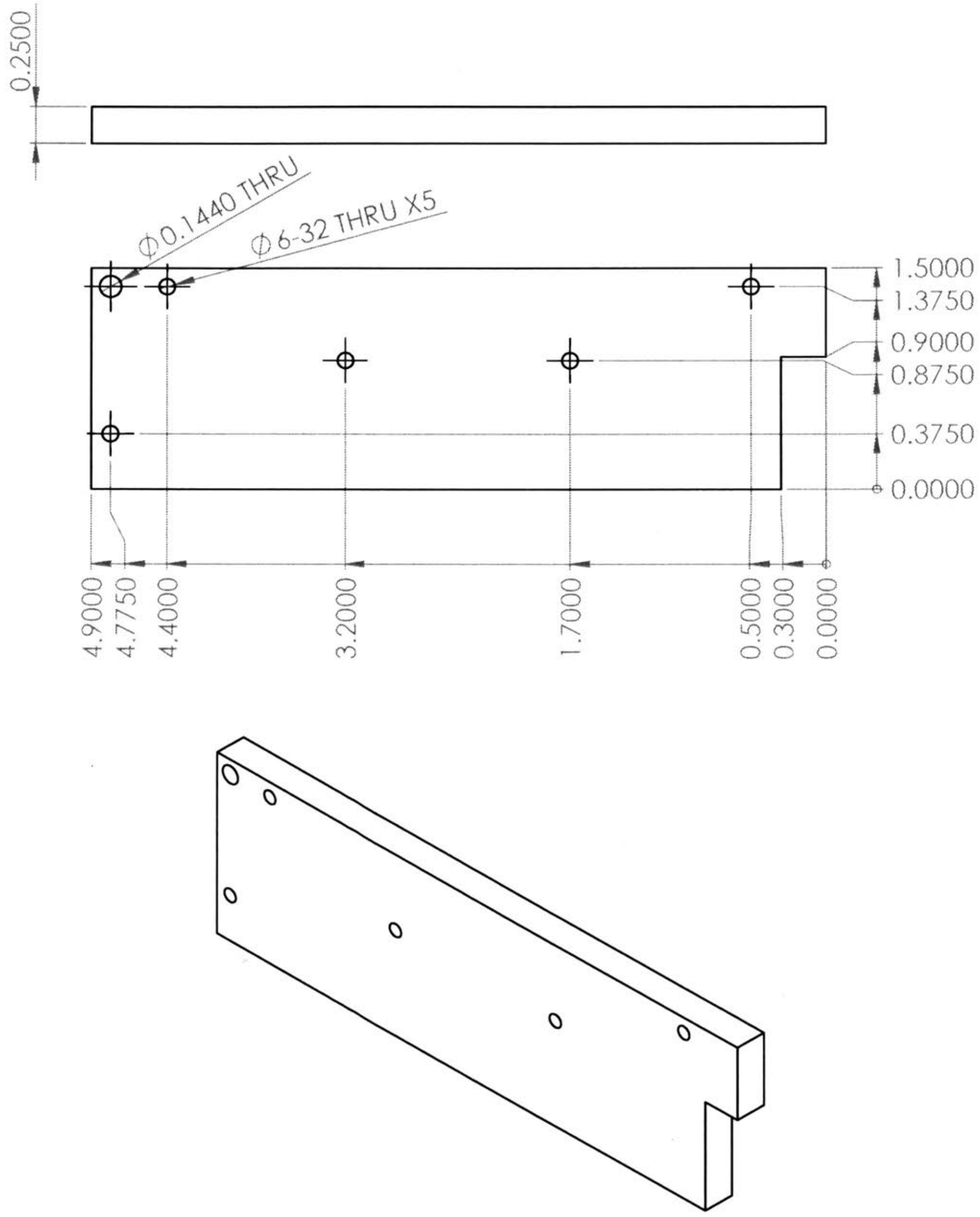
DWG NO.
Rake_Front_Flat

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



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DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

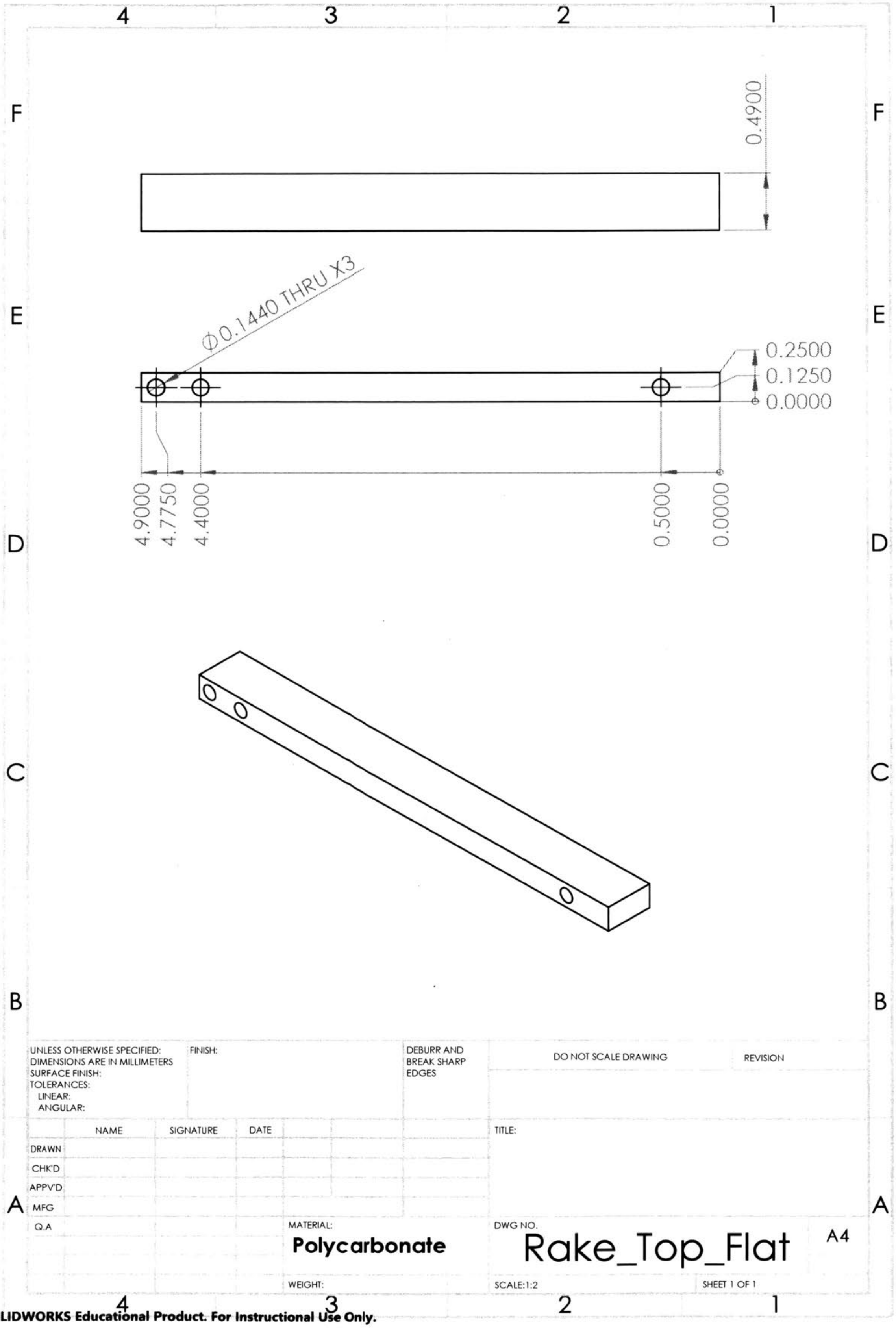
Rake_Back_Holes

A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1



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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:
Polycarbonate

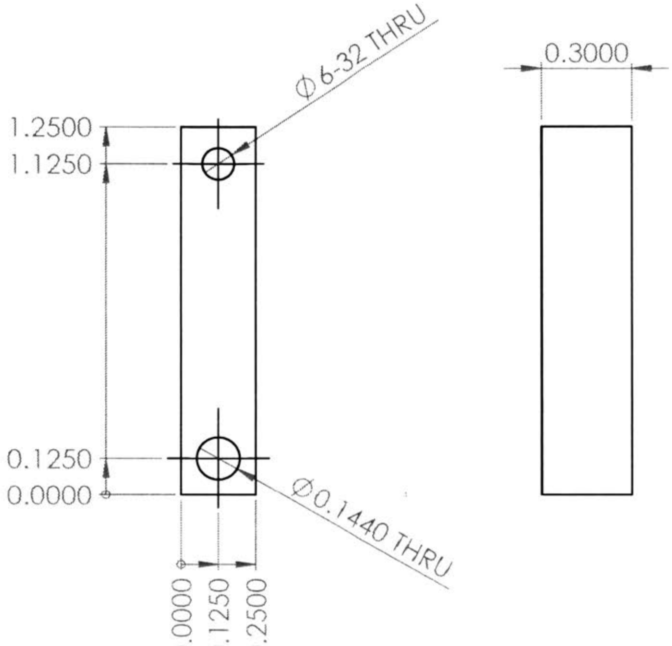
DWG NO.
Rake_Top_Flat

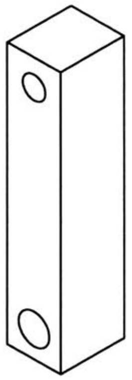
A4

WEIGHT:

SCALE:1:2

SHEET 1 OF 1





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FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

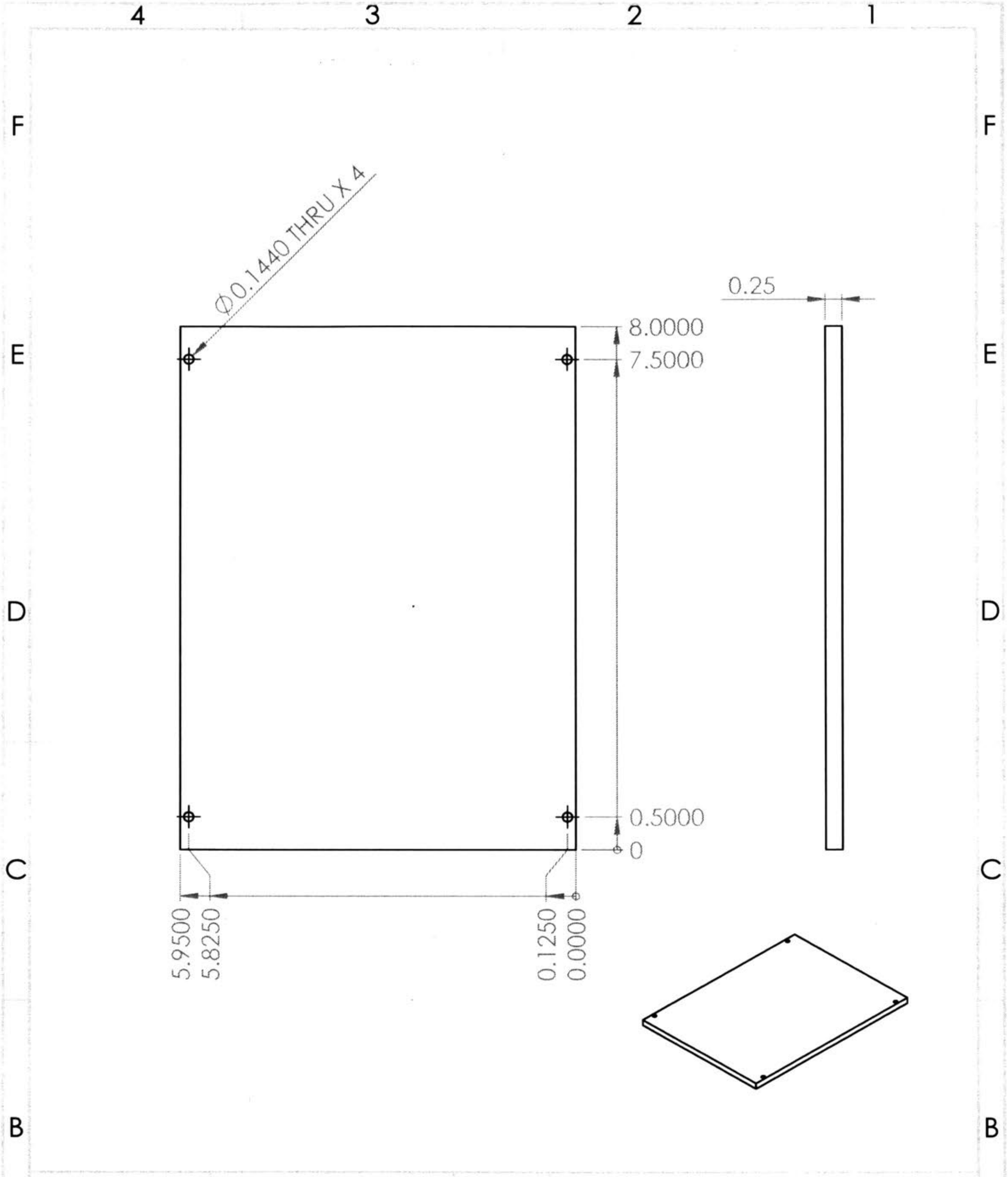
Rake_Tail

A4

WEIGHT:

SCALE:2:1

SHEET 1 OF 1



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	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

REVISION

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

Queue Base

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1

A

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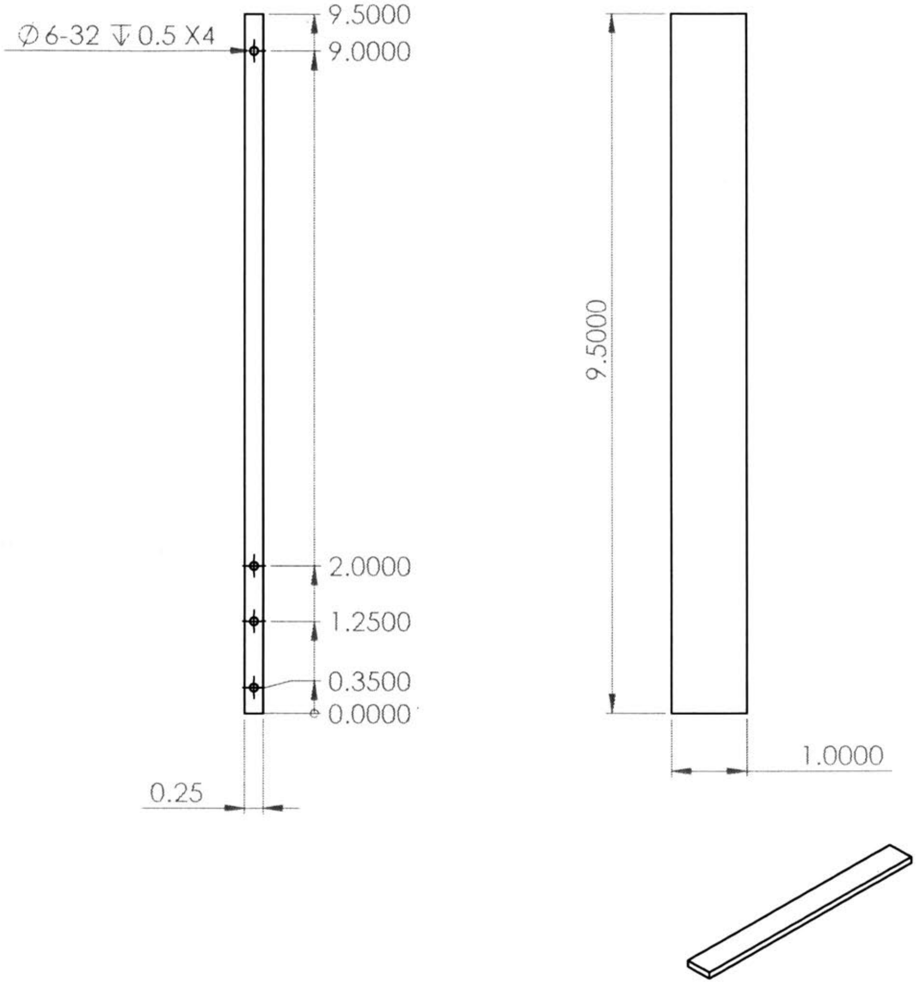

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ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

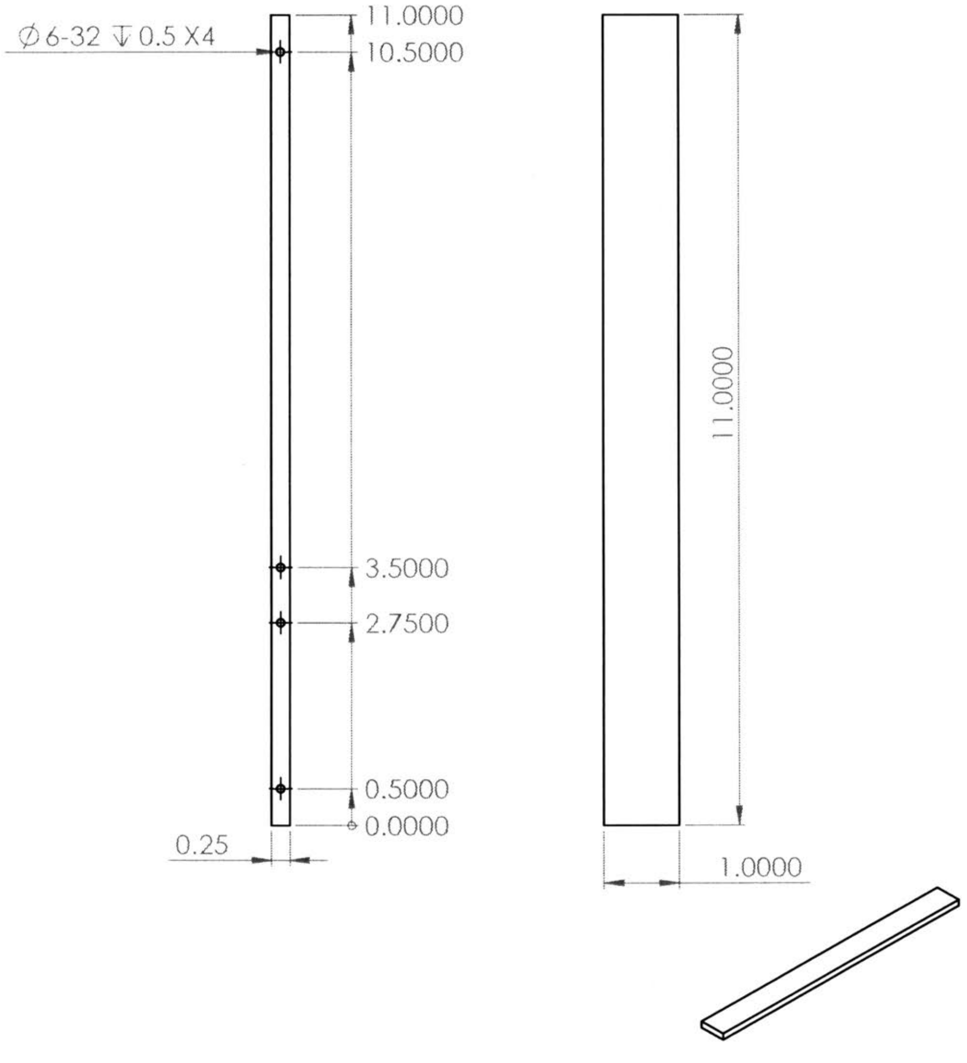
MATERIAL:
Polycarbonate

DWG NO.
Queue_Left_Wall A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



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FINISH:

DEBURR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

Polycarbonate

DWG NO.

Queue_Right_Wall

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1

Appendix B

Bill of Materials

A complete catalogue of all parts and materials purchased for prototyping the placement mechanism can be found found in the bill of materials below.

Item	Quantity	Link
Raw Materials		
1/8" Polycarbonate 6x12"	1	NA
1/4" Polycarbonate 48x48"	1	NA
1/2" Polycarbonate 6x12"	1	NA
1/2" Diam. 6061 T6 Aluminum Rod 12" Length	1	NA
1/10" 6061 T6 Aluminum 6x12"	1	NA
Screws / Nuts		
1/4" 2-56 Set Screw	1	NA
1/4" 4-40 Set Screw	1	NA
3/4" 6-32 Set Screw	2	NA
1/2" 6-32 Countersunk Screw	10	NA
1/4" 2-56 Machine Screw	2	NA
1/4" 6-32 Machine Screw	4	NA
3/8" 6-32 Machine Screw	6	NA
1/2" 6-32 Machine Screw	38	NA
5/8" 6-32 Machine Screw	11	NA
3/4" 6-32 Machine Screw	20	NA
7/8" 6-32 Machine Screw	2	NA
1" 6-32 Machine Screw	4	NA
1 1/8" 6-32 Machine Screw	5	NA
1/2" 8-32 Machine Screw	4	NA
1" 8-32 Machine Screw	4	NA
8-32 Nut	4	NA
Motors & Misc		
Stepper Motor	2	https://www.amazon.com/Stepper-Motor-Leads-Channels-Single/dp/B07D5GFZHF/ref=asc_df_B07D5GFZHF/?tag=hyprod-20&linkCode=df0&hvadid=242041198988&hvpos=1o17&hvnetw=g&hvrand=8949379198700410282&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=1018145&hvtargid=pla-487420504225&psc=1
Solenoid Motor	1	https://www.mcmaster.com/70155k661
12" Lead Screw	1	https://www.mcmaster.com/98941a735
Lead Screw Nut	1	https://www.mcmaster.com/95120a111
Clamping Flexible Shaft Coupling	1	https://www.mcmaster.com/6208k595

Bibliography

[1] Linkedin. "Waters Corporation". https://www.linkedin.com/company/waters/ Accessed 25 June 2019.

[2] Z. Zhang. Design and development of an automated sorting and orienting machine for vials. Master's thesis, Massachusetts Institute of Technology, 2019

[3] E. Moskofidis. Design and development of a transfer system for an automated vial packaging machine. Master's thesis, Massachusetts Institute of Technology, 2019

[4] S. Liu. Design and development of an automated inspection system for vials. Master's thesis, Massachusetts Institute of Technology, 2019

[5] D. Fernandes. Design and development of a precision packing stage and master control system for an automated vial packaging machine. Master's thesis, Massachusetts Institute of Technology, 2019

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[7] YouTube. "How It's Made Crayola Crayons". https://www.youtube.com/watch?v=3vtJgZFIqpc&t=242s Accessed 10 May 2019.