3D Force Sensing Module

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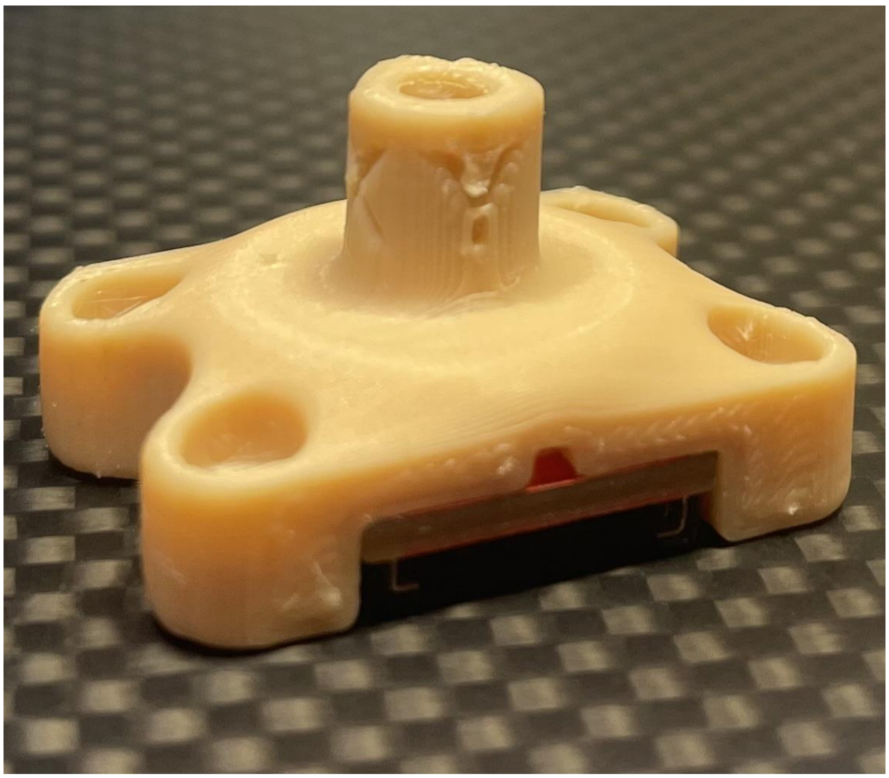

Github Link: https://github.com/andrewstrauss18/SensorModule

Abstract

In a robotic system it is often the case that there are some aspects of the robot that are unobservable. Many robots take advantage of closed loop control to accomplish tasks since it removes the robot's reliance on dead reckoning and allows the robot to be more autonomous and reliable. In this paper we will discuss a new type of 3D force sensor that can be mounted easily most anywhere on a robot and provide feedback to the device it is integrated into. We will also cover one of the possible applications by showing off an optimized robotic hand with many of these integrated force sensors within. This paper will only cover the design, manufacturing, and construction of this hand. The utilization of its features is a good place for future work to begin.

Introduction

There have been many hall effect force sensors proposed in past papers but they usually involve an array of hall effect sensors and machine learning to get results from them[1]. The design posed in this paper uses an array of 12 hall effect sensors and 16 small magnets. Machine learning is then implemented to turn the readings from the hall effect sensor into force data. The issues with this approach is difficult assembly as the magnets must be embedded into the silicone and then not shift positions over use as this could mess up the ML tuning and result in inconsistent force data. There is one similar design that uses a 1D hall effect sensor to sense the deformation of a fingertip[2]. In this paper a hall effect sensor is placed in the finger structure and a magnetic rigid component joins that to a fingertip which can be deformed. This approach is very similar to some of the methods used by our soft robotics lab in some of our past work where a very similar mechanism was implemented onto an optimized robotic hand[3]. There are two main issues with this approach, the first of which is the size. This design necessitates a long sensor that is awkward to mount and cover inside of a fingertips small profile. The second issue is that this design is not very robust, its length sees it experiencing high forces while canted against a moving mechanism. The method proposed in this paper covers the design, fabrication, signal processing and tuning of a 3D force sensing flexture module based simply on only one 3D hall effect sensor and one magnet. To demonstrate the capabilities of this new design we will build it into a bio-inspired hand-like robotic gripper. The sensor is small enough to be integrated directly into the hands entirely 3D printed flexture based design and is used to sense the forces experienced by the hand. This paper only covers the design and fabrication of this hand but these

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[1] Mohammadi A, Xu Y, Tan Y, Choong P, Oetomo D. Magnetic-based Soft Tactile Sensors with Deformable Continuous Force Transfer Medium for Resolving Contact Locations in Robotic Grasping and Manipulation. Sensors (Basel). 2019 Nov 12;19(22):4925. doi: 10.3390/s19224925. PMID: 31726702; PMCID: PMC6891814.

[2] Seo MJ, Yoo JC. Omnidirectional Fingertip Pressure Sensor Using Hall Effect. Sensors (Basel). 2021 Oct 25;21(21):7072. doi: 10.3390/s21217072. PMID: 34770376; PMCID: PMC8587916.

[3] S. Li, R. Rameshwar, A. M. Votta and C. D. Onal, "Intuitive Control of a Robotic Arm and Hand System With Pneumatic Haptic Feedback," in IEEE Robotics and Automation Letters, vol. 4, no. 4, pp. 4424-4430, Oct. 2019, doi: 10.1109/LRA.2019.2937483.

forces since they are full 3D force vectors can, in future work, be used to measure many aspects of what the gripper experiences during use. This data could be used simply to measure the weight of a held object by measuring the shear stresses on the gripper, or fully integrated with a haptic glove to allow for a remote user to fully experience the forces that the gripper is feeling during use.

Design

Sensor Module

One of the recurring issues with past work is the lack of durability and repeatability in the sensor's use as well as the sensor being difficult to fabricate, tune, and assemble. These are the main issues that will be addressed by this design.

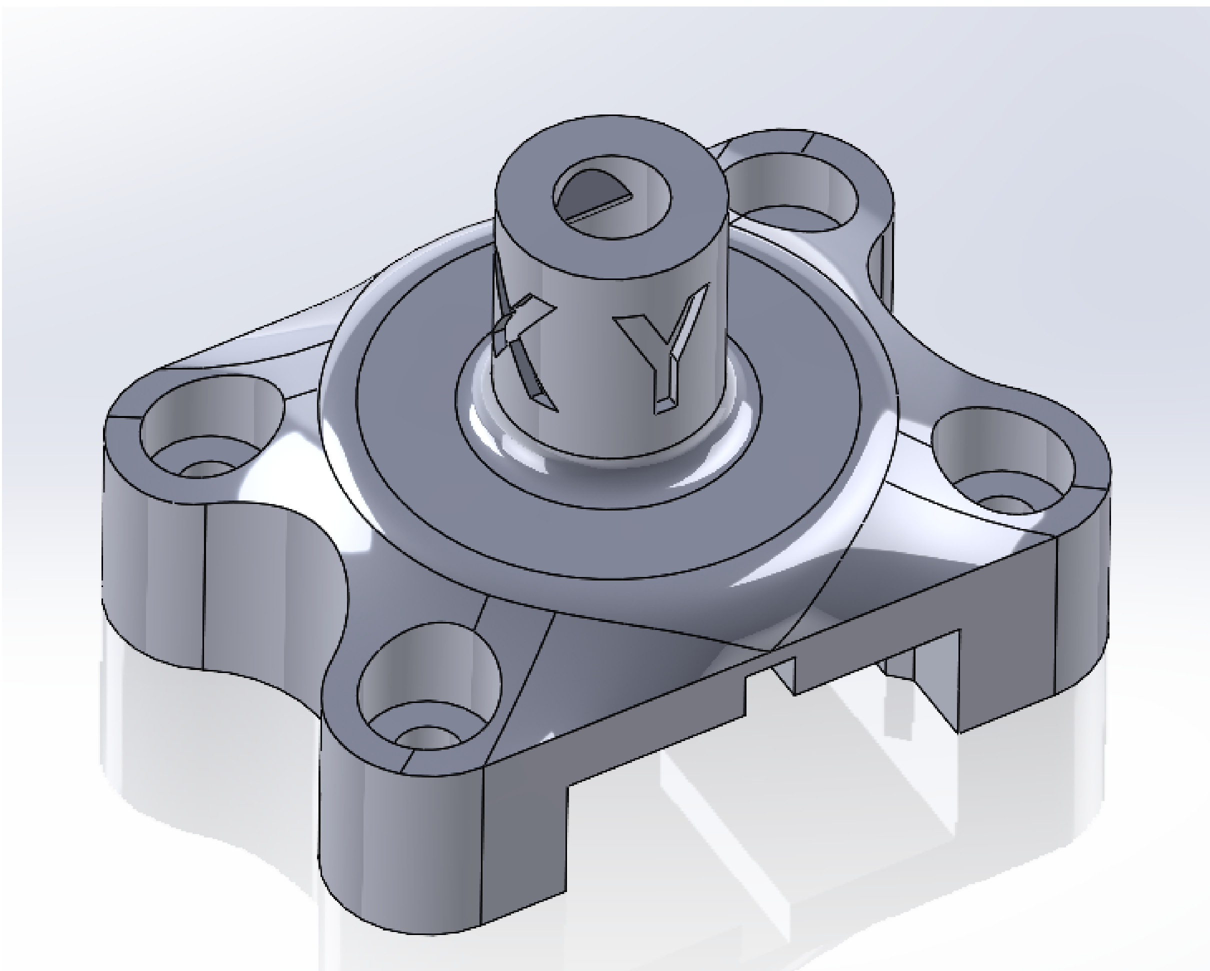


Figure 1: Sensor Module Top View

For some terminology I will be calling the XY labeled protrusion the "stick", the flat part its connected to the "membrane", and the rest of it is the "body" as shown in figure 1.

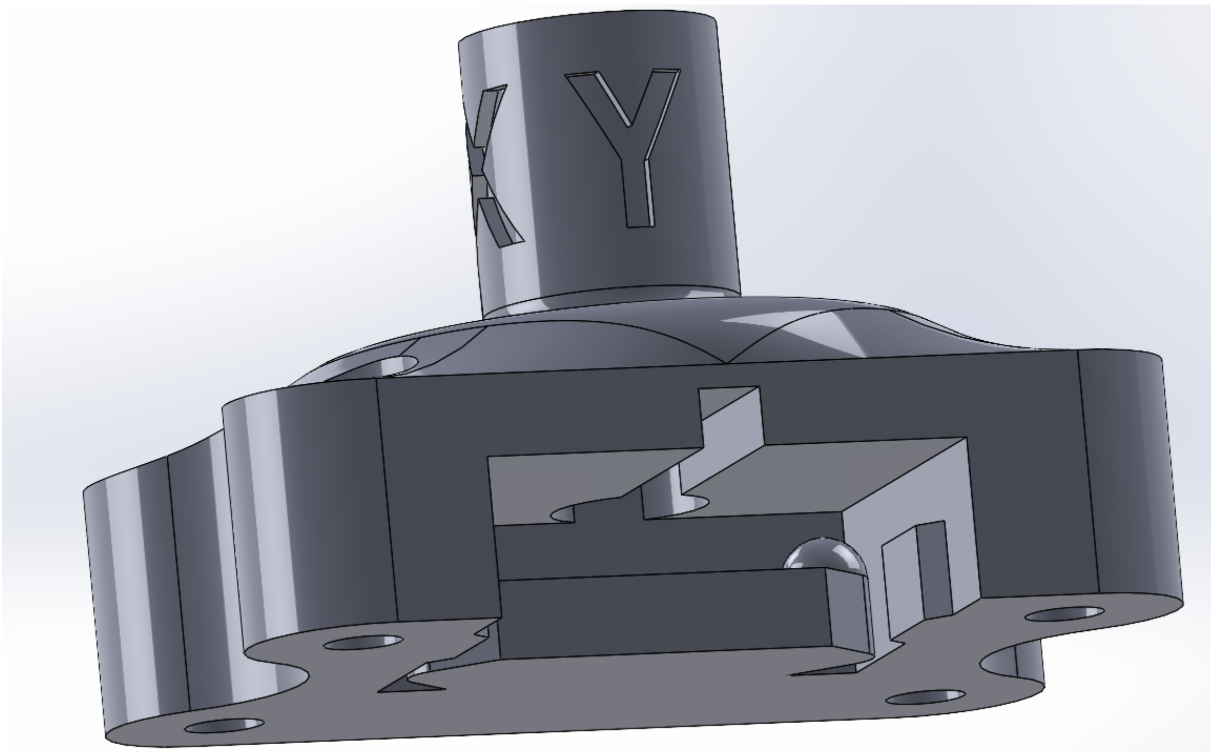


Figure 2: Sensor Module Bottom View

Underneath there is a small flexture that snaps the hall effect PCB into place called the "snap flexture" shown in figure 2.

The basis of this design is a planar flexture. Flextures are a type of mechanism that deforms to allow for some type of motion; they are well known for having zero wear and tend to last a long time. Flextures are very well studied and the entire flexural design space is well known[4]. I chose the planar flexture from this design space for its X and Y rotation and Z translation. Flextures of this kind are usually made from spring steel and use flexture blades instead of a membrane. But because I am using a much softer material I can get away with simply using a whole membrane rather than flexture blades.

The sensor module is designed to be 3D printed using a Filament Deposition (FDM) style printer which is the most accessible type of printer at the time of writing this paper. It is printed from

[4] https://web.mit.edu/mact/www/Blog/Flexures/FlexureIndex.html

Flexible PLA+ filament[5]. This filament boasts that it can be printed much more easily that similar TPUs while also being rated with a hardness of 83A compared to TPUs usual 95A. In my experience this FPLA is very effective and easy to print[6]. However, in my testing of different colors I discovered that only the “light brown” colored FPLA printed as easily as claimed, I recommend steering clear of the other colors. The sensor is designed to be printed with a 0.25mm nozzle as the membrane thickness of the sensor was tested to work best at 0.5mm and a 0.25mm nozzle can print this feature without leaving any print artifacts making for a consistent and robust sensor module. Also to aid in the printability of this sensor I modeled a custom support structure for the stick to make sure it prints exactly the same every time. And it is printed in the orientation shown in figure 3.

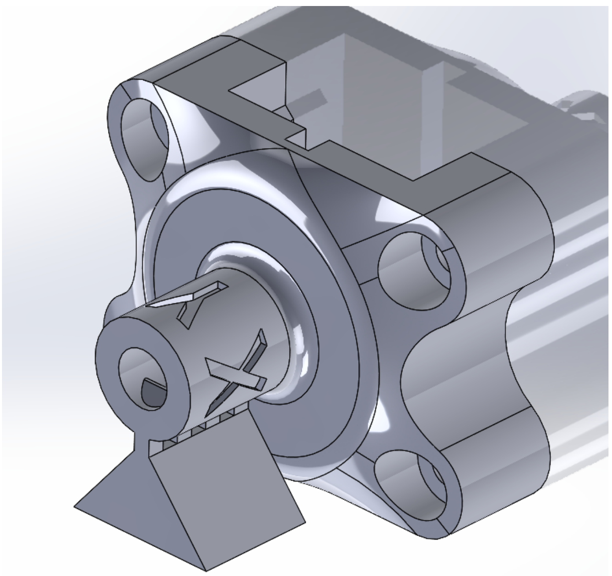


Figure 3: Support Structure

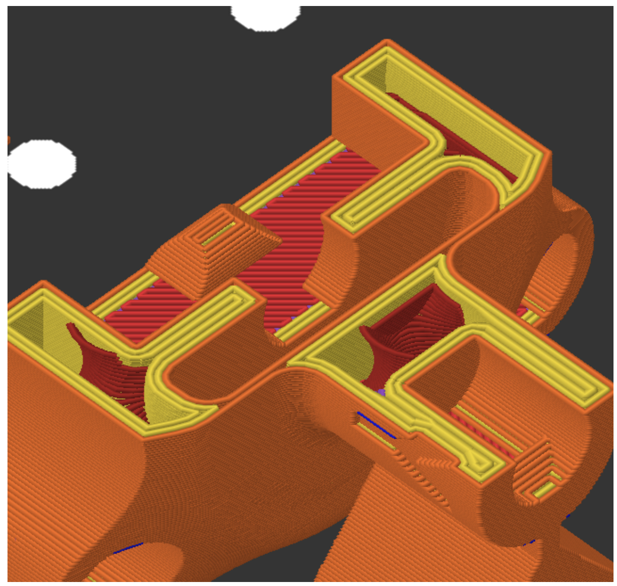


Figure 4: Clean Slicing

It can be seen in figure 4 how the nozzle size and membrane thickness lead to smooth and consistent extrusion throughout the printing process.

The sensor is easy to assemble with a snap into place PCB and magnet, eliminating the need for glue or fastening hardware anywhere in the design. The only parts are a 3x3mm Neodymium Magnet, a small PCB breakout board for the TMAG5273[7] 3D hall effect sensor, and the 3D printed flexture (shown in figure 5).

[5] https://www.amazon.com/ATARAXIA-ART-Flexible-Compatible-Resealable/dp/B099QZ55PJ?ref_=ast_sto_dp&th=1&psc=1
[6] All my print configurations and settings will be included with the submission of this project.
[7] https://www.ti.com/product/TMAG5273

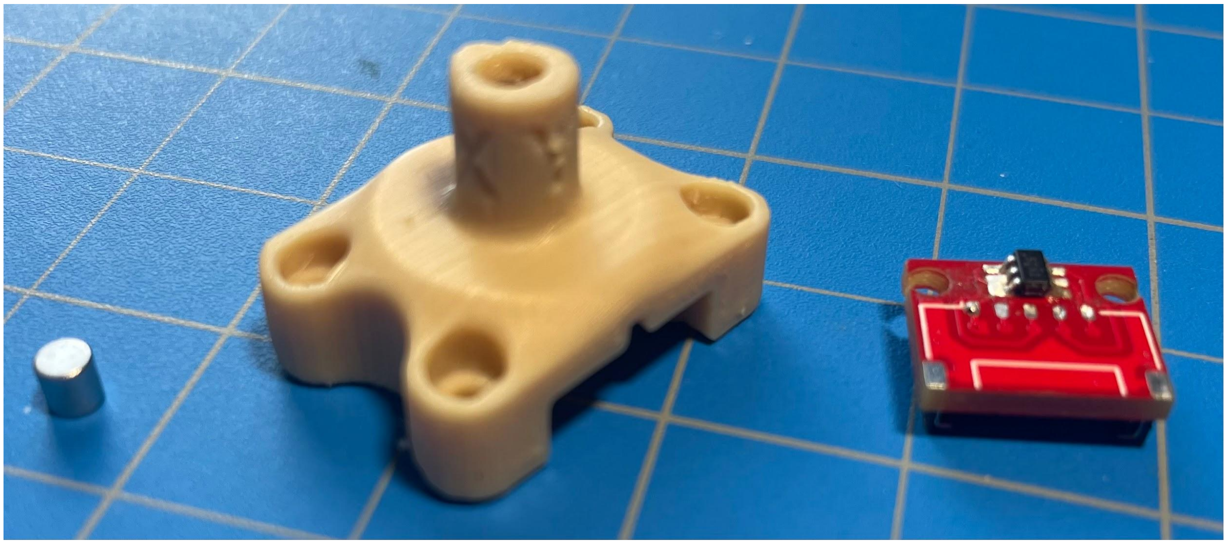


Figure 5: Sensor Components

This lack of complexity also translates into simpler data collection and processing as there is only one magnet; we only have to account for the motion of one object when calibrating each axis of the hall effect sensor. This allowed the use of standard signal matching analysis rather than needing ML to train the tuning parameters (though this may result in better data, it was not tested). The component placement is shown in figures 6 and 7. All components are a snap fit.

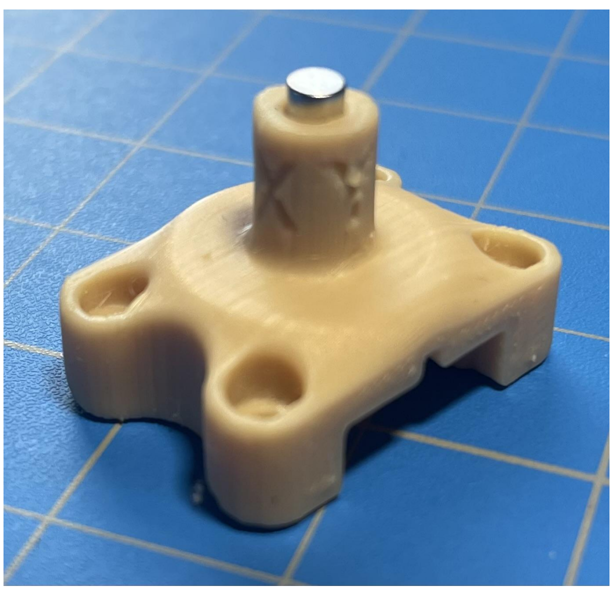


Figure 6: Magnet placement
(currently pulled out for visibility, push in for use)

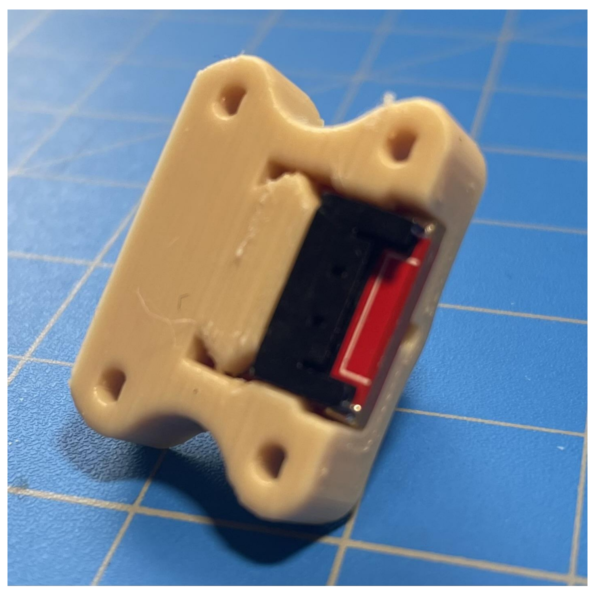


Figure 7: PCB Placement

The other consideration for this sensor module was that its intended use case is somewhat unknown. Therefore it was paramount that it be designed in such a way as it is easy to mount and customize toward the users needs. For this reason the sensor has four M2 mounting holes to ensure it can be rigidly held to whatever surface it is being attached to, and a simple stick to hold the magnet making the sensor perfect for overmolding or the addition of other types of caps that can simply be fixed to the stick.

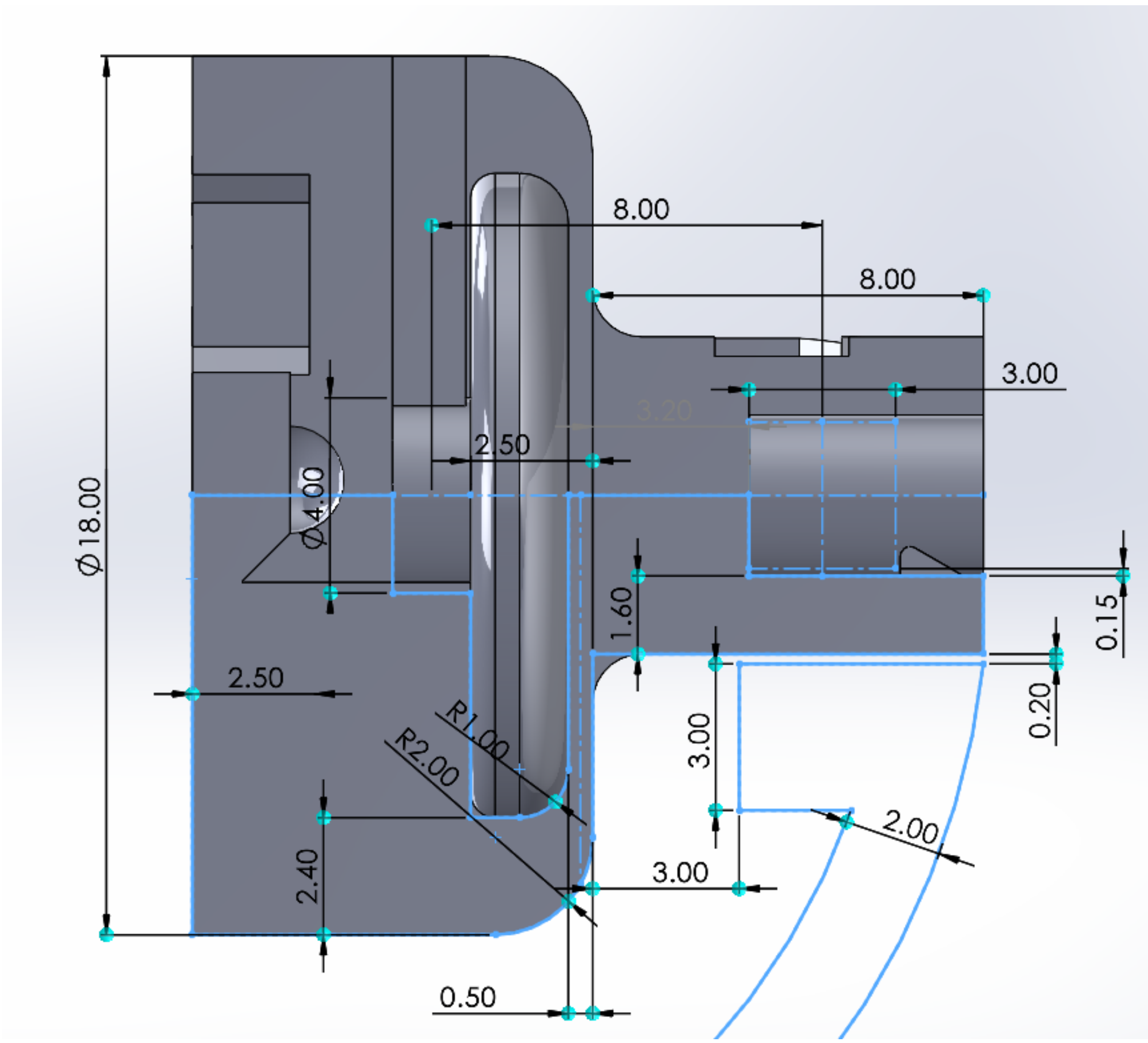
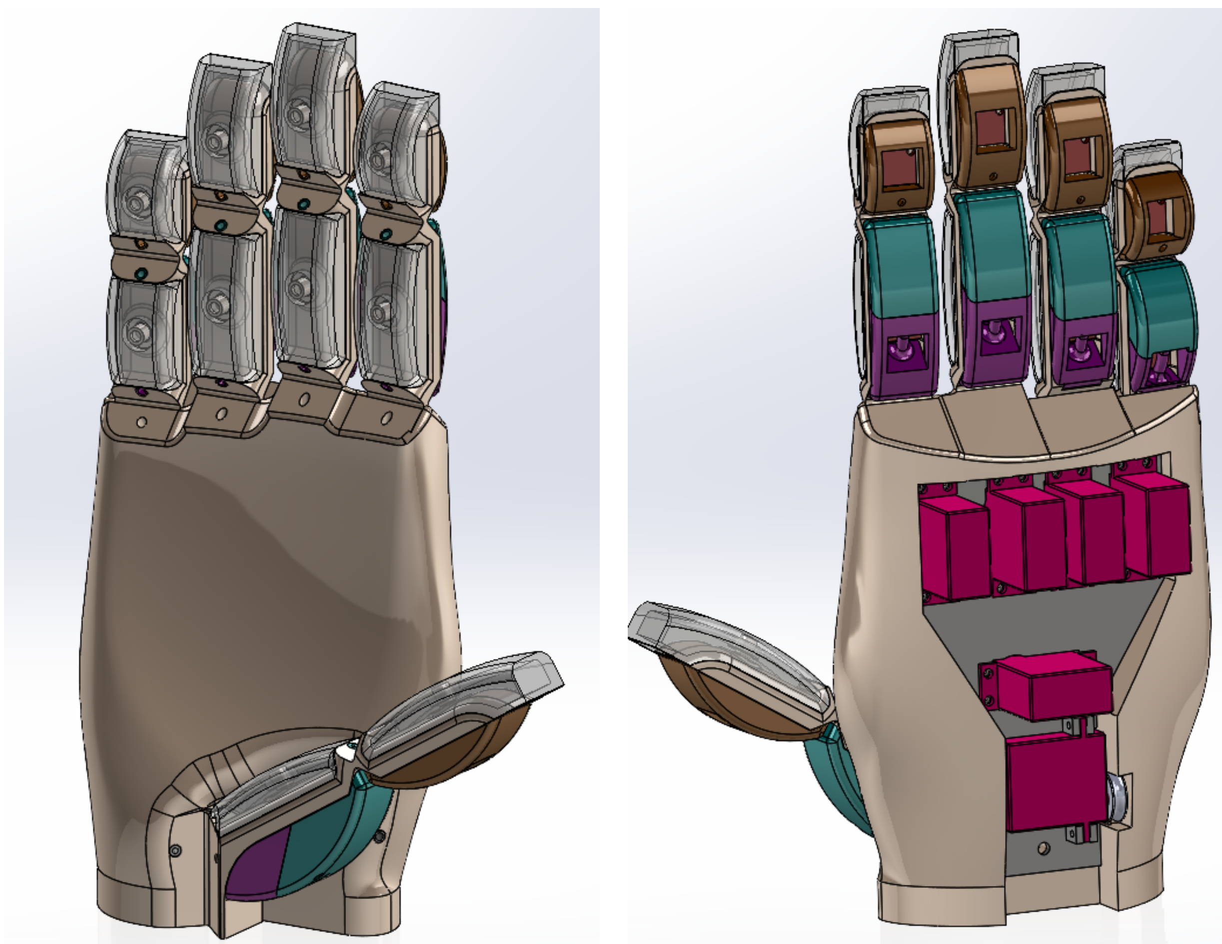


Figure 8: Cross Section of Sensor Module Including all Dimensions

The critical features of this sensor module are the placement of the hall sensor, the thickness and diameter of the membrane, and the distance that the stick holds the magnet away from the hall sensor. It is paramount that the magnet moves in a rough hemisphere relative to the hall effect sensor, if it is too close to the pivot axis of the membrane it wont move very far in X and Y and will produce worse results in those axis, thus the need for the protruding stick. Though interestingly the hall effect sensor doesn't need to be the center of that hemisphere meaning there could be an alternative design that places the magnet and stick on the other side of the membrane, this would make the membrane the sensing surface which could be ideal for some applications, and potentially be even more robust.

Hand

Because the critical aspects of this design are just some simple and general features, it is easy to integrate this sensor's design philosophy into other larger multifunctional components. To demonstrate this I have designed a new revision of my lab's past optimized hand-like gripper to integrate ten of these sensors, miniaturized on each finger joint of the hand. This hand is a 6DoF manipulator where each finger is tendon driven by one motor and the thumb can be pulled around to the front. Exactly the same configuration as in the previous work from the lab[8].



[8] A. M. Votta et al., "Kinematic Optimization of an Underactuated Anthropomorphic Prosthetic Hand," 2020 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Las Vegas, NV, USA, 2020, pp. 3397-3403, doi: 10.1109/IROS45743.2020.9341640.

Figure 9: Hand Front and Back Views

From the time I had spent with the previous hand I identified some issues that this new version needed to address. The largest of which is the difficulty of assembly and durability. This new hand is printed as one piece with some additional parts that simply fit into place that route the tendon cables and ensure that they have proper support when being driven by the servos. The Finger joints are all flextures that are designed to fatigue a controlled amount after coming off the printer. They are all quite torsionally rigid so the hand should be able to pick up heavy objects without deforming in a detrimental way. The Servos used are the "AGFRC micro-servo"[9], which can output up to 11.4kg*cm of torque which should be more than enough to move the finger and grip the object being held. The cable channels are all ridged ABS 3D printed plastic allowing for low friction and zero kinking which is a problem often observed in smaller PTFE bowden style cable runs.

Similar to the sensor module I am FDM printing this whole hand in FPLA. I tried to use the Formlab 3L+ that our lab has in conjunction with the Formlabs 80A flexible resin, but every prototype I printed was fragile and broke immediately. The flextures on each finger use the same 0.5mm membrane and thus the whole hand must be printed with a 0.25mm nozzle. The diameter of the membrane on the finger is smaller to make it fit better, but this also stiffens the flexture, this is beneficial for the use case of the gripper because we don't want the finger pads deforming too much when trying to grip an object.

Future work to be done on this hand includes:

- More extensive testing of the tuning parameters for the smaller integrated sensor.
- Programming to control the servo motors on the hand

After these steps are done the hand should be ready to use and run with.

[9]https://www.amazon.com/AGFrc-Digital-Torque-Bearing-A20CLS/dp/B0B2VVF5F9/ref=sr_1_5?keywords=high%2Btorque%2Bmicro%2Bservo&sr=8-5&th=1

Methodology

The testing procedure for the sensor module is automated to a certain extent, I created a script that runs a testing procedure. There is also a data analysis spreadsheet template which simply needs to be filled out by importing the CSV files generated during the test.

Procedure

This is the testing procedure for testing one axis on the sensor module:

1. Hold the sensor tight to a work surface
2. Run the testing code by opening a serial monitor in PuTTY
3. Wait for about 4 seconds for the sensor to produce some baseline measurements
4. Press the load cell[10] in the center of the X or Y printed into the module (be careful to be consistent about placement)
    a. Be sure to hold the measurement for a moment, but also be sure not to let your hand shake while applying force to the sensor module with the load cell. This will generate noise.
5. Save the data as a CSV and import it into the premade data analysis spreadsheet I supply.
6. Check the “constraints” tab to find the current average for the tuning constraints needed to convert the signal from hall effect to force.
7. To get through data repeat these steps at least three times per axis on each sensor tested.

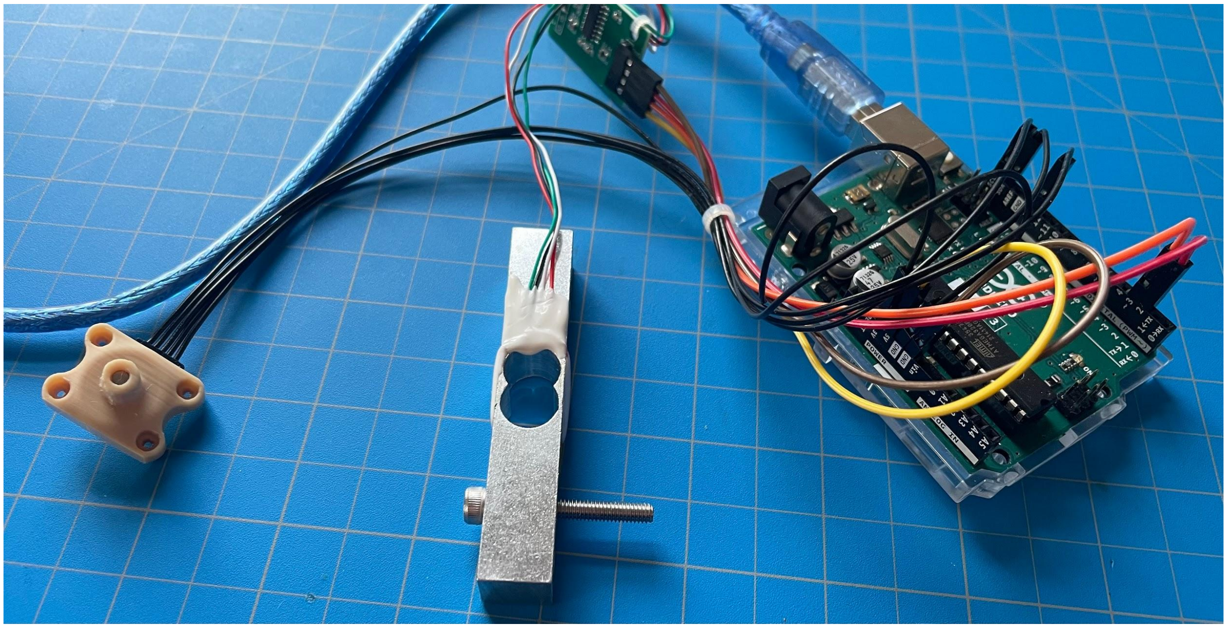


Figure 10: Components used for testing

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[10] https://www.amazon.com/ALAMSCN-Digital-Weighing-Portable-Electronic/dp/B08KRV8VYP/ref=sr_1_5?keywords=load%2Bcell&sr=8-5&th=1

Here you can see the Sensor Module, Load Cell, and arduino used during testing.

This procedure could be enhanced by building a testing jig that holds the sensor module and makes sure the load cell is always pressed into the stick at the same place with the same alignment. This did not prove necessary for me to get usable results so I skipped this step, but it's still a good thing to do.

Data Analysis

The data analysis spreadsheet[11] does all of the data analysis steps automatically. The first of these steps is "zeroing" the data to remove any offset it might have. This finds our zeroed values Xc, Yc, and Zc. Then the first two tuning constants are found by dividing the average of all the values of the main axis by the average of each other axis respectively, for example for the X axis we will get a constant

$$Cxy = avg(Yc)/avg(Xc), Cxz = avg(Zc)/avg(Xc) \quad \text{Eq.1}$$

Then the "processed" X value Xp or the value of X removing the effect of Y and Z is found by

$$Xp = Xc - Cxy * Yc - Cxz * Zc \quad \text{Eq.2}$$

Xp is then used to find Cfx which is the constant relating the force to Xp it is calculated by

$$Cfx = avg(F)/avg(Xp) \quad \text{Eq.3}$$

Finally the force is calculated by

$$Fx = Cfx * Xp \quad \text{Eq.4}$$

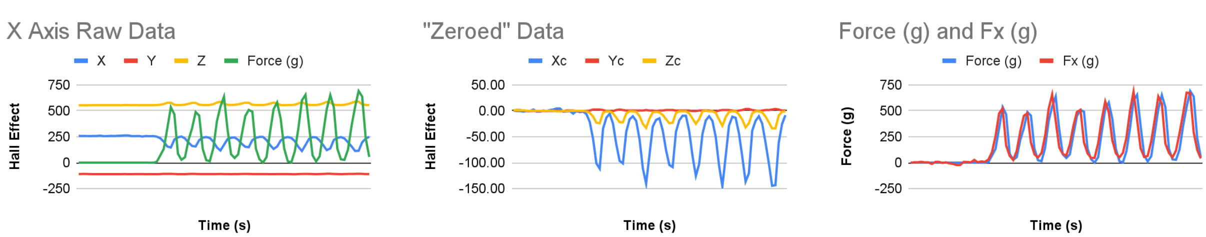


Figure 11: Example of Data

In figure 11 we can see how the data processing steps affect the signals from the sensor eventually leading to a very close matching to the force data collected.

11 Prepopulated Test Template

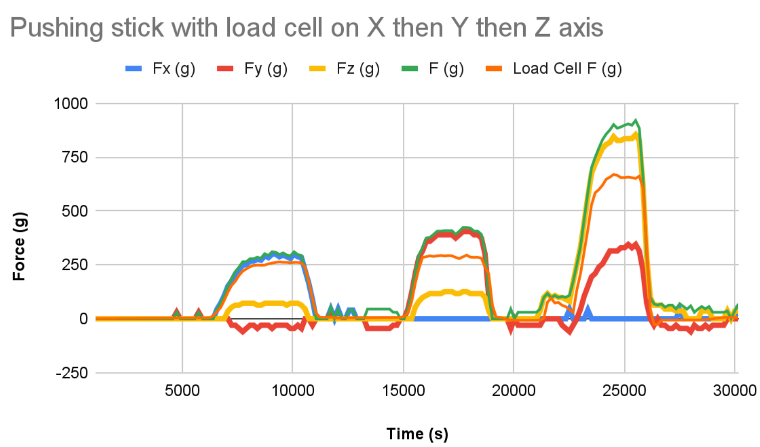
Results

The results of the testing done in the methodology section is a list of tuned constants that can be used to roughly turn our hall effect signal into force readings[12].

X offset	216.152	Cxy	0.015	Cxz	-0.071	Cfx	-4.226
Y offset	-123.468	Cyx	0.016	Cyz	-0.154	Cfy	-15.422
Z offset	615.094	Czx	0.283	Czy	-0.21	Cfz	9.264

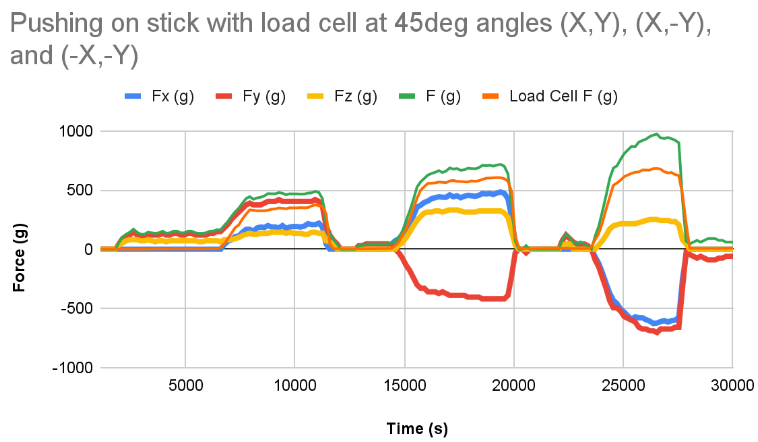
Figure 12: Constants from master spreadsheet taken from multiple tests over multiple sensors

The used to calculate these numbers is not perfect and as a result the parameters are not as good as the individually tuned parameters for each sensor tested, however, I believe that this is much more likely to be due to inconsistent testing rather than inconsistent properties of the sensor module. I know this because there are many tests that I ran on the sensors to test my data collection procedure and I got more consistent data at times while doing that. These numbers just reflect the "official tests" that I ran and it wasn't worth redoing the bad tests because the sensor still works plenty well even with the suboptimal data. Plus the sensor will rarely be used in its uncovered state and will have to be retuned for any cap or overmolding that is placed on it. For this reason I felt it was sufficient to simply show off the "good enough" results on three different sensors using the same averaged parameters.



In these graphs we can see the load cell data in orange is closely matched by the green line which represents the magnitude of the XYZ force components.
There is even a very small amount of noise from the directions that aren't being used which means that the tuning constants are properly canceling the signal from those sensors.
It is also clear to see in figure 13 and 14, especially on the tests where I pushed diagonal on the stick that the green force

12 Module Master



magnitude exceeds the real force, this is likely because there is still a Z component being measured (even though I was only pushing in XY) which adds to the magnitude. The load cell only measures force in plane with itself so it is likely that it is missing a Z component which is picked up by the sensor module.

Figures 13, 14, 15: Comparison of real force vs calculated force

This is still an acceptable result because most of the time we will be interested in the XYZ components exclusively and also the sensor will only mostly care about relative measurements, such as force has increased, or force has decreased. Essentially this sensor shows change in force very well. I am also reassured by the fact that in the diagonal tests the X and Y magnitudes are very similar which is consistent with the diagonal force being applied, which also falls in line with that theory that there is a Z component not being measured by the load cell.

These results support that the sensor modules have nearly identical properties as even the "bad" data still results in accurate measurements. This work will benefit from further data collection but honestly it works well enough as is and is ready to be implemented in individualized ways for various projects.

Conclusion

For me the conclusion of this project will include giving the lab ~50-100 of these 3D printed modules so that they never run out because I know that it may be difficult to perfectly replicate my print settings. I will also give over a cleaned up version of my test code as well as some code that just simply runs the sensor module as a force sensor.

I have LOVED working on this project, I love simple useful devices and I love when I can create some small piece of functionality that didn't exist before. I don't believe any of my work here is unique, but if you go on amazon you can't just buy small 3D force sensors. I'm proud to give that small bit of extra functionality to the lab. And I'd love to be aware of all the ways it gets used in the future.

I will also provide all the files and materials and everything else needed to replicate this project in a zip file as part of my final submission of this project. But hopefully replication is unnecessary and the lab just has a ton of these sensors lying around ready to be used.

Bibliography

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