STUDENT INTERNSHIP PROGRAMME
PROJECT DOCUMENTATION

To: Mr Matthew Ng, Supervisor

From: Shaik Siraaj

Date: 27-Mar-19

Subject: Work completed during Student Internship Programme

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i. PRELIMINARY

This report documents the work done during the period of the Student Internship Programme at the Singapore University of Technology and Design (SUTD) from 22 October 2018 to 29 March 2019.

1 INTRODUCTION AND WORK ENVIRONMENT

1.1 Background

SUTD's AIR (Aerial Innovation Research) Lab, under the Engineering Product Development (EPD), undertakes research and development relating to Unmanned Aerial Vehicles (UAVs) and drones, with a variety of projects being undertaken, such as the Transformable HOvering Rotocraft (THOR), the Samara Autorotating Wings, and a currently ongoing project funded by the PUB that involves the development of UAVs to inspect the interior of Singapore's Deep Tunnel Sewerage System (DTSS).

With regards to the DTSS project, optical flow sensors are attached onto the drone to allow for odometry during autonomous operations in such conditions, where a traditional GPS signal to guide the UAV is not possible. The sensors and cameras used to capture optical flow data captures images at high refresh rates, and an algorithm is subsequently used to calculate the distance travelled or displacement of the UAV in the sewerage tunnel, based on the captured images. In association, the task that was allocated to the author was to assist the researchers of AIR lab by conducting tests for optical flow, and analyse the data from said experiments, with the use of a compact rotational rig as an optical flow sensor platform.

1.2 Attachment Period

During the 23-week attachment from 22 October 2018 to 29 March 2019, the author was attached to SUTD's Temasek Laboratories to aid in research, experimentation and testing with regards to optical flow data for the application of odometry in drones and Unmanned Aerial Vehicles (UAVs).

2. OBJECTIVES

The aim of this internship was to assist in research regarding the study optical flow data along a rotating axis by:

- Designing and manufacturing a rotational rig on which the experiments would be conducted
- Calibrating the accuracy and precision of the aforementioned set-up to ensure results of the highest possible accuracy are achieved.
- Conducting tests and experiments for optical flow using several sensors and cameras with the set-up.
- Log and analyze the data gathered and arrive at a conclusion for further action or study.

3. WORK COMPLETED

3a. Rotational rig

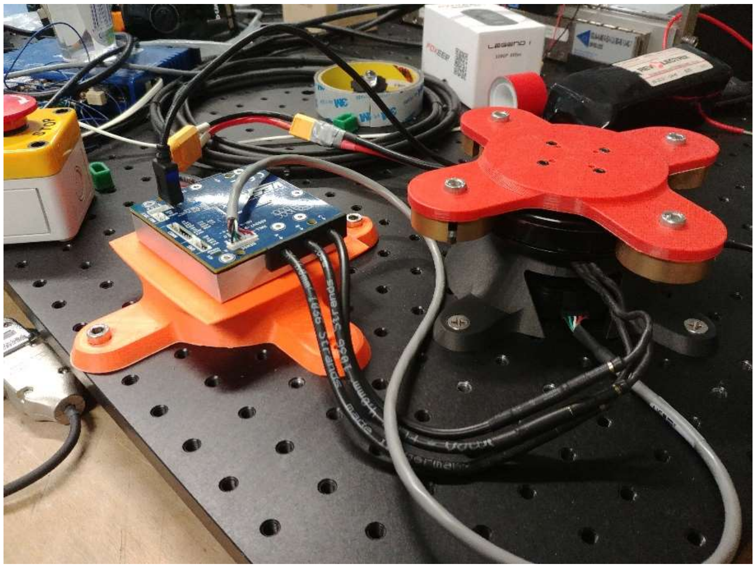


Figure 1: The complete rotational rig assembly

In setting up for the rotational rig, there were three main components that were needed to be delivered and functioned as intended to the design specifications outlined by the project objectives. These components were namely the motor, the base and the encoder, and all three were required to be optimized for the task to ensure the integrity and accuracy of the results gained from future experiments.

Figure 2: Motor Housing

Firstly, the motor to be used for the rotational rig would be a T-Motor U-8 PRO salvaged from one of the existing UAVs that the AIR Lab has fielded in the past. Due to the drone being unused for quite some time, there were concerns relating to the condition of the motors and whether they were remained useable. It took a while for the motor to be completely disassembled from the motor housing, due to the screws that fastened the motor and propeller assembly to the main fuselage of the drone being worn out, as seen in Figure 2. Subsequently, the motor was initially unable to be wired up to the Electronic Speed Controller (VESC) as there was a mismatch in size between the female connectors of the VESC and the male connectors of the motor. As such, suitable adapters needed to be purchased for the successful connection between the aforementioned components. Following that, work on the design of the base of the rotational rig could begin to support the motor and VESC during operation.

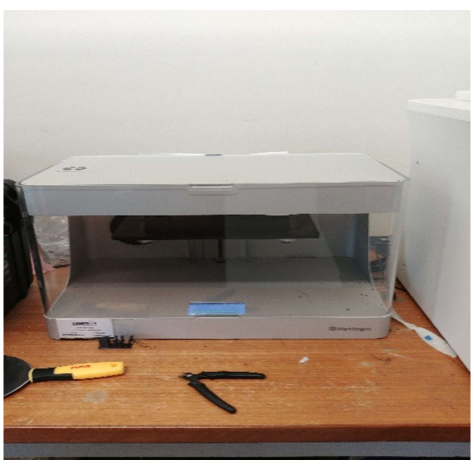


Figure 3: Markforged Airforged 3D printer

Figure 4: Cubicon 3D printer

The development of the base required the use of the 3D printers, specifically the printers from Figures 3 and 4, as it had to be done from scratch and it had to be able to be mounted on breadboards that have mounting holes at regular 25mm intervals. After the fundamental concepts of modelling with Solidworks, were understood, the design of the base could finally commence. An existing motor mount present in the lab served as a design inspiration and the design was subsequently retrofitted to fit the project specifications of supporting an encoder as well as motor in as compact a frame as possible. A significant amount of time was spent refining the design of the base and over time, it went through multiple design iterations before a final design that could securely support both the encoder and motor was settled upon, as seen in Figures 5 and 6. Additionally, the newly updated base would be miniaturized and be small enough for it to be printed with the Markforged printers that AIR Lab uses, which were utilized in this application as these printers had better support quality and finishing, as well as having the ability to pause at a desired layer for the insertion of fasteners, factors which were necessary for the proper support of the encoder that was to be mounted underneath (See Appendix C). A smaller design would also require less real estate on the breadboard, allowing for a more compact setup. Another base to secure the VESC was also developed and made to allow for a more organized and less cluttered setup.

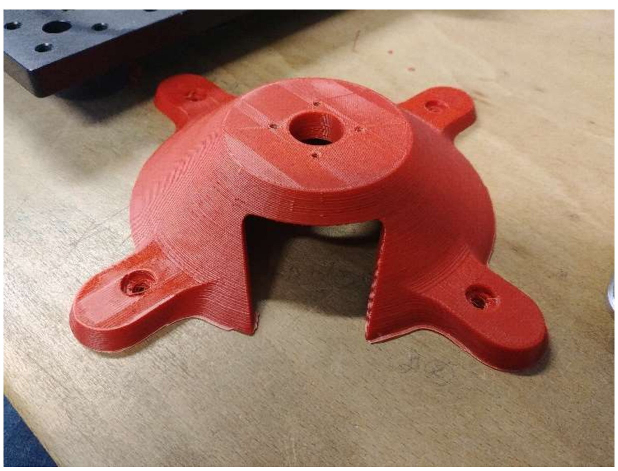


Figure 5: 1st iteration of the base

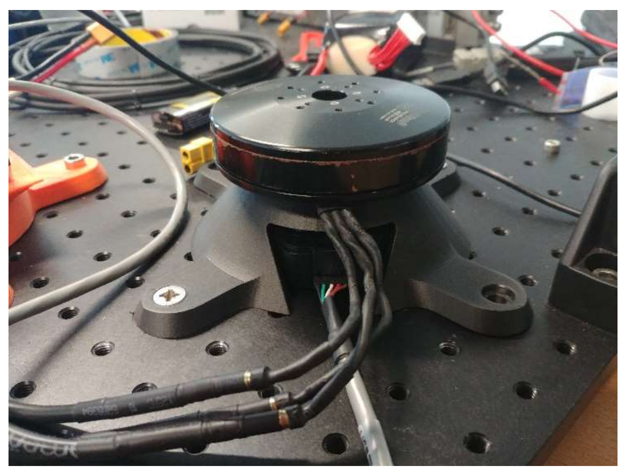


Figure 6: Final base

The encoder to be used in the rotational rig had to conform to very strict accuracy and resolution specifications to provide the most accurate position and speed result as possible as the accuracy of the encoder determined how accurately the motor would be able travel to a desired angle and hold a given speed. As such, research was conducted for the purpose of shortlisting a number of suitable encoders for the task, wherein the encoder of choice was to be finalized at a later date. With deliberation, the E6 Optical, Incremental encoder from U.S Digital was selected as it met the accuracy and resolution requirements. Though not a primary concern, the E6 encoder also possessed a suitably high RPM limit of 4320 RPM for which it could continue to accurately track the movement of the motor.

With all components of the Rotational rig ready and fully assembled, the calibration of the motor for use with the VESC was done after, as detailed in section 3b of the report, to ensure that the signal from the VESC Tool software reflected the accuracy and RPM specifications of the encoder.

3b. Motor setup and initial accuracy tune-up

Figure 6: Position control on the VESC Tool

The entire tuning process took place on the accompanying VESC software, as seen in Figure 6, named VESC Tool. From the application, the tuning of settings such as the amount of current and voltage that the motor and the VESC were receiving could be done, to prevent any instances of overvoltage or overcurrent which could result in the VESC not being able to work, as the MOSFETS and/or DRV chip inside burn up when the voltage and current levels reach beyond what the hardware of the VESC is rated for. Edits to the above settings were initially done to ensure that the motor was able to operate smoothly with no cogging, an instance where the motor is unable to run smoothly and instead rotates in steps. This abnormal behavior would have given rise to inaccuracies with regards to being able to accurately control the speed of the motor and would adversely affect the ability for the accurate logging of the motor's position. This procedure was run under 'Sensor-less Mode" through the VESC Tool as the encoder was not a factor in ensuring the smooth operation of the motor.

In contrast, tuning the rotational rig to produce a desirable and accurate response required the setup to be run under the "Sensor-Enabled Mode" as the position and speed accuracy of the system were governed by the encoder mounted onto the setup, and were major factors to get right before moving on to experimentation. Before proceeding to the tuning of the rig, the concepts of PID control needed to be properly understood as it was the type of control method that was utilized in the VESC Tool for both the speed and position controller. This process of learning the concepts of motion control took several weeks off actual tuning time, however it was a necessary investment in time as without understanding what each parameter of PID control changes in the system response, making guesses to tune the rig would have been the only alternative, which ultimately would not have been efficient.

As the tuning process continued, it was concluded that the rotational rig required more dampening due to the oscillations that were detected by VESC Tool software whenever the motor neared the input angle. As such, a weight mount to be used to mount scientific weights of 100g on the motor was designed to act as a load, which would result in the rig receiving additional dampening that would allow for a reduction in detectable oscillations. The weight mount for the rotational rig went through multiple iterations before the final design materialized in the form of an overhang for the weights to be mounted on, as detailed in Figure 7. In this instance, the mount was made of stiffer ABS plastic from AIR Lab's Cubicon 3D printer, as compared to the first iteration of the mount as seen in

Figure 8, which was made of less stiff Nylon fibers from the Markforged printers that resulted in the mount flexing under rotational stress. Additionally, because the weights were mounted on top of the mount instead of being hung below, there was lesser space to accommodate sensors on the rig, a design element accounted for in the final design of the mount.

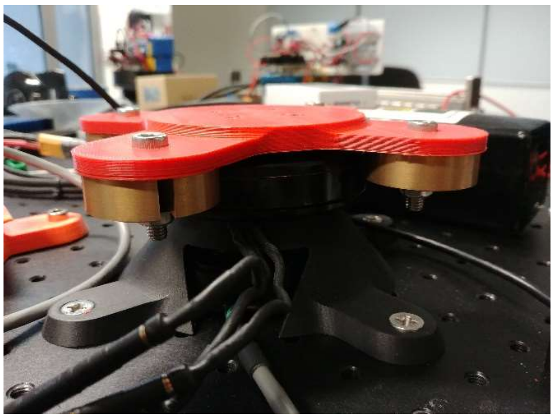


Figure 7: Current mount design

Figure 8: Old mount design

Once the time taken for the rig to settle to a steady state has been refined and that the positional accuracy has been achieved, the next course would be to determine whether the speed at which the motor would arrive to the desired angle could vary on command, and whether the RPM for the continuous rotation operation of the rotational rig can be accurately maintained.

3c. PID speed tuning

It was concluded that the speed at which the rotational rig would arrive at an input angle can be varied by tweaking the P, I and D gains of the position controller. As a result, the creation of a lookup table was done to document the different gain values for the different speeds. Through actual testing, it was established that the D gain of the position controller was the major factor in changing the speed, and attention to this helped speed up the process of creating the lookup table. Currently, the table can be used to refer to the gains necessary to achieve 450 ERPM to 1500 ERPM at increments of 50 ERPM.

Obtaining the gain values for accurate continuous rotation at different speeds required another lookup table. Despite being able to use the same gain values for different speeds that vary minimally, a deviation of no more than 3 ERPM/0.00238095238Hz from the intended speed was set as a target for the purposes of maintaining accuracy across different gain values. Through testing in effort to create the lookup table, it was determined that higher speeds require a lower P gain for the speed controller compared to lower speeds and that the P gain was the defining gain in maintaining the accuracy of the rotational rig as it rotates continuously. This characteristic shaped the lookup table for the continuous rotation operation of the rotational rig, which at the time of writing, can be used to refer to the appropriate P, I and D gains for speeds from 450 ERPM to 2100 ERPM with the aforementioned deviation.

3d. Sensor module

The experiments that were done with the rotational rig involved a sensor (a TF Mini LiDAR coupled with a PMW 3901 optical flow sensor) and a GoPro camera, placed tangentially at a known, fixed distance away from the rotational center of the rotational rig. Initially, the methodology of the experiments involved the sensors above being positioned orthogonally to the top plane of the rotational rig. As such, a 3D-printed clamp assembly to secure them in place was designed (See appendix D) with inspiration drawn from the mechanism of a table vise wherein a threaded rod is utilized to tighten or loosen the vise. In the clamp's design, two M4x70 bolts were used to give it the ability to tighten and loosen to secure the breadboard that housed the TF Mini LiDAR and PMW optical flow sensor.

However, a new experimentation method was decided upon where the sensors now, were to read features that were placed at a height directly above the rotational rig instead of reading features orthogonal to it. This change in experiment methods called for a redesign of the sensor clamp to accommodate the TF Mini and the PMW sensors to allow them to face upwards in the z- axis. This arrangement also meant that the overhanging jaw design on the clamp would have conflicted with the process of experimentation as the top jaw of the clamp would have obstructed the sensors from being able to seek the features overhead. The new sensor housing uses a slot design, with no overhead design elements, to house the breakout board which has the TF Mini and PMW 3901 optical flow sensor soldered on and keep it secure while the rotational rig is under operation (See appendix E).

3e. Calibration and experimentation

Once the rotational rig and the sensors were in place, the OptiTrack motion capture system in conjunction with 5 Prime 41 Infrared cameras and a 3D-printed housing for the necessary reflective markers mounted concentrically on the rotational rig (See appendix F), were utilized in tracking the motion of the rotational rig to obtain a ground truth for the speed and positional accuracy of the encoder and in extension, the rotational rig itself during actual experimentation. For the purposes of calibration, the rotational rig was allowed to continuously rotate at constant speeds of 100 RPM and 13Hz (780 RPM) at a minimum of 30 seconds respectively. As for the calibration of the angular function of the rotational rig, it was allowed to rotate at 90 degree increments for 5 consecutive times with the position controller being continuously turned on. Simultaneously, the real-time data collected by the VESC Tool software displaying the angles and speeds achieved by the rotational rig was captured as a series of videos for further analysis.

All of the experiments were conducted in the same environment indoors, but with varying levels of ambient illumination. The first experimental configuration of the rotational rig occurred in well-lit conditions, involving a GoPro camera that was mounted orthogonally on the top of the rotational rig, with the its lens facing directly upwards in the positive z-axis to allow it to capture the features present on the ceiling. As for data collection, the rig was made to continuously spin at 100RPM and at 13Hz (780RPM) for at least 30 seconds per test, and the GoPro footage from those tests were saved onto an on-board SD card.

The second experimental configuration was done in dimly-lit conditions, with the TF Mini and PMW3901 breakout board mounted onto the rotational rig. The lens of the PMW optical flow sensor was placed at a fixed distance of 83.55mm off the center of rotation of the rig and it was allowed to rotate at constant speeds from 1Hz to 7Hz at 1Hz increments for at least 30 seconds per interval, in order to obtain an average measured speed. A second experiment with the same set of variables was conducted, with the exception that the offset distance of the PMW3901 lens to the center of rotation now at 477.075mm by use of a carbon fiber rod supported by 3D-printed mounts at both ends. Similarly, the real-time data from the VESC Tool software was recorded and saved as a .mp4 video file to allow for the monitoring of noise, oscillations and distortions present during the experiments at a later date.

4. CONCLUSIONS & OBSERVATIONS

After comparisons were done between the measured data from the experiments and the ground truth from the OptiTrack calibration, the experiments conducted have shown that the rotational rig can be a reliable sensor test platform. From the data, it is known that the rotational rig as a platform allows sensors to produce readings below 5% deviation from the ground truth.

However, as the development of the rotational rig continued, there have been factors that have led to the measured data deviating from the calibrated data. Observations from the operation of the rig have indicated that the motor itself starts to oscillate along the horizontal plane at higher speeds, leading to the detection of unwanted vectors by the PMW3901 sensor. As such, the speed calculations will always result in a value that falls short of the ground truth, giving rise to inaccuracies that will be magnified the faster the rotational rig spins.

In the same vein, it has been observed with a spirit level that both the shorter sensor mount and the longer armature are mounted on the rig with a slight downward tilt due to them being cantilevered out from the center of rotation. Reinforcements to the unsupported ends or using a stiffer filament during the 3D-printing process must be considered in the future to account for the hardware factors that can affect the recorded readings and accuracy of data.

During the tests involving higher speeds, estimations of the suitable PID gains for each test were made on site based on the recurring trend relating the PID gains and the controller's accuracy as well as speed seen in section 3c of the report, as the exact gain values were not present in the lookup tables. As such, the inexact gains contributed to the presence of oscillations and steady state errors detected by the VESC Tool software, which in turn contributed additionally to the deviation of the measured data against the ground truth. Thus, additions to the lookup table governing the operation of the rotational rig at higher speeds must be made with the load mounted, before future experiments can be conducted for more accurate readings.

To conclude, the objectives of the internship have been fulfilled through the experimental data gathered and through the process of preparing for the experiments. Each milestone achieved in preparing the rotational rig for experimentation, supplemented by the accuracy of the data proves the viability of utilizing highly replaceable parts developed from the process of additive manufacturing and consumer-grade electronics and hardware for the development of an accurate and precise test bench for various sensors.

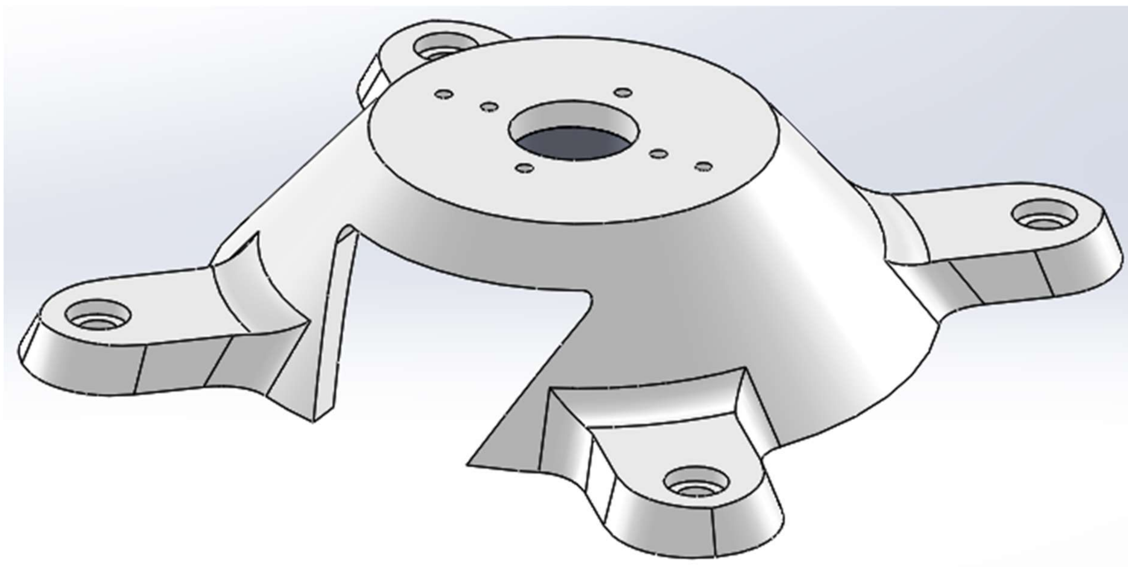
5. FEEDBACK

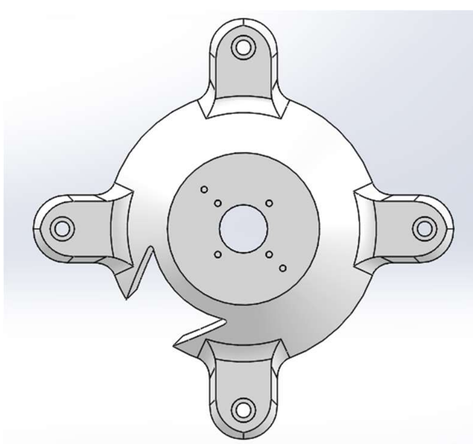
Initially, it was expected that the nature of the internship would involve the rotation of work within AIR Lab for a more rounded internship experience, as different researchers partake in work pertaining to the various aspects of designing a UAV. The author had initially pictured being attached to one researcher for a set amount of time and completing tasks assigned to him for said researcher, before being attached to another and repeating the same process. However, the author was assigned to a single, focused task for the entire duration of the internship and as a result, the author's job-scope focused more on hardware and design, leading him to be unable to experience the software aspects of UAV design such as programming.

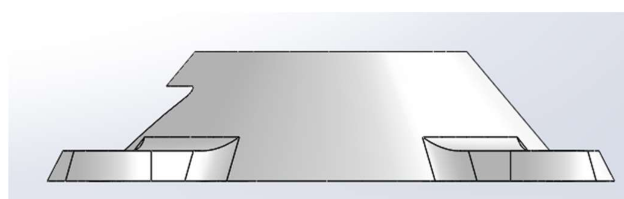
The author would also like to comment on the way communication was handled throughout the internship. Though the lines of communication between supervisor and intern remained open and transparent throughout the internship, the author feels that more supervisor-intern dialogues should occur, especially at the end of the work week to discuss topics such as progress made throughout said week, issues encountered and possible actions to take to follow-up on those issues. The author believes that such an initiative would assist in improving morale and would further bolster the intern-supervisor relationship. In addition, such dialogues would also be helpful in ensuring progress as planning for the subsequent week becomes easier thanks to guidance from the supervisor.

Overall, the author feels fortunate to have been able to be part of such a welcoming and accommodating team of researchers, who have allowed the author to feel comfortable in the work environment despite being only an intern and is grateful for being able to have the opportunity to take part in a deep and enriching internship experience.

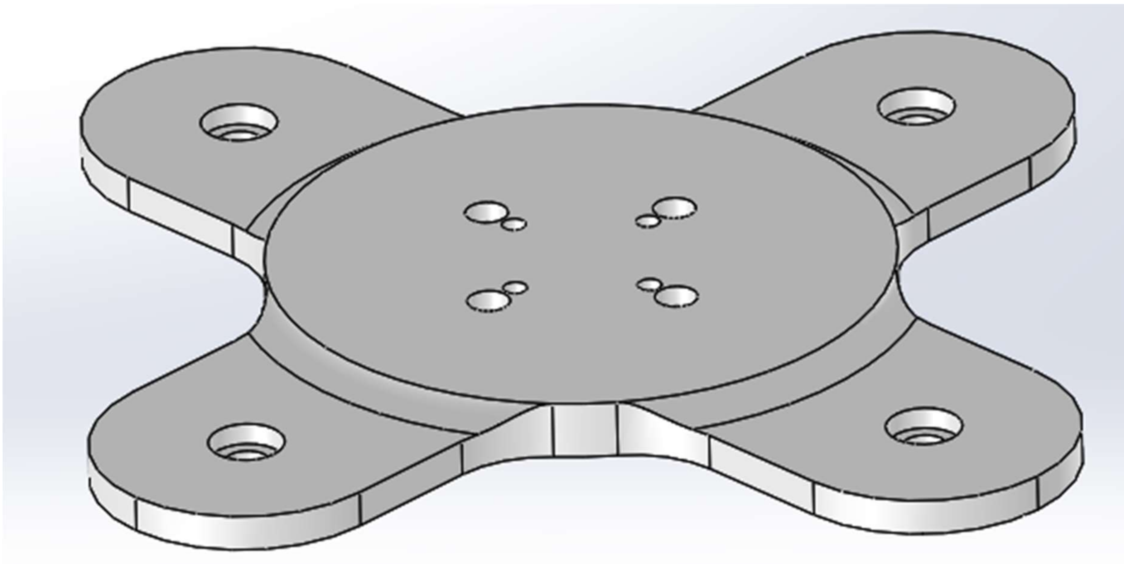
List of Appendices

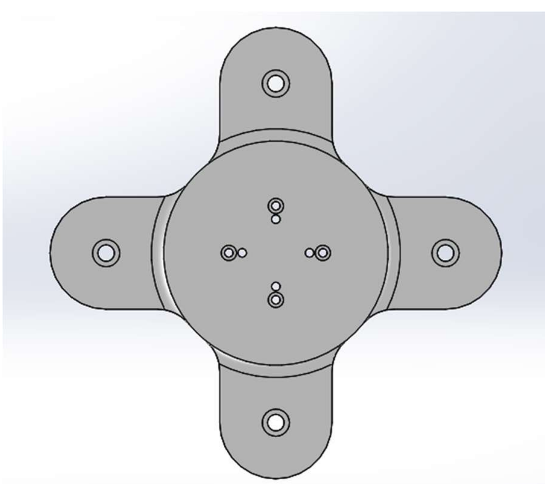


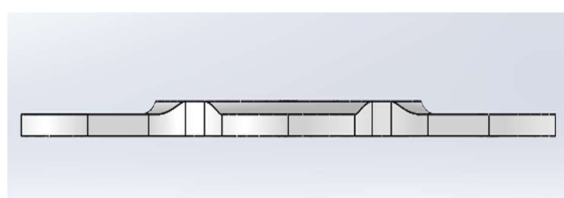




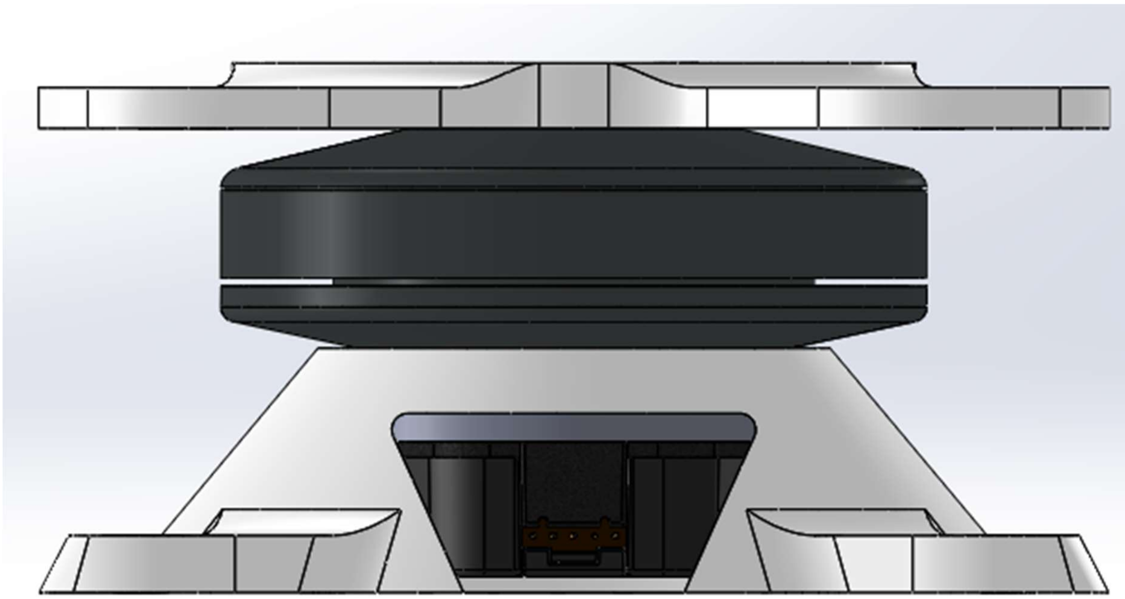
Appendix B Model of weight mount

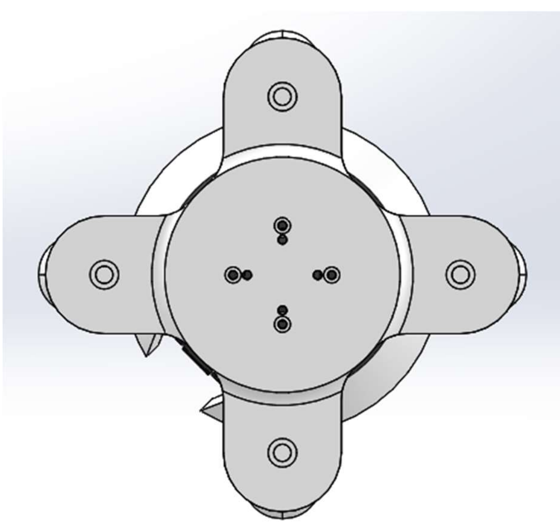


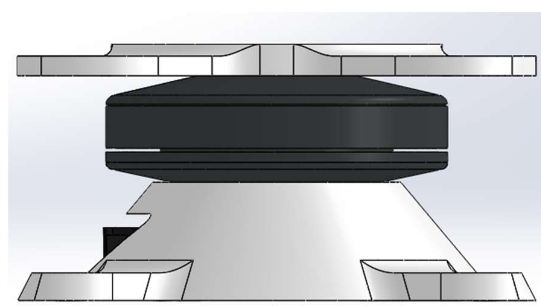




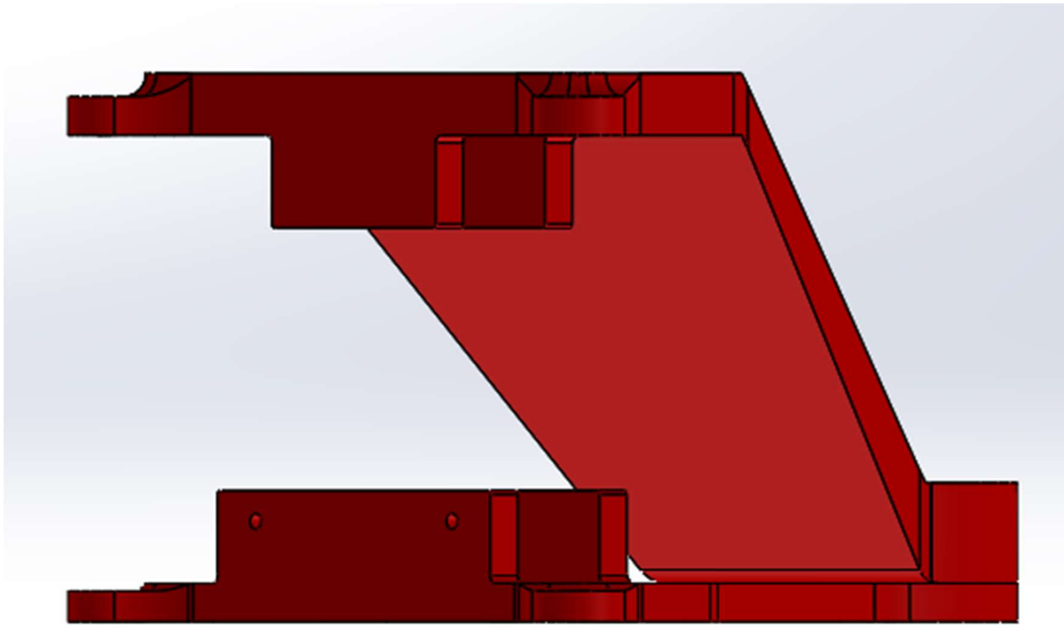
Appendix C Full Assembly of rotational rig

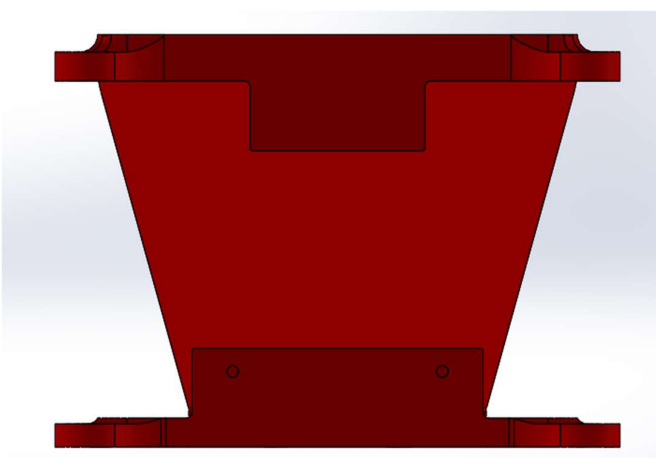


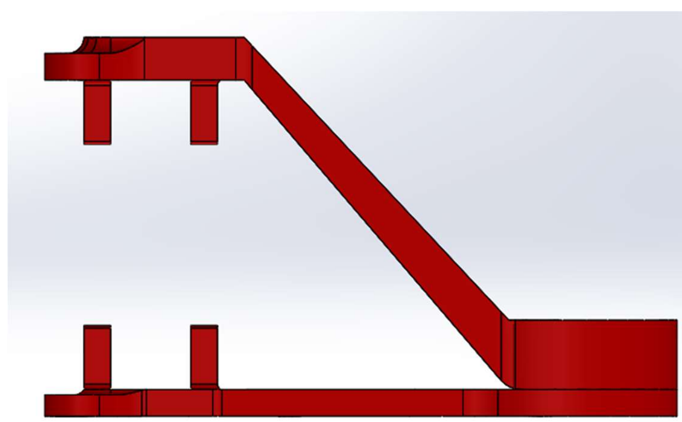




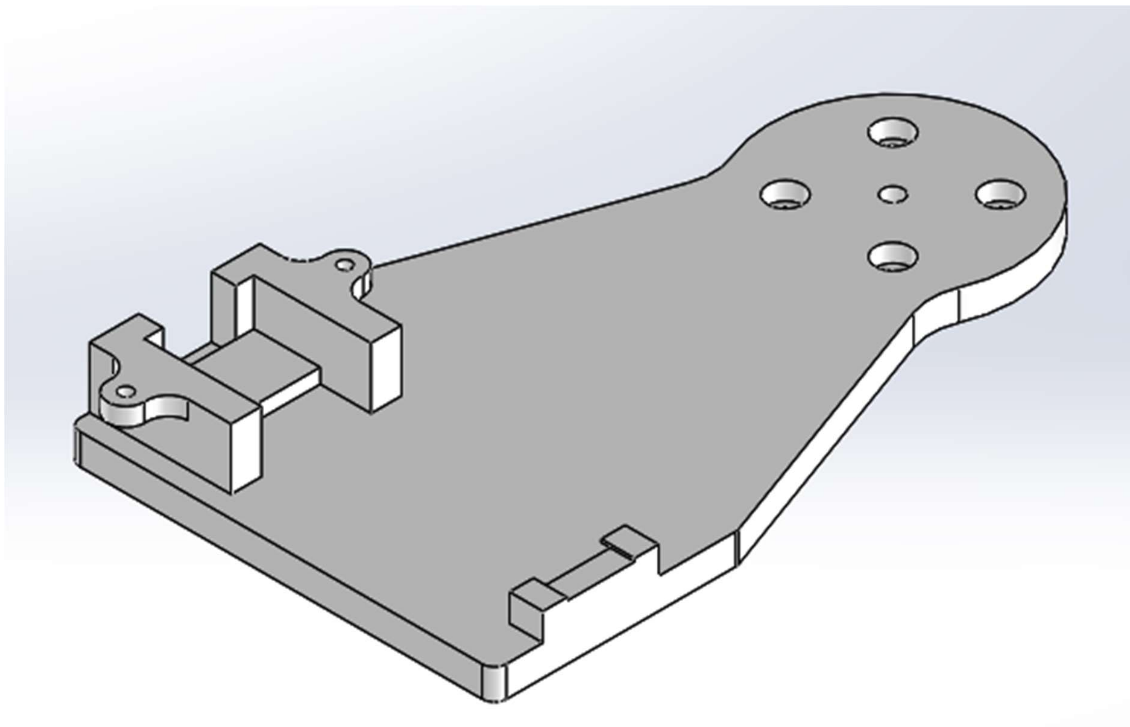
Appendix D Sensor clamp

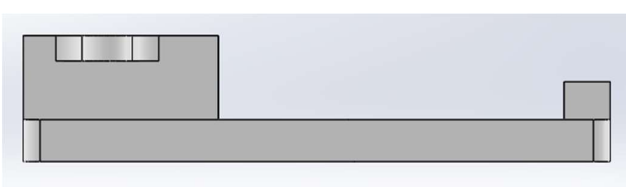






Appendix E Slotted breakout board mount





Appendix F Reflective marker housing