UNIVERSITY OF WATERLOO
Faculty of Engineering

# DESIGN OF AN END-EFFECTOR FOR A TOUCHSCREEN TEST FIXTURE

ecobee Inc.
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August 11, 2018

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August 11, 2018

William Melek, Director
Mechatronics Engineering Department,
University of Waterloo,
Waterloo, ON  N2L 3G1

Dear William Melek:

**Re: Submission of my work term report.**

I have just completed my final work term, following my 3B term. Please find enclosed my third work term report entitled: "Design of an End-Effector for a Touchscreen Test Fixture" for the Embedded Software group at ecobee Inc.. My manager was Tarun Tuli and our department was responsible for developing embedded software to run on ecobee Inc.'s products.

This report focuses on the design of an end-effector for a test fixture used to qualify capacitive touch panels in an automated manner.

I have had no direct assistance from anyone. I wish to thank Tarun Tuli for his suggestions and guidance throughout the design process.

I hereby confirm that I have received no further help, other than what is mentioned above, in writing this report. I also confirm that this report has not been previously submitted for academic credit at this or any other academic institution.

Yours sincerely,

---

Benjamin Hudson, 20530292

Encl.

# Summary

This report focuses on the design of an end-effector for a touchscreen test fixture. The test fixture is used to evaluate the performance of various capacitive touch panels in an objective and automated manner. This is an improvement on the current method, which is subjective and time-consuming.

The test fixture uses a special end-effector to physically interact with the touch panel. This end-effector must be touch-sensitive, able to tolerate un-flat surfaces, and introduce very little instrument error. The end-effector should also be easy to build, accurately simulate a human finger, and act as an end-stop. The part of the end-effector that touches with screen should be replaceable. 4 different designs are evaluated. The 4th design was selected mainly due to its replaceable stylus, its simplicity, and its reliability.

It is concluded that grounding a touch stylus greatly improves its touch-sensitivity. Furthermore, although 3D printing is versatile, using mass produced components in conjunction with 3D printed components is beneficial.

It is recommended that the end-effector be expanded to allow multi-touch testing, as well as single-touch.

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# 1 Introduction

This report focuses on the design of an end-effector for a test fixture used to qualify capacitive touch panels in an automated manner.

Beyond subjective "look-and-feel" testing, it is difficult to compare different touch panels. This test fixture was developed so that the performance of a touch panel could be quantified and objectively compared to that of another. This information is used to influence design decisions.

The test fixture tests a touch panel by physically interacting with it and recording its output. The end-effector is the part of the test fixture that interacts with the touch panel.

## 1.1 Background

Most modern touchscreens use capacitive touch technology. This section provides overview of the principles behind capacitive touch technology and how it is used in modern touch panels.

The touch-sensitive part of a touchscreen is actually a transparent layer on top of the screen. These two parts, the touch panel and the display, make up the display module (the touchscreen). It is common for the suppliers to sell a display module as a whole, rather than the separate components.

There are three main layers that make up a capacitive touch panel: a substrate (usually glass or plastic), a transparent conductive layer, and a protective coating. Figure 1 on page 2 shows the layers in a capacitive touch panel.

The conductive layer is consists of a grid very thin wires made from a transparent conductor (often indium tin oxide). The touch controller, a specialized integrated circuit, applies a low voltage to each of the wires in the grid, creating an uniform electric field around that wire. When a "touch-sensitive" object (such as a finger) approaches the screen it distorts the electric field around each wire by a different amount. The touch controller senses the amount of distortion at each point in the grid (measured as a change in capacitance) [1] and uses this to calculate the position of the touch. Any object that is able distort the electrostatic field enough for the touch controller to register a touch can be used to "touch" the screen.

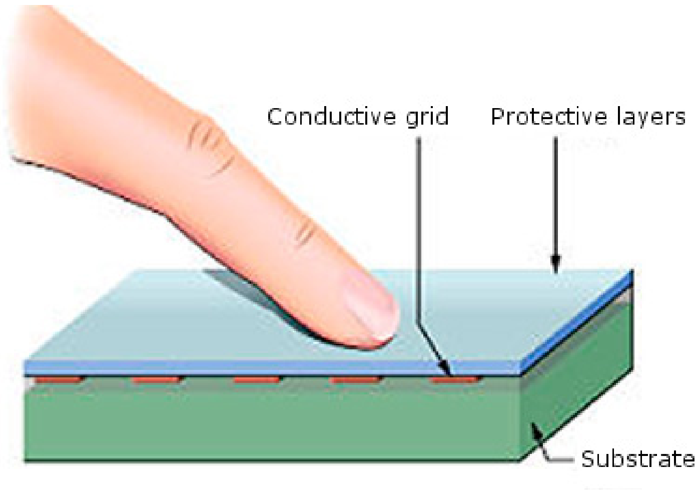



Figure 1: Layers in a capacitive touch panel. Source: `baanto.com`

## 1.2 Problem

Before a touch panel is selected for use in a mass-produced product it should be tested in many different operating conditions. For example, a certain touch panel may perform well in cold, dry environments, but poorly in hot, humid ones. If this touch panel is used in a product, consumers who live in Florida will not enjoy their user-experience as much ones who live in Ontario.

Typically, the qualification of touch panels is done manually and is subjective: the tester uses the touch panel and decides if it “feels” responsive. This is both extremely time-consuming and prone to bias. Furthermore, it is not feasible to perform very long durability/reliability tests manually.

Therefore, the need exists for an automated way to qualify capacitive touch panels.

## 1.3 Objective

The objective of this project is to design and build a test fixture to automate the qualification capacitive touch panels. It should provide a objective method to evaluate the performance of a touch panel and compare it to that of another. This is achieved by using a machine to physically interact with a touch panel.

The objective of this report is to describe the process behind the design of the test fixture’s end-effector. This report will not cover the design of the entire test fixture, but it will provide a description of its major components.

# 2 Test Fixture Layout

The test fixture is centered around a powered XYZ gantry, which is used to position the end-effector within the working area. The Device Under Test (DUT) is fixed to the bed of the test fixture at the center of the working area. By coordinating the x, y, and z axes the end-effector is able to touch or draw on the touchscreen of the DUT. Figure 2 on page 4 shows a photo of the test fixture with the major components labeled.

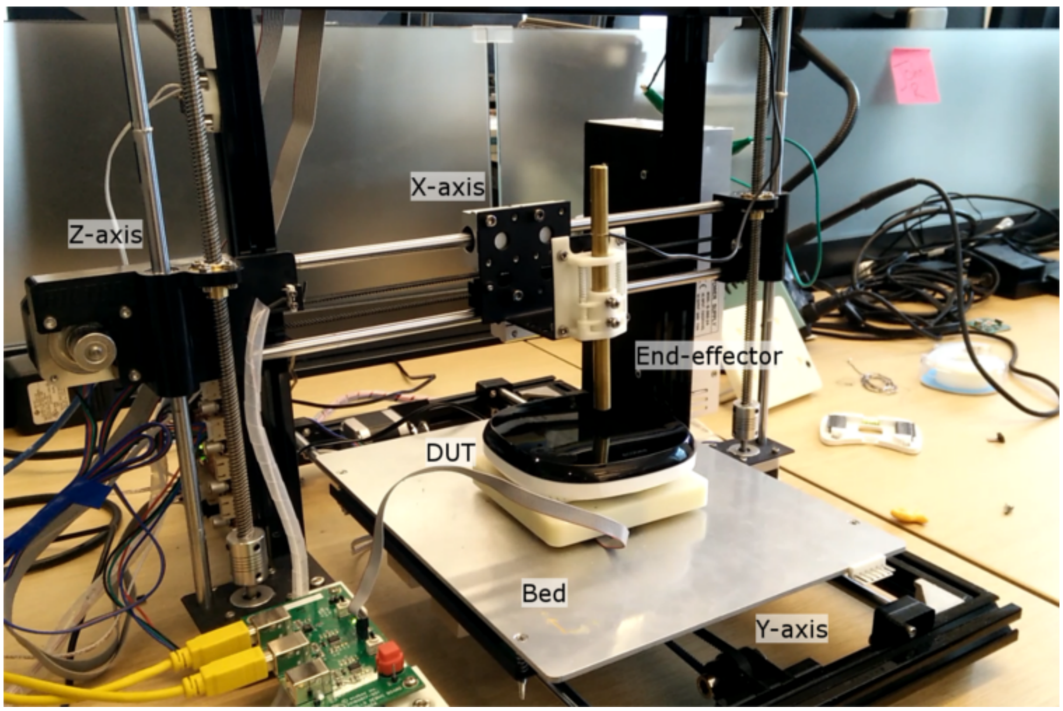



Figure 2: The test fixture

## 2.1 Overview

The test fixture is based on a Prusa i3 3D printer, an open-source design created by Joseph Prusa [2]. The filament extruder is replaced with a special end-effector used to interact with the DUT's touchscreen. The DUT is mounted to the print-bed using a special adapter which provides access to the its serial debug port. It is connected to a custom debug board which allows the host computer to communicate with the DUT as well as program the DUT with new firmware. Figure 3 on page 5 shows an overview of the system.

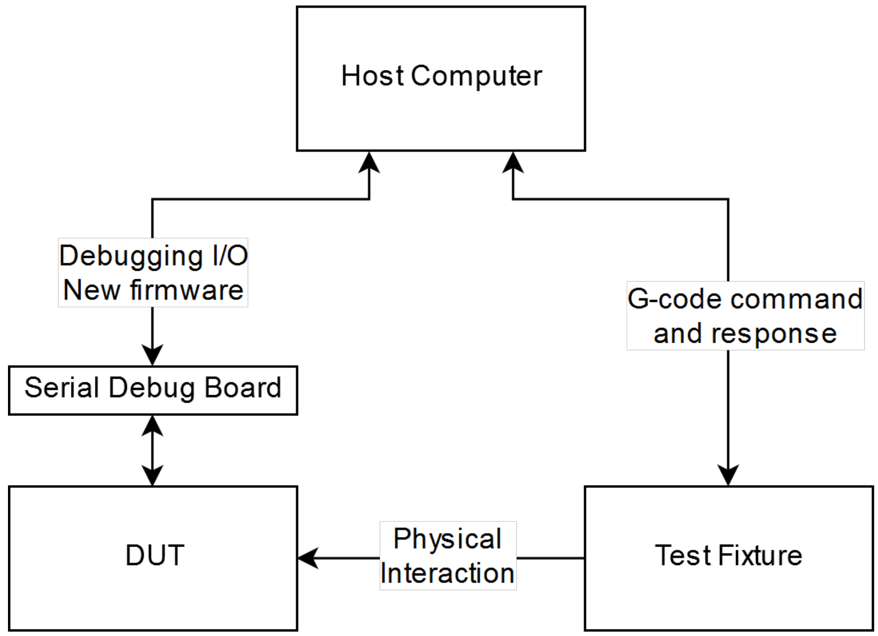



Figure 3: Overview of Test Fixture System

## 2.2 Test Fixture

The test fixture runs a custom version of Marlin, an open-source 3D printer firmware. Marlin was chosen for its extensive support of the Prusa i3 platform.

The test fixture is controlled through G-code. G-code is a programming language used in computer-aided manufacturing to control machine tools. Most 3D printers are controlled by G-code and there a number of commands specifically for 3D printers [3]. G-code commands are issued from the host computer over a serial interface. Marlin receives and executes the commands. The host computer is also able to query information from the test fixture as well as command it. For example, it can request the current position of the end-effector.

When a G-code command is issued, it is added to a buffer. The test fixture will consume commands from the buffer one-by-one. Once a command has been issued, it is not possible to remove it from the buffer or interrupt it (there is one exception – it is possible to send an emergency stop command, which requires the test fixture to be rebooted before continuing). This means that no real-time feedback is available to the host computer.

## 2.3 DUT

The DUT is a fully assembled ecobee Inc. thermostat. The test fixture is compatible with all touch-enabled models. The host computer interacts with the DUT through its serial debug interface.

Touch events are registered with the DUT's Linux operating system according to the the standard Multi-Touch (MT) Protocol [4].

Before testing begins, the host computer starts a special test application on the DUT to read touch events registered with the operating system and output them over the serial debug interface. This test application is bundled with the thermostat operating system, so a thermostat does not require special firmware to interact with the test fixture. This is important because flashing new firmware and the subsequent reboot is very time consuming.

## 2.4 Host Computer

The host computer is responsible for coordinating the test fixture and the DUT. It must simultaneously issue commands to the test fixture to move the end-effector, and collect and parse the debug logs from the DUT.

Figure 4 on page 7 shows a flowchart illustrating the steps required to draw a line. The flowchart shows one move command expanded into the individual steps.

### 2.4.1 Coordinate Transformation

In order to accurately draw on the touchscreen of the DUT, the host computer must know exactly where it is within the working area. Even a misalignment of one millimeter can produce a shift of several pixels.

When the user requests that the test fixture touch a specific pixel on the touchscreen, the host computer must convert that position (in the screen coordinate system) to an end-effector position (in the physical coordinate system). A scale (pixels to millimeters), translation (screen origin to bed origin), and even rotation (skew of DUT on bed) is required. Figure 5 on page 8 illustrates the transformations required.

These transformations can all be represented by a single 3-by-3 matrix, called an affine transformation matrix [5]. Equation 1 shows the form of the transformation

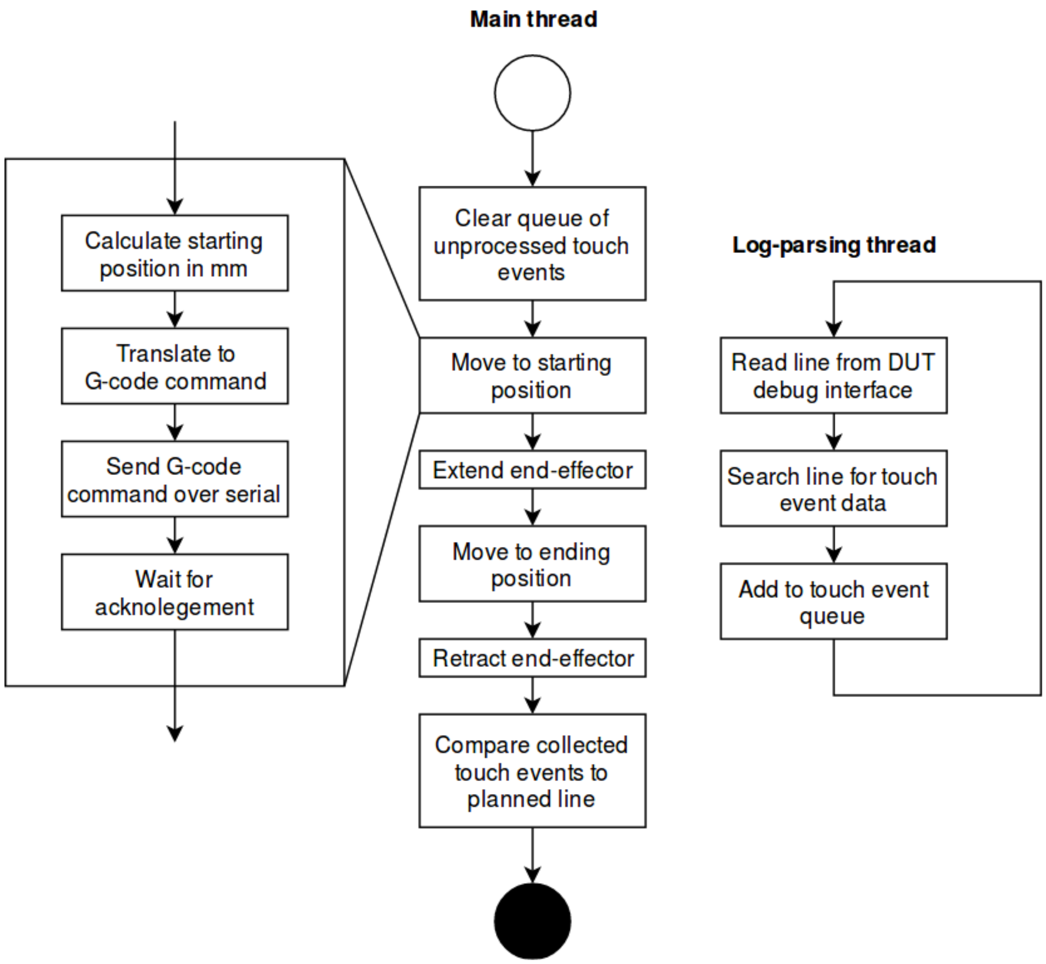



Figure 4: Flowchart for drawing a line

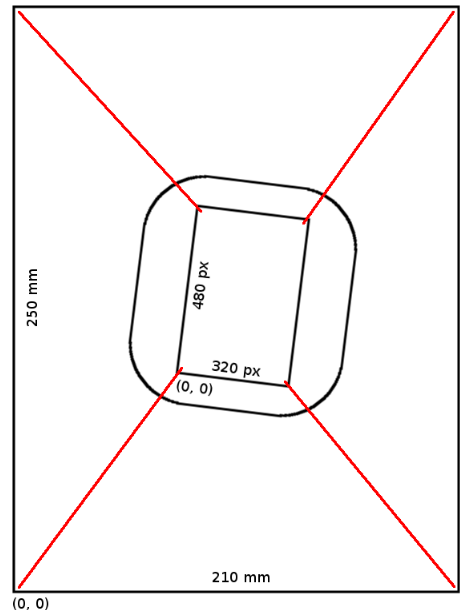



Figure 5: Screen coordinate to physical coordinate transformation

where $(u, v)$ is a point in the physical coordinate system and $(x, y)$ is a point in the screen coordinate system. Equation 2 shows an example of an affine transformation matrix for rotation by $\theta$.

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = A \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2}$$

The test fixture calculates the transformation matrix by probing points on the touch-screen. Using three point pairs ($(x, y)$ and the corresponding $(u, v)$) it is possible to calculate the transformation matrix. The transformation is given by Equation 3.

$$\begin{bmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ 1 & 1 & 1 \end{bmatrix} = A \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ 1 & 1 & 1 \end{bmatrix} \tag{3}$$

The transformation matrix $A$ calculated by Equation 4.

$$A = \begin{bmatrix} u_1 & u_2 & u_3 \\ v_1 & v_2 & v_3 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ 1 & 1 & 1 \end{bmatrix}^{-1} \tag{4}$$

The $A$ matrix only needs to be calculated once per DUT. However, different units will have slightly different matrices due to variation in the manufacturing process.

# 3 Design Challenge

The original 3D printer was modified to replace the filament extruder with custom end-effector. The end-effector allows the test fixture to interact with the touchscreen on the DUT.

This section explores the constraints and criteria for the design of the end-effector. It also details each of the 4 candidate designs and explains how the final design was chosen.

## 3.1 Criteria & Constraints

Criteria and constraints were determined before the design process began. Table 1 on page 10 summarizes the design constraints. Table 2 on page 11 shows the design criteria and their importance (scored out of 10) to the design.

| **Constraint** | **Limit** | **Description** |
|---|---|---|
| Flatness tolerance | $< 10\,\text{mm}$ | Must be able to continuously make contact with surfaces that have a flatness[1] up to 10 mm. |
| Rigidity | $< 5\,\text{mm}$ | The tip of the end-effector must have less than 5 mm of play peak-to-peak along the x- and y-axis. |
| Touch sensitivity | Absolute | The end-effector must be able to register a touch on all touch panels used in current production ecobee Inc. thermostats. |

Table 1: End-effector design constraints

## 3.2 Candidate Designs

More detailed drawings of the designs are found in Appendix A. Figure 6 on page 11 shows a photo of the prototypes used for testing. The prototypes are made using 3D printed parts.

[1]Flatness refers to the GD&T definition of flatness [6]

| Criteria | Weight | Description |
|---|---|---|
| Exchangeable tip | 6 | The stylus on the end-effector (the part that makes contact with the touch panel) should be exchangeable or replaceable, allowing "finger" sizes and shapes to be simulated. |
| Easy to build | 2 | Should be easy to manufacture and build. It should possible to disassemble the end-effector. |
| Touch sensitivity | 9 | Should be able to register touches on all production touch panels with a sensitivity similar to a human finger. |
| Rigidity | 7 | Play at the tip of the end-effector should be minimized along the x- and y-axis. This minimizes the error introduced in to the measurement by the end-effector. |
| Z-low end-stop | 3 | Should also act as an end-stop for the z-axis. |

Table 2: End-effector design criteria

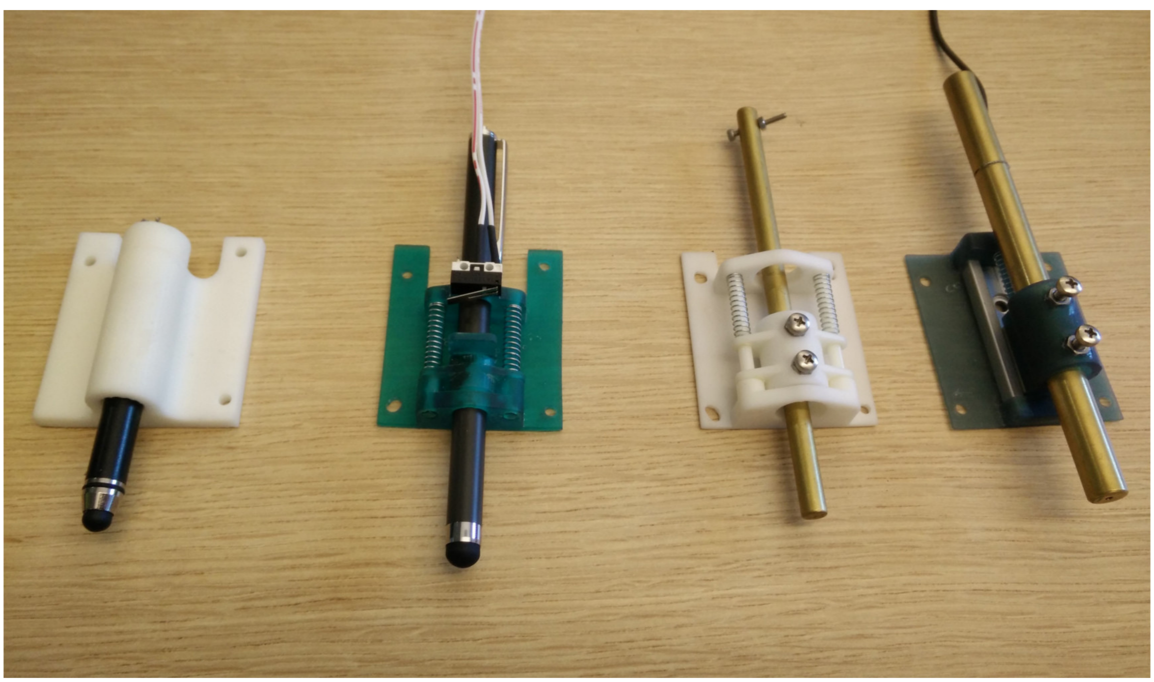


Figure 6: Photo of design prototypes

### 3.2.1 Design 1

Figure 7 on page 12 shows Design 1. This design uses part of a consumer touch stylus to interact with the touch panel. The other end of the stylus mates with a small spring-loaded rod. The stylus is able move in the z-direction up to 15 mm while the force exerted by the spring ensures it remains in contact with the touch panel. When it reaches its limit it triggers the integrated end-stop. Figure 8 on page 13 shows the spring and end-stop mechanism.

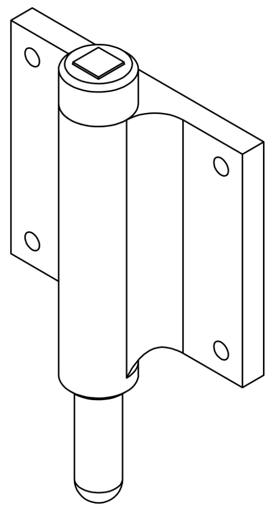


Figure 7: Design 1

Although it is able to register a touch with the DUT, the stylus in Design 1 is very unreliable and does not accurately simulate a human finger. This is most probably due to the fact that the stylus was modified. Since it is cut in half, not enough material is present to distort the electric field produced by the touchscreen and reliably register touches.

### 3.2.2 Design 2

Figure 9 on page 13 shows Design 2. Like Design 1, Design 2 uses springs to allow the stylus to move in the z-direction while maintaining contact with the screen. Design 2 also uses a consumer-touch grade stylus, however unlike that of Design 1, it is unmodified. A small clip at the top of the stylus allows the stylus to be grounded. Grounding the stylus (electrically connecting it to Earth, or a large sink, such as the chassis of the test fixture) greatly improved its touch-sensitivity, as it allows it to absorb much more electrostatic charge from the screen.

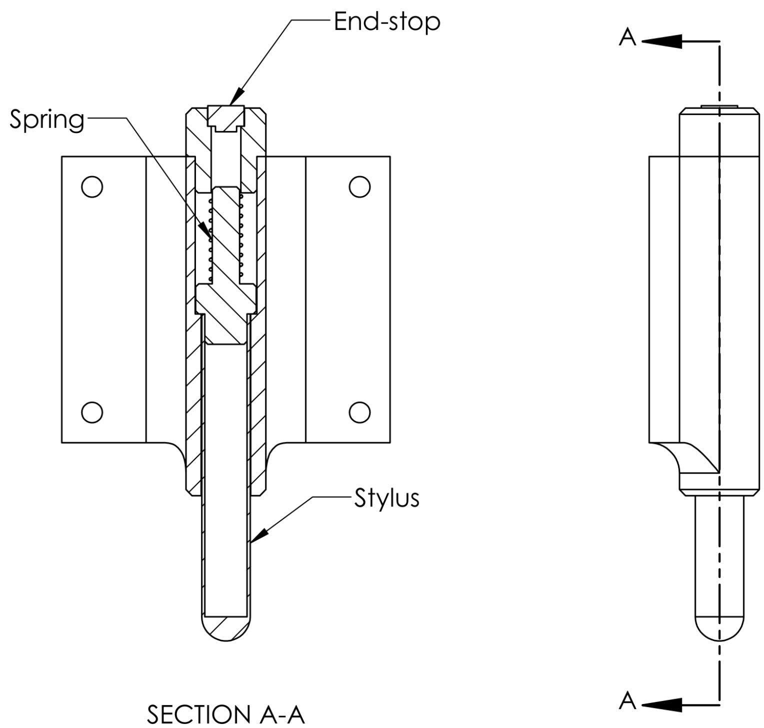



Figure 8: Section view of Design 1

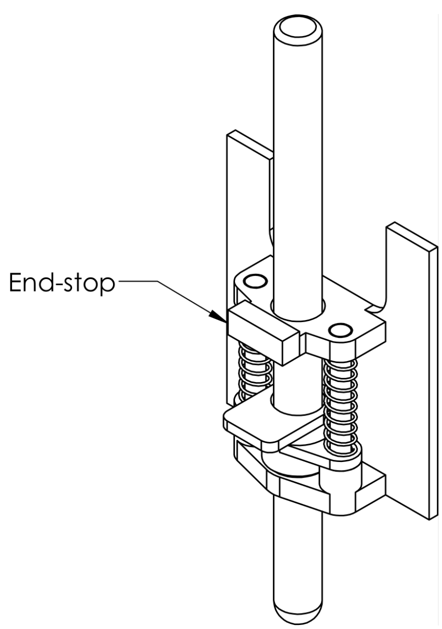



Figure 9: Design 2

Design 2 also features an end-stop, which is triggered when the tab on the collet holding the stylus trips a limit switch.

The stylus is attached to the collet with an adhesive, so it is non-removable. The stylus slides through a close-fitting guide at the base of the end-effector that keeps it in place. The design has very little play, as the diameter of the stylus is fixed.

### 3.2.3 Design 3

Figure 10 on page 14 shows Design 3. The collet is improved in Design 3. It uses two setscrews to fix the stylus in place, rather than an adhesive. Design 3 was prototyped using an 8 mm-diameter brass rod, rather than a consumer touch stylus. Brass rods are often used in the industry to simulate touch input [7] [8] [9]. However, since the rod is removable, it could be replaced by another stylus. The rod is also grounded.

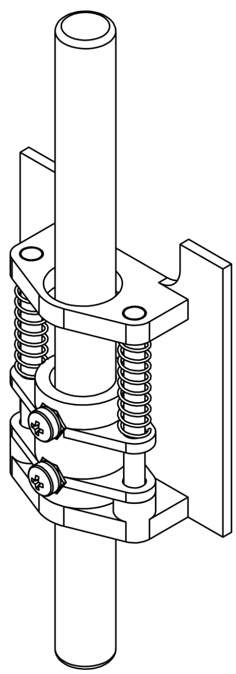


Figure 10: Design 3

Design 3 does not feature and end-stop. Instead, an end-stop is placed the maximum of the z-axis, and the height of the touch panel is calculated. Small inaccuracies in the z-position of the end-effector are tolerated due its ability to compensate for variations in height.

The rigidity of Design 3 is very poor. Since the stylus is replaceable, it is not possible to add a close-fitting guide for the stylus, as in Design 2. Only two small rods on either side of the collet keep it in place.

### 3.2.4 Design 4

Figure 11 on page 15 shows Design 4. Design 4 also uses two setscrews to fix the stylus in place. It was prototyped using the same 8 mm-diameter brass rod. Design 4 uses a low-profile sleeve bearing and guide rail to carry the collet, rather than 3D printed guides. The sleeve bearing and guide rail assembly is much more precise than the 3D printed guides, ultimately leading to much less play at the tip of the stylus.

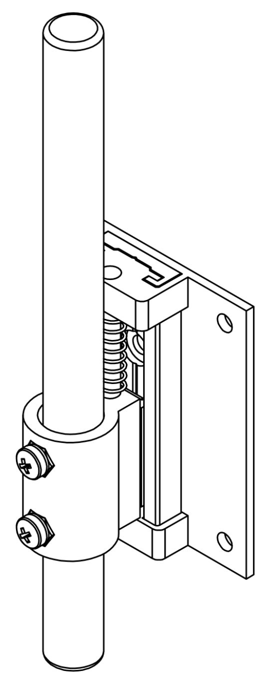


Figure 11: Design 4

Design 4 does not feature and end-stop, and uses the method described in Section 3.2.3 to estimate the height of the touch panel.

## 3.3 Final Design Selection

Designs that did not meet the constraints were discarded. Design 3 did not meet the rigidity constraint, as the 3D-printed vertical guides were not precise enough to prevent a significant amount (> 5 mm) of play at the tip of the stylus.

The remaining 3 designs were evaluated based on the criteria described in Table 2 on page 11. Table 3 on page 16 shows the multipliers for each criteria.

| **Criteria** | **Weight** | **Multiplier** |
|---|---|---|
| Exchangable tip | 6 | 0.22 |
| Easy to build | 2 | 0.07 |
| Touch sensitivity | 9 | 0.33 |
| Rigidity | 7 | 0.26 |
| Z-low end-stop | 3 | 0.11 |
| Total | 27 | 1.00 |

Table 3: Criteria multipliers

Each criteria is scored out of 11 (0 to 10), then multiplied by its corresponding multiplier. Boolean criteria are assigned a score of 0 or 10. The maximum possible score for any design is 10. Table 4 on page 16 show the scores for each design for each criteria, as well as the final score.

| | **Design 1** | | **Design 2** | | **Design 4** | |
|---|---|---|---|---|---|---|
| **Criteria** | **Score** | **Value** | **Score** | **Value** | **Score** | **Value** |
| Exchangeable tip | No | 0.00 | No | 0.00 | Yes | 2.22 |
| Easy to build | 8 | 0.59 | 2 | 0.15 | 10 | 0.74 |
| Touch sensitivity | 3 | 1.00 | 6 | 2.00 | 8 | 2.67 |
| Rigidity | 7 | 1.81 | 5 | 1.30 | 5 | 1.30 |
| Z-low end-stop | Yes | 1.11 | Yes | 1.11 | No | 0.00 |
| Total | | 4.52 | | 4.56 | | 6.93 |

Table 4: Design scores based on criteria

Design 4 meets all the constraints and scores highest in Table 4, so it is selected for use in the test fixture.

# 4 Conclusions

The following conclusions can be drawn from this report:

1. Grounding a stylus, whether it be a consumer-grade touch stylus or a brass rod, greatly improves its ability to register touches on a touch panel.
2. Although 3D printing is a versatile tool, mass-produced components are useful when more precision is required.
3. Taking the time to create a design that can be disassembled is beneficial, as it allows the design to be tweaked after the fact.
4. When designing a measurement tool, take care to minimize the error introduced by the tool itself.

# 5 Recommendations

Future development of this project could focus on:

1. Extending the end-effector to enable testing of multi-touch, rather than single-touch only.
2. Enable the end-effector to produce a desired force on the touch panel. Some touch panels can measure pressure as well as just the position of a touch. This would require replacing the spring mechanism with an active one.
3. Continue to improve the rigidity of the stylus. Although the sleeve bearing and guide rail is an improvement, the selected design still allows some play at the tip of the stylus.
4. Explore injecting an active signal, such as low-amplitude white noise, into the stylus to improve sensitivity to the touch panel. Initial development in this area was promising.

# References

[1] Various, "Projected capacitive technology," technology brief, 3M Touch Systems, 2011.

[2] "Prusa3d - 3d printers from Josef Prusa." http://www.prusa3d.com/ (current Sept. 2017).

[3] "G-code - reprapwiki." http://reprap.org/wiki/G-code (current Sept. 2017).

[4] H. Rydberg, "Multi-touch (mt) protocol." https://www.kernel.org/doc/Documentation/input/multi-touch-protocol.txt (current Sept. 2017).

[5] "Affine transformation." https://www.mathworks.com/discovery/affine-transformation.html (current Sept. 2017).

[6] "Flatness." https://www.gdandtbasics.com/flatness/ (current Sept. 2017).

[7] "System performance verification - touchscreen technology." https://developer.sonymobile.com/2014/12/04/system-performance-verification-touchscreen-technology-series-4-video/ (current Sept. 2017).

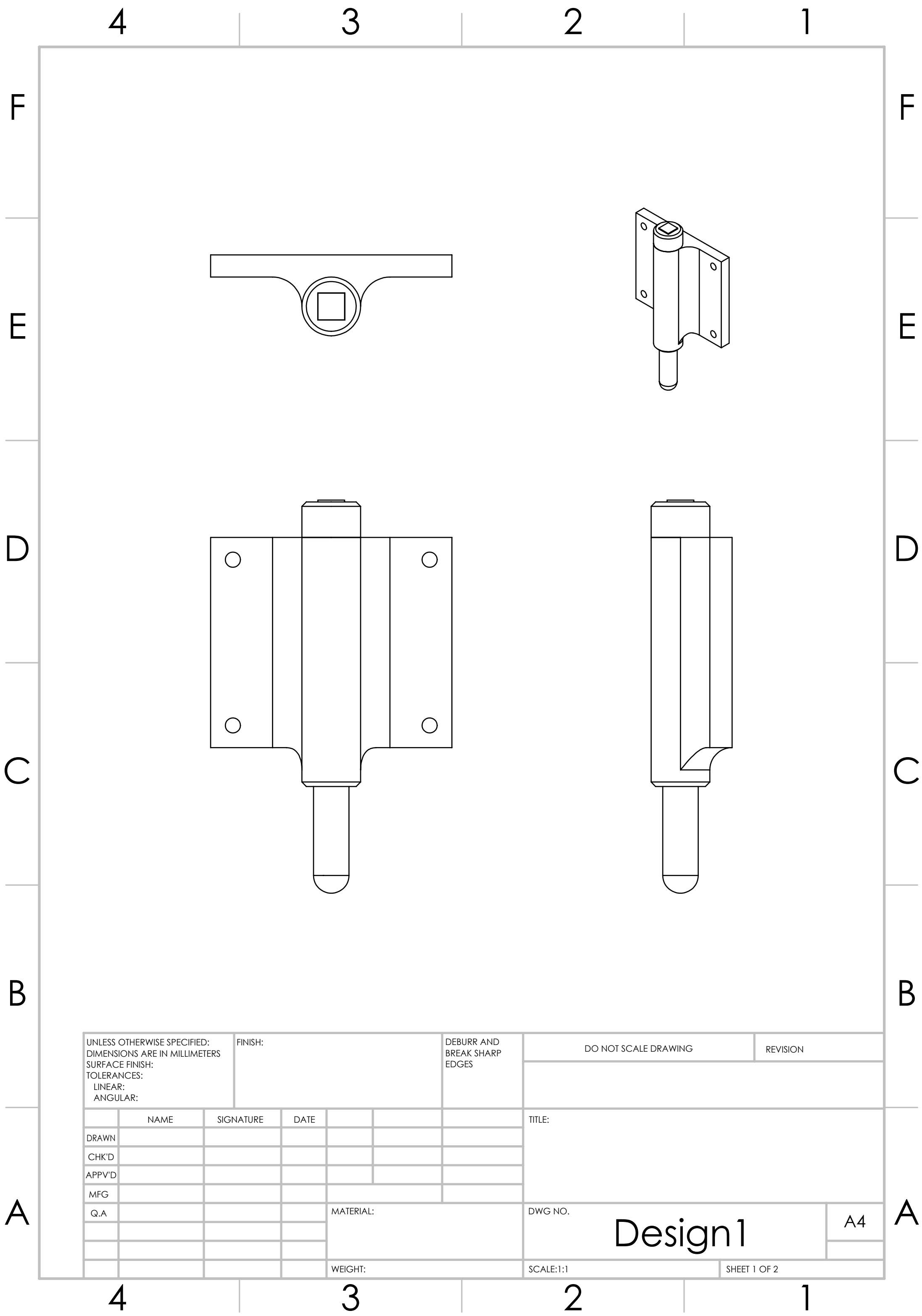
[8] S. Welch, T. Shigemitsu, T. Wright, M. Vance, and S. Wittenberg, "Input testing tool," Apr. 19 2016. US Patent 9,317,147.

[9] "Optofidelity measured the touch screen accuracy of android phones for finnish mpc magazine." https://www.optofidelity.com/optofidelity-mittasi-android-puhelinten-kosketusnayttojen-tarkkuuden-mpcn-vertailussa/ (current Sept. 2017).

# Appendix A Drawings

Drawing of each end-effector design are shown in this appendix. A standard view is shown on the first page of each drawing. An one-half scale isometric view is also shown.

# Design 1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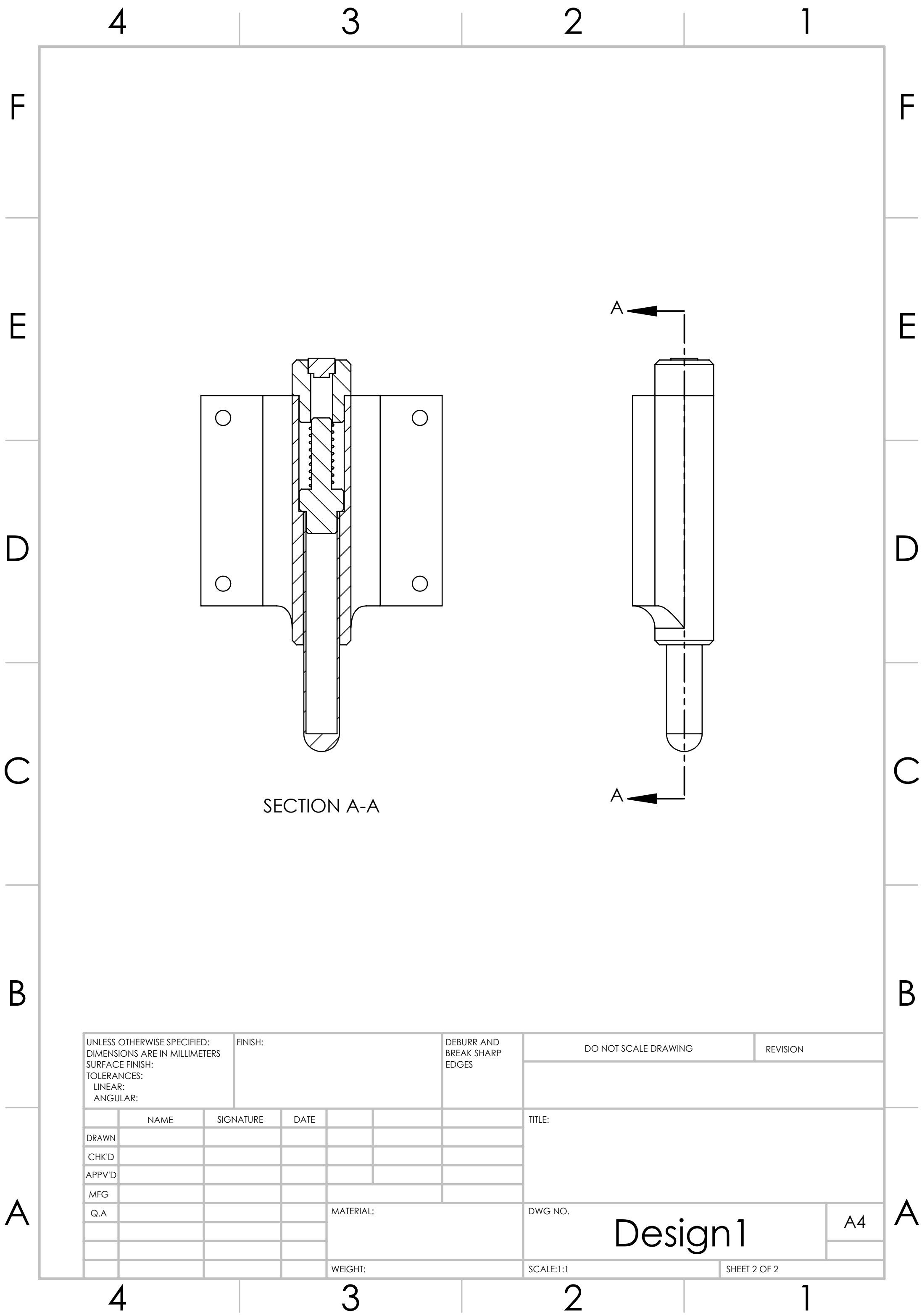
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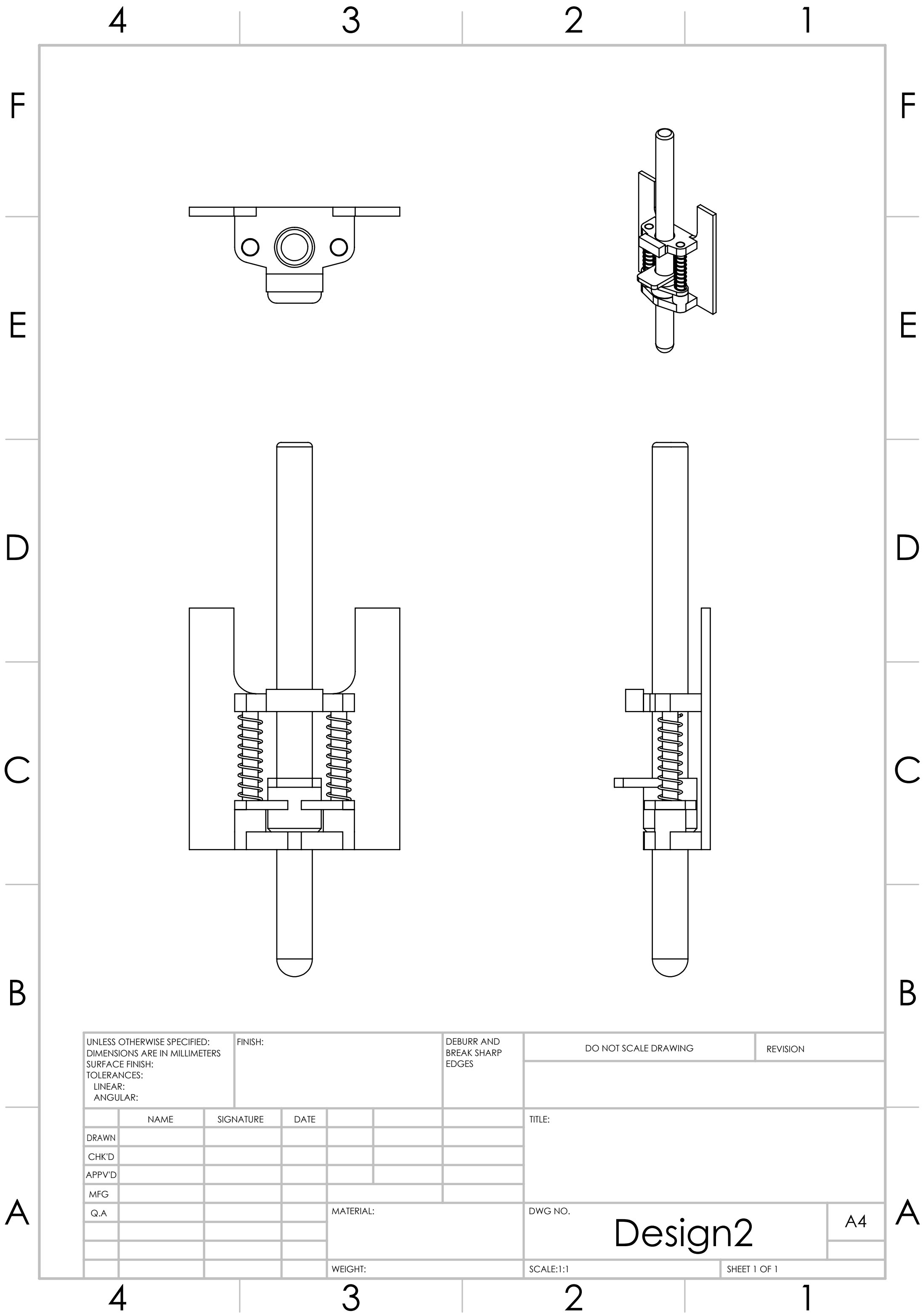

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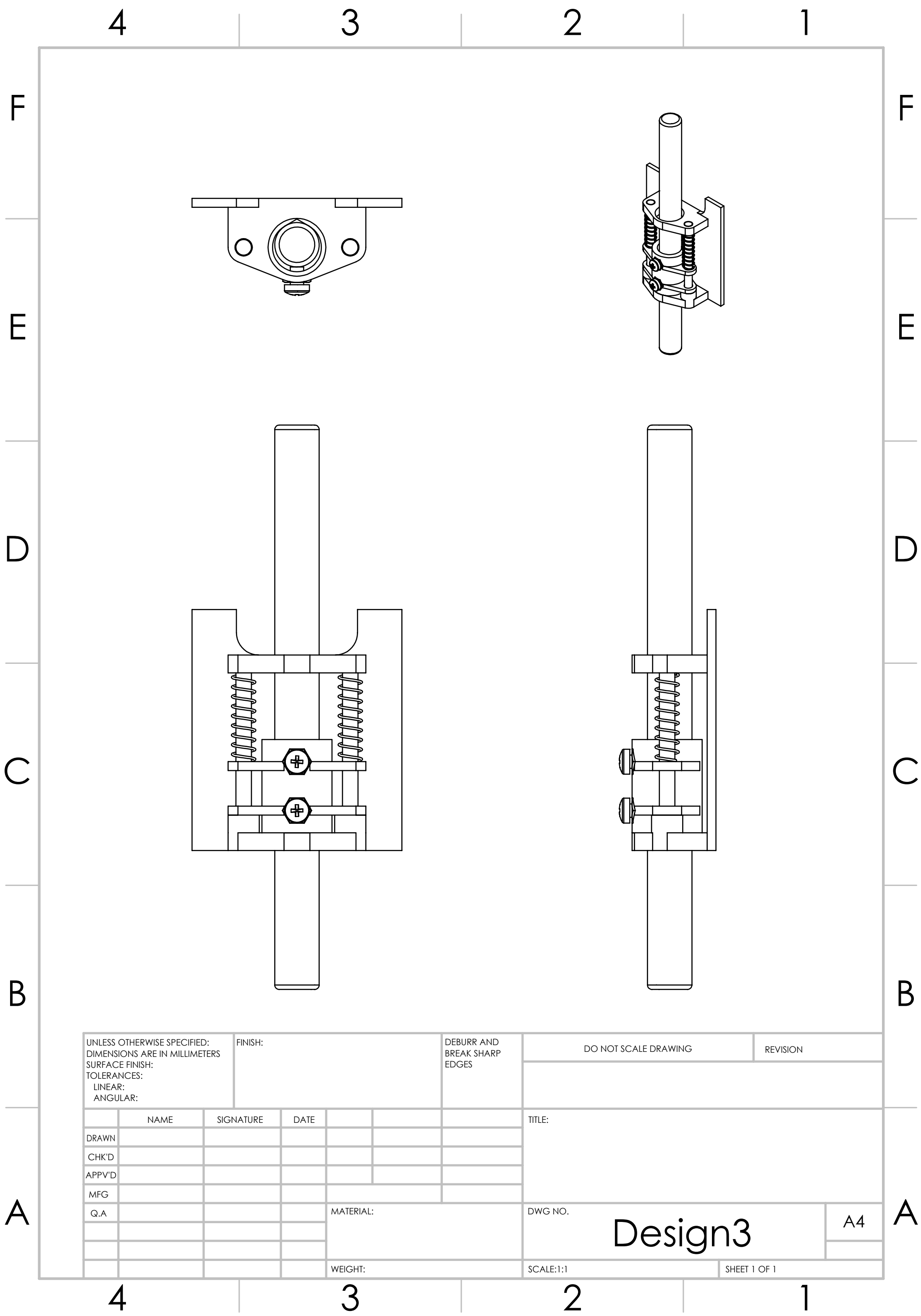
## Design 3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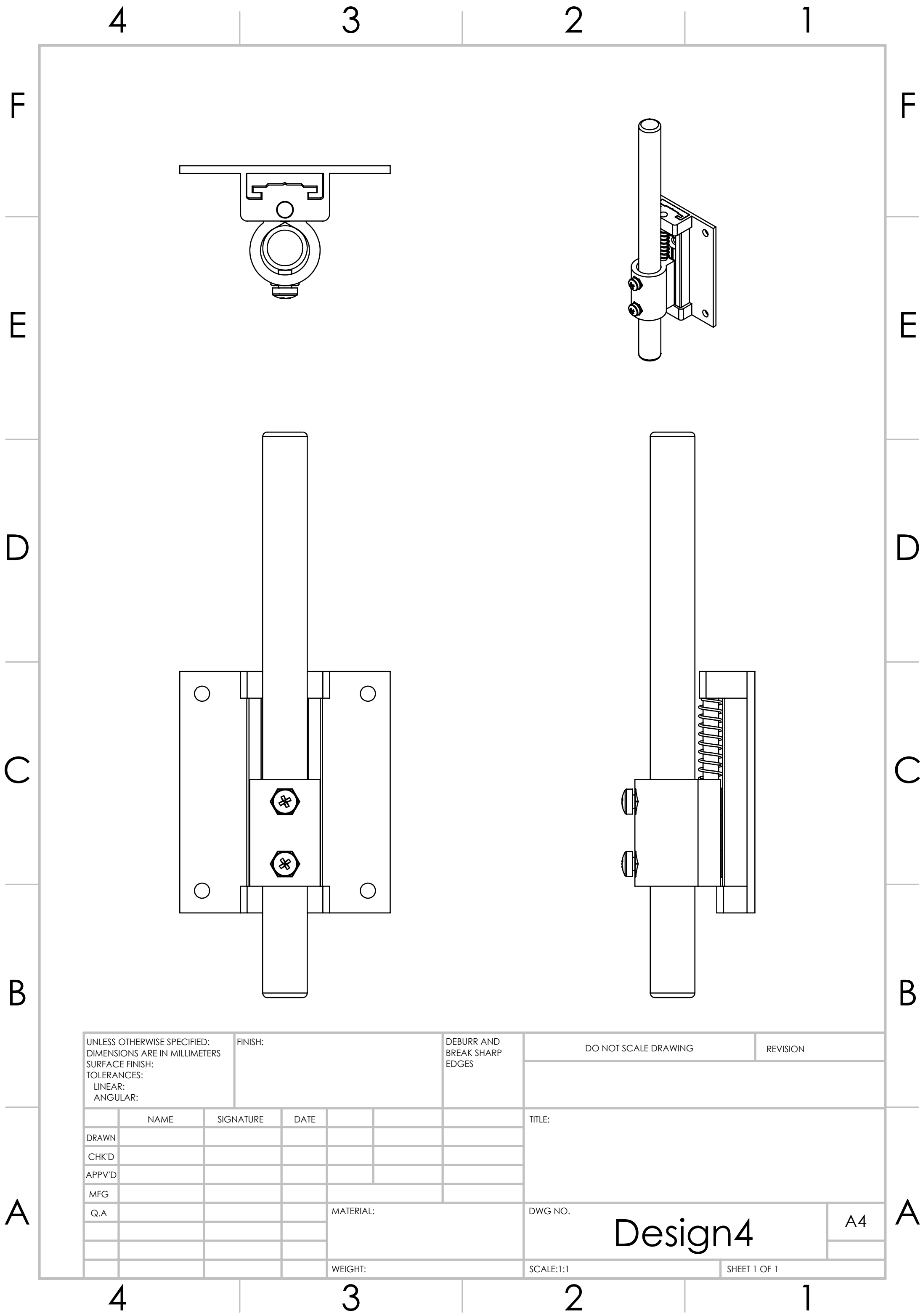
## Design 4



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