James Brady

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Physics 492R Capstone Project Report

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Design and Testing of a Stabilization Platform for the Naval Research Laboratory

Abstract

Designed and tested a robust stabilization platform for the Naval Research Laboratory. Motivation for this project was to create a means to stabilize a data sensor package.. Development led to a neck structure consisting of a four-bar linkage and gimbal mechanism. Testing of the system indicated that it had stabilization qualities through specific frequency ranges. It also demonstrated a majority of the qualities necessary to deem the project a success by the Naval Research Laboratory

Brigham Young University

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Capstone 2013-2014
Team 28 Final Report

Team Members:

By signing below, we approve the submission of this report, and agree that it accurately represents the work the team has accomplished.

James Brady	Date
Morgan Gillespie	Date
Christopher Graham	Date
Daniel Koch	Date
Jordan McDonald	Date
Addam Roberts	Date
Anton Bowden, PhD	Date

1 Executive Summary

The Naval Research Laboratory employed BYU Capstone Team Neckatronics to design, build, and test a prototype mechatronic neck that will carry a sensor package. Included in the sensor package is a camera and laser range finder. Motivation for the project stems from the NRL's purchase of a robotic quadruped known as the Allegro Dog. Their hope is to advance gait algorithms in legged robotics. With these requirements, Neckatronics developed a stabilization platform.

In terms of functionality, the product will have the ability to actuate the pitch, roll, and yaw of a camera while having the simultaneous ability to actuate a laser range finder in pitch. An active stabilization algorithm will be needed to attenuate high-frequency vibrations. A passively stabilized neck structure that emphasizes stabilization in heave will minimize high to low-frequency vibrations.

Through the application of these parameters the product will provide the NRL with a functional prototype. It will dampen strong vibrations associated with walking, jumping, and potentially running. The project will be built with the anticipation to actively stabilize subtle vibrations. The system will be designed to provide orientation control in three dimensions, plus one for the laser range finder. Proper positioning and stabilization of the platform will provide the controller with a usable video feed from the Allegro Dog's point of view.

The result of the team's efforts is a prototype characterized by a passively stabilized four-bar linkage for the neck, and a dual-seated gimbal capable of independent actuation of the camera and laser range finder. Together these two components will work to stabilize the sensor package during movement.

Implementation of a shake-table aided design choices of the neck structure. Robustness was validated using a surrogate Allegro Dog known as the Red Wagon. Robustness verification on the electronics components, including the nodes, encoders, camera, and laser ranger finder were not performed as these products have pre-specified operation limits.

Verification testing of low-frequency dynamic actuation in heave was on target with desired values. The prototype also produced the desired ranges of motion in all degrees of freedom associated with the gimbals physical orientation ability.

In the end the prototype exceeded the anticipated expectations of the team. Its ability to actuate in the desired degrees of freedom, and to stabilize the sensor package put the project on target with the NRL's desired outcomes.

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Leadership Contributions

The success of Team Neckatronics Capstone Project is due to the efforts and kindness of many individuals. First, PhD. Anton Bowden. He guided the team with a careful hand and watched the team's progress with discerning eyes. His council and wisdom helped the team maintain a steady course, both in good times and bad times. His teachings will not be forgotten.

PhD. Joe Hays. He was the team's liaison with the Naval Research Lab (NRL). Every week, in sickness or in health, he would work to meet with the team and guide them. Only when absolutely necessary did he interfere. He was always supportive and willing to assist the team during every phase of development. Team Neckatronics will ever be grateful for the stewardship he provided, and the sacrifice he made of his personal time to help the team complete the project.

Team Member Contributions

James Brady's work in handling the team's documentation alone was monumental. This report is a testament to him as he was the primary compiler, author, and editor of eight months of research. He was also the lead designer and tester of the Red Wagon. And it cannot go without mention that his physicist's perspective as an outsider to engineering proved invaluable in shaping the development process.

Morgan Gillespie worked endlessly on structural components to make sure they would function properly. He was the primary designer of the passive neck structure and the shake table, which took a great deal of his time and efforts. When he was not working on his own projects he was working with other members of the team to assist them in completing their tasks. His mechanical aptitude created many opportunities from presupposed difficulties.

Chris Graham was the lead designer of the gimbal structure. His efforts led to a design that exceeded orientation goals by more than 50% in some areas. He handled the gimbal structure documentation with exactness. The personal extension of himself has given this project a solid foundation.

Daniel Koch was given a great responsibility. He was the only man on Team Neckatronics that could deal with the complex programming that would go into the Neck Structure. Standing as a lone wolf he tirelessly worked on developing a system that the NRL would see as a success. His sacrifice in time alone cannot be properly measured. Thanks to his efforts the NRL has a platform they can use in their gait research.

Jordan McDonald was an important asset to the team. His understanding of design and ability to machine were invaluable in development of the neck and shake table. Evidence of his efforts can goes well beyond design. He was either in charge of, or a primary contributor to the majority of documentation of the team, including this final report.

Addam Roberts was the leader of Team Neckatronics. He kept the team focused and moving forward, even when it seemed nothing would move. He made sure that everyone knew what they were doing, and he always offered a helping hand. Aside from his efforts in leading the team his abilities in manufacturing were priceless, as he produced high-quality components for the gimbal structure.

Truly every member played vital role to the success of this project. In concept development alone, due to the diversity of individuals on this team, they were able to generate over a 100 different ideas in a matter of a few hours. Each individual truly extended themselves beyond what could have been required. This concerted effort led ultimately to what this project became in the end. A genuine success.

Notable Contributors

Other notable mentions include Ken Forster. His help with machining, CNC, and materials were indispensable. PhD. Stephen Charles assistance in defining the shake table procedure helped make the verification test possible. John Ellsworth, in a time when things were blowing up, helped the team make vital electronics decisions that opened the path forward. Kevin Cole's provision of materials helped the team bring many portions of the project to life. A fellow student Allen (unable to locate last name) assisted in proper design of the cam wheels for the Red Wagon. Aside from those mentioned there are countless others that helped this project succeed.

Sponsor Contribution

Last, and not least there is of course the team sponsor, the NRL. The NRL, truly in the strictest sense made this project possible. Their willingness to place such an important project in the hands of BYU students is admirable. Their contribution gave the members of Team Neckatronics the chance to show their stuff. Thank you, from every member of Team Neckatronics.

6 Introduction

6.1 Background

The Naval Research Laboratory (NRL) recently purchased a legged robot known as the Allegro Dog (see Figure 1). One of the potential end results of the NRL's research is to develop a robot that can be used by troops in environments where other robots like UAV's or rolling type vehicles would be ineffective. Before they can get to this point, however, they need to develop an in-depth understanding of the gait algorithms in with quadruped robotics. To this end they asked Brigham Young University for assistance.

Capstone Team Neckatronics was assigned to the project. The goal was to design, build, and test a prototype mechatronic neck meant to carry a sensor package. It would need to have several integral components. Among the most vital would be its ability to actuate in multiple degrees of freedom and simultaneously offer stability in each.

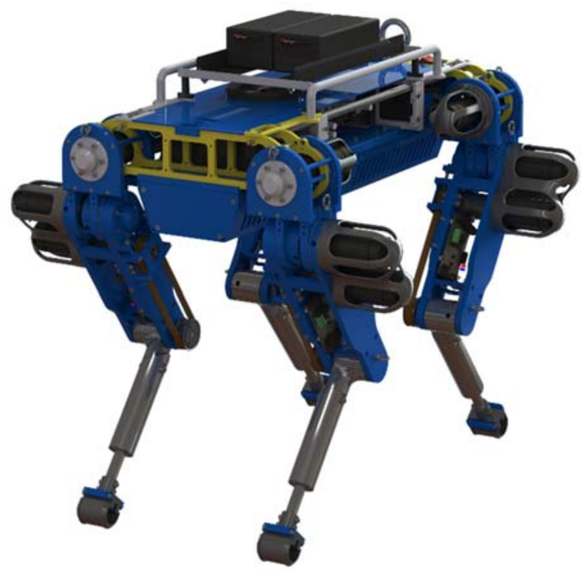

Figure 1: Allegro Dog

6.2 Development Process

Team Neckatronics broke down the development process into four stages: opportunity development, concept development, sub-system engineering, and system integration. The following is a brief overview of each stage.

6.3 Opportunity Development

Careful analysis of the project and broad research of data feed stabilization, gave the team an understanding of the diversity of potential solutions for the project. Topics that were included in the research process included everything from vector thrusters to biomechanics in chickens. More information about this stage of development is located in the Fall Report, Appendix H: Fall Semester Report.

6.4 Concept Development

Developing the concept was initialized with a brainstorming session. This yielded over 100 different ideas. These ideas were categorized and measured. After careful analysis, elimination, and recombination, the team was able to select the best design for the project. A four-bar linkage with a gimbal mechanism. More information about this stage is located in the Fall Report, Appendix H: Fall Semester Report.

6.5 Sub-System Engineering

The concept was broken down into different areas. Each area was sectioned off into individual development projects. Neckatronics' members were assigned to each project, according to their abilities. The projects were defined as the gimbal group, neck structure group, and electronics and controls group.

6.6 System Integration

After designing the different aspects of the structure, the team combined the structures and detailed the integration of the subsystem components. Though this step is portrayed as the last step in the process of development it was more of a parallel phase with subsystem engineering.

6.7 Verification and Validation Overview

Throughout development the concept was continually verified and validated for functionality and applicability. Especially in the final stages of development the prototype underwent extensive verification testing to ensure that it was to the standards of the project guidelines. Validation testing was limited due to the constraints of the project.

7 Project Requirements

7.1 Market Performance

The prototype required several distinct features centered on data stabilization and comprehensive data acquisition. In order to obtain a significant amount of information about the dynamic environment of the Allegro Dog, the system needed to be able to change its orientation to encompass an extensive field of view around the robot. To maintain the integrity of the data collection, which would take place via a laser range finder and camera, the platform had to be designed to attenuate a range of stimuli.

Implicit to the previously mentioned qualities, the system required a standard communications protocol, a quick response to commands either external or internal, limited weight, limited volume, possess a modular interface, and a self-contained power supply. Lastly, the prototype required a resistance to rollover or ground impact. Complete analysis of the requirements yielded 15 evaluation criteria (Table 1). An in depth view of the criteria is located in the product contract as well as the requirements matrix which can be found in Appendix A: Product Requirements.

Table 1: Market Requirements

#	Market Requirement
1	The product produces stabilized sensor platform
2	The product allows control of sensor platform pose
3	The product allows enables 3D scanning of the environment
4	The product provides accurate estimates of sensor platform pose
5	The product quickly responds to control inputs
6	The product is within the weight constraints of the robot
7	The product fits within size constraints of the robot
8	The product uses a modular mounting interface
9	The product mounts on the Allegro Dog robotic system
10	The product supports the sensor platform payload
11	The product withstands physical impulses from base
12	The product uses a standard communications protocol
13	The product has a sufficient communications bandwidth for control inputs
14	The product uses standard electrical connections
15	The product is designed for robustness withstand impacts from the robot rolling over

7.2 Surrogate Evaluation Criteria

Investigation of the market requirements generated 19 associated surrogate evaluation criteria (see Table 2). Each of the criteria were generated according to the categories of orientation, stabilization, survivability, modularity, electronics, and programing. Specifically 7 criteria for orientation, 6 for stabilization, 1 criteria for survivability, 1 criteria for modularity, and 11 criteria for electronics and programing. There were 3 criteria that did not fall into any one category. This includes: weight limit, volume limit, and mount-ability to the Allegro Dog. Noting that there are only 19 surrogate evaluation criteria there are 7 areas of interdependency.

Through brainstorming, communication with the client, and prototyping, test value ranges were created and refined. Each surrogate evaluation criteria has minimal, ideal, and target values. Of the 19 criteria, 14 are quantitative and 5 are qualitative. Specific values are located in the product contract and requirements matrix in Appendix A: Product Requirements.

Table 2: Surrogate Evaluation Criteria

#	Surrogate Evaluation Criterion
1	Average attenuation of acceleration from base to camera (6 DOF) from 5-10 Hz
2	Average attenuation of acceleration from base to camera (6 DOF) from 30-60 Hz
3	Actuated camera field of view in yaw
4	Actuated camera field of view in pitch
5	Pitch range of motion for laser scanner
6	Pitch Frequency of laser scanner
7	Heave range of motion
8	Yaw and pitch positioning accuracy when robot is stationary
9	Translational pose estimate accuracy
10	Rotational pose estimate accuracy
11	Maximum closed loop positioning bandwidth for yaw and pitch
12	Total weight of system not including battery pack
13	Convex enclosing volume of product in resting configuration
14	The product mounts on the Allegro Dog system
15	Mounting bracket is interchangeable
16	The product uses a standard communications protocol
17	Minimum control input frequency
18	Uses commercially available connectors
19	Employs robust design techniques

8 Product Description

8.1 Introduction

The prototype is broken down into two mechanical structures with one integrated electrical system. The first mechanical structure is the neck, second is the gimbal. Integrated circuitry, motors, and encoders make up the electrical system of the prototype. These parts work together to provide the capability of stabilizing the sensor package.

8.2 Neck Structure

The neck structure consists of a four-bar mechanism and a dual crossed spring damper system (see Figure 2). This configuration allows for a large range of motion in heave and compensates for low frequency vibrations and large impulses from the robot. The structure mounts directly to the front of the Allegro Dog and is designed to be modular for use with other robots. This component was given a robust mechanical design and aluminum was chosen as the primary construction material to ensure durability without significantly increasing the weight of the prototype.

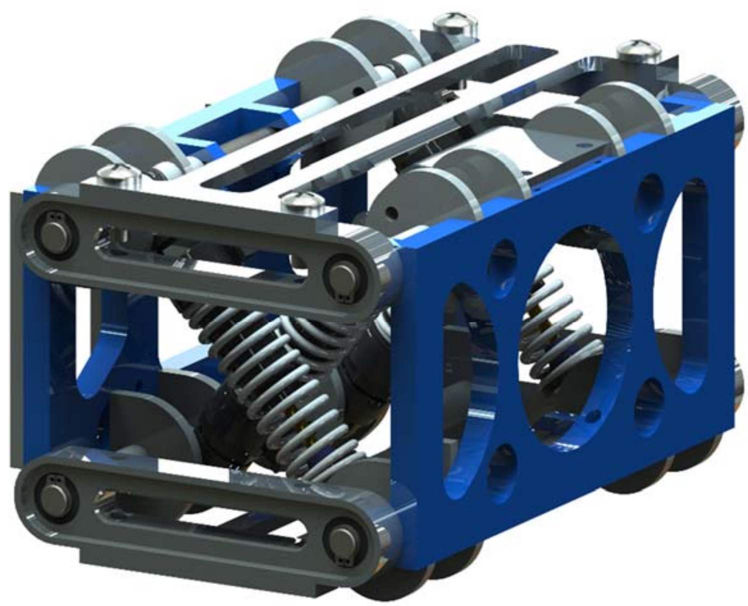

Figure 2: Four-bar Linkage with Spring Dampers

This system integrates to Allegro Dog through four preexisting mounting holes on the front of the robot. Its primary purpose is to stabilize the gimbal and protect it from large impulses. The cantilever design also increases the viewable range for the gimbal structure, allowing having a full range of motion. The gimbal structure is secured to the neck structure with four bolts and supported with a bearing to accommodate any moments caused by the gimbal structure.

8.3 Gimbal Structure

Design of the gimbal includes two sensor package seats (see Figure 3). The upper seat holds the camera, and the lower seat holds the laser range finder. This system can orient the camera in roll, pitch and yaw. Also inclusive in the structure is the ability to actuate the laser range finder in pitch.

Accommodating the NRL's desire to view the feet of the robot, the gimbal was mounted below the cantilever. This forms a direct connection with the yaw motor.

There are three additional motors that can be seen in Figure 3. Two motors orient pitch, either of the camera, laser range finder, or both. The other motor handles the roll of the entire gimbal structure.

The primary material used in the system was aluminum. This, in combination with techniques focusing on robustness, resulted in a structure that can handle potential impacts. For additional information regarding the design of the gimbal consult Appendix B: Product Design

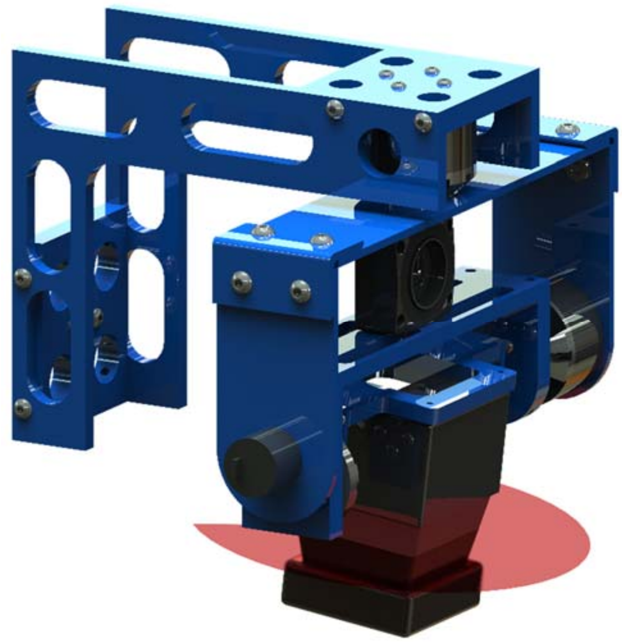

Figure 3: CAD rendering of gimbal with camera and laser range finder

8.4 Electronics and Controls

The electronics and controls are responsible for sensing the pose of the sensor platform, actuating the gimbal, and providing orientation control for the gimbal.

Absolute encoders are used to sense the pose of the sensor platform. Five encoders are used to sense the angle of the yaw, pitch, roll, laser pitch, and neck structure deflection degrees of freedom. The selected encoders provide a sensing accuracy of ±0.1 degrees. In addition, a six-axis inertial measurement unit (IMU) is used to sense the inertial accelerations and rotational rates experienced by the sensor platform.

Figure 4: SOMANET node hardware. Source: www.synapticon.com

The gimbal is actuated using brushless DC (BLDC) motors designed specifically for gimbal applications. These motors have a high magnetic pole count and high internal resistance, allowing for high torques and smooth operation at low rates of rotation.

The sensor integration, motor control, and position control are done using SOMANET hardware and software from Synapticon. The SOMANET platform takes a distributed approach to motion control, where each degree of freedom is controlled by a dedicated, modular hardware stack—referred to as a *node*—and associated software. Figure 4 shows an example of a SOMANET hardware node. Figure 5 shows a block diagram of the entire electronics system for the prototype design. The system consists of a series of nodes, each connected to one or more sensors and most connected to a BLDC motor. The nodes communicate with each other and with the master Linux PC using the EtherCAT protocol. The master reads sensor data from the SOMANET nodes, runs the position control loop, and sends torque commands to each of the nodes. The nodes are responsible for reading the sensors and controlling the motors to provide the specified torque. Details on the design of the hardware and software can be found in Appendix B: Product Design.

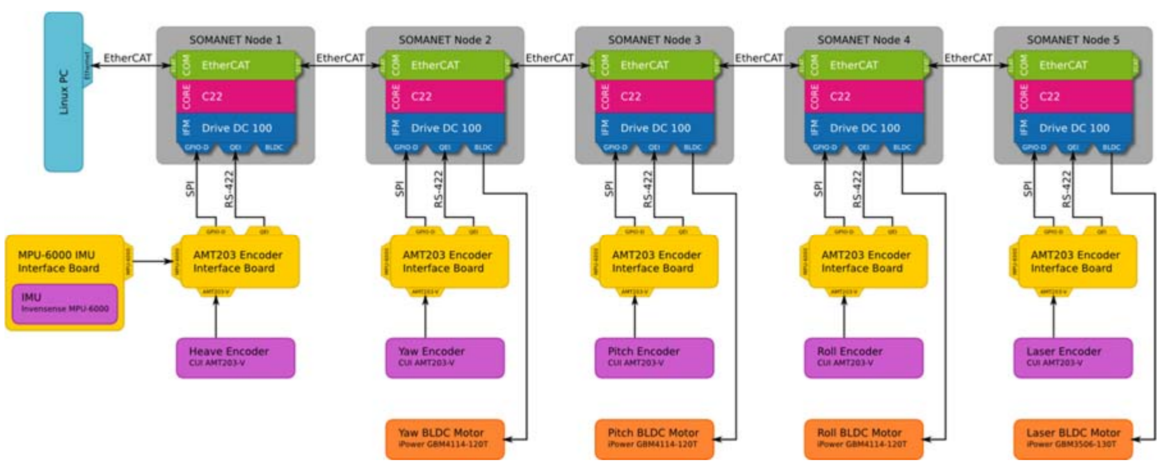

Figure 5: Electronics System Block Diagram

9 Critical Design Parameters

Preliminary development showed that there were specific traits of the prototype that had to be within specific limits or the prototype would not function. Through prototyping, modeling, thought experiments, and close communication with the sponsor, the team determined which market criteria were critical. Similar methods also helped the team identify additional critical criteria not specified in the market requirements. Additional information regarding this decision process is located in Requirements and G[1].

9.1 Actuated Camera Field of View in Yaw, Pitch

A requirement of the NRL is that the sensor package be able to gather a significant amount of data about the environment of the Allegro Dog. If the prototype is unable to actuate in yaw and pitch it will make the system ineffective as it will not give the NRL a comprehensive understanding of the dynamic environment associated with the robot.

9.2 Pitch Range of Motion for the Laser Scanner

The ability to pitch the laser range finder is detrimental to the project as it must scan through pitch in order to provide a depth analysis of the environment of the Allegro Dog. If the laser range finder cannot be actuated as described it will make the product useless.

9.3 Standard Communications Protocol

The system must be able to communicate with the NRL's computers. If the prototype cannot communicate then data cannot be acquired and therefore the product would be of no value to the client.

9.4 Average Attenuation

The system should achieve an average attenuation of -6 dB over the range of 5-15 Hz and 30-60Hz. If the prototype cannot reduce low and high frequency vibrations, the camera cannot produce a good picture and the gimbal will likely be damaged over time.

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[1] Specifically see the market requirements matrix in the product contract. This is located in Appendix A. In Appendix F see the fall report and FMEA.

9.5 Mounts to the Allegro Dog

The structure must be mountable to the Allegro Dog chassis in such a way that it is removable and will not shear off the connection hardware. This mount should not interfere with normal operations of the Allegro Dog and should be modular, such that it can be easily modified for mounting on other robotic platforms.

10 Verification and Validation

10.1 Verification

Several methods were used to verify the functionality of the prototype. Among the selected methods were decision matrices, low-fidelity prototypes, computer modeling, finite element analysis, and shake-table tests. A summary of the key verification tests performed is given below. Verification of other design requirements that did not require explicit testing is also included in this section.

10.1.1 Shake-Table

The first testing system designed was a vibrating shake-table. This was used as a verification tool for the neck structure. It was used as a means to demonstrate that the neck structure would move according to external stimuli and reduce attenuation of the input vibrations. Mounting an accelerometer at the base and end of the neck allowed for a check of acceleration values and a calculation of achieved attenuation. Associated values for this test are located in Figure 6and Table 3, and extensive data and methods used are located in Appendix D: Acceptance Information.

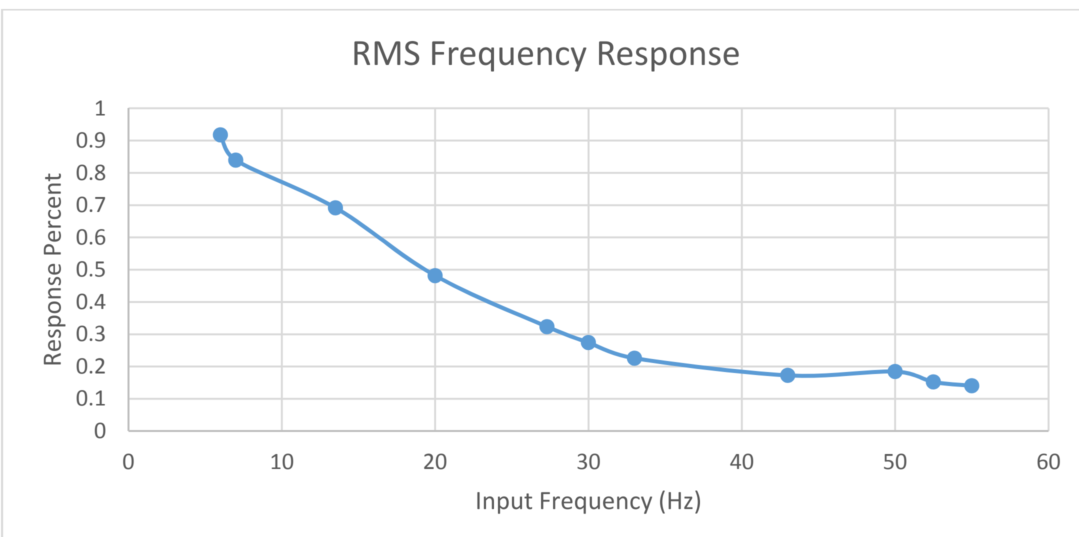

Figure 6: RMS Frequency Response

Table 3: Frequency Response Range Averages

Frequency Range	Percent Reduction	dB
5 to 10 Average	**0.184**	**-2.96**
30 to 60 Average	**0.808**	**-14.58**
Full Range Average	**0.400**	**-9.920**

Results of this test show that there was a significant reduction over the full range of target frequencies. On the low end, -3 dB was achieved over the very low range frequencies. In contrast -14.5 dB was achieved for high range frequencies, which was well beyond target values. To take it further the attenuation of the higher frequencies is also underrepresented due to the accelerometers only being limited to 25 Gs. The raw data for these tests can be found on the attached DVD under /Raw Data/Neck Attenuation Data.xlsx

This test also allowed for verification that the neck design was robust under the relatively harsh environment of the shake table, which vibrated at an amplitude of 0.25 inches at up to 56 Hz. These tests put the neck through over 10,000 cycles.

10.1.2 Heave Modeling

Through the use of computer aided design the heave range of motion was analyzed. It was found that the heave had the value of ±0.71 inches at theoretical maximum. This value was verified by measuring on the hardware. A summary of the verification results from this year is found in Table 4.

Table 4: Summary of Verification Results of Surrogate Evaluation Criteria

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Average attenuation of acceleration from base to camera from 5-10Hz	Yes	-3	-6	-1	Decibels
Average attenuation of acceleration from base to camera (6 DOF) from 30-60Hz	No	-14.6	-6	-1	Decibels
Heave range of motion	No	±0.71	±1	0	Inches
Employs robust design techniques	No	Yes	Yes	No	N/A

10.1.3 Finite Element Analysis

In an effort to lighten the gimbal, the largest structural elements for weight removal—the large booms suspending the camera from above—were targeted. Weight had to be removed and robust design maintained. This was done through iterative FEA, where material was removed and the part was then analyzed. This checked that even when material was removed that the boom was still able to hold up the gimbal in harsh operating conditions.

To replicate operating conditions, the bolt holes at the base of the boom were fixed, while a 6G load of the entire gimbal weight was distributed over the two mounting holes at the end. Figure 7 depicts the load distribution on the part and shows the resulting stress concentrations.

This analysis showed that even under a 6G load, the principal stress on the gimbal boom was still only 50% of 6061 aluminum yield strength. See Table 5 for a summary of the results.

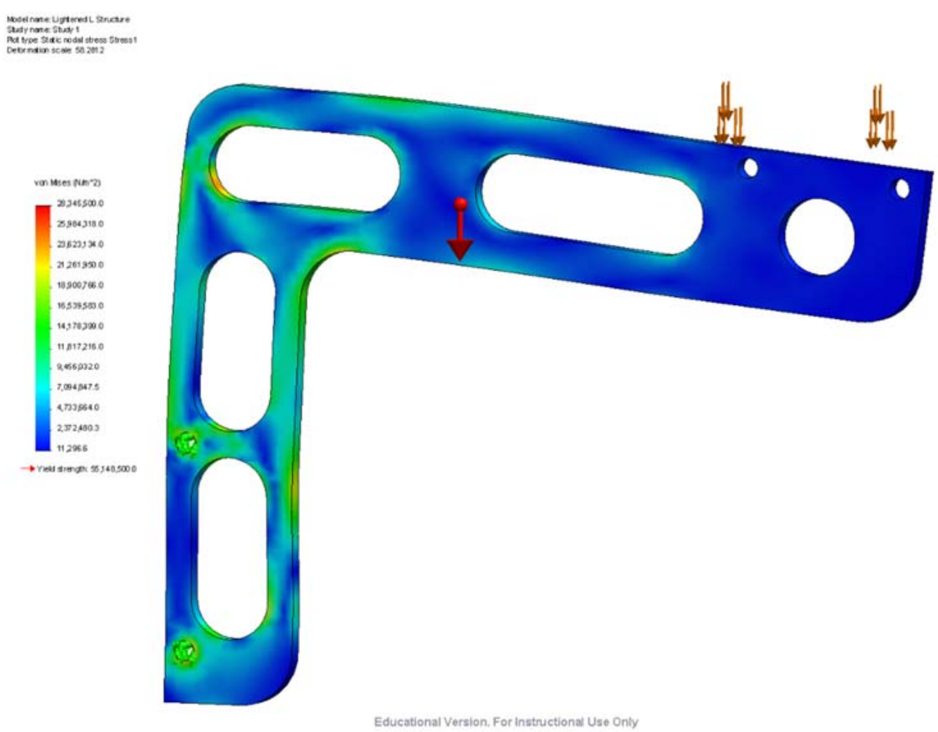

Figure 7: Gimbal Boom FEA Analysis

Table 5: Summary of Results from FEA

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Employs robust design techniques	No	Yes	Yes	No	N/A

10.1.4 Motor Performance Tests and Simulations

Because design of the active control algorithms was removed from the scope of this project, the closed-loop positioning bandwidth for the gimbal and the frequency of the laser scanner pitch actuation could not be verified directly. Instead, the team verified the ability of the prototype to meet these requirements through the use of motor performance tests and simulations. The motor performance tests were done to evaluate the torque capabilities of the motors. The response of a simple control algorithm on the gimbal dynamics was then simulated to verify that the measured torque values would be sufficient to obtain the desired performance characteristics. A summary of the results for these procedures is located in Table 6 and extensive details are located in Appendix D: Acceptance Information.

Table 6: Summary of Results from Motor Performance Tests

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Pitch frequency of laser scanner	No	0.5	0.5	0.125	Hertz
Maximum closed loop positioning bandwidth for yaw and pitch	No	0.75	1	0.5	Hertz

10.1.5 Verification of Other Design Requirements

Other design requirements did not require explicit tests to verify. A summary of the verification for these requirements is provided below, with values given in Table 7.

- The weight of the system was measured by weighing the fully assembled prototype on a scale
- The convex enclosing volume was measured using a CAD system by calculating the volume of a rectangular prism that completely encloses the neck and gimbal structures

- The mounting system was designed to mount to the Allegro Dog, using CAD models of the Allegro Dog as a reference; see Appendix B: Product Design for detailed design information. The mounting holes in the bracket correspond to available holes on the robot. The team did not have physical access to an Allegro Dog, so validation of mounting compatibility will be performed by the sponsor upon receipt of the prototype.
- The mounting bracket was designed as an interchangeable and inexpensive component so that it can be switched out to accommodate different robotic platforms. It consists of a single piece that can be laser cut out of plastic sheet material. See Appendix B: Product Design for detailed design information.
- The product uses the EtherCAT communication protocol, which is an industry-standard protocol for control applications. See Appendix B: Product Design for detailed design information.
- The EtherCAT protocol supports transfers of up to 1486 bytes in a single frame, which takes only 300µs to transfer (source: http://www.ethercat.org/en/technology.html#3.4). This is a worst-case scenario, and in practice the control commands for this application are sent in smaller frames. Therefore, the EtherCAT communications used support an input frequency for control commands in excess of 3300Hz, which far exceeds the 250Hz requirement.
- All connectors used in the design are commercially available connectors. See Appendix B: Product Design for detailed design information.

Table 7: Summary of Design Requirements Verification

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Total weight of system not including battery pack	Yes	6.2	8.8	15.4	Pounds
Convex enclosing volume of product in resting configuration	No	642	800	2000	Cubic Inches
The product mounts on the Allegro Dog system	Yes	Yes	Yes	No	N/A
Mounting bracket is interchangeable	No	Yes	Yes	No	N/A
The product uses a standard communications protocol	Yes	Yes	Yes	No	N/A

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Minimum control input frequency	No	>3300	250	100	Hz
Uses commercially available connectors	No	Yes	Yes	All Custom	N/A

10.2 Validation Testing

Final project validation will take place using the Allegro Dog with the NRL's chosen camera and laser range finder. This will allow for static and dynamic validation of the prototype. Because of NRL restrictions, it was not possible to obtain an Allegro Dog or the NRL's sensor package. As a surrogate for final validation which will take place after the project is transferred back to NRL, approximate testing procedures were developed to validate the device.

10.2.1 Orientation Test

In order to validate orientation limits the neck structure was each DOF of the gimbal was manually rotated through its full range of motion. It was found that range of orientation exceeded expectations in all DOFs (see Table 8). For information about the methods and analysis used see Appendix D: Acceptance Information.

Table 8: Summary of Orientation Test Results

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Actuated camera field of view in yaw	Yes	±145	±135	±45	Degrees
Actuated camera field of view in pitch	Yes	±140	±70	±35	Degrees
Pitch range of motion for laser scanner	Yes	+15 to-120	+15 to -90	0 to -45	Degrees

10.2.2 Rollover Test

The team validated impact resistance by tipping the Red Wagon over with the neck structure attached. After completely tipping the system over, the neck structure was examined for damages, and it was found that it was undamaged. Thus the system past the rollover test (see Table 9). A video file of the rollover test has been included in the supplemental DVD.

Table 9: Summary of Rollover Test Results

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Employs robust design techniques	No	Yes	Yes	No	N/A

10.2.3 Red Wagon

Figure 8: Image of Red Wagon with Neck Structure Attached

The "Red Wagon" is neither red, nor a wagon, however its name stems from the original brainstorming session where the team tried to devise a surrogate validation testing protocol that could provide real world simulation of the Allegro Dog motion. In basic, the Red Wagon is a wheeled base with cam wheels (see Figure 8) that were designed to correspond to the frequency and amplitude of the Allegro Dog motion as obtained through observation of publicly available video sources. The Red Wagon has a mounting point for the neck structure that mimics the mount points on the Allegro Dog. Testing of the Red Wagon consisted of placing the wagon on a treadmill at 1.2mph for an hour. This test was intended to validate the robustness of the design under simulated gait conditions. The result of this test is in Table 10. The result was selected because the neck handled 3000 cycles without any damage. The testing methods and design of the Red Wagon are located in Appendix D: Acceptance Information.

Table 10: Validation Results of Surrogate Evaluation Criteria for Red Wagon Test

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Employs robust design techniques	No	Yes	Yes	No	N/A

10.3 Summary of Results

Verification and Validation testing quantified the 19 evaluation criteria. Through the use the shake table, Red Wagon, and other verification and validation tests, the measured performance for each evaluation criterion was acquired. For a complete summary of the surrogate evaluation criteria values, see Table 11.

Table 11: Summary of Verification and Validation Results of Evaluation Criteria

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
Average attenuation of acceleration from base to camera (6 DOF) from 5-10 Hz	Yes	-3	-6	-1	Decibels
Average attenuation of acceleration from base to camera (6 DOF) from 30-60Hz	No	-14.6	-6	-1	Decibels
Actuated camera field of view in yaw	Yes	±145	±135	±45	Degrees
Actuated camera field of view in pitch	Yes	±140	±70	±35	Degrees
Pitch range of motion for laser scanner	Yes	+15 to-120	+15 to -90	0 to -45	Degrees
Pitch frequency of laser scanner	No	0.5	0.5	0.125	Hertz
Heave range of motion	No	±0.71	±1	0	Inches
Yaw and pitch positioning accuracy when robot is stationary	No	±0.2	±0.5	±2	Degrees
Translational pose estimate accuracy	No	±0.012	±0.04	±0.2	Inches
Rotational pose estimate accuracy	No	±0.346	±0.5	±2	Degrees
Maximum closed loop positioning bandwidth for yaw and pitch	No	0.75	1	0.5	Hertz
Total weight of system not including battery pack	Yes	6.2	8.8	15.4	Pounds
Convex enclosing volume of product in resting configuration	No	642	800	2000	Cubic Inches
The product mounts on the Allegro Dog system	Yes	Yes	Yes	No	N/A
Mounting bracket is interchangeable	No	Yes	Yes	No	N/A

Surrogate Evaluation Criteria	Critical Design Parameter	Actual Performance, with citation (from report) of verification	Ideal Values	Minimal Values	Units of Measurement
The product uses a standard communications protocol	Yes	Yes	Yes	No	N/A
Minimum control input frequency	No	>3300	250	100	Hz
Uses commercially available connectors	No	Yes	Yes	All Custom	N/A
Employs robust design techniques	No	Yes	Yes	No	N/A

11 Final Product vs. Initial Goals

Initially, the NRL desired that Team Neckatronics create an actively stabilized platform for a stereoscopic camera. This meant that the Team would be responsible for all of the hardware, software, and control algorithms.

During the development process the NRL made significant design requirements changes to better suit their needs. The smaller changes to this project included a smaller and much lighter camera, and the inclusion of a Laser range finder (LIDAR). The second addition required another degree of freedom in pitch to orient the LIDAR.

The big change to the project was the removal of the need to design an active stabilization controller and position controller. It was seen appropriate by the NRL to remove these project requirements from the scope as they were deemed beyond reasonable expectations for the time frame and allotted resources of the capstone project.

11.1 Current Status

The project is ready for the NRL to begin implementation of the active stabilization controller and position controller. Every piece of needed hardware and skeletal software has been prepared for adaptation. Additionally, the platform provides adequate passive stabilization, and exceeds the requirements for orientation in all areas.

11.2 Recommendations

After gaining hands-on experience with the hardware, the team has a few recommendations for the NRL as they move forward with using this prototype design in their research efforts. These recommendations are itemized below:

- **Motors:** The motors used in this prototype were selected because they have desirable characteristics for gimbal applications (refer to Appendix B: Product Design). However, because they do not have integrated Hall-effect sensors they introduce additional complexity into the motor commutation portion of the control software. The fact that they are hobby-grade motors also raises some concerns about their long-term durability. If the NRL decides at a future time that these risks outweigh the performance benefits, it is recommended that they consider professional grade motors such as Maxon Motor’s 200142 model for the gimbal drive motors and the 339268 model for the LIDAR pitch drive motor.

- **Encoder cables:** The team encountered some difficulties with the selected encoder cable solution. The flat ribbon cable does not work well with the crimp terminals for the encoder connector, which makes assembly difficult and resulted in one short that damaged a SOMANET board. The team recommends that the NRL purchases pre-made encoder cables from Digi-Key (P/N: CP-AMT-14C-0-036-1-ND) and splice them with solder joints into the flat ribbon cables that connect to the encoder interface board.
- **IMU:** The inertial measurement unit selected is a viable option for sensing the motion of the sensing platform. However, the NRL may want to consider switching to individual MEMS rate gyros that could be mounted on each axis of the gimbal and that produce analog rather than digital outputs. This would eliminate the need to transform the gyro readings from the gimbal coordinate frame to each of the axis coordinate frames. It would also simplify software development by allowing the rate gyros to interface with the SOMANET IFM board through the analog input ports rather than through the SPI interface.

12 Conclusion

The NRL requested that Team Neckatronics develop an apparatus capable of stabilizing the data feed from a camera and laser range finder. Through the process of development the team choose the four-bar linkage and gimbal structure as the concept to develop the requested prototype. Verification and validation testing of the prototype yielded satisfactory results for the NRL. At this point in time the product is ready for reproduction and active stabilization development. The required information for alteration has been assessed and made available for future projects the NRL will have in measuring gait algorithms.

13 References

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Phone: (801) 783-6788

Useful Websites for future development

1) http://www.synapticon.com Contains contact information for the micro controller company as well as information related to the product.

2) http://doc.synapticon.com/wiki/index.php/Main_Page Synapticon's Documentation Wiki. Contains specific information regarding the SOMANET line of products.

3) https://www.youtube.com/watch?v=_dPlkFPowCc Video of a chicken's head automatically stabilizing itself. Helps understand the concepts of stabilization.

4) https://www.youtube.com/watch?v=rhc8_ppGX1U&list=PL_wqc9s24wGRXIhMwXC-8lwd495PWJ4Aw Videos of Allegro Dog. Useful in understanding purpose of project.

5) http://www.iflight-rc.com/product/iPower-Brushless-Motor-iPower-GBM-Series-iPower-GBM4114-120T.html Large motor used in the gimbal

6) http://www.iflight-rc.com/product/iPower-Brushless-Motor-iPower-GBM-Motor-iPower-GBM3506-130T.html Small motor used in the gimbal

7) http://www.digikey.com/product-detail/en/MPU-6000/1428-1005-1-ND/4038006 Six axis IMU used in gimbal

8) http://www.digikey.com/product-detail/en/AMT203-V/102-2050-ND/2278846 Absolute encoder used in pose estimation

14 Appendix A: Product Requirements

This appendix includes a copy of the project contract and Requirements Matrix. These document contains the surrogate evaluation criteria, their associated values, the justification for these values, the development budget, etc.

Mechatronic Robotic Neck Project Contract

U.S Naval Research Laboratory and BYU Capstone Team 28

James Brady, Team Member	3/4/2014 Date
Morgan Gillespie, Team Member	3/3/2014 Date
Christopher Graham, Team Member	3/3/2014 Date
Daniel Koch, Team Member	3/3/2014 Date
Jordan McDonald, Team Member	3/3/2014 Date
Addam Roberts, Team Member	3/3/14 Date
Anton Bowden, Team Coach	3/3/2014 Date
SEE ATTACHED EMAIL Joe Hays, Project Liaison	3/3/14 Date
Carl Sorenson or Christopher Mattson, Capstone Instructor	Date

Mechatronic Robotic Neck Project Contract

U.S. Naval Research Laboratory and BYU Capstone Team 28

This contract defines the agreement between the U.S. Naval Research Laboratory (referred to as the sponsor) and BYU Capstone Team 28 (referred to as the team) to fulfill the desired outcomes for the mechatronic robotic neck with camera system project. It provides a statement of the objective of the project, project team and sponsor information, a definition of the project scope, the product requirements, a description of the development milestones and anticipated schedule, details on the development budget, identification of market surrogates, grading criteria for the purposes of the Capstone course, and procedures for revising this contract.

1 Project Objective Statement

Design, prototype, and test a proof of concept mechatronic neck capable of accepting sensor platform orientation commands and producing stabilized video output for a legged robot by 3 April 2014 within a development budget of $6500.

2 Project Team Information

2.1 Identifying Information

Team Name: Neckatronics
BYU Capstone Team Number: 28

2.2 Team Members

- James Brady (jamesbrady0813@gmail.com)
- Morgan Gillespie (scrtcwlvl@gmail.com)
- Christopher Graham (graham.christopher18@gmail.com)
- Daniel Koch (daniel.p.koch@gmail.com)
- Jordan McDonald (jormcd@gmail.com)
- Addam Roberts (roberts.addam@gmail.com)

2.3 Team Coach

Anton E. Bowden, PhD, PE
Weidman Professor in Leadership
Director, BYU Applied Biomechanics Engineering Laboratory
Brigham Young University
Office Phone: 801-422-4760
Email: abowden@byu.edu

3 Project Owner Information

3.1 Project Sponsor
U.S. Naval Research Laboratory (NRL)

3.2 Project Liaison
Joe Hays, PhD
Roboticist
U.S. Naval Research Laboratory
Office Phone: 202-404-4281
Fax: 202-767-0365
Email: joe.hays@nrl.navy.mil

4 Project Scope
The project team will complete the opportunity development, concept development, sub-system engineering, and system integration stages of product development for the mechatronic robotic neck project. The anticipated outcome of this product development process is a tested and validated proof of concept prototype, along with the necessary documentation to use, maintain, and duplicate that prototype.

5 Product Requirements
The product requirements and associated evaluation criteria for verifying that those requirements have been met are detailed in the following requirements matrix. The marginal and ideal values in this revision are preliminary estimates only, and will be finalized at the end of concept development phase (refer to Section 6 for anticipated completion date).

See attached requirements matrix spreadsheet

6 Development Milestones
Development milestones and an anticipated schedule for the project are detailed below. Boldface items are major development milestones, while other items are intermediate milestones that are likely to be modified as the project progresses.

Milestone	Date
Requirements Matrix	Fri, 27 September 2013
Project Contract	Wed, 2 October 2013
Opportunity Development Stage Complete	**Wed, 2 October 2013**
Brainstorming	Mon, 14 October 2013
Concept Selection and Refinement	Tue, 29 October 2013
Preliminary Prototyping and Feasibility Studies	Thu, 7 November 2013
Concept Development Stage Complete	**Thu, 7 November 2013**
Dynamics Definition	Fri, 12 December 2013
Sensor and Actuation Design	Fri, 12 December 2013

Gimbal Design	Fri, 24 January 2014
Controls Engineering	Fri, 24 January 2014
Structure Design	Fri, 24 January 2014
Electronics Design	Fri, 24 January 2014
Sub-System Engineering Stage Complete	**Fri, 24 January 2014**
Design Finalization	Fri, 31 January 2014
Alpha Prototype Constructed	Fri, 28 February 2014
Testing of Alpha Prototype	Fri, 7 March 2014
Final Prototype Constructed	**Thu, 20 March 2014**
Validation Testing Complete	**Thu, 27 March 2014**
System Integration Phase Complete	**Mon, 31 March 2014**

7 Development Budget

Expenditures by the team shall not exceed $6500 for development, prototyping, and testing of the product. The first $1500 dollars will be provided to the team as part of the standard Capstone team budget. The sponsor will be financially responsible for any expenditures exceeding $1500, up to the $6500 limit.

8 Market Surrogates

The market surrogates are those people who provide information about the product requirements and who validate the final product. The market surrogates for this project are:

- **Joe Hays**, PhD
  Roboticist
  U.S. Naval Research Laboratory
  Office Phone: 202-404-4281
  Fax: 202-767-0365
  Email: joe.hays@nrl.navy.mil
- **Team MeRLIn**
  U.S. Naval Research Laboratory
- **Mark Colton**, PhD
  Associate Professor of Mechanical Engineering
  Brigham Young University
  Office Phone: 801-422-6303
  Email: colton@byu.edu

9 Grading Criteria

These grading criteria are used for the purposes of the Capstone course to assign grades to the team members for fall and winter semesters.

9.1 Fall Semester

Grading Criterion	A Criteria	B Criteria	C Criteria
Concept Generation	The sponsor is excited about the selected concept	The sponsor is satisfied with the selected concept	The sponsor has major concerns about the selected concept
Subsystem Engineering	Design of subsystems is complete and parts have been ordered	Design of subsystems is in the final stages of completion	Subsystem engineering is ongoing
Positioning Accuracy	Design allows for ±0.1° orientation accuracy and ±0.04in accuracy in heave	Design allows for ±0.5° orientation accuracy and ±0.07in accuracy in heave	Design allows for ±1.0° orientation accuracy and ±0.1in accuracy in heave
Position Estimation Accuracy	Design should provide accuracy of ±0.1° in orientation and ±0.04in in translation	Design should provide accuracy of ±0.3° in orientation and ±0.07in in translation	Design should provide accuracy of ±0.5° in orientation and ±0.1in in translation
Positioning Rage of Motion	Design allows for ±140° in yaw, ±70° in pitch, and ±3in in heave	Design allows for ±115° in yaw, ±55° in pitch, and ±2in in heave	Design allows for ±90° in yaw, ±45° in pitch, and ±1in in heave
Camera Stabilization	Design should produce -20dB attenuation of base inputs at camera in 2-60 Hz range	Design should produce -18dB attenuation of base inputs at camera in 2-60 Hz range	Design should produce -10dB attenuation of base inputs at camera in 2-60 Hz range
Volume	Design fits within a 100in^3 convex volume in rest configuration	Design fits within a 500in^3 convex volume in rest configuration	Design fits within a 1000in^{3}convex volume in rest configuration
Weight	Predicted weight is 3.3lbs or less not including battery	Predicted weight is 4lbs or less not including battery	Predicted weight is 5lbs or less not including battery

9.2 Winter Semester

Grading Criterion	Units	A Criteria	B Criteria	C Criteria
Average attenuation of acceleration from base to camera (6 DOF) from 5-10 Hz	dB	-6	-2.5	-1
Average attenuation of acceleration from base to camera (6 DOF) from 30-10 Hz	dB	-6	-2.5	-1
Actuated camera field of view in yaw	deg	±135	±90	±45
Actuated camera field of view in pitch	deg	±70	±45	±35
Pitch range of motion for laser scanner	deg	+15 to -90	0 to -65	0 to -45
Pitch Frequency of laser scanner	Hz	0.5	0.25	0.125
Heave range of motion	in	±1	±0.5	0
Yaw and pitch positioning accuracy when robot is stationary	deg	±0.5	±1	±2
Translational pose estimate accuracy	in	±0.04	±0.1	±0.2
Rotational pose estimate accuracy	deg	±0.5	±1	±2
Maximum closed loop positioning bandwidth for yaw and pitch	Hz	1	0.75	0.5
Total weight of system not including battery pack	lbs	8.8	12.5	15.4
Convex enclosing volume of product in resting configuration	in^3	800	1400	2000
The product mounts on the Allegro Dog system	N/A	Yes	Partially	No
Mounting bracket is interchangeable	N/A	Yes	Partially	No
The product uses a standard communications protocol	N/A	Yes	Modified	No
Minimum control input frequency	Hz	250	175	100
Uses commercially available connectors	N/A	Yes	Some Custom	All Custom
Employs robust design techniques	N/A	Yes	Partially	No

10 Change Management

This contract is a working document, and changes may be made to it as the project progresses. Changes to this contract may only be made with the mutual consent of the project sponsor, team members, and team coach. The changes will not be effective until signatures are obtained from the project sponsor, all members of the team, and the team coach. This contract will be placed under version control, and a revision history will be maintained along with a record of the approvals for each change.

11 Revision History

The major revision number is incremented when changes are made after the previous version of the contract has been approved and signed by all relevant parties. The minor revision number is incremented when changes are made after the contract has been reviewed by both the team and the sponsor, but before final approval and signing.

Product: Mechatronic Robotic Neck with Camera System
Subsystem: N/A
Revision: 1.5

#	Market Requirement (What is wanted)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1	The product produces stabilized sensor platform	●	●					●												
2	The product allows control of sensor platform pose			●	●				●	●	●	●								
	The product allows enables 3D scanning of the environment					●	●													
3	The product provides accurate estimates of sensor platform pose									●	●									
4	The product quickly responds to control inputs											●						●		
5	The product is within the weight constraints of the robot												●							
6	The product fits within size constraints of the robot													●						
7	The product uses a modular mounting interface														●	●				
8	The product mounts on the Allegro Dog robotic system														●	●				
9	The product supports the sensor platform payload											●								
10	The product withstands physical impulses from base																			●
12	The product uses a standard communications protocol																●		●	
13	The product has a sufficient communications bandwidth for control inputs																	●		
15	The product uses standard electrical connections																		●	
16	The product is designed for robustness withstand impacts from the robot rolling ove																			●

#	Surrogate Evaluation Criterion (How to measure)	Unit of measurement	Market desired values: Marginal	Market desired values: Ideal	Product performance: Target	Product performance: Achieved
1	Average attenuation of acceleration from base to camera (6 DOF) from 5-10 Hz	dB	-1	-2.5	-6	
2	Average attenuation of acceleration from base to camera (6 DOF) from 30-60 Hz	dB	-1	-2.5	-6	
3	Actuated camera field of view in yaw	degrees	±90	±135	±135	
4	Actuated camera field of view in pitch	degrees	±45	±90	±70	
5	Pitch range of motion for laser scanner	degrees	0 to -65	+15 to -90	+15 to -90	
6	Pitch Frequency of laser scanner	hertz	0.25	0.5	0.5	
7	Heave range of motion	inches	±0	±3	±1	
8	Yaw and pitch positioning accuracy when robot is stationary	degrees	±2.0	±0.1	±0.5	
9	Translational pose estimate accuracy	inches	±0.1	±0.02	±0.04	
10	Rotational pose estimate accuracy	degrees	±2.0	±0.1	±0.5	
11	Maximum closed loop positioning bandwidth for yaw and pitch	Hz	0.5	2	1	
12	Total weight of system not including battery pack	lbs	15.4	3.3	8.8	
13	Convex enclosing volume of product in resting configuration	in^3	2000	600	800	
14	The product mounts on the Allegro Dog system	N/A	No	Yes	Yes	
15	Mounting bracket is interchangeable	N/A	No	Yes	Yes	
16	The product uses a standard communications protocol	N/A	Some modifications to standard protocol	Uses existing standard protocol	Uses existing standard protocol	
17	Minimum control input frequency	Hz	175	250	250	
18	Uses commercially available connectors	N/A	Some connectors are custom	All connectors used are commercially available	All connectors used are commercially available	
19	Employs robust design tecniques	N/A	No	Yes	Yes	

Product: Mechatronic Robotic Neck with Camera System
Subsystem: N/A
Revision: 1.5

#	Market Requirement (What is wanted)
1	The product produces stabilized sensor platform
2	The product allows control of sensor platform pose
3	The product allows enables 3D scanning of the environment
4	The product provides accurate estimates of sensor platform pose
5	The product quickly responds to control inputs
6	The product is within the weight constraints of the robot
7	The product fits within size constraints of the robot
8	The product uses a modular mounting interface
9	The product mounts on the Allegro Dog robotic system
10	The product supports the sensor platform payload
11	The product withstands physical impulses from base
12	The product uses a standard communications protocol
13	The product has a sufficient communications bandwidth for control inputs
14	The product uses standard electrical connections
15	The product is designed for robustness withstand impacts from the robot rolling ove

Product performance		Market desired values																				
Achieved	Target	Ideal	Marginal	Unit of measurement	15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	#	Surrogate Evaluation Criterion (How to measure)
-3	-6	-2.5	-1	dB															●	1	Average attenuation of acceleration from base to camera (6 DOF) from 5-10 Hz
-14.6	-6	-2.5	-1	dB															●	2	Average attenuation of acceleration from base to camera (6 DOF) from 30-60 Hz
±145	±135	±135	±90	degrees														●		3	Actuated camera field of view in yaw
±140	±70	±90	±45	degrees														●		4	Actuated camera field of view in pitch
±67.5	+15 to -90	+15 to -90	0 to -65	degrees													●			5	Pitch range of motion for laser scanner
0.5	0.5	0.5	0.25	hertz													●			6	Pitch Frequency of laser scanner
±.71	±1	±3	±0	inches															●	7	Heave range of motion
±0.2	±0.5	±0.1	±2.0	degrees														●		8	Yaw and pitch positioning accuracy when robot is stationary
±0.012	±0.04	±0.02	±0.1	inches												●		●		9	Translational pose estimate accuracy
±0.346	±0.5	±0.1	±2.0	degrees												●		●		10	Rotational pose estimate accuracy
0.75	1	2	0.5	Hz						●					●			●		11	Maximum closed loop positioning bandwidth for yaw and pitch
6.2	8.8	3.3	15.4	lbs										●						12	Total weight of system not including battery pack
642	800	600	2000	in^3									●							13	Convex enclosing volume of product in resting configuration
Yes	Yes	Yes	No	N/A							●	●								14	The product mounts on the Allegro Dog system
Yes	Yes	Yes	No	N/A							●	●								15	Mounting bracket is interchangeable
Uses existing standard protocol	Uses existing standard protocol	Uses existing standard protocol	Some modifications to standard protocol	N/A				●												16	The product uses a standard communications protocol
>3300	250	250	175	Hz			●								●					17	Minimum control input frequency
All connectors used are commercially available	All connectors used are commercially available	All connectors used are commercially available	Some connectors are custom	N/A		●		●												18	Uses commercially available connectors
Yes	Yes	Yes	No	N/A	●				●											19	Employs robust design tecniques

15 Appendix B: Product Design

The information included in this section will facilitate in the reproduction of the prototype. All necessary parts and drawings are included. Additional information regarding distributers and retailers in also located in this section. Specifications of purchased parts are also included in this appendix.

This appendix is broken down into several sections. First there is the Prototype breakdown, which consists of the subsections of Neck Structure, Gimbal Structure, and electronics and controls. These sections contain a complete breakdown of each structure along with details of parts needed for assembly.

Purchased Parts is the second section. This includes all information relating to specifications for each purchased part, and retail information for where and when the part was purchased.

The third section contains file information. This is a list of all files contained on the accompanying DVD and contains a file tree for navigation. This DVD contains all files that were used in development of the prototype.

The final section contains all detailed CAD drawings necessary to completely reproduce the prototype

15.1 Prototype Break Down

15.1.1 Neck Structure

Fundamentally, the neck structure is a set of two parallel four bar linkage mechanisms working in unison. Spanning between diagonal joints of these mechanisms is a set of four spring dampers in an X pattern. These shock absorbers support the weight of the gimbal, resist impulses, and damp vibrations.

15.1.1.1 Materials

Aluminum 6061-T6 extruded stock was the primary material of choice. With its machinability, availability, and lighter weight characteristics, this was an ideal material to work with. Steel was selected for the pivot shafts in order to better resist shear. In order to facilitate modularity in the shock mounts, Lexan was selected for its ability to be laser cut quickly. Delrin was selected for shaft spacers because it is light, easy to machine, and reduces friction in shock pivoting.

15.1.1.2 Manufacture

15.1.1.2.1 TRANSVERSE LINKAGES

The transverse linkages were machined out aluminum bar stock. The bearing through holes and slots were machined by hand, and the rounded ends were machined using a CNC machine to ensure a uniform radius for all four links. Holes were then drilled and tapped for attachment of the stiffeners.

15.1.1.2.2 BASE PLATES

The complex geometry, which varied for each base plate, facilitated the use of a CNC machine. 1”x3” of aluminum bar stock was the material used. The G code for this process is included on the DVD containing all pertinent files.

15.1.1.2.3 STIFFENERS

The two stiffeners were machined by hand from aluminum stock. The eighth inch plates were clamped together and faced. Using a half inch end mill, the appropriate cuts were made to remove material. To remove the middle section, the end mill was used to plunge through the material and afterwards followed the appropriate path to remove the remaining material. In order to avoid vibrations when removing material along the thin sections, several small clamps were used to hold the material together.

15.1.1.2.4 SHOCK MOUNTS

The shock mounts were laser cut on an Epilogue 64x Laser Engraver/Cutter from Lexan. Drawings of the shock mount were created from the corresponding CAD models, iterated 16 times and in a layout that corresponded to the size of material and sent to the laser cutter.

15.1.1.2.5 SHAFTS

The steel shafts, which act as the pivot point for the neck structures linkages, were cut from quarter inch steel rod stock, and parted to provide higher tolerances. One rod was longer than the rest to accommodate an encoder.

15.1.1.2.6 FASTENERS

To secure the shocks to the mounts, we use a 2” 4-40 Machine Screw and 2x 4-40 nuts per shock. These two nuts are torqued together to prevent vibrating off.

To secure the stiffeners to the links, use 8x 10-24 machine screws and get the screws hand tight.

To secure the neck to the Allegro Dog, use either 4x 4-40 1” or longer machine screws through the specified mounting holes on the base plate, through the Lexan mount plate, to the designated holes on the Allegro Dog. Secured on the alternate side of the Allegro Dog with 4-40 Nylock Nuts.

Alternatively, one can use 4x M3 1” or longer machine screws.

To secure the neck to the gimbal, use 4x 8-32 machine screws to affix the mounting plate.

15.1.1.2.7 BEARINGS

Quarter inch ID steel needle roller bearings, McMaster-Carr - 5905K21, were used to interface the linkages and the rods. These bearings were press fit into the aluminum links and allow smooth motion of the links about the fixed steel shaft.

15.1.1.2.8 SPACERS

To secure the shocks and shock mounts from lateral movement, spacers were cut from 3/8” Delrin. On a lathe, the Delrin spacers were drilled to fit the corresponding shafts, and parted to the required lengths. Drawings, quantity, and location of these spacers can be found in the attached drawings.

15.1.1.2.9 ALLEGRO DOG INTERFACE

A laser cut Lexan 1/8” plate provides a flush interface on the back of the neck structure to the Allegro Dog and preserve the anodic finish of both the Allegro Dog and the neck. This plate can be adjusted for future changes or interfaces with other robots.

15.1.1.2.10 GIMBAL INTERFACE

The roll motor, which supports the weight of the gimbal, fit inside a sheath that slides into a two inch circular hole in the base plate, this sheath serves to align the thrust bearing around the smaller diameter motor. To assist with the resultant moment of cantilevering the gimbal off the neck structure, a steel thrust roller bearing, McMaster – 5909K43 along with 2x 0.032” thick steel washers – 5909K56, was fitted to the outer surface of the base plate, rolling against the back plate of the gimbal. This allows for smooth rotation in roll, without putting unneeded stress on the shaft of the motor.

15.1.1.3 Shock Selection

Several shock options were considered for the neck structure. Shake table testing outlined their superior performance in all testing, Traxxas 4 inch RC car shocks were selected, available through the Traxxas 5862 Big Bore Shock Set. If less damping and stiffer springs are desired, we recommend Redcat Racing Shock Absorbers - BS903-003-b. The Redcat shocks seem to perform better at high frequencies – above 10, while the Traxxas shocks perform better in the 5-10 Hz range.

15.1.1.4Assembly

Steps to aid the assembly and disassembly of the neck structure are provided here:

1. Gather Parts
    a. 2 Base Plates
    b. 4 Steel Rods
        i. 1 rod is 0.5” longer to mount the encoder
    c. 16 Lexan Shock Mounts
    d. 4 Needle Roller Bearings
    e. 4 Linkages
    f. 2 Aluminum Stiffeners
    g. 4 Shocks
    h. 8 0.5” 10-24 Machine Screws
    i. 8 2” long 4-40 Machine Screws
    j. 20 Delrin Spacers
2. Base Plate Assembly
    a. Insert a steel rod into one of the quarter inch holes.
    b. Push the steel rod through the hole, inserting each shock mount in its corresponding location, with the corresponding spacers as the rod progresses through the base plate. Leave about a half inch of rod sticking from the base plate on each side for the linkage bearings.
        i. Do this according to the assembly drawings included.
    c. Repeat this process for each rod. Four mounts should be present on each rod. Two rods should be present on each base plate.
3. Linkage Assembly
    a. Prepare each transverse linkage by press-fitting two bearings per linkage in the corresponding holes.
4. Base Plate and Linkage Assembly
    a. Place the linkages on the corresponding rods. Each linkage should attach to both base plates. Two linkages should be on each side. The rods should be on the inside of the assembly.
    b. Take the stiffeners and attach them using the 0.5” 10-24 machine screws to the top of each link. This will secure the linkages to the base plates, restricting slop in the mechanism and limiting inaccuracies in roll.
5. Shock Mounting
    a. Take a shock and the two corresponding spacers and hold them in place between the shock mounts. Make sure to insert the shock in the general direction that it will be fitted.
    b. Take the long 4-40 machine screws and insert them through the shock mount, spacers and shock absorber, and fasten the bolt.

c. To attach the shock to the other side, depress the shock if needed, and place the corresponding spacers with the shock and place them between the shock mounts.
d. Repeat the fastening process.
e. Repeat steps a. through d. for each additional shock.

15.1.2 Gimbal Structure

Comprised of four different sections, the gimbal structure is linked together through brushless motors and adjoining shafts. The complete assembly is capable of controlled movement and passive stabilization in yaw, pitch, and roll.

15.1.2.1 Stress and Load Reduction

The motors manage the majority of the structural load, but to reduce strain on the system several additional components were added. As cases in point, there is a thrust bearing on the motor responsible for roll. It reduces stress on the bearings and shaft. On each of the pitch motor points there is a large moment arm that is produced by the weight of the sections. A shaft and bearing were added to the opposing side of the structure. This removed the moment arm and produced an area for which we could attach and encoder. Together with the motors, these components manage the structural loads.

15.1.2.2 Friction Reduction

Movement was facilitated by small ball bearings which were pressed into several joint intersection components. This reduced the friction on the associated shafts, and allowed for free movement of the whole structure.

15.1.2.3 Manufacturing Method

15.1.2.4 Electronics Components

15.1.2.4.1 ENCODERS

In terms of electronics, absolute encoders have been installed in structure to measure the position of each joint, and to communicate with the motors. Specific locations of the encoders are either on the shaft of the motor or on a preceding shaft on an opposing side of any given motor location.

15.1.2.4.2 MOTORS

All though the four motors of the system had a secondary application as structural links, their primary uses were in orientation and active stabilization. Of the four motors the only one that focused solely on vibration attenuation was the motor responsible for rolling the gimbal structure. The motors that controlled the yaw and pitch of the camera had the dual purpose of vibration attenuation and camera orientation. The last motor held a key role, in that when it actuated it would move both the camera and the laser range finder in sink. This was done to maintain location accuracy[2].

15.1.2.5 Materials

The material used for the structure was aluminum. It was chosen because it has high machinability, high strength to weight ratio, sufficient tensile strength, low cost, high availability, and corrosion resistance.

15.1.3 Electronics and Programming

15.1.3.1 Hardware Components

15.1.3.1.1 MOTORS

The motors that were selected for actuating the gimbal are brushless DC (BLDC) motors that are designed specifically for gimbal applications. These motors have a high pole count to reduce torque ripple at low speeds. They also have a relatively high resistance in the motor windings and a high torque constant to maximize efficiency and torque output at low speeds. An iPower GBM4114-120T motor was used to actuate the roll, pitch, and yaw degrees of freedom, and a smaller iPower GBM3506-130T motor was used to actuate the laser scanner pitch DOF.

The torque characteristics of the motors were measured by energizing one of the motor phases at 12V, and using a torque gage to measure the torque required to rotate the motor shaft. The electrical current draw through the motor was also measured so the motor torque constant could be calculated. See Appendix D: Acceptance Information for details on the testing procedures. Table 12 summarizes the characteristics of each of the motors used.

Table 12: Motor Characteristics

	iPower GBM4114-120T	iPower GBM3506-130T	Units
Outer Diameter	45	42	mm
Height	35	14	mm
Shaft Diameter	4	4	mm

[2] Once the desired location is achieved the camera will hold its location and the second pitch motor will move the laser up and down until the same field of view, from the camera, is captured. The combination of both camera and laser will give a viewable image for the operator as well as accurate depth readings of the preceding objects.

	iPower GBM4114-120T	iPower GBM3506-130T	Units
Weight	142	64	g
Magnetic Poles	22	14	N/A
Stall Torque	247	127	mNm
Stall Current	0.82	0.98	A
Torque Constant	300	130	mNm/A
Winding Resistance	14.4	11.3	Ω

15.1.3.1.2 ENCODERS

Absolute encoders were selected in order to avoid complications associated with calibrating or indexing incremental encoders on system startup. The selected encoder is the CUI AMT203 absolute, capacitive modular encoder. This encoder has a resolution of 0.088° and accuracy of 0.2°. It provides a traditional incremental quadrature encoder output as well as an absolute 12-bit digital output using the SPI communication protocol. Datasheets, assembly instructions, and SPI application instructions for this encoder can be found online at http://www.cui.com and in the included files (see Appendix G).

15.1.3.1.3 INERTIAL MEASUREMENT UNIT

The InvenSense MPU-6000 six-axis inertial measurement unit (IMU) was chosen to sense motion of the sensor platform in an inertial reference frame. This sensor includes a 3-axis accelerometer to provide acceleration data in each of the axes, and a 3-axis rate gyroscope to provide data on the rate of rotation about each axis. A 16-bit digital output is available over either the SPI or I^2C protocol. The MPU-6000 is operated in SPI mode for this application. The datasheet and register map are available for download at http://invensense.com, and are also included with the accompanying files (see Appendix G).

15.1.3.1.4 SOMANET NODES

The SOMANET platform is a motion control solution produced by Synapticon. It provides functionality for onboard processing using an XMOS microcontroller, communications, and motor control. Each DOF is controlled by a *node*, which consists of a modular stack of three boards: a CORE board that handles the processing, a COM board that handles the communications, and an IFM board that handles interfaces with the motors and sensors. A series of these nodes is connected together to control multiple degrees of freedom.

For this prototype, five identically configured SOMANET nodes were used. Each node consists of a CORE C22 board, COM EtherCAT board, and IFM Drive DC 100 board. The CORE C22 board contains a 4-core XMOS microcontroller, where each core can run up to eight concurrent threads. The COM EtherCAT board provides an EtherCAT slave controller and two ports for EtherCAT communications. The IFM DC Drive 100 board provides position, velocity, or torque control capabilities for a brushless DC motor, for digital I/O ports, four analog inputs, and a quadrature encoder interface. Datasheets for each of these components can be found online at http://doc.synapticon.com, and are included in the accompanying files (see Appendix G).

The SOMANET nodes are connected to each other and to the other hardware as shown in **Error! Reference source not found.**. Inter-node communications are handled over EtherCAT, and the nodes also communicate with the Linux PC master over EtherCAT through the first node's physical Ethernet connection with the computer.

15.1.3.1.5 MPU-6000 IMU INTERFACE BOARD

The purpose of this board is to mount the MPU-6000 IMU and make the digital interface available over a standard connector. The MPU-6000 can be operated in either SPI or I^{2}C mode by populating one of resistors R1 and R2 (see schematic for details). When operating in I^{2}C mode, the least-significant address bit can be set using switch S1. For this prototype the MPU-6000 should be operated in SPI mode. Table 13: Connectors on the MPU-6000 Encoder Interface Board. provides details for each of the connectors on the board. The schematic can be found in Appendix C: Drawings, and datasheets for all components are in the included files (see Appendix G: Project DVD File Tree).

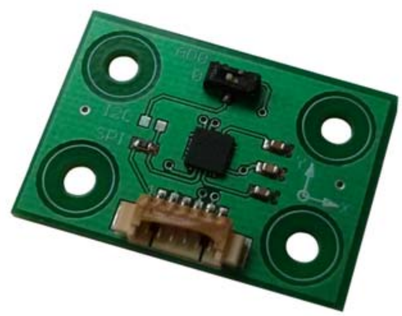


Figure 9: MPU-6000 IMU Interface Board

Table 13: Connectors on the MPU-6000 Encoder Interface Board.

Refer to Table 15 for details on cable specifications.

Connector	Connects To	Cable
J1	IMU connector on the AMT203 encoder interface board	3

15.1.3.1.6 AMT203 ENCODER INTERFACE BOARD

The purpose of this board is to interface the AMT203 encoder and MPU-6000 IMU to the SOMANET IFM DC Drive 100 board. It makes the AMT203's quadrature encoder output available over an RS-422 serial connection for interfacing with DC Drive 100's quadrature encoder interface (QEI) input, and connects the AMT203 and MPU-6000's SPI interface to digital I/O (GPIO-D) input on the DC Drive 100. Because the DC Drive 100 only provides enough I/O pins to have one slave-select line for the SPI interface, this board also includes an inverter that inverts the slave-select line going to the IMU so that the currently selected slave can be toggled using only a single digital output from the DC Drive 100. The board also includes a logic level translator to interface the 5V digital I/O of the AMT203 with the 3.3V digital I/O of the DC Drive 100. Table 14 provides details for each of the connectors on the board. The schematic can be found in Appendix C, and datasheets for all components are in the included files (see Appendix G).

Figure 10: AMT203 Encoder Interface Board

Table 14: Connectors on AMT203 Encoder Interface Board.

Refer to Table 15 for details on cable specifications.

Connector	Silkscreen Label	Connects To	Cable
J1	AMT203	AMT203 encoder connector	2
J2	GPIO-D	GPIO-D connector of SOMANET IFM DC Drive 100	5
J3	QEI	QEI connector of SOMANET IF DC Drive 100	4
J4	IMU	Connector J1 of MPU-6000 IMU interface board	3

15.1.3.1.7 CABLES AND CONNECTORS

Table 15: Cable Specifications provides details on all of the cables needed to connect the various hardware components of the system. Figure 11 shows a picture of each of these cables for reference. Table 16 provides additional details on which cable strands correspond to which connector pins for the AMT203 encoder connector. For all other cables, pin 1 on the first end should correspond to pin 1 on the other end, and so forth.

Table 15: Cable Specifications

Cable	Qty.	Cable Spec	Length	Connections	Parts (Qty.)	Part Numbers
1	4	3-strand, 22-28 gage	4 ft	BLDC Motor	Solder	N/A
				SOMANET IFM DC Drive 100 motor connector	Molex SPOX HSG 8P Connector Housing (1)	Molex 50-37-5083
					Crimp Terminal (3)	Molex 0008701039 or 0008701040
2	5	10-strand ribbon cable, 28 gage	4 ft	AMT203 Encoder[3]	Connector Housing (1)	SAMTEC ISDF-07-D
					Crimp Terminal (10)	SAMTEC CC03L-2830-01-G
				AMT203 Encoder Interface Board AMT203 connector	TE Micro-Match connector (1)	TE Connectivity 1-215083-0
3	1	6-strand, 28-32 gage	4 ft	MPU-6000 IMU Interface Board connector	Connector Housing (1)	Molex 0510210600
					Crimp Terminal (6)	Molex 0500588000
				AMT203 Encoder Interface Board IMU connector	Connector Housing (1)	Molex 0510210600
					Crimp Terminal (6)	Molex 0500588000
4	5	10-strand ribbon cable, 28 gage	2 in	AMT203 Encoder Interface Board QEI connector	TE Micro-Match connector (1)	TE Connectivity 1-215083-0

[3] The AMT203 connector has 14 pins, but only 10 are used. Refer to Table 16 for details on which pins are used and which cable strands they connect to.

Cable	Qty.	Cable Spec	Length	Connections	Parts (Qty.)	Part Numbers
				SOMANET IFM DC Drive 100 QEI connector	TE Micro-Match connector (1)	TE Connectivity 1-215083-0
5	5	8x single strand, 32 gage	2 in	AMT203 Encoder Interface Board GPIO-D connector	JST SUR Connector (1)	JST 08SUR-32S
				SOMANET IFM DC Drive 100 GPIO-D connector	JST SUR Connector (1)	JST 08SUR-32S
6	10	Single strand, 18-24 gage	User-defined	SOMANET IF DC Drive 100 power connector	M3 ring terminal	Molex 0193240002
				Power supply	User-defined	User-defined

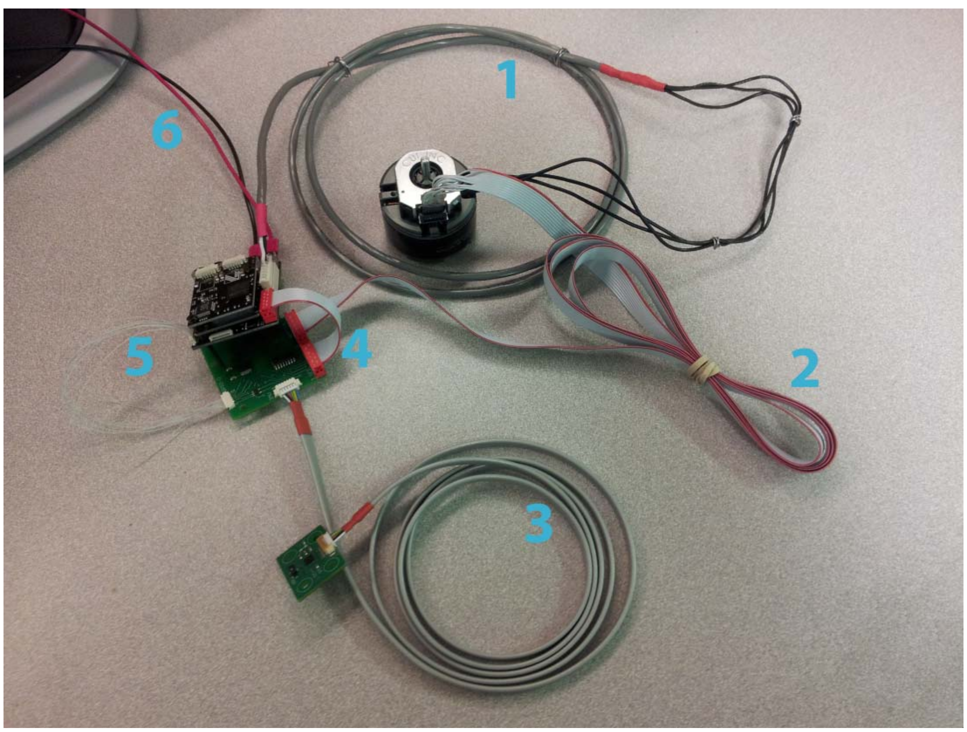


Figure 11: Cables needed for connecting hardware components.

Labels correspond to the numbers in Table 15.

Table 16: AMT203 Encoder Connector Pin Specifications

Signal Name	Cable Strand	Connector Pin
CSB	1	2
MISO	2	3
GND	3	4
SCK	4	5
5V+	5	6
MOSI	6	7
B	7	8
A	8	10
X	9	12
T_Bit	10	14

15.1.3.2 Software

The SOMANET system includes a large repository of open-source modules and example applications. Using this repository as a starting point, custom software was developed for this application. This software includes the firmware that runs on the SOMANET nodes as well as the master application that runs on the Linux PC. Additional open-source software was used to enable EtherCAT communications over the PC's standard Ethernet port.

15.1.3.2.1 SOMANET FIRMWARE

The SOMANET firmware developed for this application is based off of the examples in the Synapticon repository (https://github.com/synapticon), and consists of the following main components:

- Motor control: This portion of the firmware is responsible for reading position data using the quadrature encoder interface and for performing motor commutation and control. Because the motors used do not include integrated commutation sensors, commutation is performed using position data from the encoders.
- EtherCAT communications handling: This portion of the firmware handles inbound and outbound EtherCAT communications. Inbound communications consist primarily of control commands, while outbound communications consist primarily of position information.
- SPI communication: This portion of the firmware runs the SPI communications needed to read data from the encoders' absolute position SPI output and from the IMU.

Additional firmware components are needed to run the core functionalities of the SOMANET hardware and to handle inter-process communications between the components described above. The current state of the firmware is that motor control and EtherCAT communications handling are implemented and functioning, and majority of the infrastructure for SPI communication has been implemented but is not fully functioning. Detailed information on the contents, organization, and configuration of the firmware code is included with the source code contained in the accompanying files (see Appendix G).

15.1.3.2.2 LINUX PC MASTER APPLICATION

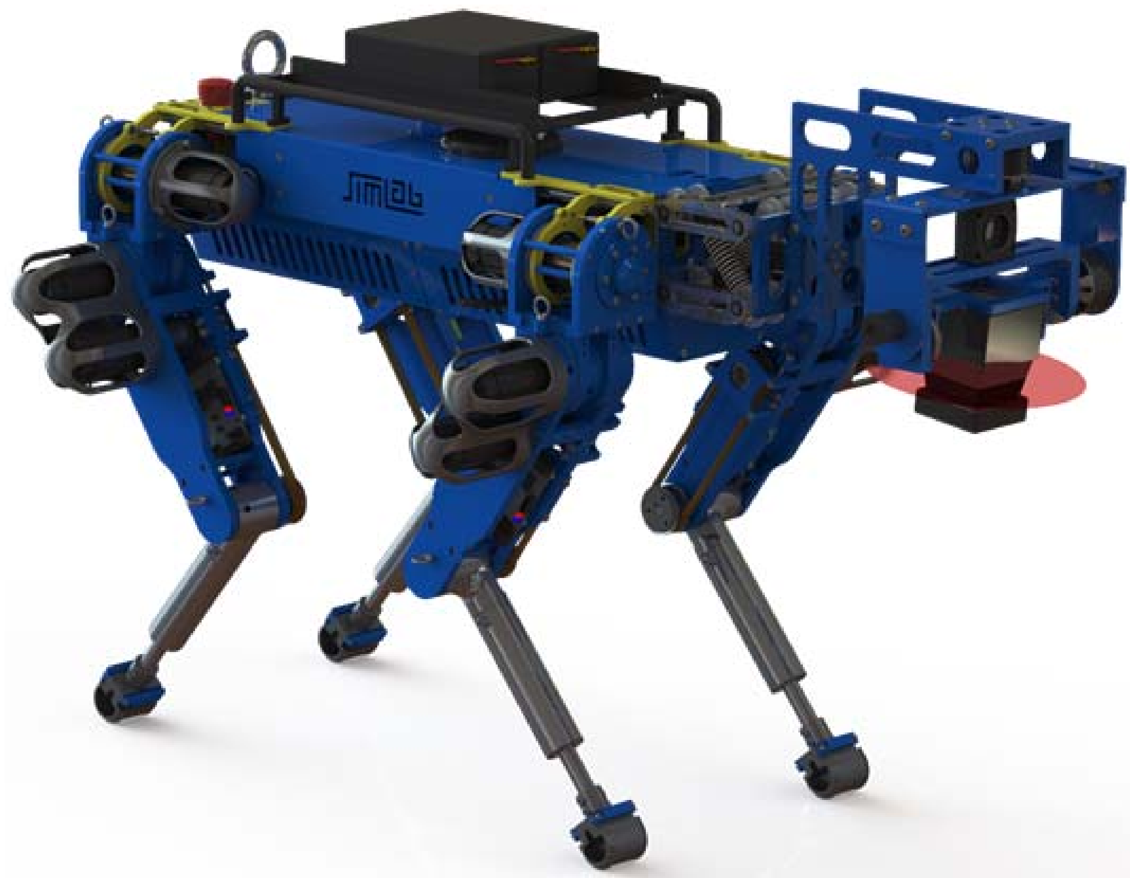
The Linux PC master application is responsible for handling EtherCAT communications on the PC side and for implementing the control algorithms for the gimbal. Because the design of the control algorithms was removed from the scope of this project, the current master application only implements EtherCAT communications. This application is also based on the examples included in the Synapticon repository (https://github.com/synapticon). Detailed documentation on the contents, organization, and configuration of this code is included with source code contained in the accompanying files (see Appendix G).

15.1.3.2.3 ETHERCAT MASTER SOFTWARE

The IgH EtherCAT Master stack from IgH EtherLAB (http://www.etherlab.org/en/ethercat/index.php) needs to be installed on the master PC in order to provide EtherCAT communications over a standard Ethernet port. In order to install this software we recommended using the instructions and installation files provided at http://doc.synapticon.com/wiki/index.php/EtherCAT_Master_Software. It is also recommended that this software be installed on a computer running Ubuntu 12.04 as its operating system. Additional information on the installation and configuration of this software is included with the source code contained in the accompanying files (see Appendix G).

16 Appendix C: Drawings

Contained in this section are complete drawings for the entire stabilization platform assembly. The first set of drawings describes the Gimbal Structure. Following these are the Neck Structure Drawings and Electronics Drawings.



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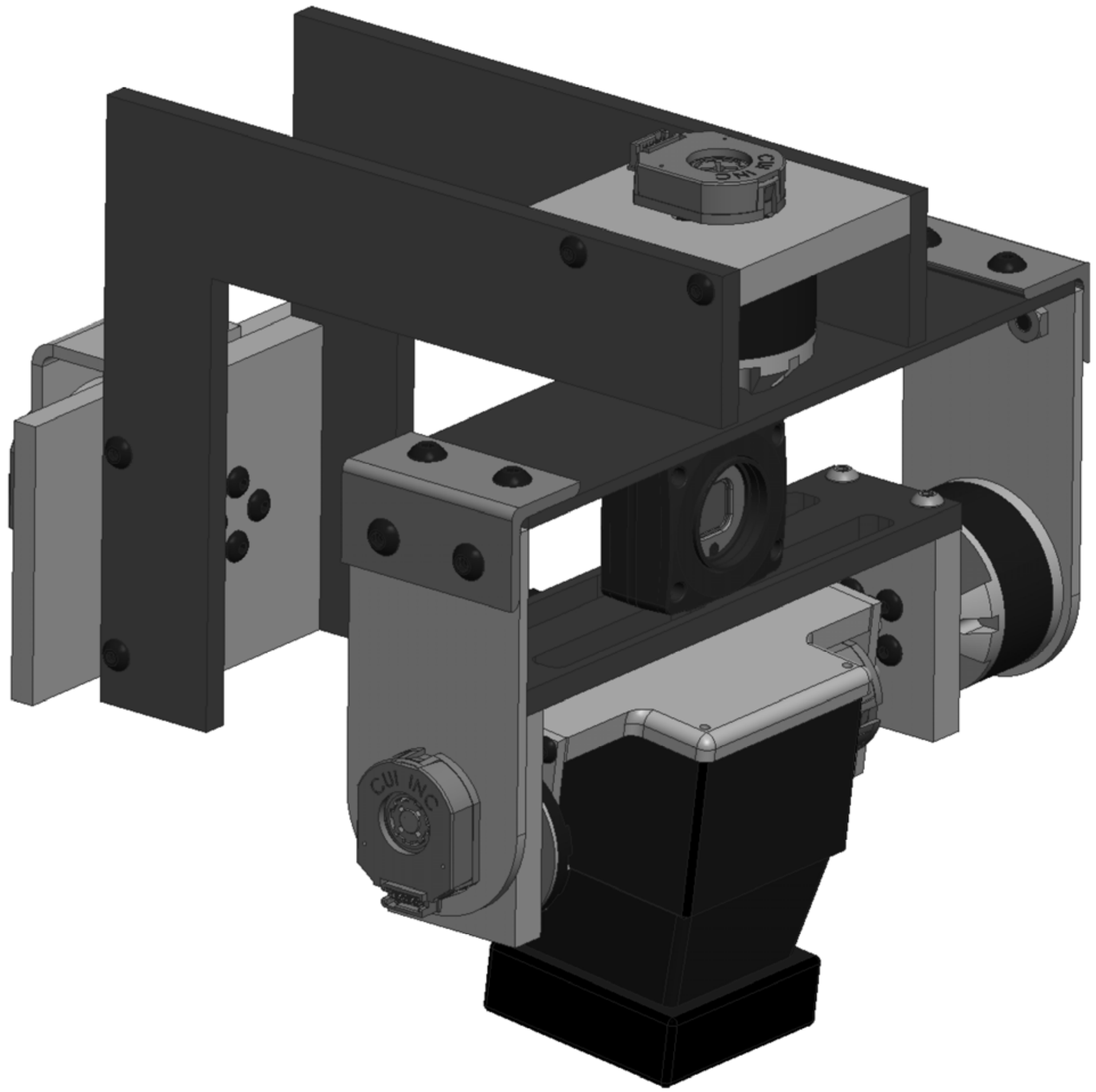

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.XXX = ±.005		
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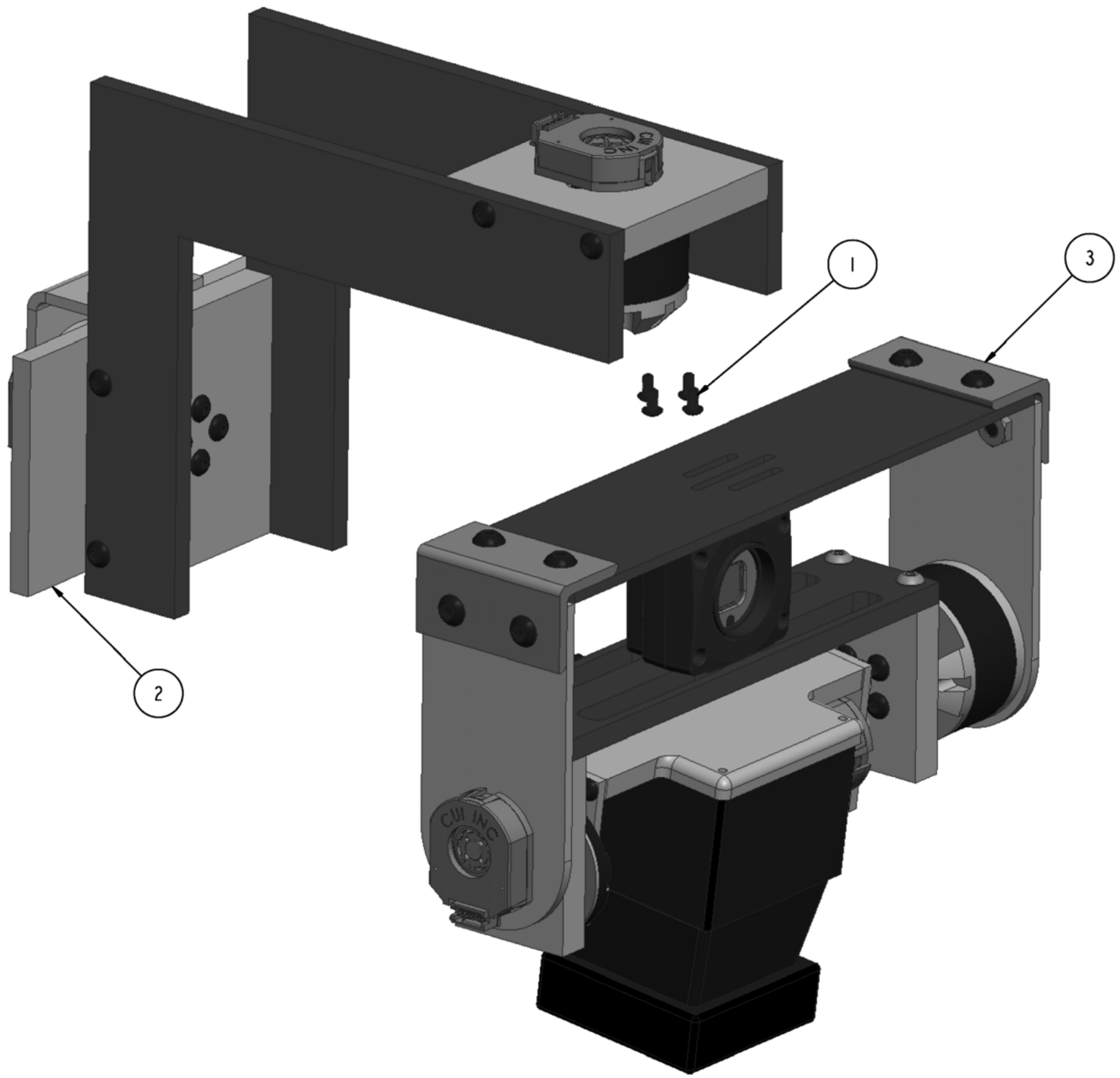

BILL OF MATERIALS				
#	P/N	SUPPLIER	DESCRIPTION	QTY
1	91239A113	MMC	Class 10.9 Steel Button-Head Socket Cap Screw, M3 Size, 8 mm Length, .5 mm Pitch	16
2	0100	BYU	Gimbal Upper Assembly	1
3	0200	BYU	Gimbal Camera Assembly	1

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.XX = ±.01		
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PART NAME: Gimbal Main Assembly

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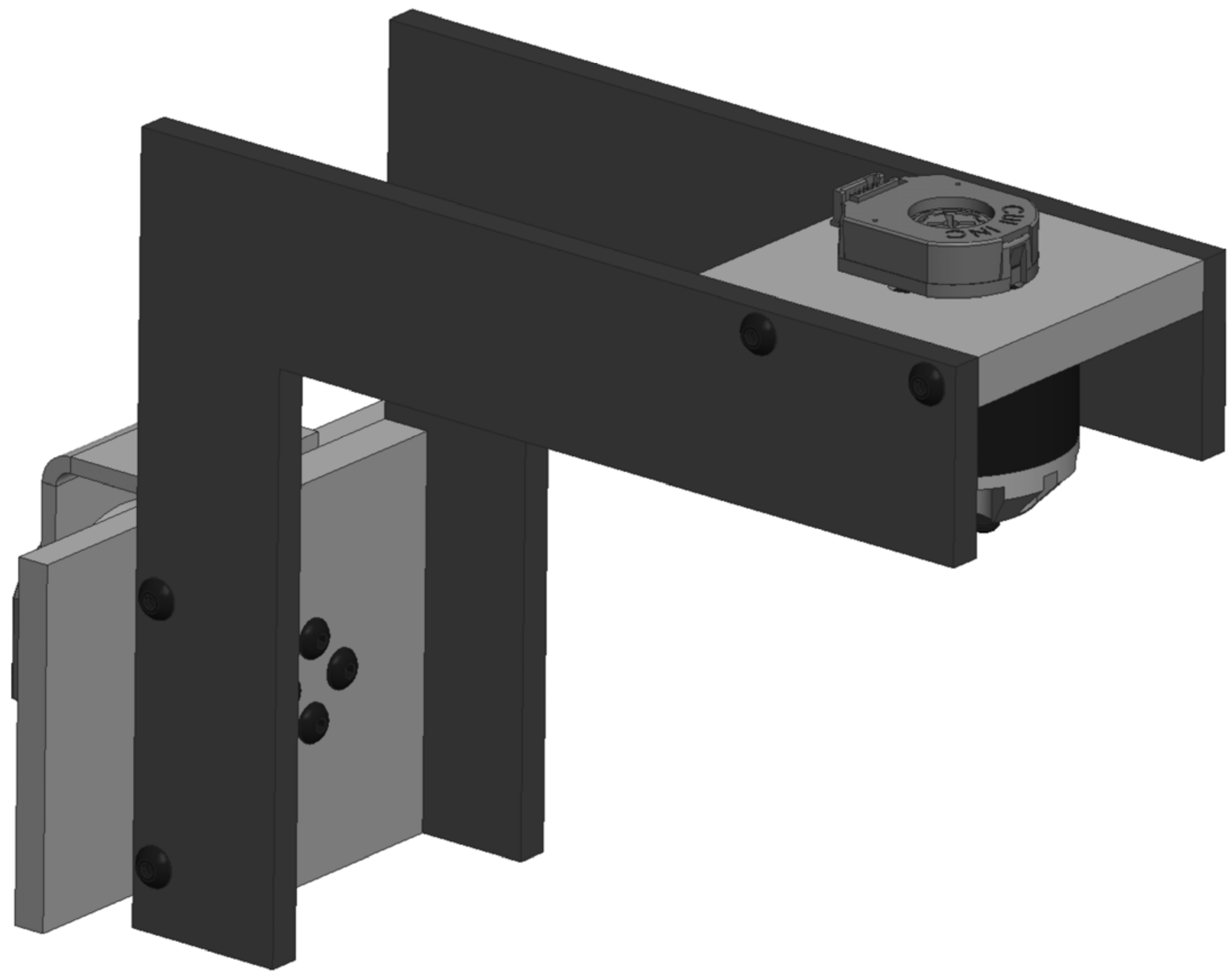

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PART NAME: Gimbal Upper Assembly

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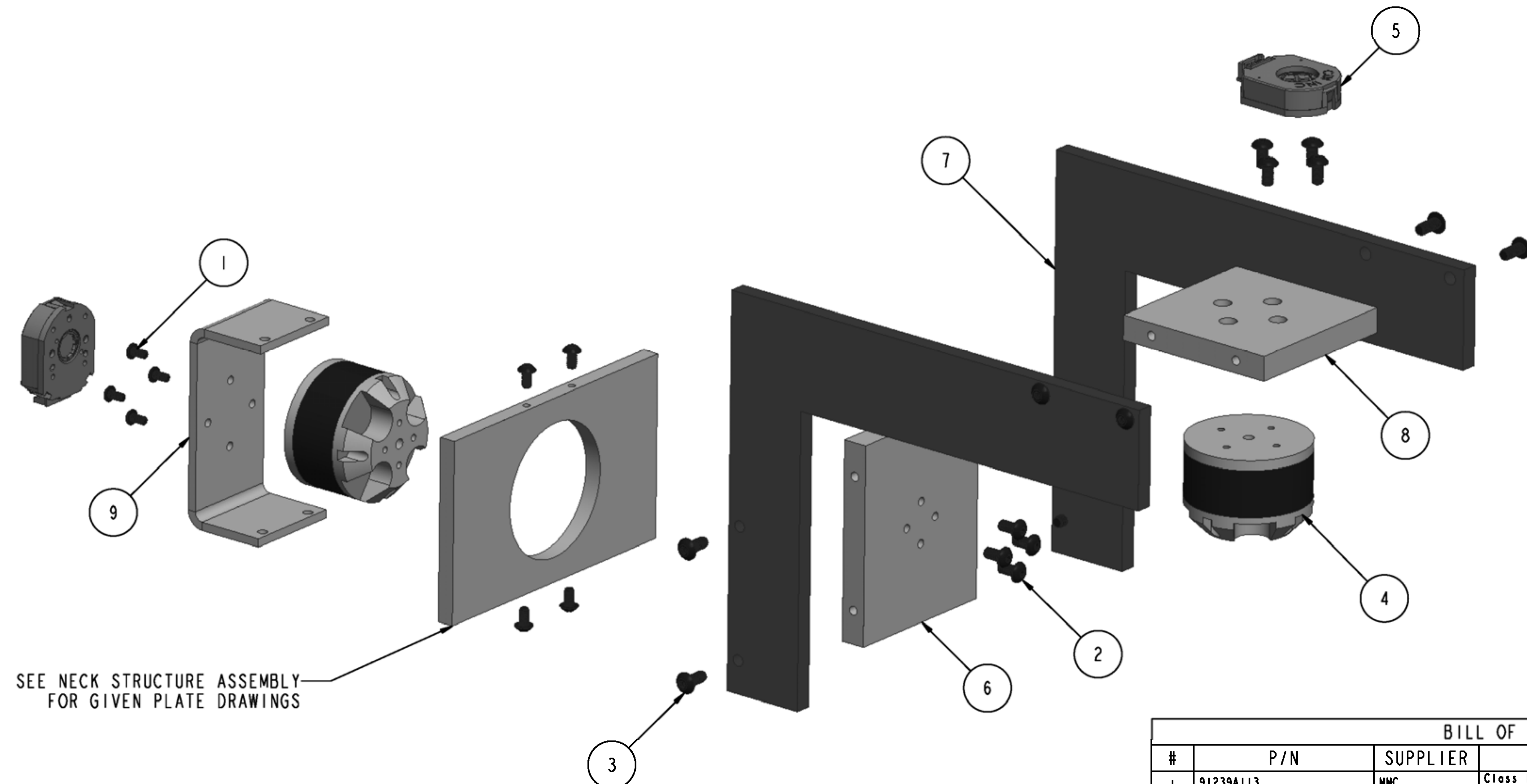

BILL OF MATERIALS

#	P/N	SUPPLIER	DESCRIPTION	QTY
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2	91239A117	MMC	Class 10.9 Steel Button-Head Socket Cap Screw, M3 Size, 12 mm Length, .5 mm Pitc	8
3	91255A192	MMC	Alloy Steel Button-Head Socket Cap Screw, Black-Oxide, 8-32 Thread, 3/8" Long	8
4	GBM4144-120T	iFlight	Brushless Gimbal Motor (Large)	2
5	AMT203-V	CUI INC.	AMT203 ABS SPI ENCODER	2
6	0101	BYU	BACK PLATE	1
7	0102	BYU	SIDE ARM	2
8	0103	BYU	TOP PLATE	1
9	0104	BYU	ROLL MOTOR BRACKET	1

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PART NAME: Gimbal Upper Assembly

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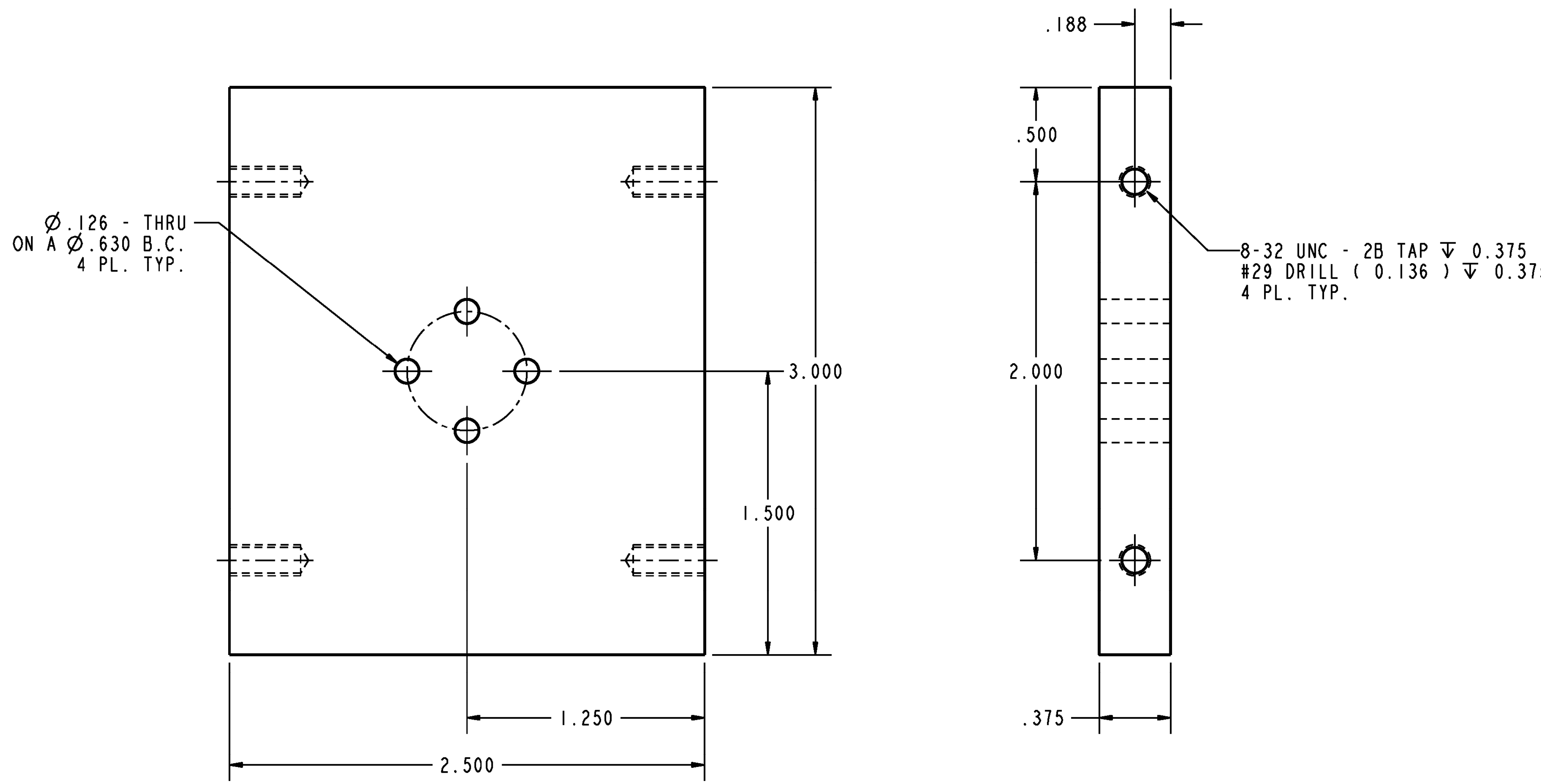

NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

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PART NAME: BACK PLATE

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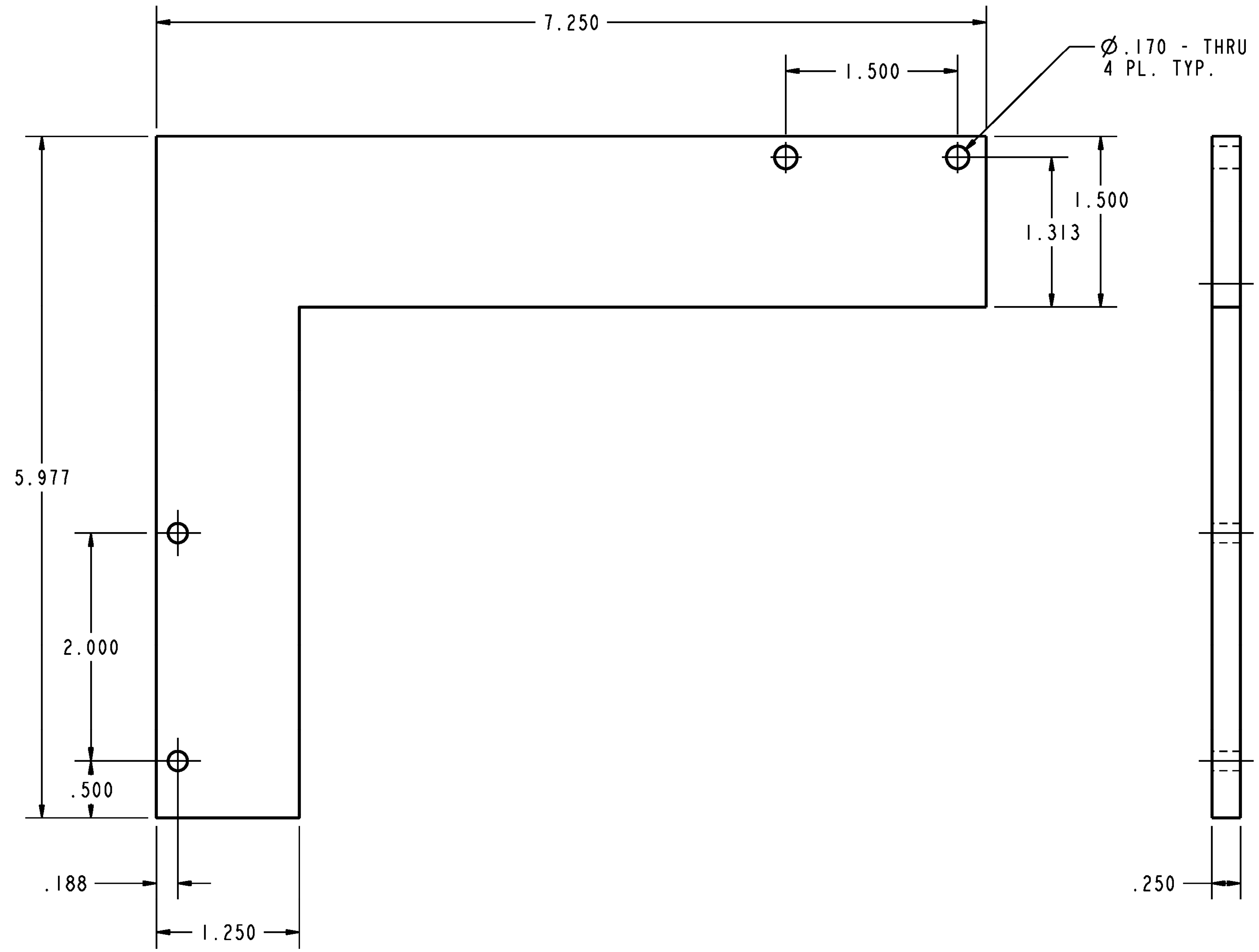

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PART NAME: SIDE ARM

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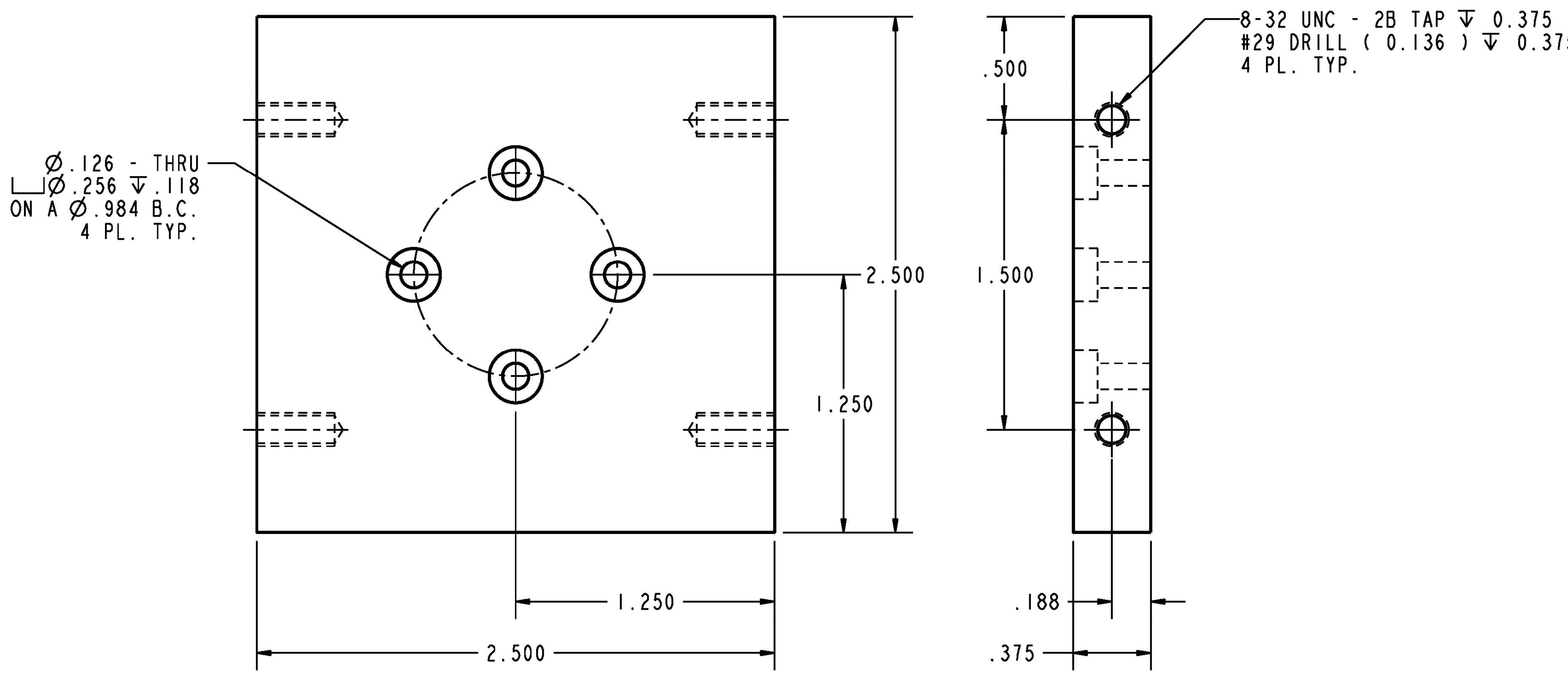

NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

U.O.S.: DIMENSIONS ARE IN INCHES

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PART NAME: TOP PLATE

DWG SIZE	SHEET 7 OF 22	PART NO.	REV.
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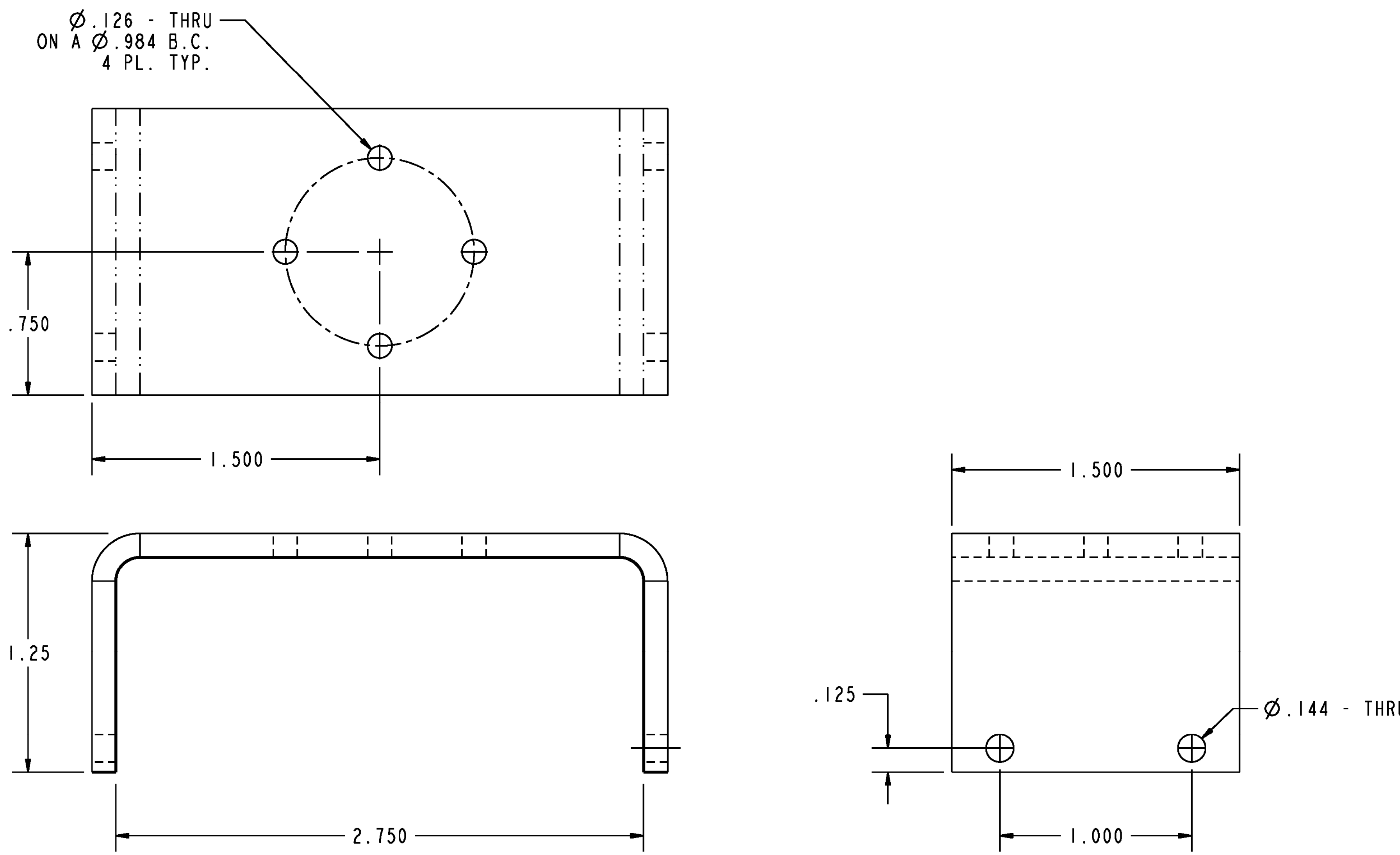

NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

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PART NAME: ROLL MOTOR BRACKET

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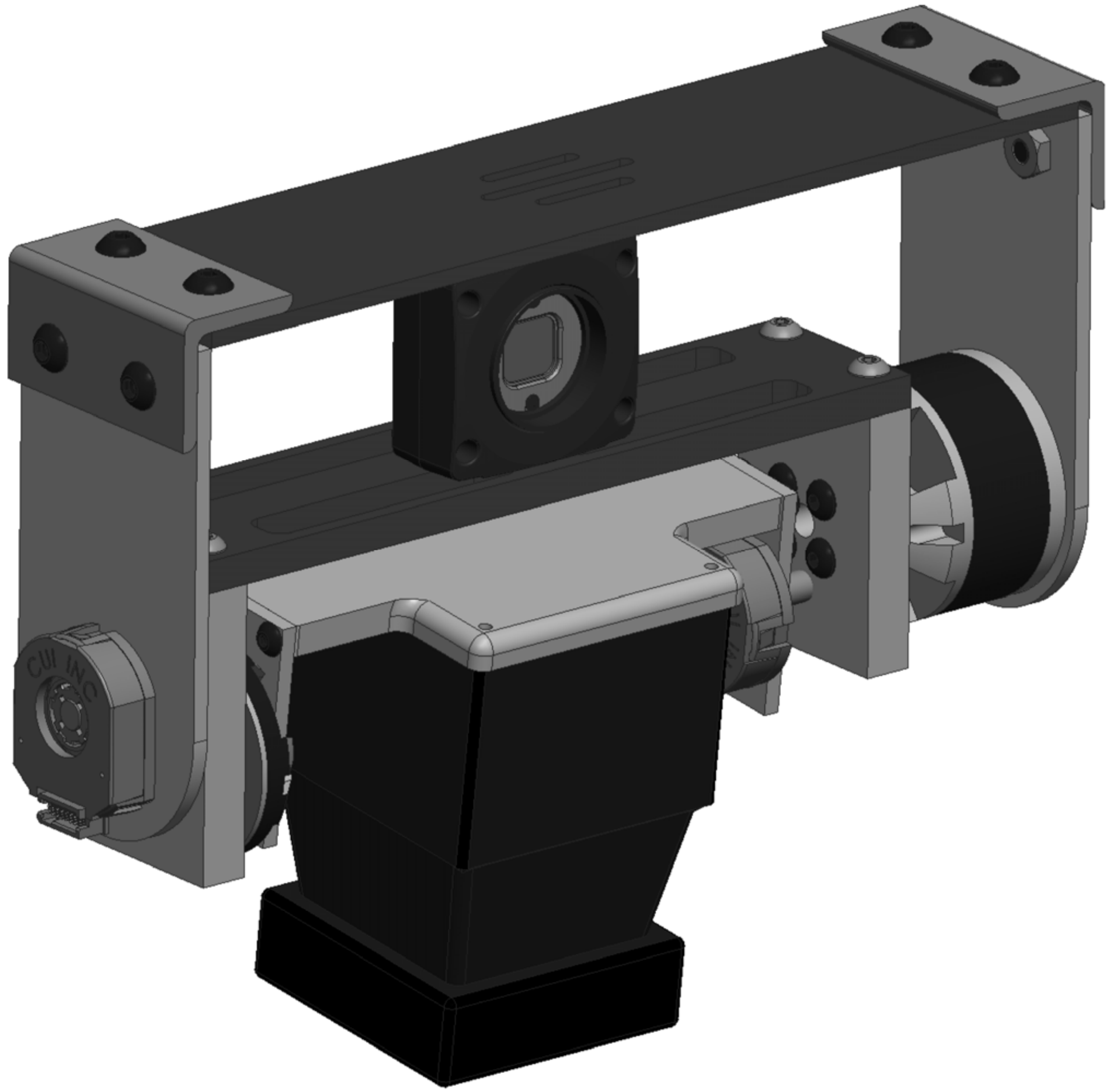
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



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NECK ATRONICS

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ± .1	X° ± 1°	X/X ± 1/32
.XX = ± .01		
.XXX = ± .005		
.XXXX = ± .0005		

ALL MACHINED SURFACES 32

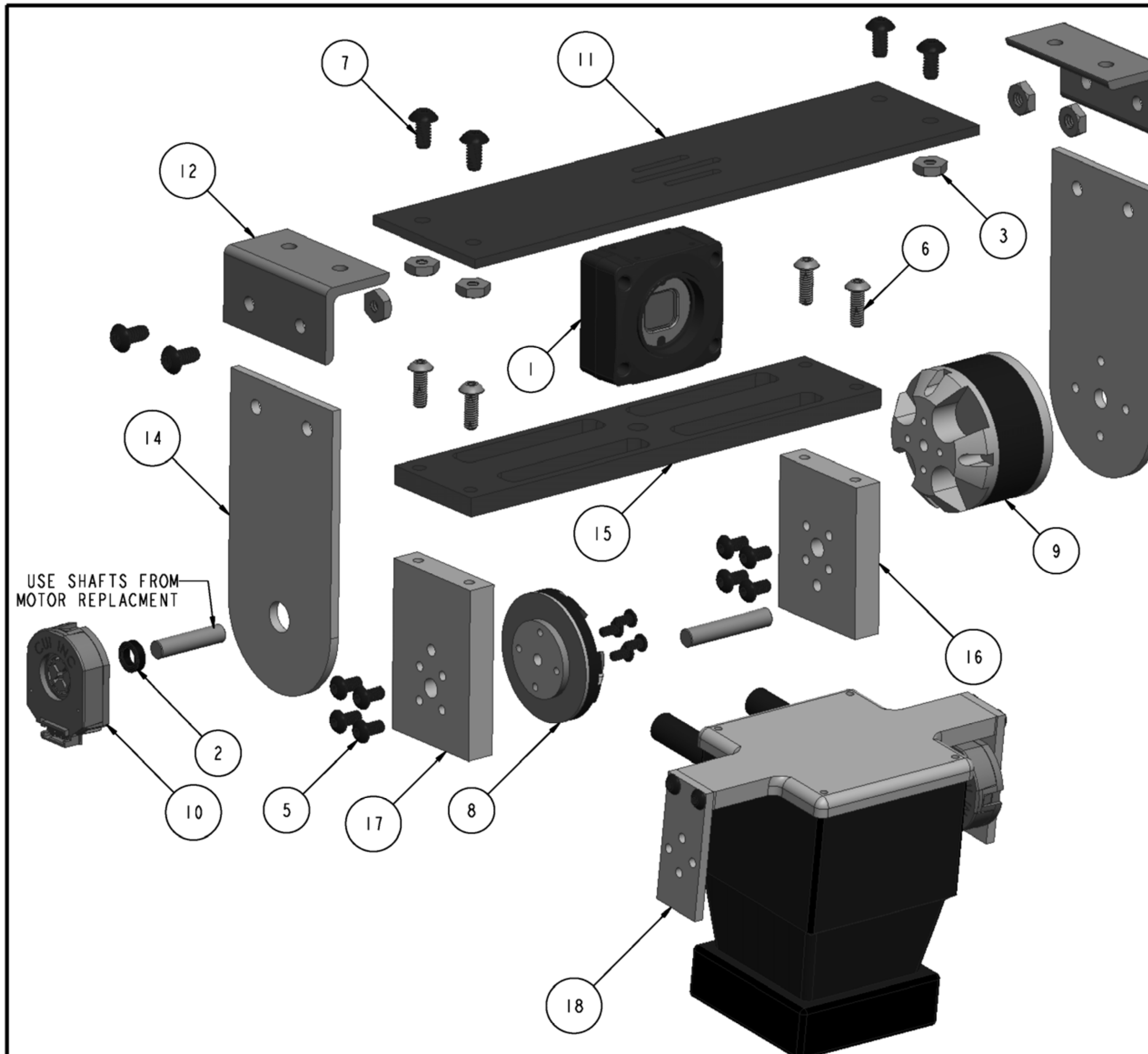
UNCONTROLLED IF PRINTED

DRAWN BY	CHECKED BY	DATE	SCALE
CGG	ADDAM R	04/10/14	NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: Gimbal Camera Assembly

DWG SIZE		PART NO.	REV.
B	SHEET 9 OF 22 / DO NOT SCALE DRAWING	0200	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



BILL OF MATERIALS

#	P/N	SUPPLIER	DESCRIPTION	QTY
1	CMLN-13S2M-CS	Point Grey	Chameleon Point Grey Camera	1
2	7804K100	MMC	Miniature High-Precision Stainless Steel Ball Bearing - ABEC-5, Double Shielded,	2
3	90480A011	MMC	Zinc-Plated Steel Machine Screw Hex Nut, 10-24 Thread Size, 3/8" Width, 1/8" Hei	8
4	91239A113	MMC	Class 10.9 Steel Button-Head Socket Cap Screw, M3 Size, 8 mm Length, .5 mm Pitch	8
5	91239A117	MMC	Class 10.9 Steel Button-Head Socket Cap Screw, M3 Size, 12 mm Length, .5 mm Pitc	8
6	91255A194	MMC	Black-Oxide, 8-32 Thread, 1/2" Long	4
7	91255A240	MMC	Alloy Steel Button-Head Socket Cap Screw, Black-Oxide, 10-24 Thread, 3/8" Long	8
8	GBM3506-130T	iFlight	Brushless Gimbal Motor (Small)	1
9	GBM4144-120T	iFlight	Brushless Gimbal Motor (Large)	1
10	AMT203-V	CUI INC.	AMT203 ABS SPI ENCODER	2
11	0201	BYU	CAMERA TOP PLATE	1
12	0202	BYU	CORNER BRACKET	2
13	0203	BYU	CAMERA SIDE PLATE (RIGHT)	1
14	0204	BYU	CAMERA SIDE PLATE (LEFT)	1
15	0205	BYU	CAMERA MOUNT PLATE	1
16	0206	BYU	CAMERA PITCH PLATE (RIGHT)	1
17	0207	BYU	CAMERA PITCH PLATE (LEFT)	1
18	0300	BYU	Gimbal Laser Assembly	1

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U.U.S.. DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

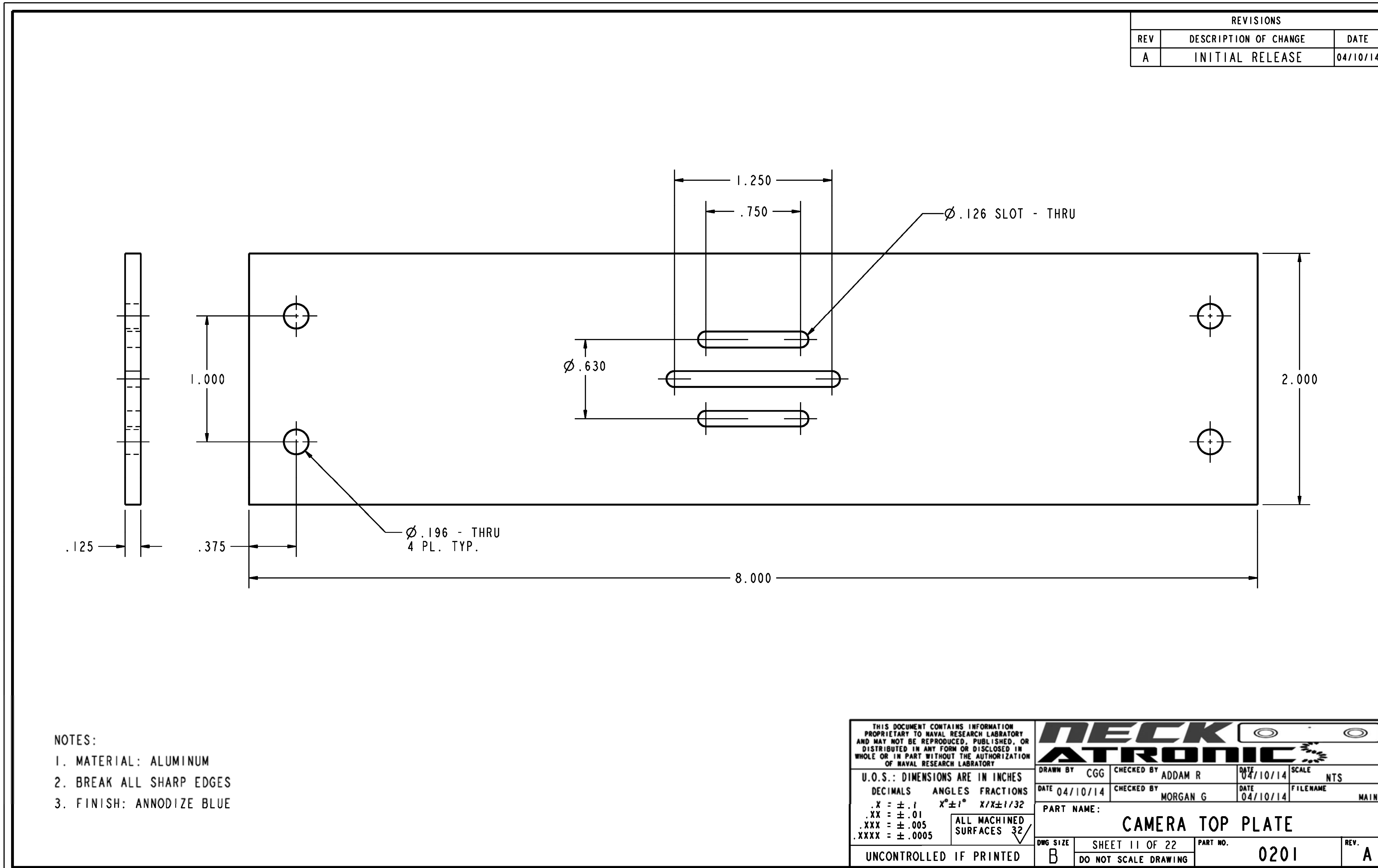
ALL MACHINED SURFACES 32√

UNCONTROLLED IF PRINTED

DRAWN BY CGG	CHECKED BY ADDAM R	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

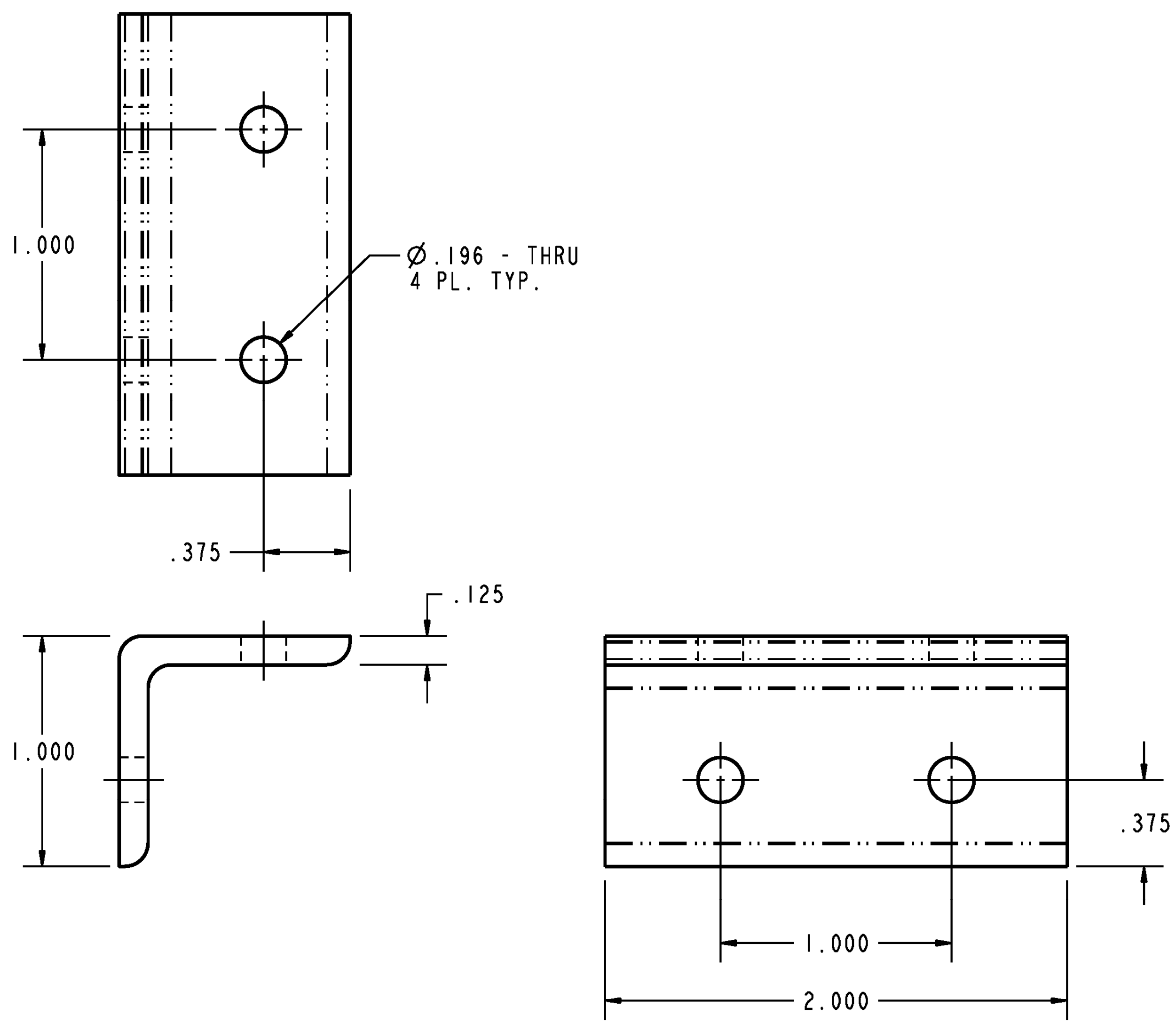
PART NAME: Gimbal Camera Assembly

DWG SIZE	SHEET 10 OF 22	PART NO.	REV.
B	DO NOT SCALE DRAWING	0200	A



NOTES:
1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

NECK ATRONICS

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

ALL MACHINED SURFACES 32

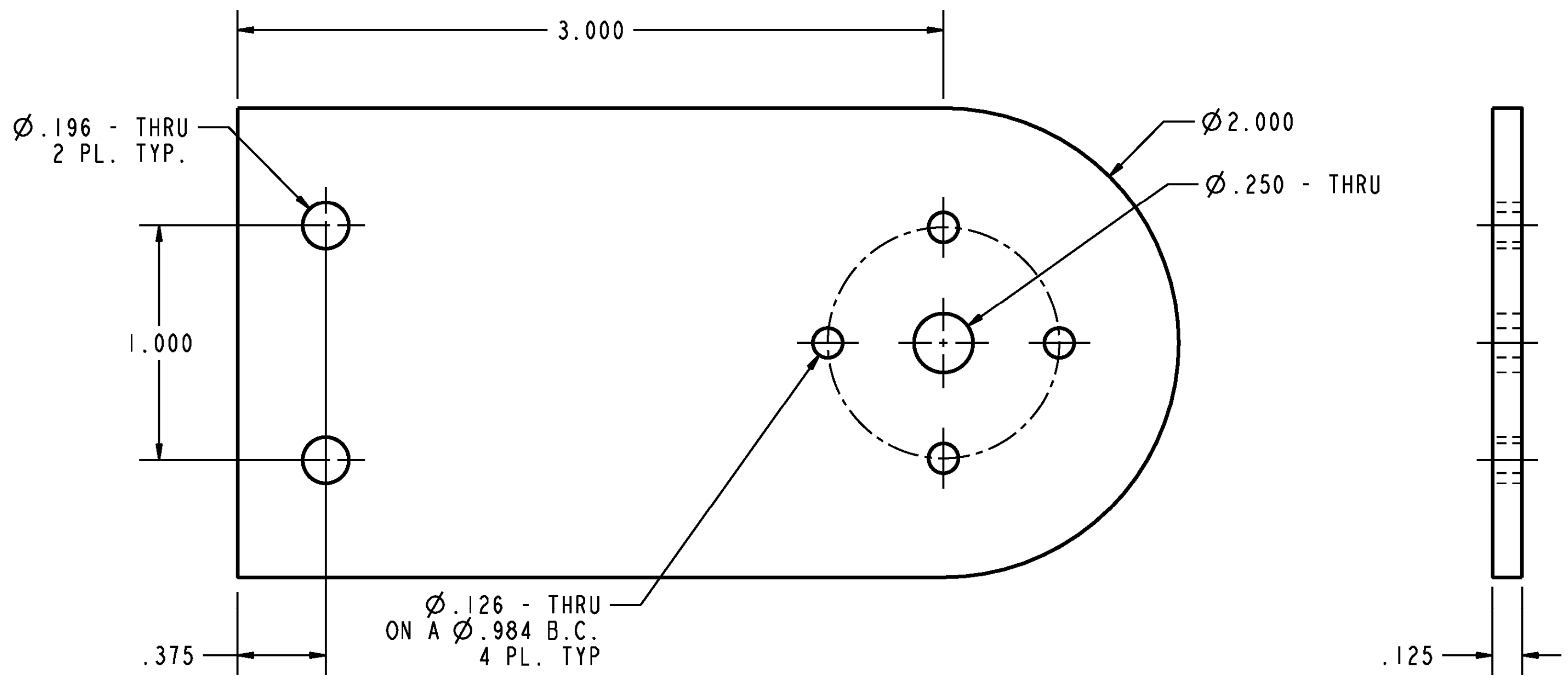
UNCONTROLLED IF PRINTED

DRAWN BY CGG	CHECKED BY ADDAM R	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: CORNER BRACKET

DWG SIZE		PART NO.	REV.
B	SHEET 12 OF 22 / DO NOT SCALE DRAWING	0202	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS: .X = ±.1, .XX = ±.01, .XXX = ±.005, .XXXX = ±.0005
ANGLES: X° ±1°
FRACTIONS: X/X ±1/32
ALL MACHINED SURFACES 32√

UNCONTROLLED IF PRINTED

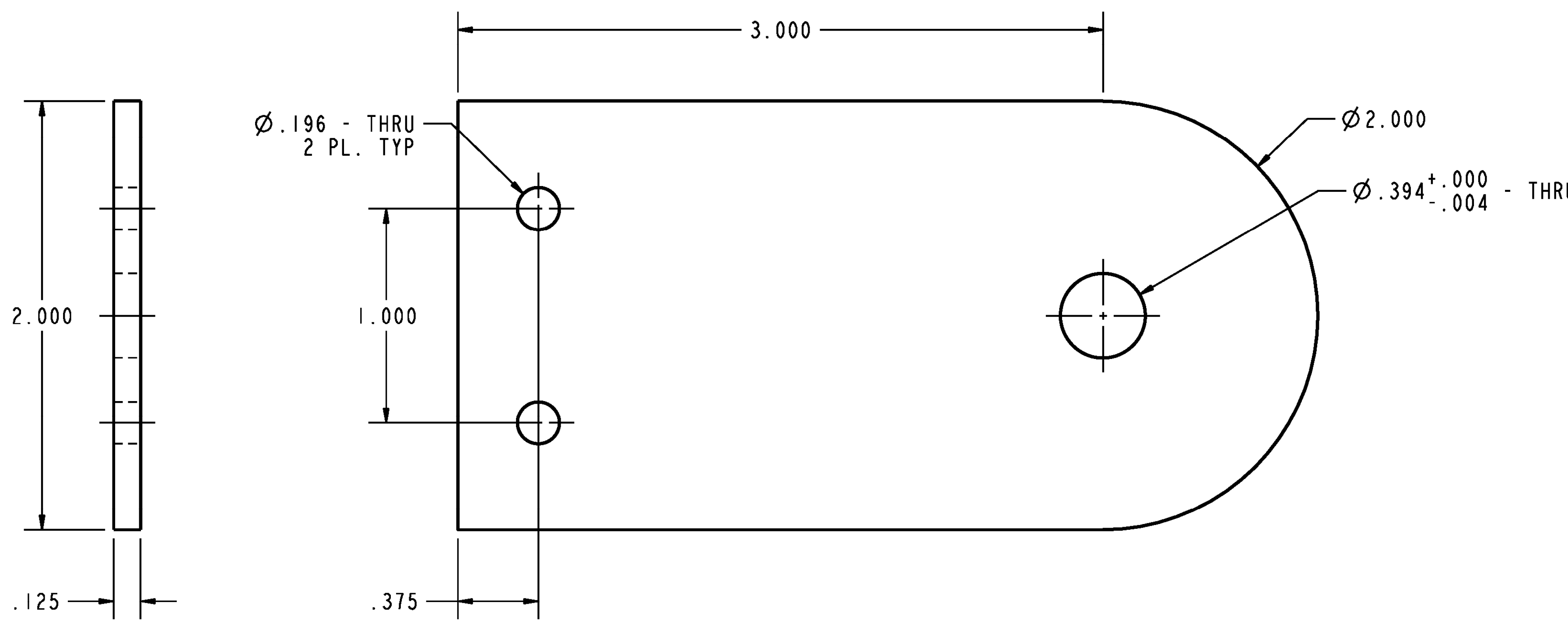
NECK ATRONICS

DRAWN BY CGG	CHECKED BY ADDAM R	DATE 04/10/14	SCALE NTS
DATE 04/14/10	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: CAMERA SIDE PLATE (RIGHT)

DWG SIZE		PART NO.	REV.
B	SHEET 13 OF 22 / DO NOT SCALE DRAWING	0203	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

ALL MACHINED SURFACES 32

UNCONTROLLED IF PRINTED

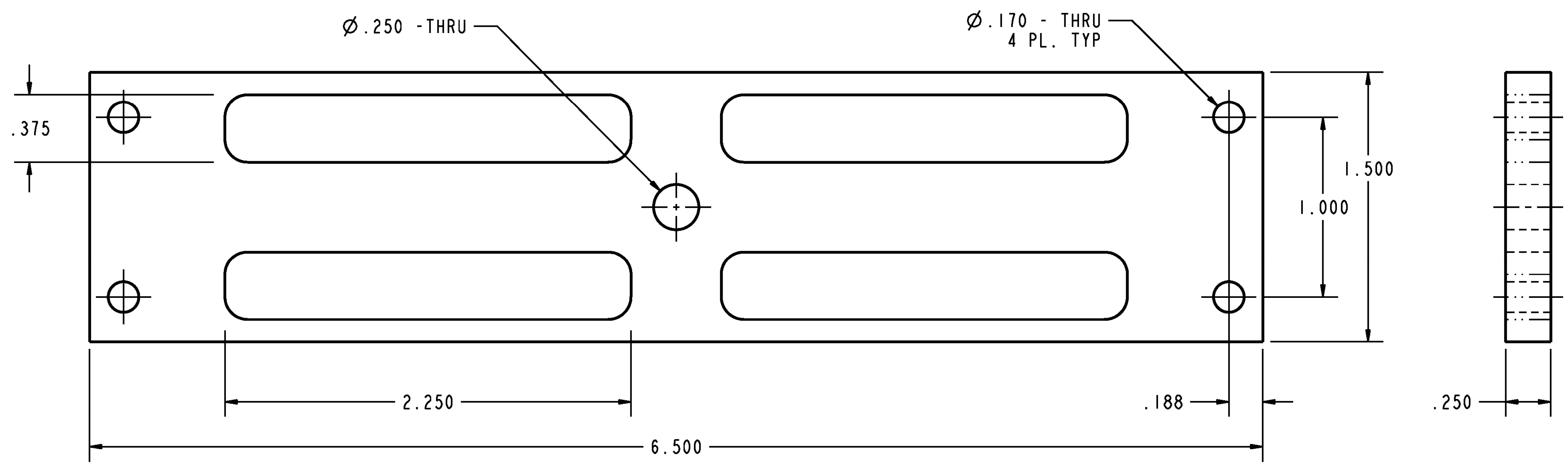
NECK ATRONICS

DRAWN BY CGG	CHECKED BY ADDAM R	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: CAMERA SIDE PLATE (LEFT)

DWG SIZE		PART NO.	REV.
B	SHEET 14 OF 22 / DO NOT SCALE DRAWING	0204	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

ALL MACHINED SURFACES 32

UNCONTROLLED IF PRINTED

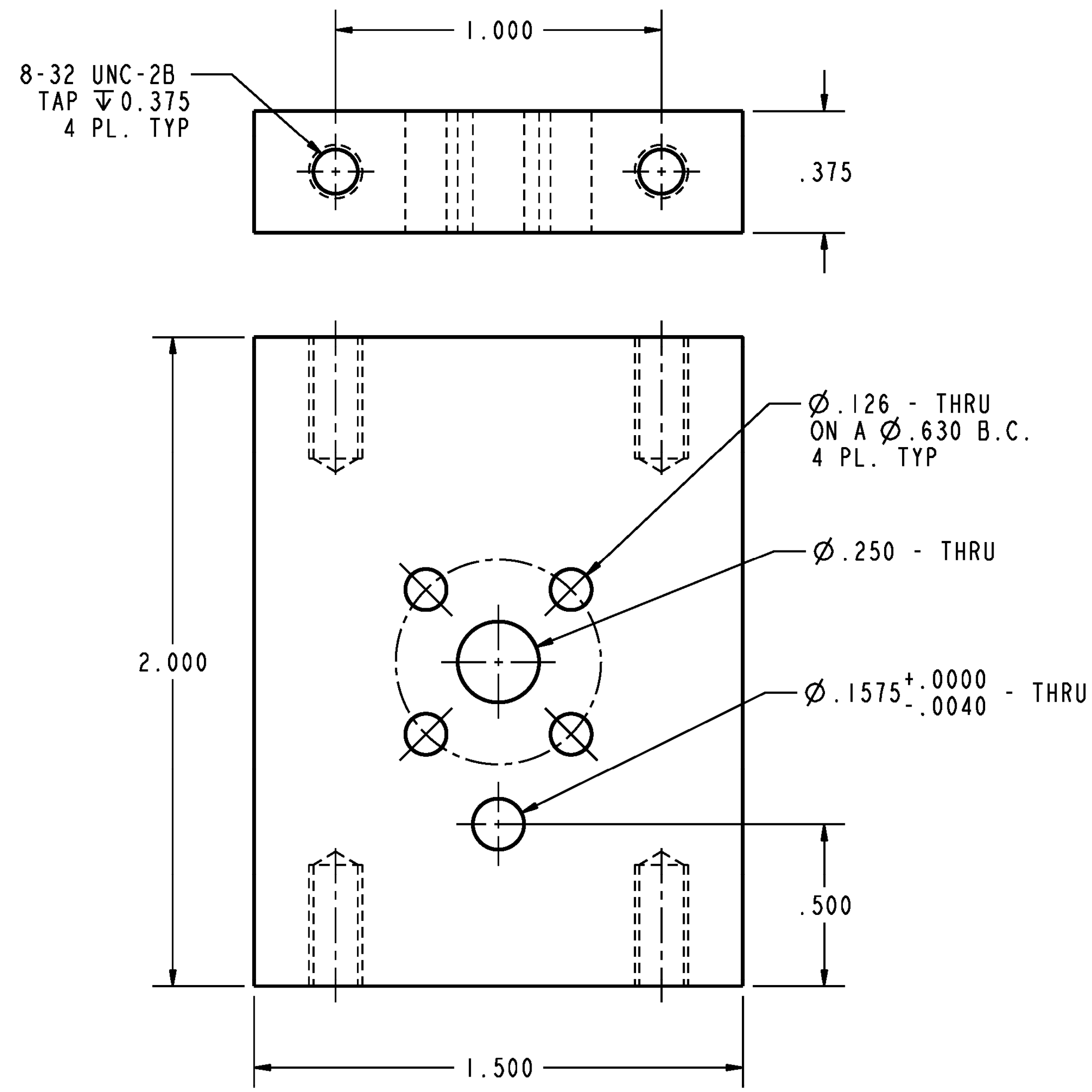
NECK ATRONICS

DRAWN BY CGG	CHECKED BY ADDAM R	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: CAMERA MOUNT PLATE

DWG SIZE	SHEET 15 OF 22	PART NO.	REV.
B	DO NOT SCALE DRAWING	0205	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:
1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

NECK ATRONICS

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS: .X = ±.1, .XX = ±.01, .XXX = ±.005, .XXXX = ±.0005
ANGLES: X° ±1°
FRACTIONS: X/X ±1/32

ALL MACHINED SURFACES 32

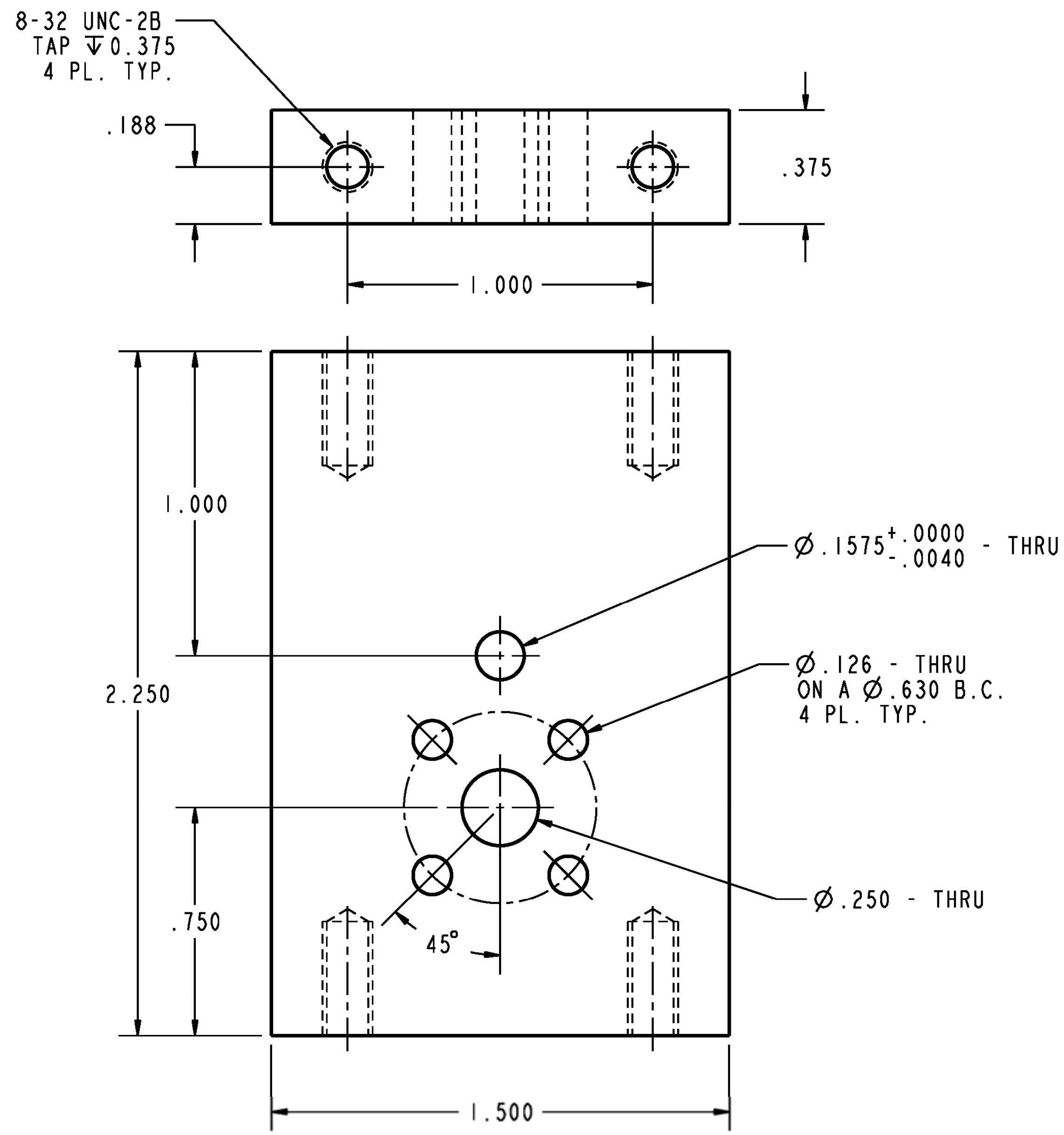
UNCONTROLLED IF PRINTED

DRAWN BY CGG	CHECKED BY ADDAM R	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: CAMERA PITCH PLATE (RIGHT)

DWG SIZE	SHEET	PART NO.	REV.
B	SHEET 16 OF 22 — DO NOT SCALE DRAWING	0206	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

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NECKATRONICS

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

ALL MACHINED SURFACES 32√

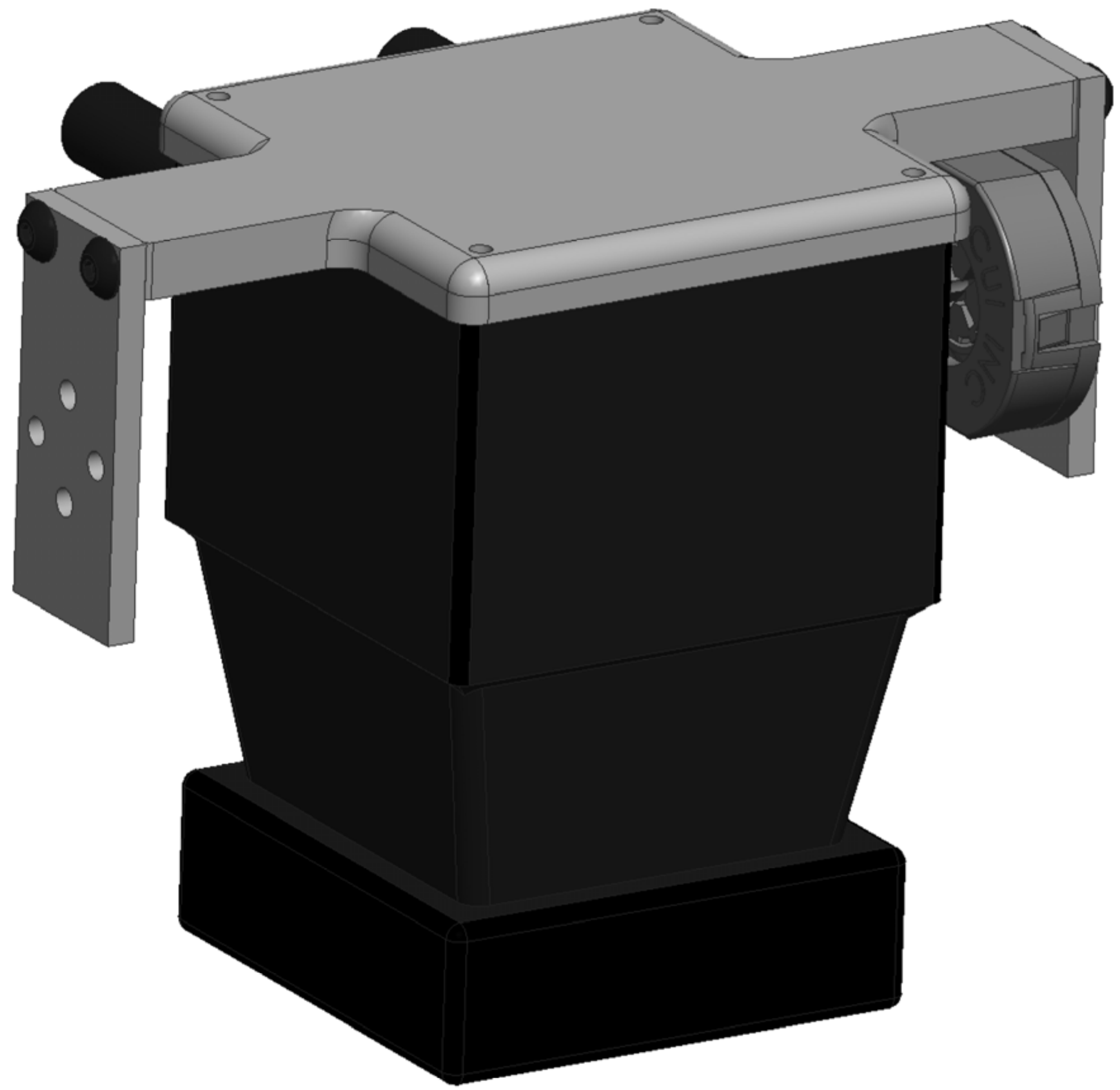
UNCONTROLLED IF PRINTED

DRAWN BY CGG	CHECKED BY ADDAM R	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: CAMERA PITCH PLATE (LEFT)

DWG SIZE	SHEET 17 OF 22	PART NO.	REV.
B	DO NOT SCALE DRAWING	0207	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



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U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

ALL MACHINED SURFACES 32√

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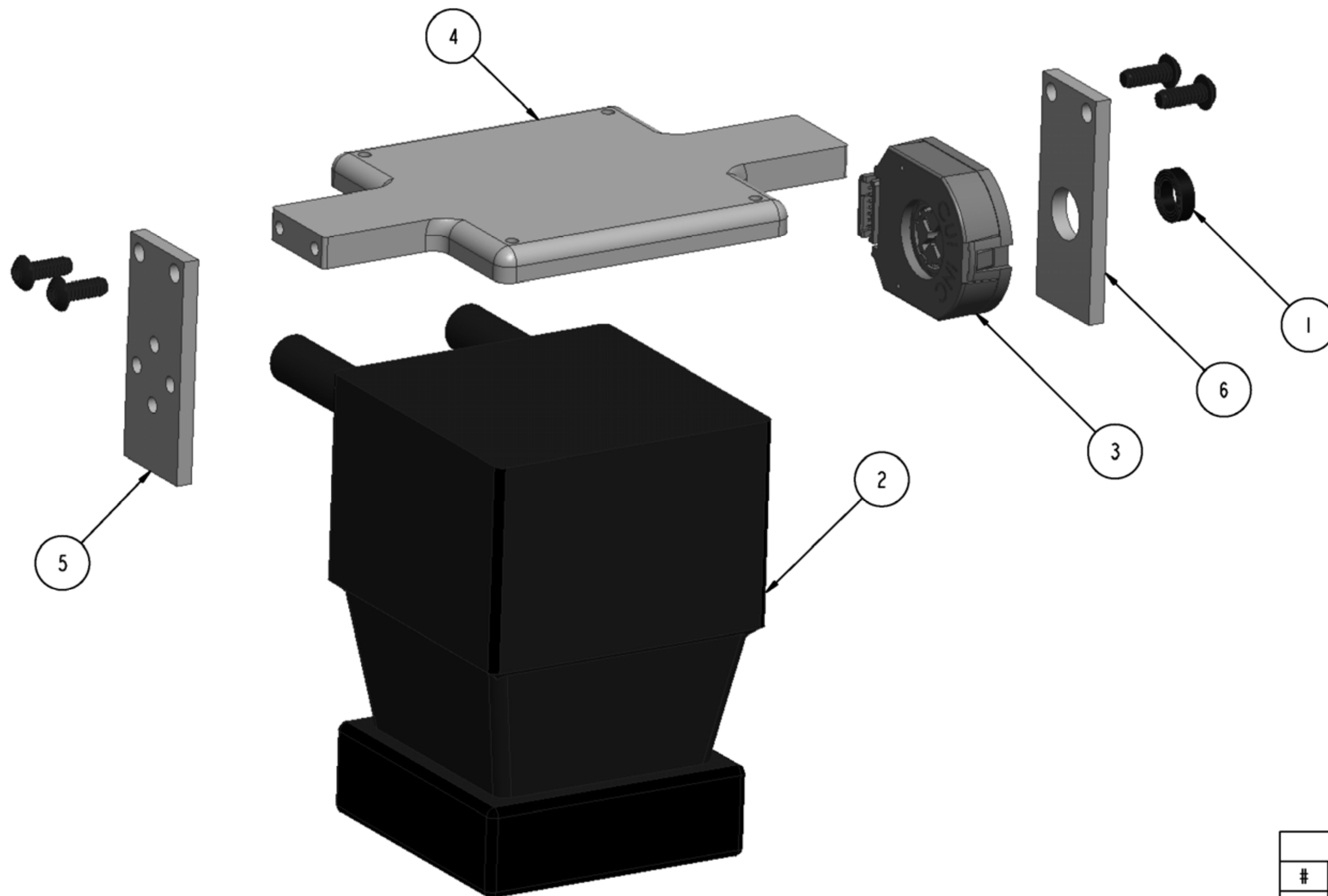
NECK ATRONICS

DRAWN BY CGG	CHECKED BY JAMES B	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: Gimbal Laser Assembly

DWG SIZE		PART NO.	REV.
B	SHEET 18 OF 22 / DO NOT SCALE DRAWING	0300	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



BILL OF MATERIALS				
#	P/N	SUPPLIER	DESCRIPTION	QTY
1	7804K100	MMC	Miniature High-Precision Stainless Steel Ball Bearing - ABEC-5, Double Shielded,	1
2	UTM-30LX	HOKUYO	LIDAR - Scanning Range Finder	1
3	AMT203-V	CUI INC.	AMT203 ABS SPI ENCODER	1
4	0301	BYU	LASER TOP PLATE	1
5	0302	BYU	LASER SIDE PLATE (LEFT)	1
6	0303	BYU	LASER SIDE PLATE (RIGHT)	1

NECK ATRONICS

DRAWN BY CGG	CHECKED BY JAMES B	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

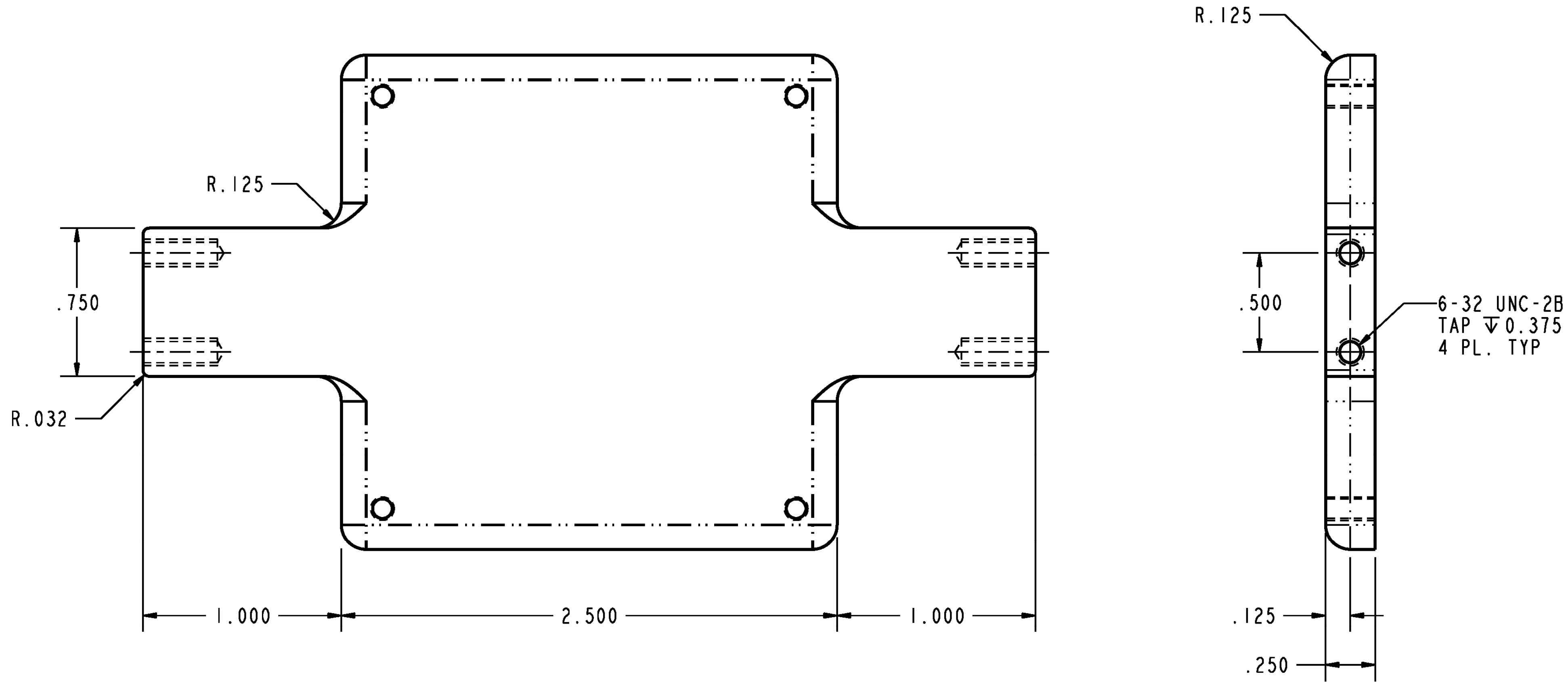
ALL MACHINED SURFACES 32√

PART NAME: Gimbal Laser Assembly

DWG SIZE		PART NO.	REV.
B	SHEET 19 OF 22 / DO NOT SCALE DRAWING	0300	A

UNCONTROLLED IF PRINTED

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

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U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

ALL MACHINED SURFACES 32

UNCONTROLLED IF PRINTED

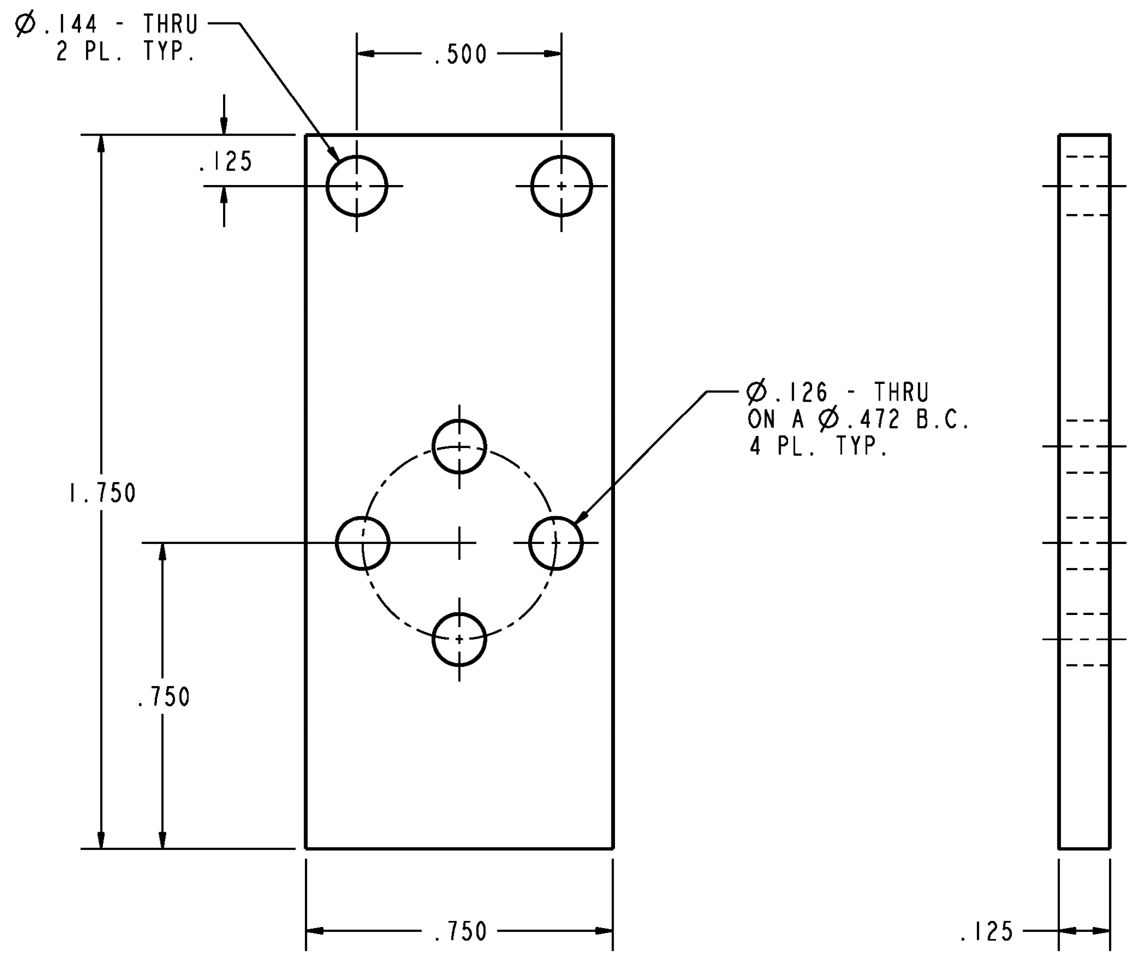
NECK ATRONICS

DRAWN BY CGG	CHECKED BY JAMES B	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: LASER TOP PLATE

DWG SIZE	SHEET 20 OF 22	PART NO.	REV.
B	DO NOT SCALE DRAWING	0301	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

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NECK ATRONICS

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS	ANGLES	FRACTIONS
.X = ±.1	X°±1°	X/X±1/32
.XX = ±.01		
.XXX = ±.005		
.XXXX = ±.0005		

ALL MACHINED SURFACES 32

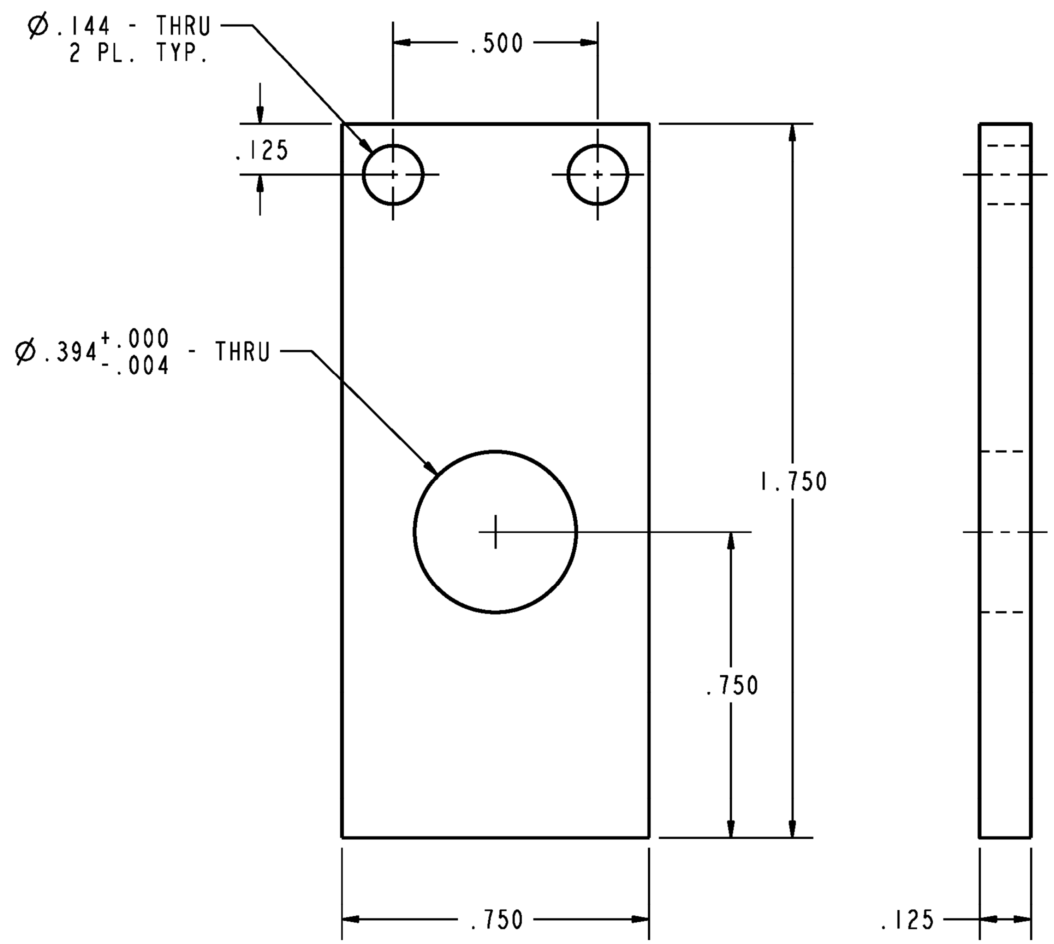
UNCONTROLLED IF PRINTED

DRAWN BY CGG	CHECKED BY JAMES B	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: LASER SIDE PLATE (LEFT)

DWG SIZE		PART NO.	REV.
B	SHEET 21 OF 22 / DO NOT SCALE DRAWING	0302	A

REVISIONS		
REV	DESCRIPTION OF CHANGE	DATE
A	INITIAL RELEASE	04/10/14



NOTES:

1. MATERIAL: ALUMINUM
2. BREAK ALL SHARP EDGES
3. FINISH: ANNODIZE BLUE

U.O.S.: DIMENSIONS ARE IN INCHES

DECIMALS .X = ±.1 .XX = ±.01 .XXX = ±.005 .XXXX = ±.0005

ANGLES X° ± 1°

FRACTIONS X/X ± 1/32

ALL MACHINED SURFACES 32

UNCONTROLLED IF PRINTED

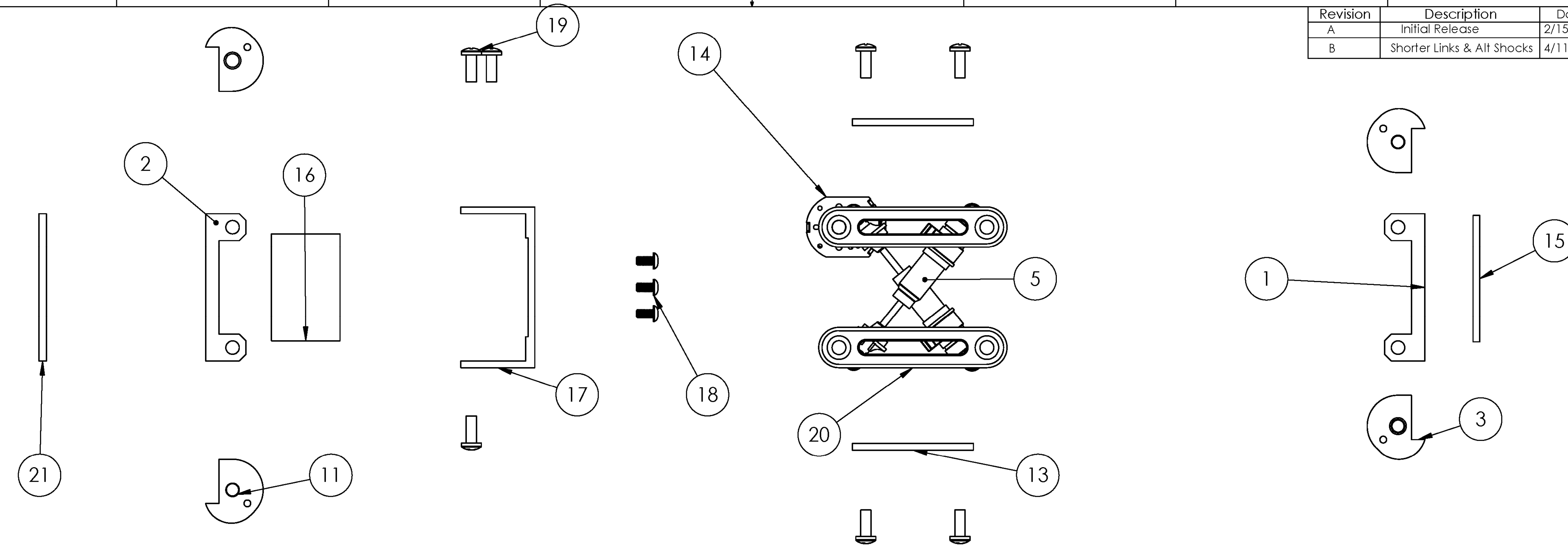
NECK ATRONICS

DRAWN BY CGG	CHECKED BY JAMES B	DATE 04/10/14	SCALE NTS
DATE 04/10/14	CHECKED BY MORGAN G	DATE 04/10/14	FILENAME MAIN

PART NAME: LASER SIDE PLATE (RIGHT)

DWG SIZE		PART NO.	REV.
B	SHEET 22 OF 22 / DO NOT SCALE DRAWING	0303	A

Revision	Description	Date
A	Initial Release	2/15/2014
B	Shorter Links & Alt Shocks	4/11/2014



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	Final Base Plate	Config 1	1
2	Final Base Plate	Config 2	1
3	HardShockMount	Config 2	16
5	Traxxas Tall		4
7	NylonSpacer	Shock Alignment Spacer 2	4
8	NylonSpacer	Shock Alignment Spacer 1	12
9	NylonSpacer	Shock Mount Spacer 1	8
10	NylonSpacer	Shock Mount SPacer 2	8
11	Steel Shaft	0.25 OD Steel Shaft	3
12	Steel Shaft	0.25 OD Steel Shaft for Encoder	1
13	Twsiting Plate	Connects Links - Prevents Twsiting	2
14	AMT203 Optical Encoder		1
15	LexanSpacer	Flush mount to Allegro Dog	1
16	Motor Thrust Spacer	Collar that rides around motor	1
17	NEW MOUNT PLATE	Connects GImbal to Neck Structure	1
18	91239A140_1	Steel Button-Head Socket Cap Screw, M4	4
19	CR-PHMS 0.19-24x0.5x0.5-C	Steel Cap Screw - 10-24 - 1/2"	13
20	Short Link		4
21	5909K43-5909K56	Thrust Bearing Assembly	1

U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001

MATERIAL: 6061 Aluminum
FINISH: Anodized Blue 32
DO NOT SCALE DRAWING

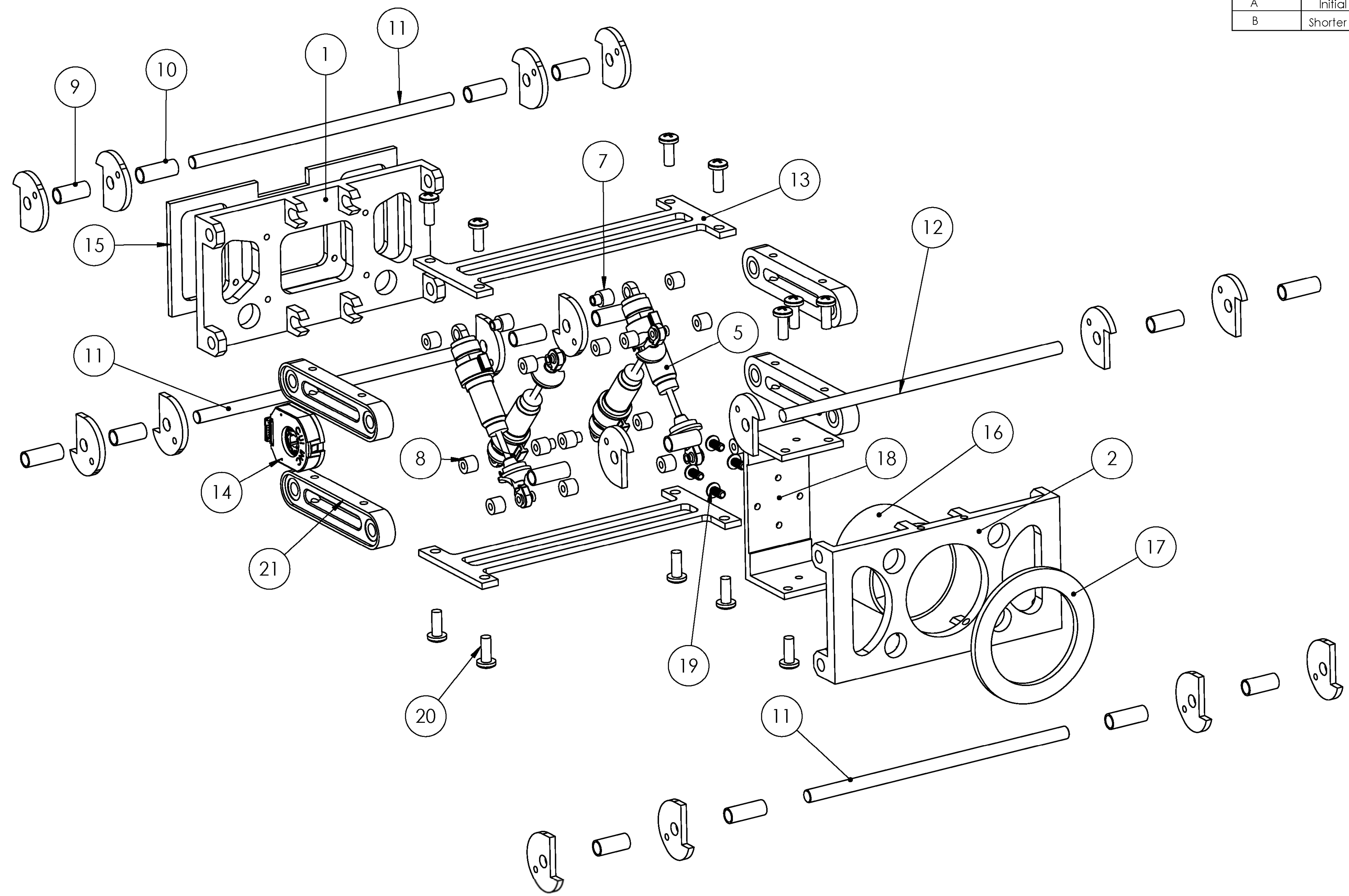
	NAME	DATE
DRAWN	Morgan Gillespie	4/11/2014
CHECKED	Jordan McDonald	4/11/2014
APPROVED	James Brady	4/11/2014

NECK ATRONICS

Part Name:
Final Neck Structure Assembly

SIZE B | SCALE: 1:2 | SHEET 1 OF 2 | REV B

Revision	Description	Date
A	Initial Release	2/15/2014
B	Shorter Links & Alt Shocks	4/11/2014



U.O.S.: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ±1/32 .X ±0.1 .XX ±0.01 .XXX ±0.005 .XXXX±0.001		NAME	DATE
	DRAWN	Morgan Gillespie	4/11/2014
	CHECKED	Jordan McDonald	4/11/2014
	APPROVED	James Brady	4/11/2014
MATERIAL: 6061 Aluminum			
FINISH: Anodized Blue 32			
DO NOT SCALE DRAWING			

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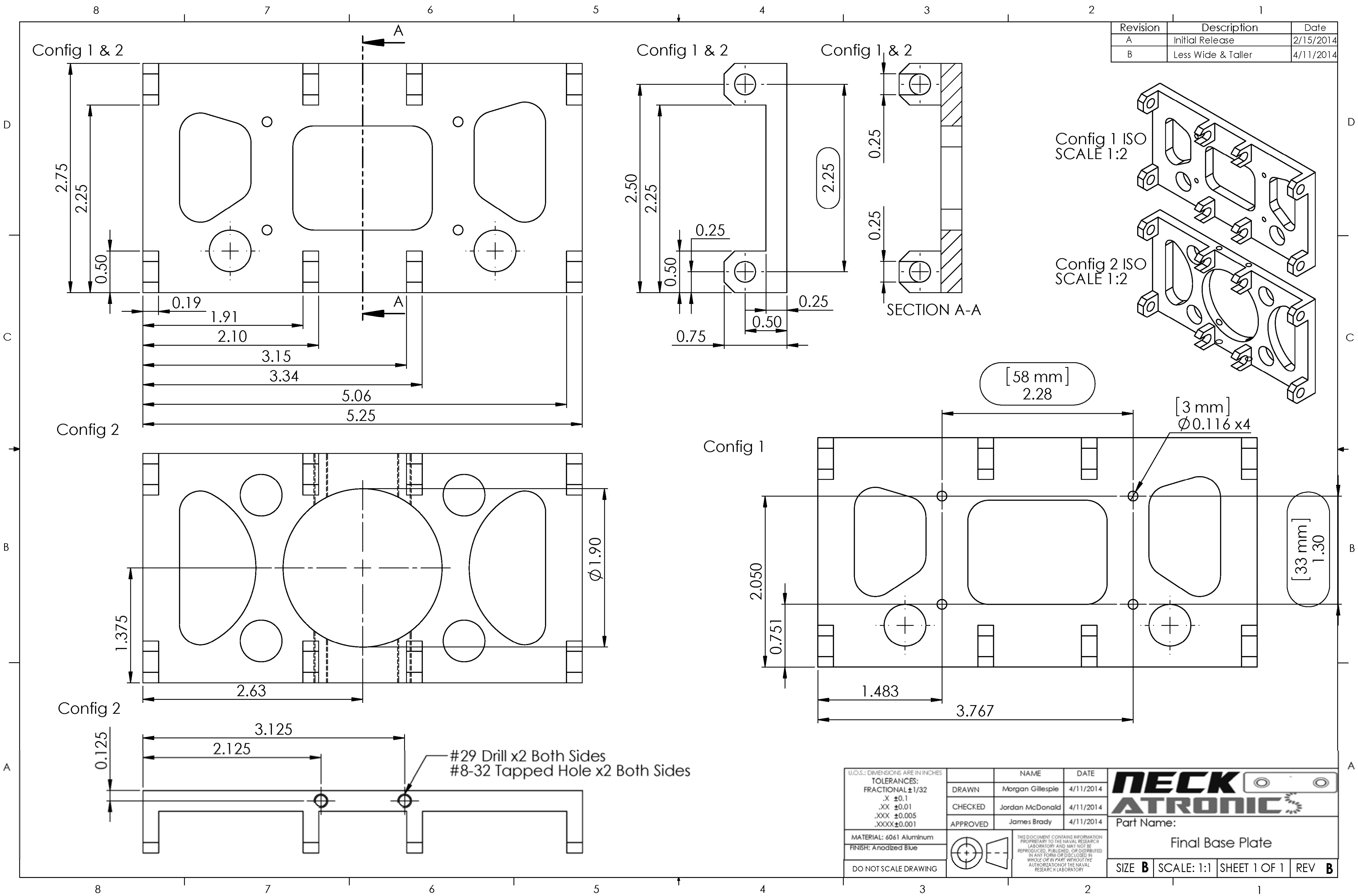
NECK ATRONICS

Part Name:

Final Neck Structure Assembly

SIZE B	SCALE: 1:5	SHEET 2 OF 2	REV B


Revision | Description | Date
A | Initial Release | 2/15/2014
B | Less Wide & Taller | 4/11/2014
Config 1 & 2
Config 1 & 2
Config 1 & 2
SECTION A-A
Config 1 ISO SCALE 1:2
Config 2 ISO SCALE 1:2
2.75
2.25
0.50
0.19
1.91
2.10
3.15
3.34
5.06
5.25
2.50
2.25
2.25
0.25
0.50
0.25
0.50
0.75
0.25
0.25
Config 2
Ø1.90
1.375
2.63
Config 1
[58 mm] 2.28
[3 mm] Ø0.116 x4
[33 mm] 1.30
2.050
0.751
1.483
3.767
Config 2
0.125
3.125
2.125
#29 Drill x2 Both Sides
#8-32 Tapped Hole x2 Both Sides
U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001
MATERIAL: 6061 Aluminum
FINISH: Anodized Blue
DO NOT SCALE DRAWING
NAME | DATE
DRAWN | Morgan Gillespie | 4/11/2014
CHECKED | Jordan McDonald | 4/11/2014
APPROVED | James Brady | 4/11/2014
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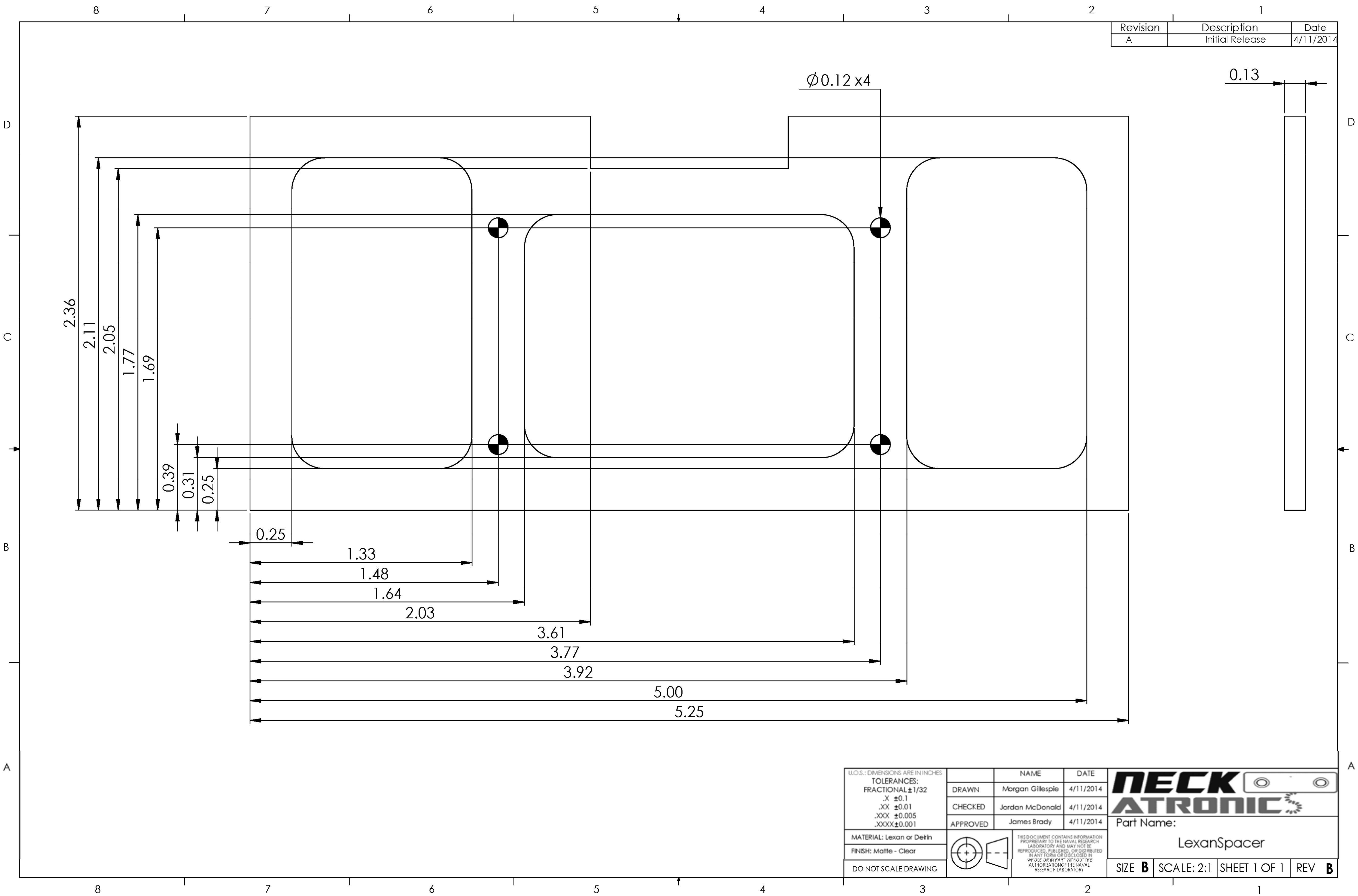
NECK ATRONICS
Part Name:
Final Base Plate
SIZE B
SCALE: 1:1
SHEET 1 OF 1
REV B


Revision | Description | Date
A | Initial Release | 4/11/2014
∅0.12 x4
0.13
2.36
2.11
2.05
1.77
1.69
0.39
0.31
0.25
0.25
1.33
1.48
1.64
2.03
3.61
3.77
3.92
5.00
5.25
U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001
MATERIAL: Lexan or Delrin
FINISH: Matte - Clear
DO NOT SCALE DRAWING
NAME | DATE
DRAWN | Morgan Gillespie | 4/11/2014
CHECKED | Jordan McDonald | 4/11/2014
APPROVED | James Brady | 4/11/2014
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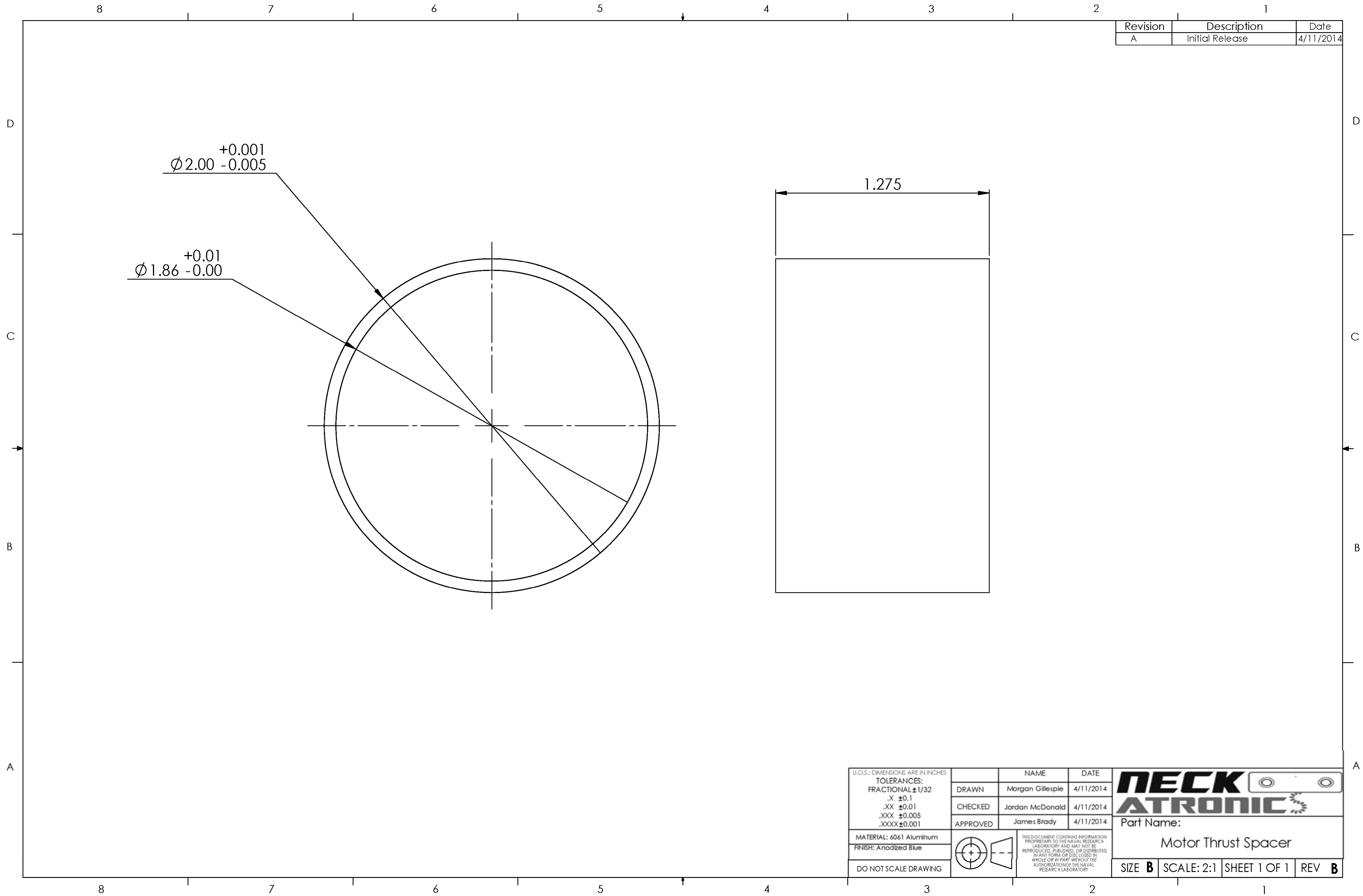
NECK ATRONICS
Part Name:
LexanSpacer
SIZE B
SCALE: 2:1
SHEET 1 OF 1
REV B


Revision
Description
Date
A
Initial Release
4/11/2014
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∅2.00 -0.005
+0.01
∅1.86 -0.00
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U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
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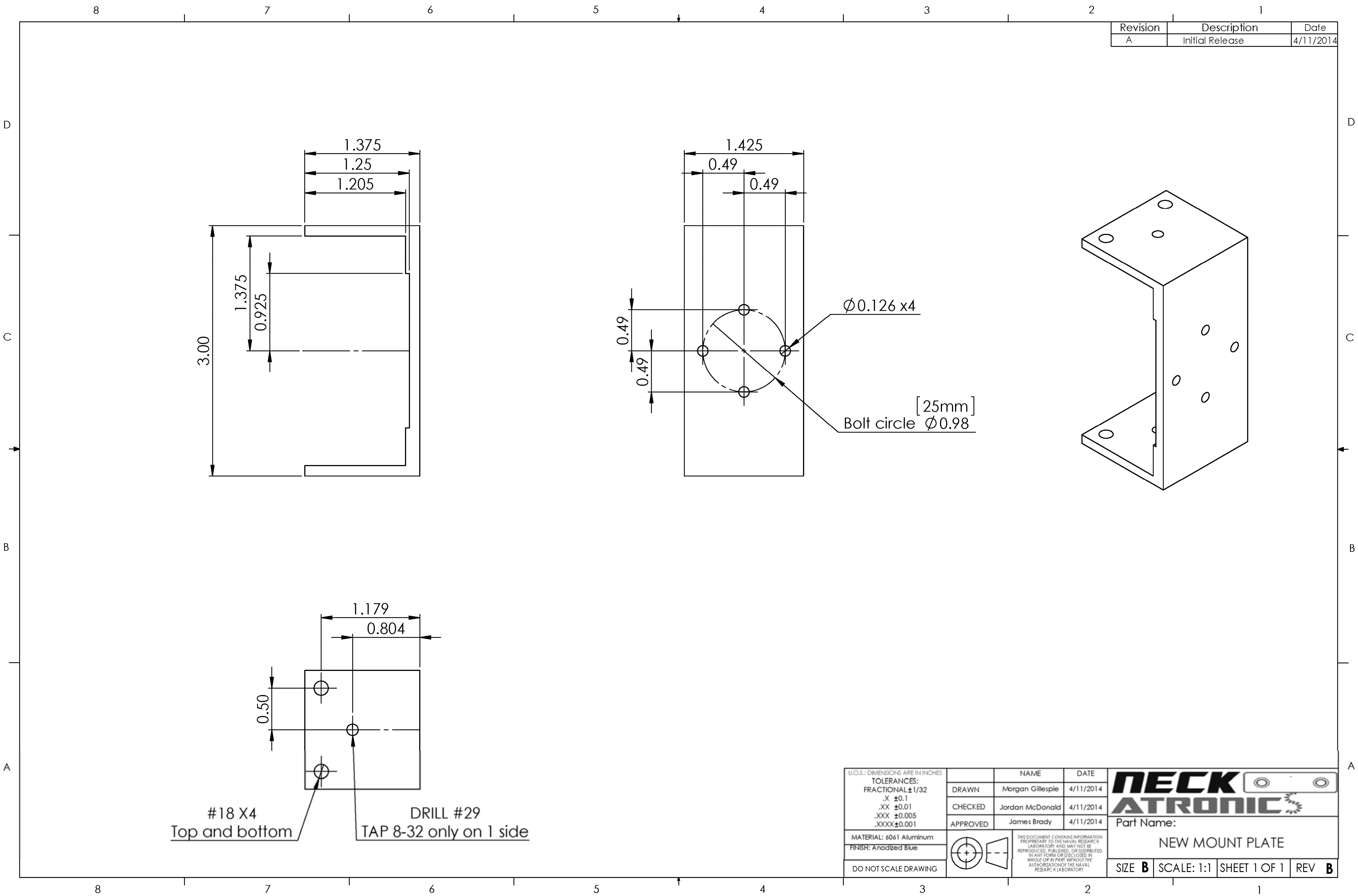
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001
MATERIAL: 6061 Aluminum
FINISH: Anodized Blue
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
Morgan Gillespie
4/11/2014
CHECKED
Jordan McDonald
4/11/2014
APPROVED
James Brady
4/11/2014
NECK ATRONICS
Part Name:
Motor Thrust Spacer
SIZE B
SCALE: 2:1
SHEET 1 OF 1
REV B


Revision
Description
Date
A
Initial Release
4/11/2014
1.375
1.25
1.205
1.375
0.925
3.00
1.425
0.49
0.49
0.49
0.49
Ø0.126 x4
[25mm]
Bolt circle Ø0.98
1.179
0.804
0.50
#18 X4
Top and bottom
DRILL #29
TAP 8-32 only on 1 side
U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001
NAME
DATE
DRAWN
Morgan Gillespie
4/11/2014
CHECKED
Jordan McDonald
4/11/2014
APPROVED
James Brady
4/11/2014
NECK ATRONICS
Part Name:
NEW MOUNT PLATE
MATERIAL: 6061 Aluminum
FINISH: Anodized Blue
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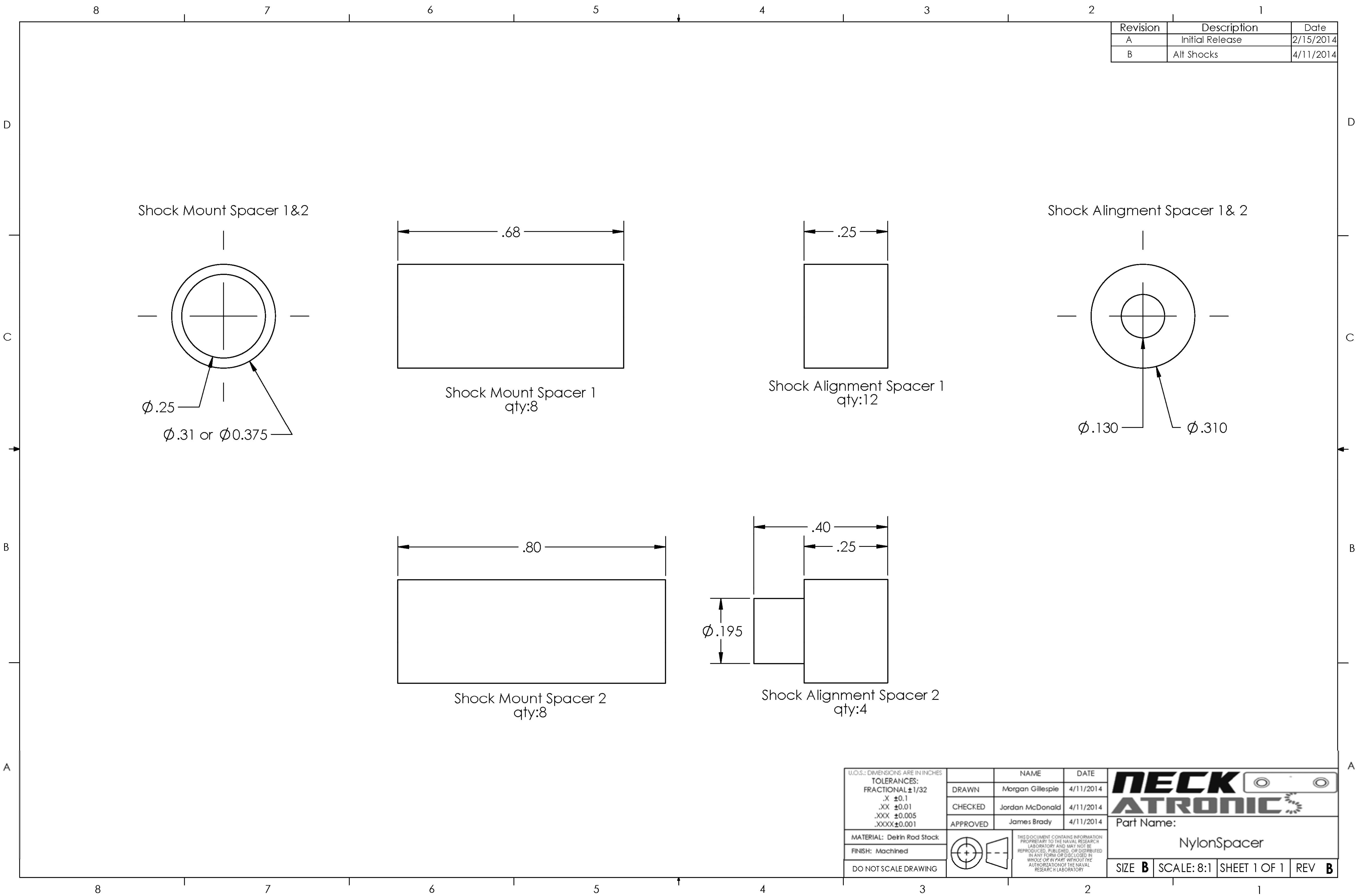
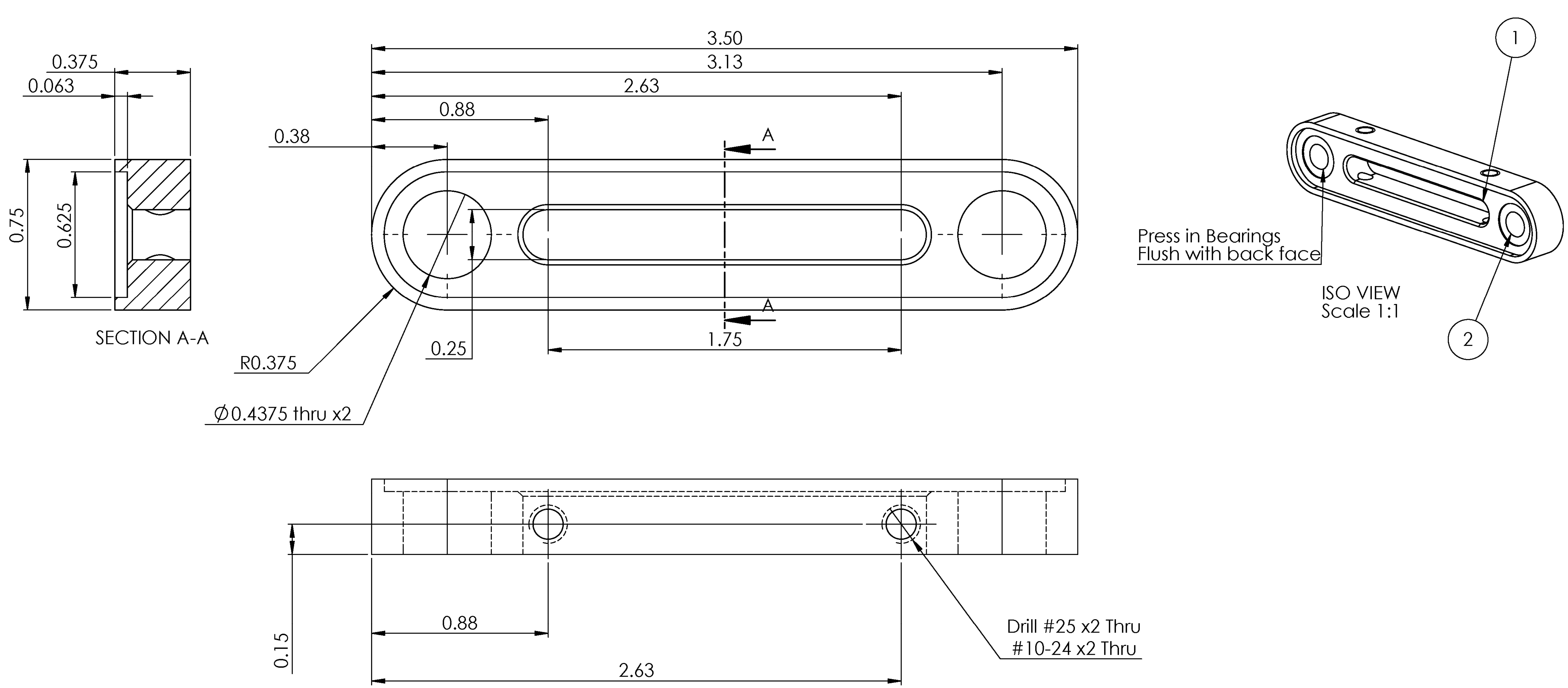
DO NOT SCALE DRAWING
SIZE B
SCALE: 1:1
SHEET 1 OF 1
REV B


Revision | Description | Date
A | Initial Release | 2/15/2014
B | Alt Shocks | 4/11/2014
Shock Mount Spacer 1&2
Ø.25
Ø.31 or Ø0.375
.68
Shock Mount Spacer 1
qty:8
.25
Shock Alignment Spacer 1
qty:12
Shock Alingment Spacer 1& 2
Ø.130
Ø.310
.80
Shock Mount Spacer 2
qty:8
.40
.25
Ø.195
Shock Alignment Spacer 2
qty:4
U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001
MATERIAL: Delrin Rod Stock
FINISH: Machined
DO NOT SCALE DRAWING
NAME | DATE
DRAWN | Morgan Gillespie | 4/11/2014
CHECKED | Jordan McDonald | 4/11/2014
APPROVED | James Brady | 4/11/2014
NECK ATRONICS
Part Name:
NylonSpacer
SIZE B | SCALE: 8:1 | SHEET 1 OF 1 | REV B

Revision	Description	Date
A	Initial Release	2/15/2014
B	Shorter Links	4/11/2014



ITEM NO.	QTY.	DESCRIPTION
1	1	Machined Body
2	2	Needle Bearing - 5905K21

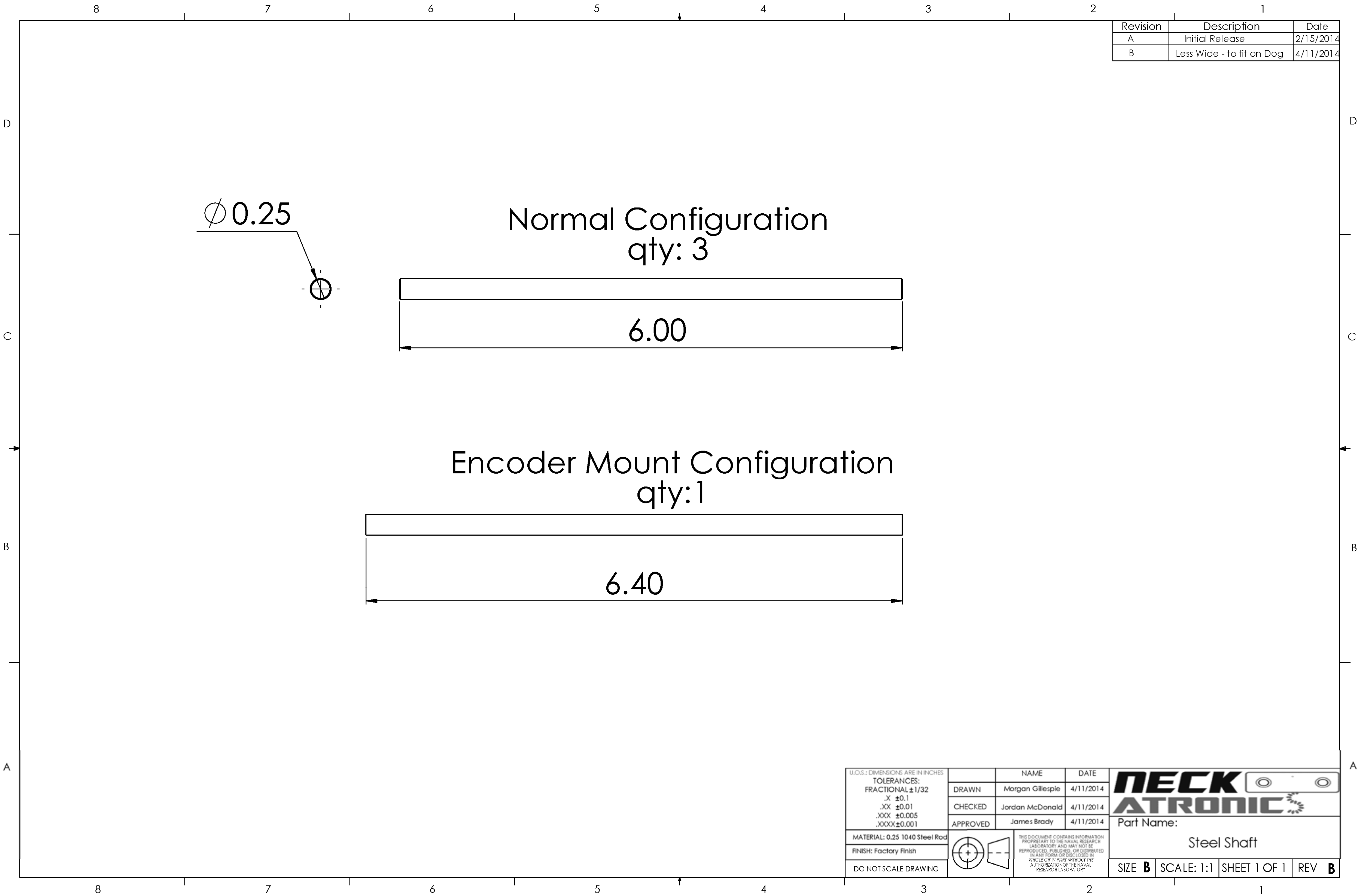
U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001

	NAME	DATE
DRAWN	Morgan Gillespie	4/11/2014
CHECKED	Jordan McDonald	4/11/2014
APPROVED	James Brady	4/11/2014

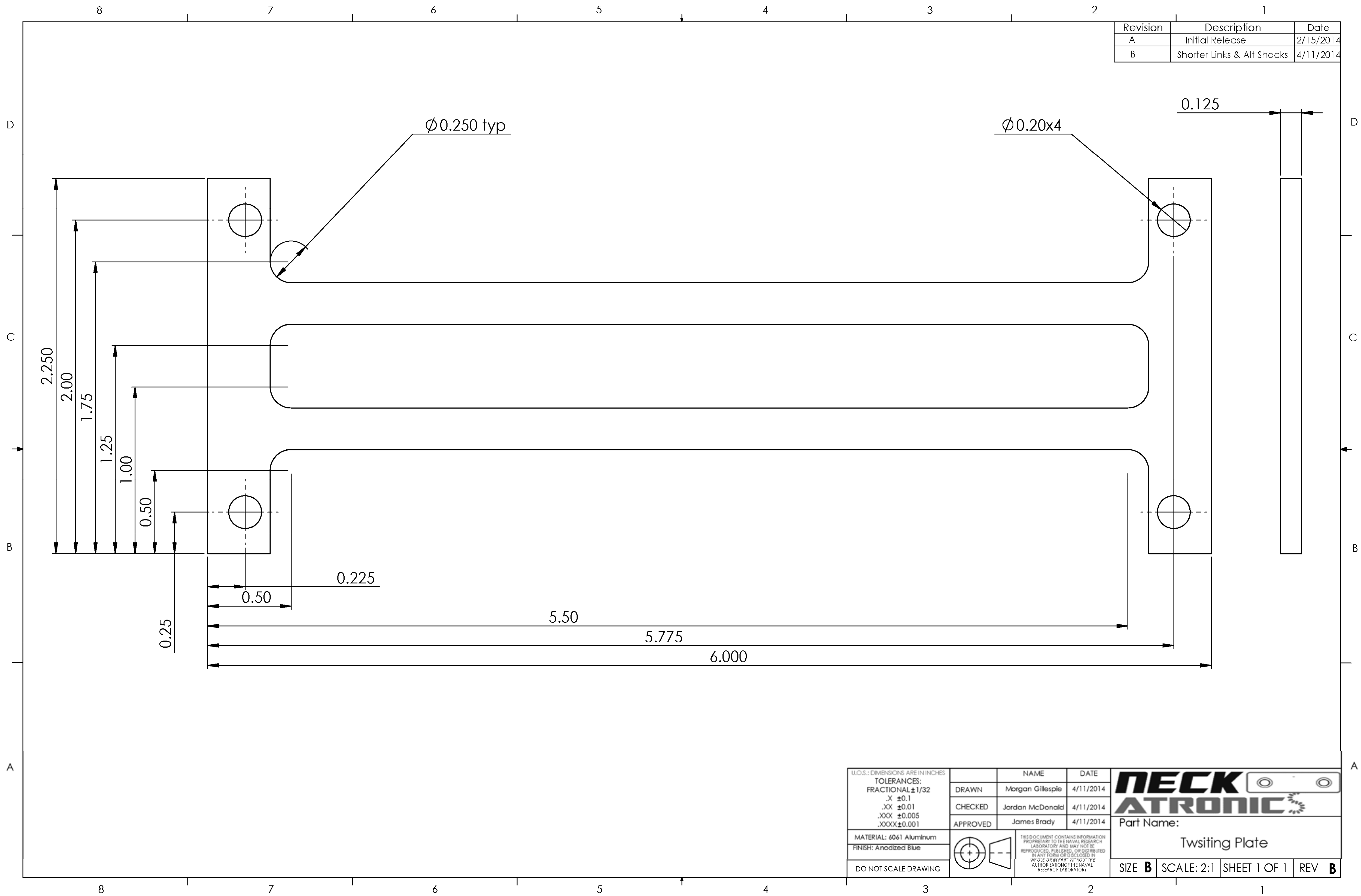
MATERIAL: 6061 Aluminum
FINISH: Anodized Blue
DO NOT SCALE DRAWING

NECK ATRONICS
Part Name:
Short Link

SIZE B	SCALE: 2:1	SHEET 1 OF 1	REV B



Revision | Description | Date
A | Initial Release | 2/15/2014
B | Less Wide - to fit on Dog | 4/11/2014
∅0.25
Normal Configuration
qty: 3
6.00
Encoder Mount Configuration
qty:1
6.40
U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001
MATERIAL: 0.25 1040 Steel Rod
FINISH: Factory Finish
DO NOT SCALE DRAWING
NAME DATE
DRAWN Morgan Gillespie 4/11/2014
CHECKED Jordan McDonald 4/11/2014
APPROVED James Brady 4/11/2014
NECK ATRONICS
Part Name:
Steel Shaft
SIZE B SCALE: 1:1 SHEET 1 OF 1 REV B


Revision | Description | Date
A | Initial Release | 2/15/2014
B | Shorter Links & Alt Shocks | 4/11/2014
Ø0.250 typ
Ø0.20x4
0.125
2.250
2.00
1.75
1.25
1.00
0.50
0.25
0.225
0.50
5.50
5.775
6.000
U.O.S.: DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±1/32
.X ±0.1
.XX ±0.01
.XXX ±0.005
.XXXX ±0.001
MATERIAL: 6061 Aluminum
FINISH: Anodized Blue
DO NOT SCALE DRAWING
NAME
DATE
DRAWN Morgan Gillespie 4/11/2014
CHECKED Jordan McDonald 4/11/2014
APPROVED James Brady 4/11/2014
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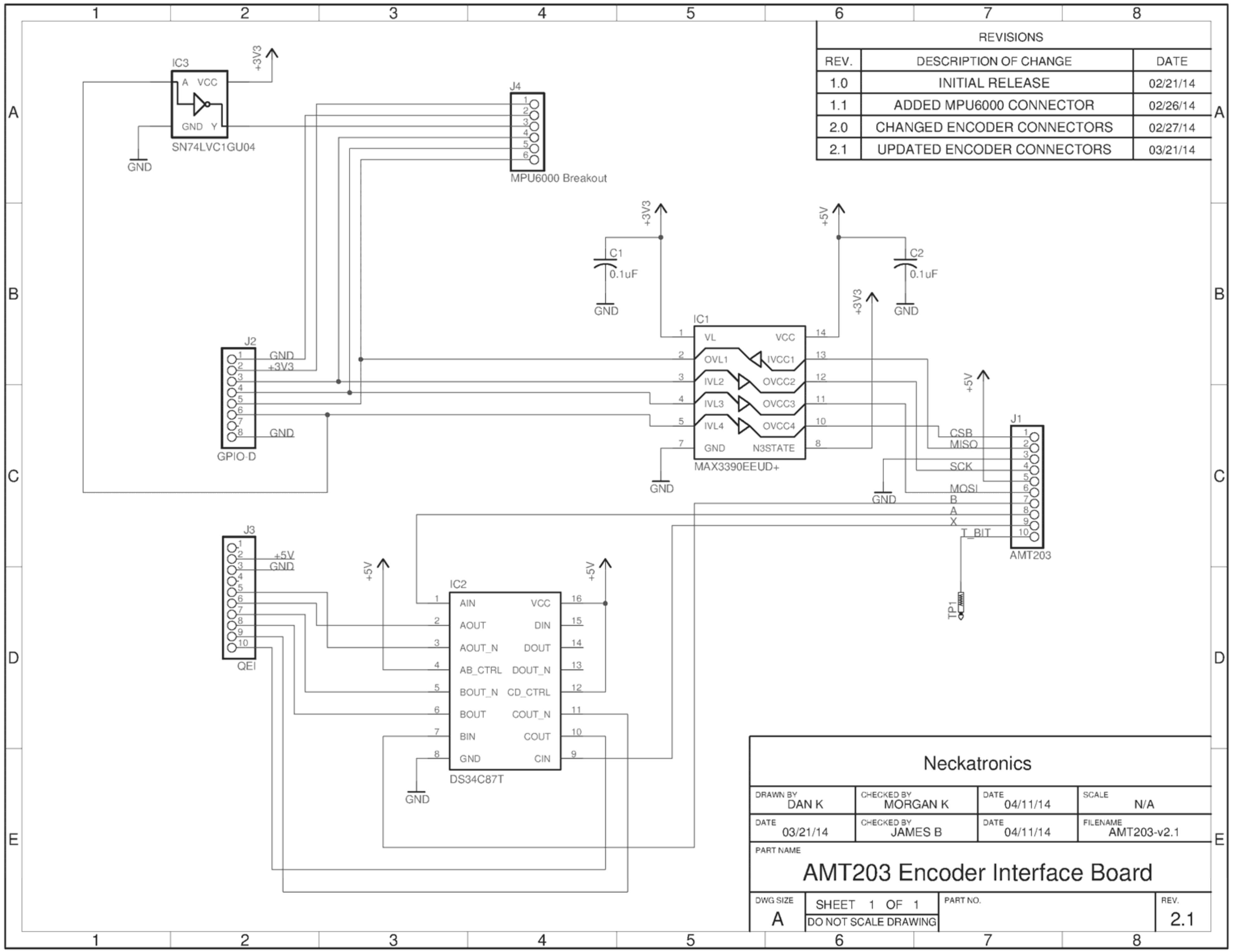
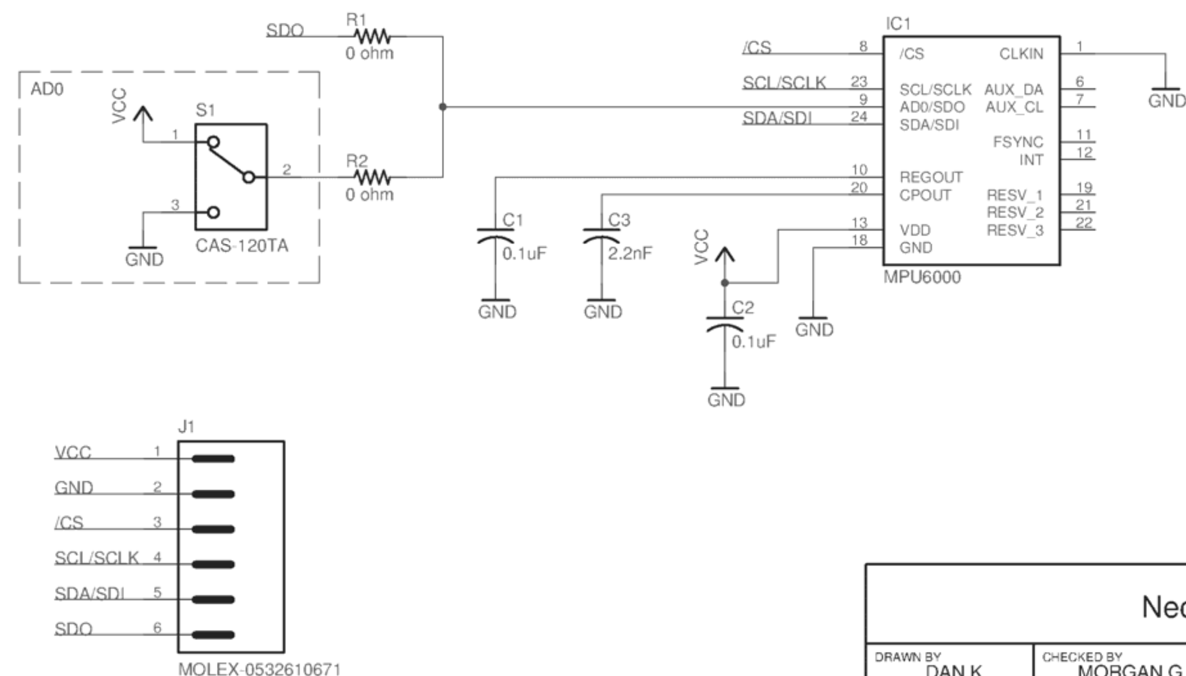
NECK ATRONICS
Part Name:
Twsiting Plate
SIZE B
SCALE: 2:1
SHEET 1 OF 1
REV B


REVISIONS
REV. | DESCRIPTION OF CHANGE | DATE
1.0 INITIAL RELEASE 02/21/14
1.1 ADDED MPU6000 CONNECTOR 02/26/14
2.0 CHANGED ENCODER CONNECTORS 02/27/14
2.1 UPDATED ENCODER CONNECTORS 03/21/14
IC3
SN74LVC1GU04
J4
MPU6000 Breakout
C1
0.1uF
C2
0.1uF
IC1
MAX3390EEUD+
J2
GPIO-D
J1
AMT203
CSB
MISO
SCK
MOSI
T_BIT
TP1
J3
QEI
IC2
DS34C87T
Neckatronics
DRAWN BY DAN K
CHECKED BY MORGAN K
DATE 04/11/14
SCALE N/A
DATE 03/21/14
CHECKED BY JAMES B
DATE 04/11/14
FILENAME AMT203-v2.1
PART NAME
AMT203 Encoder Interface Board
DWG SIZE A
SHEET 1 OF 1
DO NOT SCALE DRAWING
PART NO.
REV. 2.1

NOTES
1. Either R1 or R2 should populated, but not both. Populating R1 configures the board to work in SPI mode, while populating R2 configures the board to work in I2C mode
2. Switch S1 is used to set the LSB of the I2C address for the MPU6000 when operating in I2C mode
3. When operating in I2C mode, pins 3 and 6 of connector J1 are not used
4. Connector J1 mates with Molex 0510210600 connector housing

REVISIONS		
REV.	DESCRIPTION OF CHANGE	DATE
1.0	INITIAL RELEASE	01/15/14



Neckatronics			
DRAWN BY DAN K	CHECKED BY MORGAN G	DATE 04/11/14	SCALE N/A
DATE 01/15/14	CHECKED BY JAMES B	DATE 04/11/14	FILENAME MPU6000_SPI_I2C-v1.0
PART NAME MPU-6000 IMU Interface Board			
DWG SIZE A	SHEET 1 OF 1 DO NOT SCALE DRAWING	PART NO.	REV. 1.0

17 Appendix D: Acceptance Information

In this appendix you will find succinct information regarding the verification and validation process. Included are descriptions of testing procedures, testing apparatus construction, and detailed testing data. Additionally, alternative concept designs are included in this section.

This appendix is broken down into two primary sections. Validation testing is the first section. Included is information relating to the testing of the prototype. The second section is the verification section. Verification related task data and assessment items are included. Additionally, section covers other concepts that were considered in the development process. This information is represented via images of the initial concept generation, low fidelity prototypes, and verification matrices used to eliminate and alternate concepts.

17.1 Verification Tests

17.1.1 Shake-table

A custom designed shake table was built in order to facilitate the testing and guide the design choices of the neck structure.

17.1.1.1 Procedures

The first step of testing is to mount the neck onto the sliding carriage of the shake table. This is accomplished through 4x 4-40 screws, screwed directly into the top plate of the sliding carriage. Once mounted, affixed a representative mass. In our tests, a 1.5 kg steel block was used to represent the gimbal.

A single axis accelerometer is then mounted to the base of the neck structure, while a second single axis accelerometer is mounted to the end of the neck. This was done through Hot Glue, which notably does not adhere to steel.

These both feedback to a LabQuest digital acquisition device, capable of recording values from both units over time.

The power supply was started up, supplying a set voltage. Once a steady state was achieved, data was collected from both accelerometer at 250 samples a second for two seconds. The voltage was then increased in 1 V increments, with data being collected at each increment once steady state was reached. These tests were performed 3 times.

17.1.1.2 Formulas

$$\mathrm{GravityOffset}_i = \mathrm{data}_i + 9.8$$

$$\mathrm{RMS} = \sqrt{\frac{1}{n}\cdot\sum_{i=n}^{i}\left(\mathrm{GravityOffset}_i\right)^2}$$ Where n = number of samples

$$\mathrm{Percent} = 1 - \left(\frac{\mathrm{RMS}_{in} - \mathrm{RMS}_{out}}{\mathrm{RMS}_{in}}\right)$$

$$\mathrm{dB} = 20\cdot\log(\mathrm{Percent})$$

Gravity Offset removed the negative 9.8 m/s^2 offset inherent to earthly operations.

RMS allowed used to look specifically at the average peaks in acceleration over the data range.

Percent allowed us to calculate the percent reduction from the input and output acceleration.

dB converted percentage reduction to dB.

17.1.1.3Apparatus Construction

This table consisted of 2x FR801-001 Chiaphua Components Group Industrial Motor, each connected to a cam linkage system. This cam placed a shaft offset by 0.125” from the center of the motor shaft connected to an aluminum link. This aluminum link connected from there to a sliding platform mounted on linear bearings which provided lubrication across stainless steel rods.

The motors, connected in parallel to a variable power supply, allowed for the control of the platform shaking frequency by changing the input voltage which controls the motor RPM.

This shaking system was then mounted to section of steel C channel and welded to a large steel block (215 lbs) for stability.

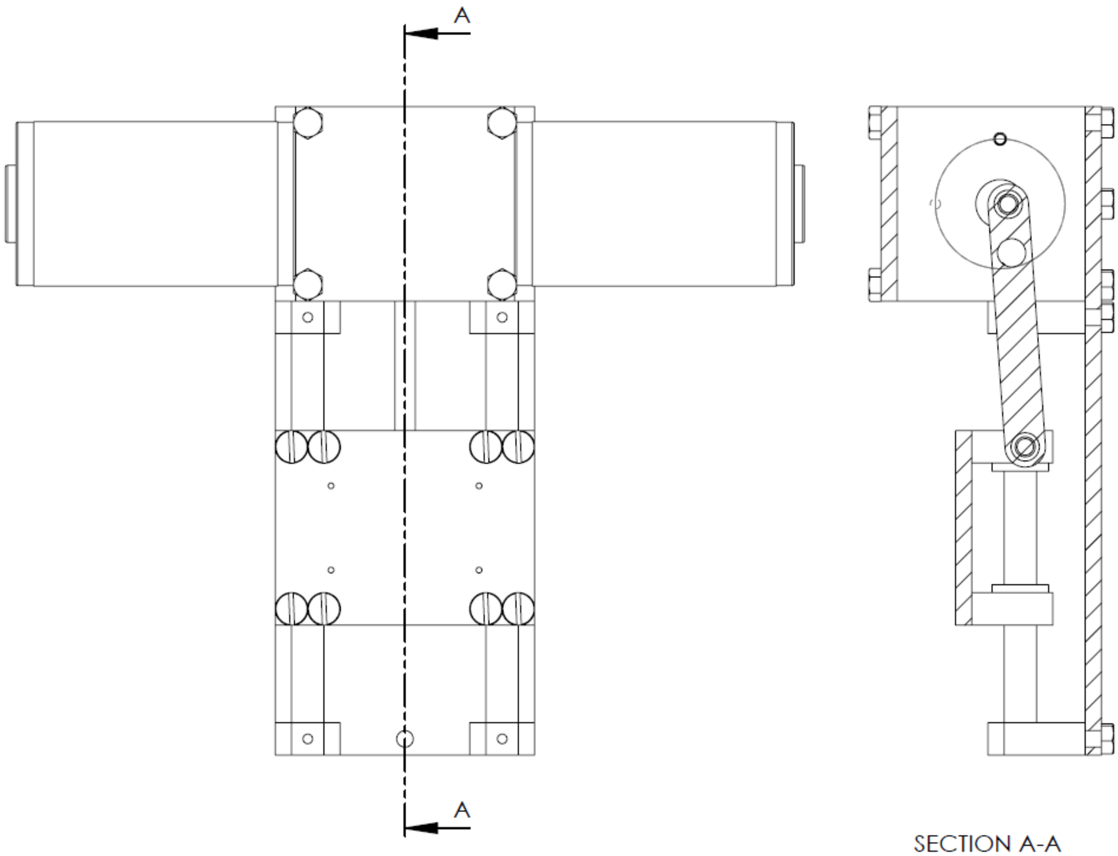


Figure 12: Shake Table Top and Section View

17.1.2 Motor Performance Tests and Simulations

The tests and simulations described in this section were performed to measure the performance characteristics of the motors and to verify that this performance would be sufficient to attain the desired control performance for the gimbal system.

17.1.2.1 Motor Torque Tests

The stall torque of each type of motor, which is the maximum torque that can be produced by a motor, was measured using a torque gage. The torque gage was attached to the motor shaft, and one phase of the motor was energized with 12V by applying the voltage directly across two of the motor leads. The torque gage was then slowly rotated until the applied torque exceeded the stall torque of the motor and the motor moved, and the maximum torque was then recorded as the stall torque. The electrical current draw through the motor was also measured using an ammeter, and the torque constant for the motor was approximated by dividing the stall torque by this current draw. Figure 13 shows the experimental test setup, and Table 17 summarizes the results.

Figure 13: Motor Performance Test Setup

Table 17: Motor Performance Test Results

Motor	Stall Torque (mNm)	Current (A)	Torque Constant (mNm/A)
GBM4114-120T	247	0.82	300
GBM3506-130T	127	0.98	130

17.1.3 Gimbal Dynamics Simulations

The dynamics simulations presented in this section were performed to verify that the motors could provide sufficient torque to obtain the desired control performance characteristics. Two simulations were performed. The first simulated the response of a simple PID controller for rotational motion of the gimbal in response to a sinusoidal position command input, and the second simulated the response of a PID controller for rotational motion of the laser scanner in response to a triangle wave position command input. The simulation setups were identical except for the values of the moments of inertia, control gains, input wave shape, input wave frequency, and input wave amplitude.

17.1.3.1 System Dynamics

Both systems were modeled as simple masses rotating around a fixed point with an applied torque. This results in system dynamics represented by the equation

$$\ddot{\theta} = \frac{\tau}{I}$$

where θ is the angle of the gimbal or laser scanner, τ is the applied torque, and I is the mass moment of inertia about the axis of rotation. The values for the moments of inertia were computed using a CAD program.

17.1.3.2 PID Controller

A simple PID controller was implemented to test the system response. The gains were selected by equating the coefficients of the closed-loop transfer function with the coefficients of a canonical 2nd-order dynamic system, and choosing the desired performance characteristics. The gains were further tuned by hand to improve the performance. The values of the performance characteristics and gains are included in Table 18.

17.1.3.3 Simulation

The simulation was carried out in MATLAB/Simulink using the parameters given in Table 18. Figure 15 shows the block diagram used for the gimbal simulation. The block diagram for the laser scanner simulation is identical except that the sinusoidal wave input is replaced with a triangle wave. The amplitude of the sinusoidal wave for the gimbal simulation is ±135°, and the triangle wave ranges from -15° to -90°. The simulation files are included in the accompany files (see Appendix G: Project DVD File Tree).

Table 18: Simulation Parameters

Parameter	Gimbal	Laser Scanner
I	0.0060 kg*m^2	0.0002 kg*m^2
$\tau_{\max}$	0.247 N*m	0.127 N*m
$\omega_{n,desired}$	1.0 rad/s	0.5 rad/s
$\zeta_{desired}$	0.7	0.7
K_p	7.6	0.039
K_d	0.84	0.0043

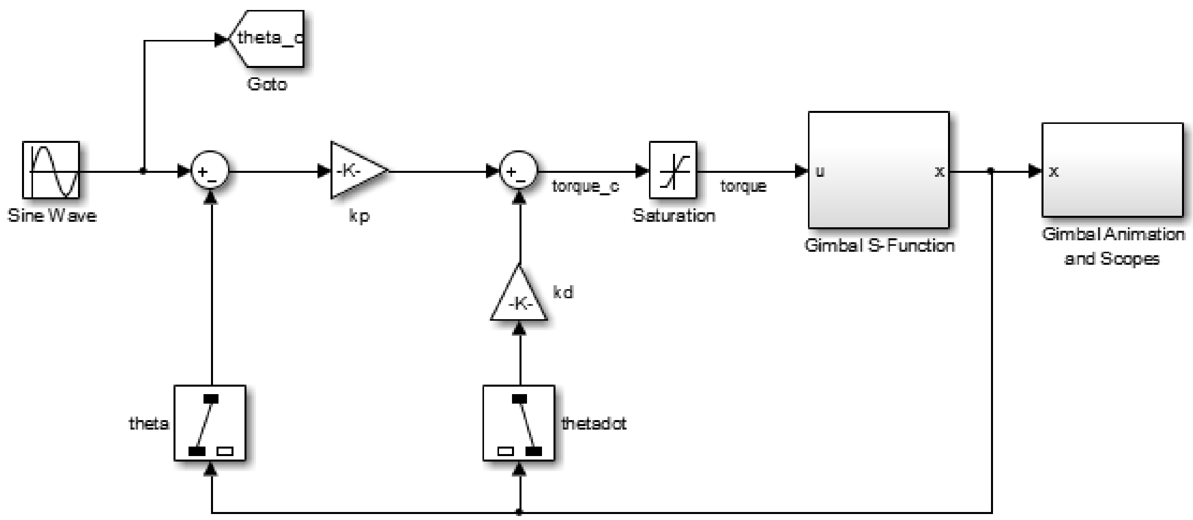


Figure 14: Simulation block diagram

17.1.3.4 Results and Conclusions

By varying the input frequencies and observing the responses, it was found that the gimbal motors could provide a maximum closed-loop bandwidth of 0.75Hz, and that the laser scanner pitch motor could easily provide the desired 0.5Hz pitch frequency. XX shows the response and torque inputs for the gimbal simulation at 0.75Hz, and XX shows the same plots for the laser scanner simulation at 0.5Hz.

17.2 Surrogate Validation Testing

17.2.1 Procedures

Range of orientation was validated using manual apparatus manipulation. Each axis of rotation was manipulated individually by hand through its physically allowed range of motion.

Range of motion was extrapolated from pictures of the axis at negative and positive maximums. This was done by superimposing a protractor onto the images. Vectors were then created and the angle between the vectors was analyzed to give the ranges of motion. Images of this validation test have been included (see Table 19[4]).

[4] Please note that full size images have been included on the DVD provided by Team Neckatronics. They are found under the folder titled 'Orientation Test.'

17.2.2 Data

Table 19: Data from Orientation Test

Roll of Gimbal	±96.5	Degrees
Yaw of Gimbal	±145	Degrees
Pitch of Camera	±140	Degrees
Pitch of LIDAR	+15 to-120	Degrees

17.2.3 Orientation Test

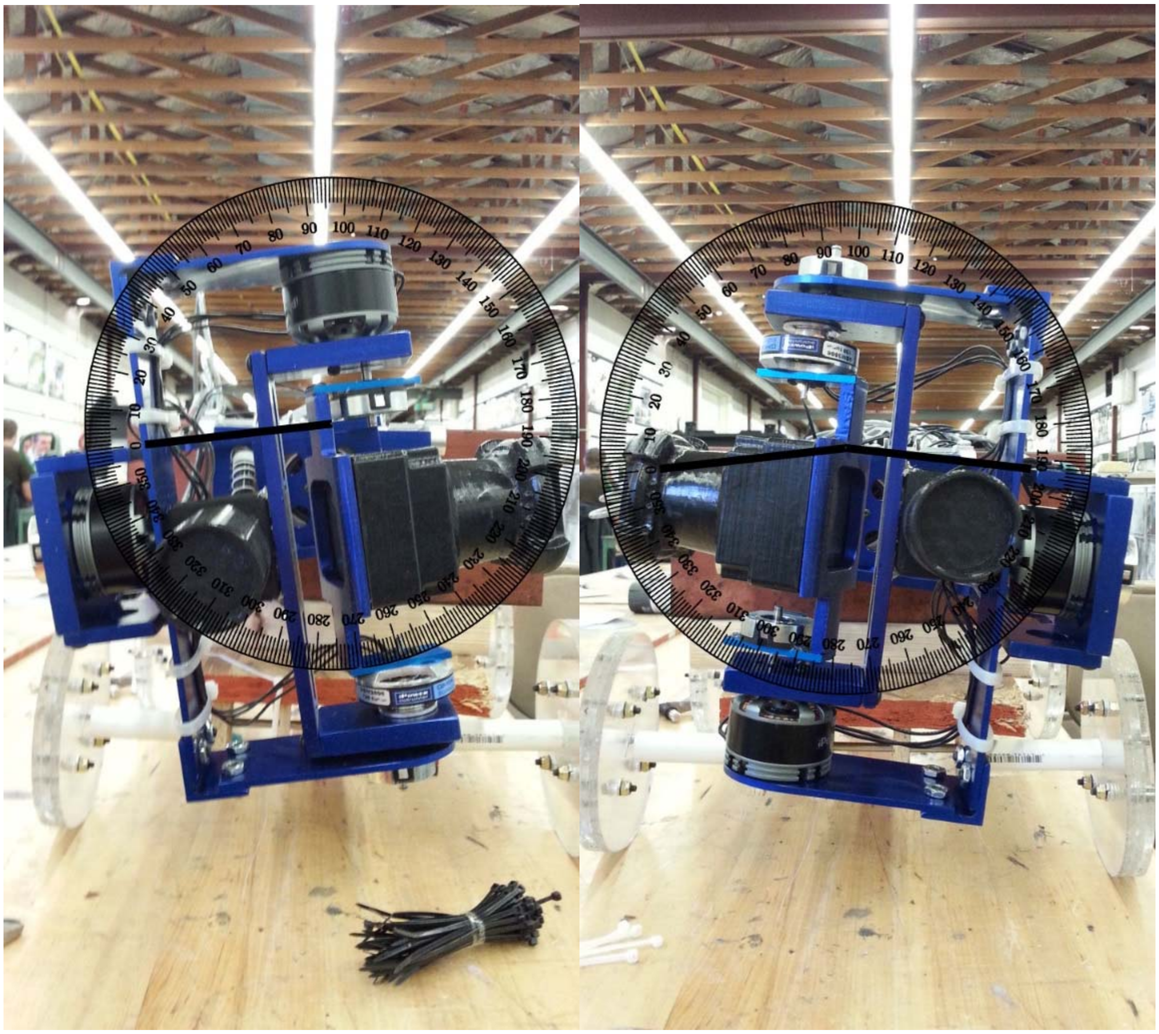


Figure 15: Roll Range of Motion of Gimbal, 0 to 193 Degrees

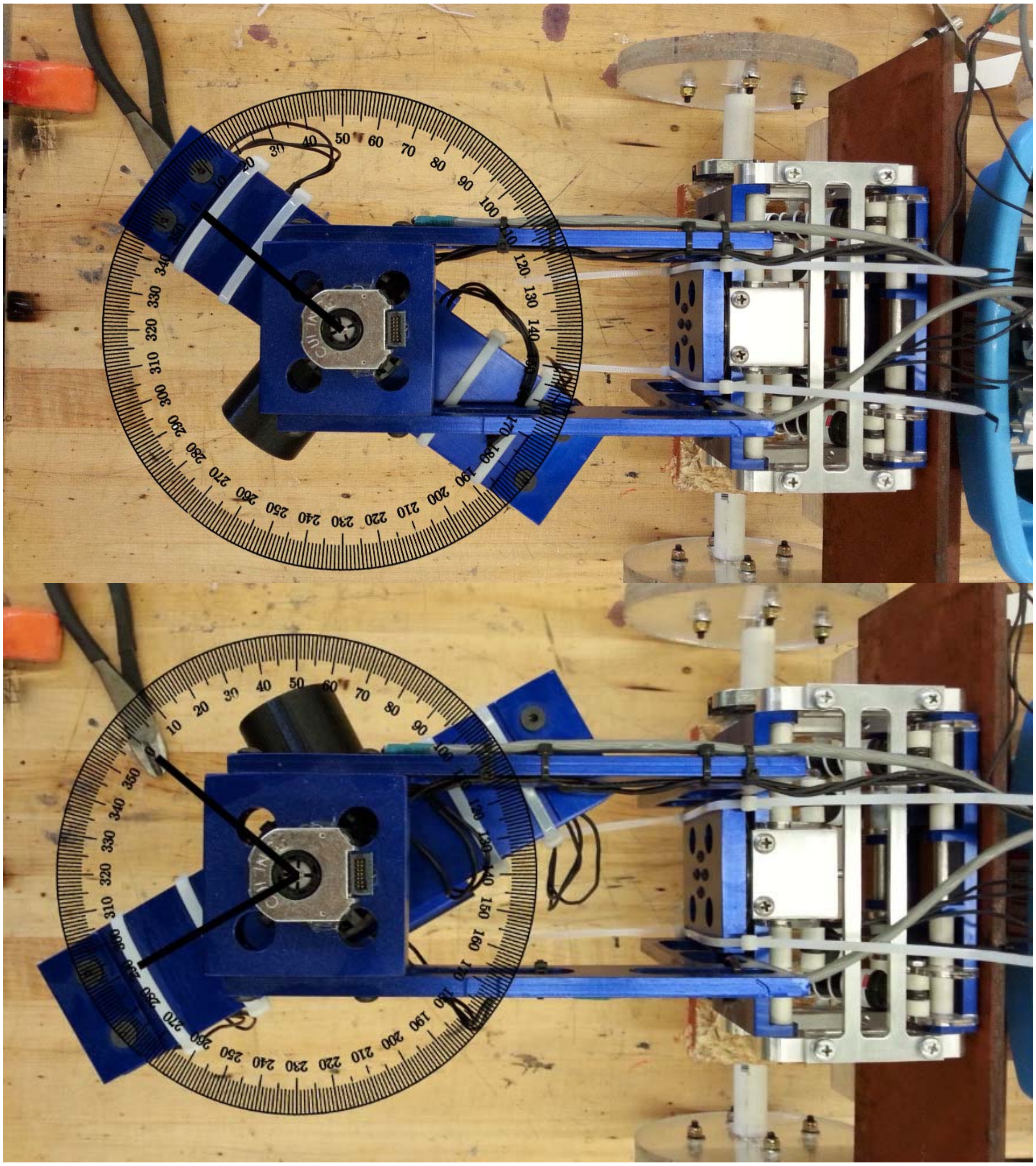


Figure 16: Yaw Range of Motion of Gimbal, 0 to 290 Degrees

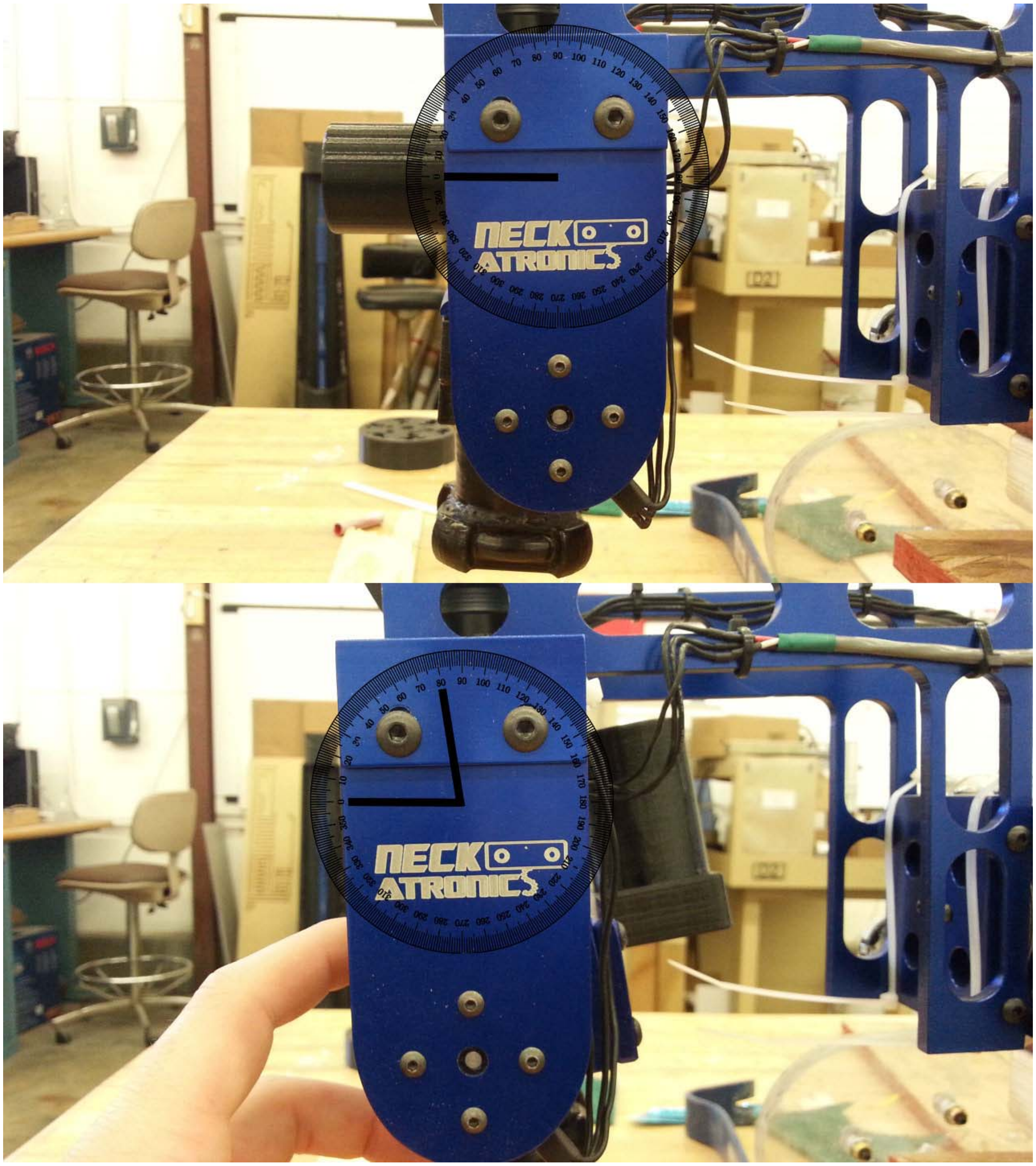


Figure 17: Pitch Range of Motion of Gimbal, 0 to 280 Degrees

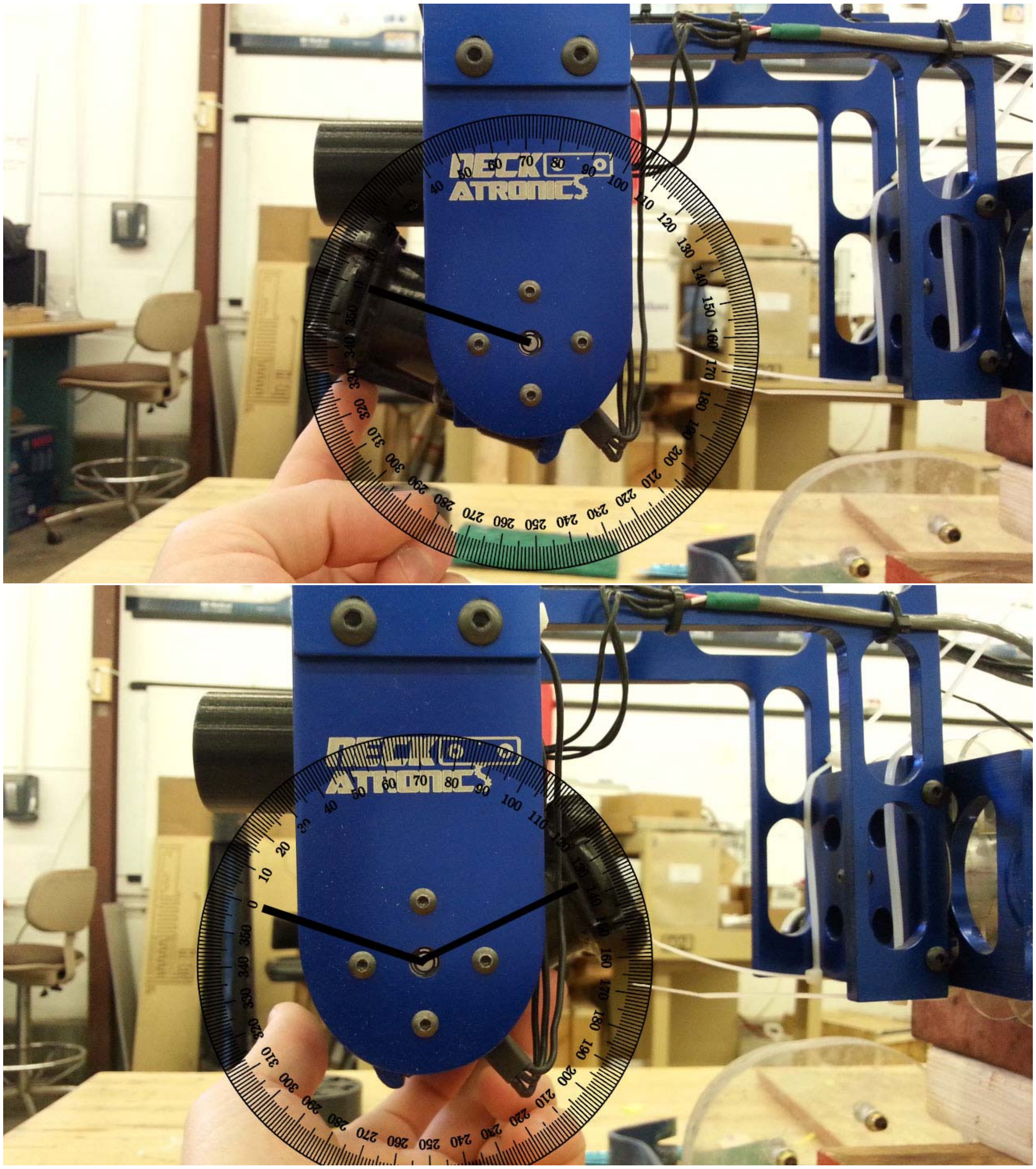


Figure 18: Pitch Range of Motion of LIDAR, 0 to 135 Degrees

17.2.4 Rollover Test

17.2.4.1 Procedures

The rollover test was a scenario designed to demonstrate rollover conditions. The Neck Structure was attached to the Red Wagon, and was then forcefully tipped over. The structure landed on itself upside down. After tipping the wagon back up the Neck Structure was analyzed. The structure did not take any damage. A video file of the procedure has been included on the DVD (See Appendix G: Project DVD File Tree)

17.2.5 Red Wagon

The Red Wagon is a gait simulation platform, designed to approximate the walking of an Allegro Dog. Its design features: custom cam wheels, plywood mounts, plywood base, steel angle as the mounting plate and a plastic wagon as counter weight carriage.

The following contents are a breakdown of each of the individual components and their construction.

17.2.5.1 Custom Cam Wheel Design

The Cam wheels were structured based off of visual gait analysis. This was done via analysis of YouTube videos of the Allegro Dog walking. In order to properly interpret the gait pattern, careful comparisons were made to items in the background. Using relative depth and height approximations, the step height of .5 inches was acquired.

From the step height and a rough visual approximation of the frequency of stepping, 6 inch diameter wheels with a .5 inch step were designed. The step was given a wide arc to help minimize the chances of skipping.

In consideration of variability in gait patterns the wheels were designed around the concept of gait pattern adjustment. The design feature a center plus sign broach in a middle wheel. Two external wheels secure an axel pin that is placed in a selected grove. This is

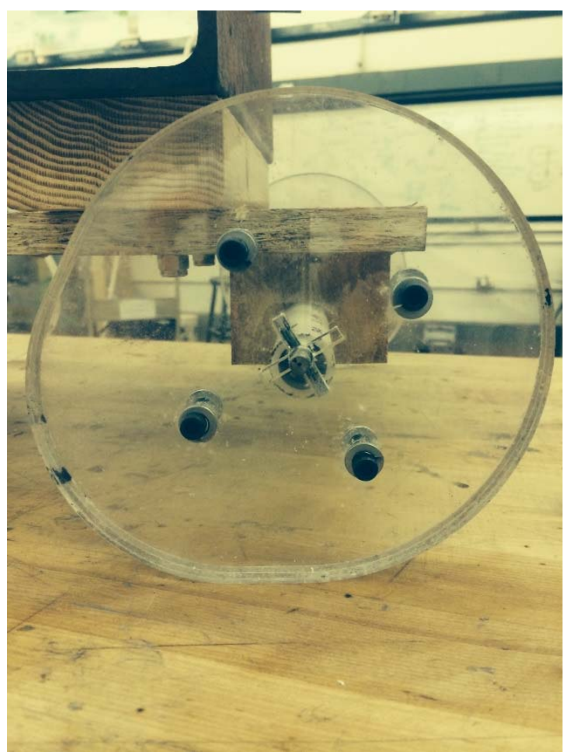


Figure 19: Lateral View of Assembled Cam Wheels

done via lock tight nuts and four screws. Drawings of the parts have been included in Appendix C: Drawings for further clarification

17.2.5.2 Axels and related parts

The axel design consists of two 15 inch steel rods which measure a quarter inch in diameter. There are two pin holes in each axel that hold a half inch long locking steel pin. The pin measures an eighth of an inch in diameter. There are a total of 4 PVC pipe spacers. Each measures 3.25±.3 inches.

17.2.5.3 Mounts, Base, and Mounting Point

Construction of the base and mounts was don with plywood. The eight axel mounts were constructed from .5 inch plywood. They measure 2 inches by 3.875 inches. . Each mount has a single quarter inch hole. Using wood glue, the mounts were attached to the base.

The base consists of a single .75 inch plywood sheet that measures 8 inches by 16 inches. Attached to the base is a 2 by 4 base mount that measures 8.9375 inches. Two 3/8-24 X 3 holes are used as attachment points for the base mount and the angle steel mount. Measurements of the mount are 5.125 inches, by 3.5 inches, with a length of 1ft. See Figure 12 for clarification.

Figure 20: Inferior View of Red Wagon

17.2.5.4 Counter Weight Carriage

Because the angel bar in combination with the Neck Structure moved the center of mass so far forward, there was a worry that the system would be unstable during movement. As a results the team implements a small plastic wagon as a weight carriage to redistribute the total mass of the system.

17.2.5.5 Procedures

Validation of the Neck Structure's robust design was done using the Red Wagon. The wagon was placed on a treadmill and the treadmill was set to a speed of 1.2mph. The test was conducted for one hour. Throughout the test, there was no observable issues.

Upon completion, the Neck Structure was examined for any possible damage. The system was found undamaged.

It was calculated that the Neck Structure went undamaged for 4000 cycles. This estimation was made based off of a single rotation of one wheel. Multiple wheels were not taken into consideration because of the possibility of skipping.

There was a much higher level of strain placed on the system then the team could properly quantify. This was noted from visual impulses coming from the rope inconsistently pulling on the structure to maintain an average speed of 1.2 mph.

17.2.5.6 Data

Treadmill Test	Speed of Treadmill	Distance Traveled	Calculated cycles from distance traveled and wheel circumference of 20.5 inches	Duration of test
	1.2 mph	1.3 mi	4017 cycles	1 hr

17.2.5.7 Materials List

Chassis

- 8 .5 inch pieces of plywood that measures 2 inches by 3.875 inches
- 1 .75 inch piece of plywood that measures 8 inches by 16 inches
- 1 2 by 4 that measures 9.9375 inches long
- 1 angle steel piece that measures 5.125 inches by 3.5 inches, with a length of 1ft and thickness of .25 inches
- 2 SHCS 3/8-24 X3 bolts
- 2 3/8-24 YZ 8 NYLOCK NE nuts
- 4 3/8 USS F/W Z washers
- A small plastic box to act as the weight counter balance carriage
- 4 DARCO DECK 10 X 4 C screws

Axle and Wheels

- 2 .25 inch diameter steel rods measuring 15 inches each
- 4 .125 inch diameter steel rods measuring .5 inches each
- 4 3.25 inch pieces of .5 inch PVC
- 1 33 inch by 24 inch sheet of .25 inch Lexan for the wheels
- 16 10-32 NYLOCK YELLZINC nuts
- 16 10-32 1 ¼ SHCS bolts
- 32 ¼ SplitL/W Z washers

18 Bill of Materials

This appendix is a complete breakdown of costs and materials for the final version of the neck structure. The cost breakdowns are separated by neck, gimbal, and electronics.

18.1 Neck Structure

Item	Dimension	Cost	Package Of	Qty	Total	Stock #
1" x 3" Alu Bar	12"	$ 24.34	1	1	$ 24.34	8975K239
1.5" x 1.5" Alu Bar	3"	$ 10.11	6	1	$ 10.11	9008K46
3/8" x 3/4" Alu Bar	15"	$ 5.23	24	1	$ 5.23	8975K615
1/8" x 6" Alu Sheet	2.25"	$ 2.39	1	1	$ 2.39	8975K83
2" OD Alu Rod	1.5"	$ 12.10	3	1	$ 12.10	1610T15
0.25" OD Steel Rod	25"	$ 2.46	3	1	$ 2.46	8920K115
0.375" OD Delrin Rod	20"	$ 0.92	1	2	$ 1.84	8572K53
4-40 Machine Screw	1.5"	$ 5.22	50	8	$ 5.22	90272A190
4-40 Machine Screw	1"	$ 2.80	100	4	$ 2.80	90272A115
4-40 Hex Nut	3/32"	$ 0.81	100	16	$ 0.81	90480A005
10-24 Machine Screw	0.5"	$ 4.02	100	12	$ 4.02	90272A242
8-32 Machine Screw	0.25"	$ 2.44	100	1	$ 2.44	90272A190
1/8" Polycarbonate Sheet	12" x 12"	$ 8.73	1	1	$ 8.73	8574K26
0.25 ID Thrust Roller Bearing	0.3125"	$ 5.00	1	8	$ 40.00	5905k21
Thrust Roller Bearing	2" ID 2.5" OD	$ 4.74	1	1	$ 4.74	5909K43
Thrust Washer	0.032"	$ 2.38	1	2	$ 4.76	5909K56
Total					$ 131.99	

18.2 Gimbal

Gimbal Assembly

TECH: Chris G

Order Qty	Qty On Machine	Part Name / Description	Supplier	Supplier Part Number	Manufacturer	Manufacturer Part Number	Unit-cost	Sub-total
1	1	Back Plate	McMaster-Carr	0101		8975K468	$5.45	**$5.45**
2	2	Side Arm	McMaster-Carr	0102		8975K443	$10.97	**$21.94**
1	1	Top Plate	McMaster-Carr	0103		Shared with 101	$0.00	**$0.00**
1	1	Roll Motor Bracket	McMaster-Carr	0104		In Neck BOM	$0.00	**$0.00**
1	1	Camera Top Plate	McMaster-Carr	0201		8975K582	$4.65	**$4.65**
2	2	Corner Bracket	McMaster-Carr	0202		8982K4	$3.22	**$6.44**
1	1	Camera Side Plate (Right)	McMaster-Carr	0203		Shared with 201	$0.00	**$0.00**
1	1	Camera Side Plate (Left)	McMaster-Carr	0204		Shared with 201	$0.00	**$0.00**
1	1	Camera Mount Plate	McMaster-Carr	0205		8975K518	$3.75	**$3.75**
1	1	Camera Pitch Plate (Right)	McMaster-Carr	0206		Shared with 205	$0.00	**$0.00**
1	1	Camera Pitch Plate (Left)	McMaster-Carr	0207		Shared with 205	$0.00	**$0.00**
1	1	Laser Top Plate	McMaster-Carr	0301		8975K68	$3.96	**$3.96**
1	1	Laser Side Plate (Left)	McMaster-Carr	0302		Shared with 201	$0.00	**$0.00**
1	1	Laser Side Plate (Right)	McMaster-Carr	0303		Shared with 201	$0.00	**$0.00**
4	5	AMT203 ABS SPI ENCODER	Dgi-Key	102-2050-ND	CUI INC.	AMT203-V	$48.65	**$194.60**
1	2	Miniature High-Precision Stainless Steel Ball Bearing - ABEC 5, Double Shielded	McMaster-Carr	7804K100			$6.18	**$6.18**
2	8	Zinc-Plated Steel Machine Screw Hex Nut, 10-24 Thread Size, 3/8" Width, 1/8" Height	McMaster-Carr	90480A011			$1.72	**$3.44**
1	16	Class 10.9 Steel Button-Head Socket Cap Screw, M3 Size, 8 mm Length, .5 mm Pitch	McMaster-Carr	91239A113			$6.43	**$6.43**
1	16	Class 10.9 Steel Button-Head Socket Cap Screw, M3 Size, 12 mm Length, .5 mm Pitch	McMaster-Carr	91239A117			$8.25	**$8.25**
1	8	Alloy Steel Button-Head Socket Cap Screw, Black-Oxide, 8-32 Thread, 3/8" Long	McMaster-Carr	91255A192			$12.40	**$12.40**
1	4	Alloy Steel Button-Head Socket Cap Screw, Black-Oxide, 8-32 Thread, 1/2" Long	McMaster-Carr	91255A194			$12.48	**$12.48**
1	8	Alloy Steel Button-Head Socket Cap Screw, Black-Oxide, 10-24 Thread, 3/8" Long	McMaster-Carr	91255A240			$13.06	**$13.06**
1	1	Brushless Gimbal Motor (Small)	iFlight	GBM3506-130T			$30.00	**$30.00**
3	3	Brushless Gimbal Motor (Large)	iFlight	GBM4144-120T			$50.00	**$150.00**

18.3 Electronics

Part	Value	Description	Manufacturer	Manufacturer P/N	Vendor	Vendor P/N	Cost
C1	0.1uF	CAPACITOR, American symbol	Kemet	C0603C104K4RACTU	Digi-Key	399-1096-1-ND	$ 0.10
C2	0.1uF	CAPACITOR, American symbol	Kemet	C0603C104K4RACTU	Digi-Key	399-1096-1-ND	$ 0.10
IC1	MAX3390EEUD+	MAX3390E Voltage Level Translator, TSSOP-14 Package	Maxim Integrated	MAX3390EEUD+	Digi-Key	MAX3390EEUD+-ND	$ 2.44
IC2	DS34C87T	TI DS34C87T CMOS Quad TRI-STATE Differential Line Driver	Texas Instruments	DS34C87TMX/NOPB	Digi-Key	DS34C87TMX/NOPBCT-ND	$ 1.48
IC3	SN74LVC1GU04	TI SN74LVC1GU04 Single Inverter Gate	Texas Instruments	SN74LVC1GU04DBVR	Digi-Key	296-8487-1-ND	$ 0.40
J1	AMT203	TE MicroMatch 10 Position Wire to Board	TE Connectivity	1-338068-0	Digi-Key	A99504CT-ND	$ 1.01
J2	GPIO-D	JST SUR 8 Position Side Entry Header	JST Sales America Inc	SM08B-SURS-TF(LF)(SN)	Digi-Key	455-2040-1-ND	$ 1.10
J3	QEI	TE MicroMatch 10 Position Wire to Board	TE Connectivity	1-338068-0	Digi-Key	A99504CT-ND	$ 1.01
J4	MPU6000 Breakout	Molex PicoBlade 1.25mm 6 Position SMD R/A	Molex Inc	532610671	Digi-Key	WM7624CT-ND	$ 1.65
						Total	$ 9.29

Qty.	Description	Manufacturer	Manufacture P/N	Vendor	Vendor P/N	Price	Subtotal
1	3-Conductor 24AWG Cable, 30m	Tensility	30-00006	Digi-Key	T3006-30-ND	$ 50.0000	$ 50.00
4	SPOX HSG 8P Connector Housing	Molex	50-37-5083	Digi-Key	WM18878-ND	$ 0.6400	$ 2.56
12	22-28AWG Crimp Terminal	Molex	0008701039	Digi-Key	WM18889CT-ND	$ 0.1100	$ 1.32
1	10-Conductor Flat Ribbon Cable, 25ft	3M	3365/10 300SF	Digi-Key	MC10G-25-ND	$ 8.7900	$ 8.79
5	Connector Housing, 14 Position	Samtec	ISDF-07-D	Newark	18T1615	$ 1.7900	$ 8.95
50	28-30AWG Crimp Terminal	Samtec	CC03L-2830-01-G	Newark	74R6747	$ 0.6130	$ 30.65
15	Ribbon Cable Connector	TE Connectivity	1-215083-0	Digi-Key	A107014CT-ND	$ 1.0030	$ 15.05
1	6-Conductor 28AWG Cable, 100ft	Alpha Wire	M2406 SL005	Digi-Key	M2406 SL005-ND	$ 88.7100	$ 88.71
2	PicoBlade Connector, 6 Position	Molex	0510210600	Digi-Key	WM1724-ND	$ 0.4600	$ 0.92
12	28-32AWG Crimp Terminal	Molex	0500588000	Digi-Key	WM1775CT-ND	$ 0.0720	$ 0.86
1	32AWG Wire, 100ft	Alpha Wire	2840/7 WH005	Digi-Key	2840/7 WH005-ND	$ 72.5200	$ 72.52
10	Shrouded Connector Housing, 8 Position	JST	08SUR-32S	Digi-Key	455-2177-ND	$ 0.9110	$ 9.11
1	24AWG Wire, Red, 100ft	Alpha Wire	3050 RD005	Digi-Key	A2015R-100-ND	$ 37.2200	$ 37.22
1	24AWG Wire, Black, 100ft	Alpha Wire	3050 BK005	Digi-Key	A2015B-100-ND	$ 37.2200	$ 37.22
10	M3 Ring Crimp Terminal	Molex	0193240002	Digi-Key	WM9606-ND	$ 0.4450	$ 4.45
						Total:	$ 368.33

Qty.	Part Number	Description	Price	Subtotal
5	S-001-2-I	SOMANET Core C22	€ 109.00	€ 545.00
5	S-002-1-I	SOMANET COM EtherCAT	€ 79.00	€ 395.00
5	S-006-1-I	SOMANET IFM Drive DC 100	€ 169.00	€ 845.00
1	S-007-1	SOMANET Core to XTAG Debug Adapter	€ 89.00	€ 89.00
1	S-007_O-01	SOMANET XMOS XTAG2 Programming/Debugging Device	€ 19.00	€ 19.00
4	S-002_O-04	SOMANET COM EtherCAT Cable STP 0.1m PicoBlade 5pin plug to	€ 15.00	€ 60.00
1	S-002_O-03	SOMANET COM EtherCAT Cable STP 4m RJ45 plug to PicoBlade 5	€ 18.00	€ 18.00
5	S-006_O-06	SOMANET IFM Drive DC 100 Connector Kit	€ 15.00	€ 75.00
5	S-001_O-01	SOMANET Node Mounting Kit	€ 25.00	€ 125.00
			Total (EUR)	€ 2,171.00
			Conversion rate:	1.38
			Total (USD)	$ 2,995.98

19 Appendix F: List of Terms

These terms have been included because it is expected that one or more of these concepts may be ambiguous.

1. Orientation Control - the ability to input a command and have the sensor array position itself accurately according to the desired location.
2. Pose Estimation - the ability to have the sensor array report where it is positioned at any given time.
3. Yaw - moving the camera left and right. Example: looking left over one shoulder and then over the other.
4. Pitch - rotating the sensor array up and down. Example: looking up to the sky and then down towards your feet.
5. Roll - tilting the camera back and forth in a left or right motion.
6. Heave - vertical translation of the camera.
7. Command Rate – the frequency at which the system can receive and process control commands
8. Standard Communications - our communication protocol being an industry standard protocol currently on the market.
9. Closed-loop positioning bandwidth - the maximum frequency at which the system will track control inputs.
10. Power Requirements - the amount of power consumed by the product at any given time.
11. Structural Integrity - the mechanism being able to withstand an impulse from the base.
12. Convex Enclosing Volume - the volume of space being occupied while the mechanism is in its resting position.

20 Appendix G: Project DVD File Tree

1. CAD Files
    a. Electronics
        i. AMT203 Encoder Interface Board
        ii. MPU-6000 IMU Interface Board
    b. Neck and Gimbal
        i. Export
        ii. Native SolidWorks Files
    c. Shake Table
        i. Export
        ii. Native SolidWorks Files
2. Code
3. Data Sheets
4. Documentation
    a. Fall Presentation
    b. Fall Report
    c. Project Fair Poster
    d. Winter Presentation
5. Drawings
    a. Electronics
    b. Gimbal
    c. Neck Structure
        i. Native SolidWorks Files
        ii. PDF
6. Raw Data

Videos

21 Appendix H: Fall Semester Report

This documents is a complete synopsis of Team Neckatronics' work from September 2013 to December 2013. Notable inclusions: opportunity development, concept development, low-fidelity prototyping, decisions matrices, and statement of work

Brigham Young University

Fall Semester Report
Team Neckatronics

Team Members:

Dan Koch
Morgan Gillespie
Addam Roberts
Chris Graham
Jordan McDonald
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Anton Bowden

Capstone Instructors:

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Sponsor:

Naval Research Laboratories

Liaison:

Joe Hays

Signatures **Date**

12/12/2013
12/12/2013
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12/12/2013
12/12/2013
12/12/2013

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Executive Summary

The Naval Research Laboratory (NRL) has obtained a quadruped robot and desires to integrate a stabilized sensor package. Team Neckatronics is working with the NRL to produce a system capable of stabilizing the data feed. The objective is to design and build a functional prototype that delivers steadied video and data output while being modular for potential use on other robotic systems. This will be completed by March 31st, 2014 within a development budget of $6,500.

Concept generation began with brainstorming a large volume of different ideas to meet the requirements of the sponsor. This ranged from very simple mechanisms to some very elaborate, far-reaching concepts. After grouping similar ideas, the less feasible concepts were screened out and the team created simple prototypes for those that remained.

With the completion of the early prototypes, a secondary screening matrix was compiled to enhance understanding of the remaining concepts' fidelity. This resulted in three promising designs and their associated higher caliber prototypes. The new prototypes identified the shortcomings of each option and narrowed down the selection to one design.

The chosen concept is a pivot arm mechanism, consisting of a parallel four-bar linkage with a controllable gimbal attached at the end. The gimbal provides active stabilization and control in yaw, pitch, and roll, while the pivot arm provides passive stabilization in heave. This stabilization will be achieved through the use of brushless motors, absolute encoders, and accelerometers controlled by a central processing unit.

1 Introduction

The objective of this project is to design, prototype, and test a mechatronic neck capable of accepting camera orientation commands and producing stabilized video output for a legged robot by 26 March 2014 within a development budget of $6500.

1.1 Background

The U.S. Naval Research Laboratory (NRL) is the joint research laboratory for the Marine Corps and Navy. They conduct a vast number of programs in advanced development, scientific research, and technology. Recently the NRL has obtained a robotic quadruped, the Allegro Dog, from a company called SimLab. Their main objective with the Allegro Dog is to develop new quadruped locomotion techniques while also exploiting and improving the associated algorithms. It has also been suggested that this robot, or one of its future derivatives, could someday be a personal assistant to soldiers in the field.

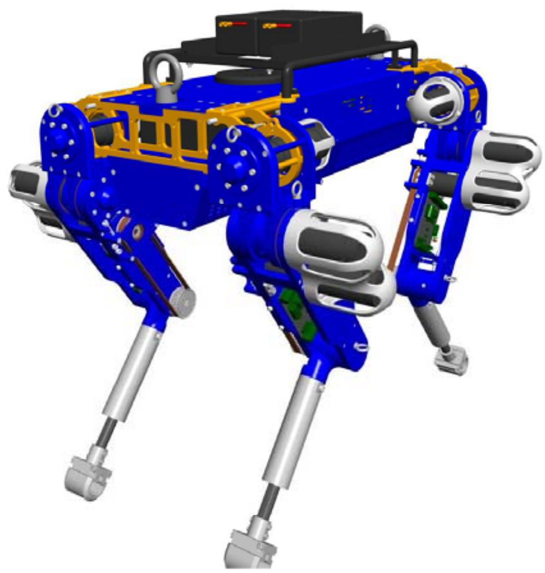


Figure 1. The Allegro Dog Robot

In order for the NRL to effectively work on these objectives, this robot must be able to perceive the environment around itself. Other autonomous robotic systems currently in the industry use sensors such as cameras, GPS, and rangefinders to accomplish this task. Environmental perception in legged robots is notably difficult to accomplish on account of the exorbitant vibrational noise that is experienced during dynamic locomotion, such as running or even walking. Current technologies allow for some limited stabilization in the sensor feed through algorithmic image stabilization techniques. While this solution is less complicated, more effective stabilization and noise reduction can be achieved through mechanically damping vibrations before they reach the sensors.

1.2 Project Purpose

The NRL is seeking to obtain a multi-purpose, 3+ DOF, robotic neck-like joint design for positioning a sensing array. In the future, and dependent upon the final chosen solution, NRL may choose to leverage components of the same design to produce a tail capable of substituting as a controllable counterbalance.

Neckatronics is tasked to design, build, and test a robust mechatronic neck to meet the needs of the NRL. The apparatus will need to be capable of positioning a sensing array to the desired orientations given in the statement of work (see Appendix B). It will also need to isolate any accelerations, vibrations, or noise experienced by the base of the neck. This robotic neck also needs to provide estimates of the pose of the sensing array relative to the base of the neck. The anticipated outcome of this project is a validated and tested functional prototype of the final mechatronic neck design, along with the necessary documentation to use, maintain, and duplicate the prototype.

Listed below are the main tasks for this project:

1. Design a controllable robotic joint that meets specifications as outlined in the requirements matrix (see Appendix C)
2. Prototype the design
3. Evaluate the prototype's positioning and vibration isolation performance.
4. Document the design and results of the prototyping test.

2 Project Requirements

2.1 Opportunity Development

The team worked collaboratively with the project sponsor to complete the opportunity development phase of the project and to define the product requirements, project budget, and project milestones. The NRL project liaison originally provided a statement of work describing the general requirements for the neck system. This statement of work is included as Appendix B. The team worked with the project liaison to translate this statement of work into a well-defined set of requirements for the project. These requirements are presented in the remainder of this section.

2.2 Product Requirements

Basic terminology associated with the product performance requirements is provided in Appendix A. Table 1 outlines some of the major product performance requirements and target performance specifications. The relative importance of each performance requirement is indicated and has been validated through discussions with the NRL Project Liaison. Appendix C provides a comprehensive requirements matrix for the project, which gives the detailed product performance requirements, evaluation criteria detailing how performance is to be measured, and target values for each of these evaluation criteria.

Table 1. Weighted Requirements Matrix

	Target Values	Marginal Values	Importance (out of 3)
Concept Generation	The sponsor is excited about the selected concept	The sponsor is satisfied with the selected concept	3
Subsystem Engineering	Design of the subsystems is complete and parts have been ordered	Design of subsystems is in the final stages of completion	2
Positioning Accuracy	Design allows for ±0.5° orientation accuracy	Design allows for ±1° orientation accuracy	2
Position Estimation Accuracy	Design should provide accuracy of ±0.5° in orientation ±0.1	Design should provide accuracy of ±1° in orientation and ±0.25 translation	2
Position Range of	Design allows for ±135° in yaw and ±70° in pitch	Design allows for ±115° in yaw and ±55° in pitch	2

Motion			
Camera Stabilization	Design should produce -20 dB attenuation of base inputs at camera in 2-60 Hz range.	Design should produce -18 dB attenuation of base inputs at camera in 2-60 Hz range.	3
Volume	Design fits within a 500in^3 convex volume in rest configuration	Design fits within a 1000in^3 convex volume in rest configuration	1
Weight	Predicted weight is less than 8.8lbs (4kg)	Predicted weight is less than 11lbs (5kg)	3

2.3 Project Budget

The development budget for this project is $6500.

2.4 Project Milestones

A detailed overview of the project schedule and development milestones is included in Appendix D. Some of the major development milestones for this project are listed below:

- 2 Oct. 2013: Opportunity development phase complete
- 7 Nov. 2013: Concept development phase complete
- 10 Jan 2014: Sub-system engineering phase complete
- 30 Jan 2014:Prototype 1 construction and testing complete
- 24 Feb 2014:Prototype 2 construction and testing complete
- 21 Mar 2014: Prototype 3 construction and testing complete
- 31 Mar 2014: System integration phase complete

3 Proposed Solution

3.1 Concept Development

After the team and sponsor agreed upon the set of product specifications, a large brainstorming session was initiated. The session generated around 120 ideas. Each one was written onto a sticky note and stuck onto a whiteboard. Every concept was subsequently sorted and grouped into related categories. This process revealed ill-defined groups. Focusing on these lacking areas generated additional concepts and ultimately, resulted in an extensive concept cloud (See Appendix E.).

3.2 Proposed Solution

A pivot arm mechanism with a gimbal is the chosen solution. This concept is illustrated in Figure 2. The pivot arm consists of a parallel four-bar linkage neck with incorporated springs and dampers. The gimbal is attached onto the end of the neck. It possesses three degrees of freedom, which are controlled by one motor for each axis of rotation. Additional degree of freedom is included to allow the laser scanner to tilt up and down relative to the gimbal.

The basic idea is that the neck's passive springs will stabilize the low to midrange frequencies associated with robot locomotion and interaction with the environment. High frequency stabilization is handled through active stability control programmed into the gimbal.

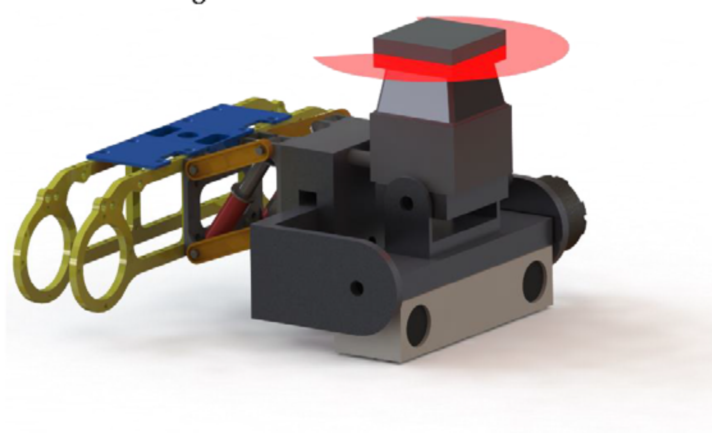


Figure 2. Complete Stabilization System

3.3 Verification

Throughout the entire concept selection process, a continuous concept verification process was employed, wherein candidate concepts were evaluated based on potential to achieve quantitative and qualitative alignment with surrogate evaluation criteria. Initially, the process of elimination was based off of a general understanding of each of the overarching ideas associated with the evaluation criteria and this evaluation was done with the use of matrices, and rough prototypes (See Appendix F.1). As the team and the sponsor gained a better understanding of the project, the surrogate evaluation criteria were refined and further steps were taken to eliminate the infeasible candidates. The final concept selection process was done through the use of functional prototyping (See Appendix F.2).

The proposed design has the ability to fulfill the requirements of the project, which are listed as follows:

- The chosen concept provides the ability to control the yaw and pitch orientation of the sensor through the gimbal mechanism.
- The chosen concept produces stabilized video output. Through the use of passive springs in neck's four-bar network the system attains passive stability in the middle and low frequency range, and with active controls in the gimbal, the system is able to stabilize the high frequencies.
- The chosen concept is within the weight constraints of the robot. The bar network allows for minimum weight, and optimizing the gimbal with composite materials places the concept within the weight range. This includes the potential weight of all electrical components and sensor packages.
- The chosen concept withstands physical impulses from the base. The spring system in the bars provides freedom of motion during jarring movements to help prevent damage to the system.
- The chosen concept uses standard communications protocol. The teams are currently only considering electrical components that will fall under the criteria.
- The chosen concept can be transitioned between different mounts.
- The chosen concept fits within the design constraints of the robot. Because of the bar network the concept fits within the desired 'relaxed volume.'
- The chosen concept is compatible with the power constraints. The simple design minimizes power consumption through elimination of unnecessary degrees of freedom and passive environmentally reactive stabilization.
- The chosen concept supports the visual payload through the use of strong linkages between the base and the payload.
- The chosen concept does all of its own processing contained within the structure.
- The chosen concept has the ability to mount on the Allegro Dog
- The chosen concept will respond quickly to commands because the selected electronics, motors, and physical kinematics, combine to give a dynamic movement rate within the target range
- The chosen concept uses standard electrical connections
- The chosen concept has a sufficient communications bandwidth for control inputs. This holds true because all considered electrical compatible components are within the desired criteria.

3.4 Subsystem Breakdown

Our concept is divided into three primary subsystems; this division facilitates parallelized workflow between sub-systems. The subsystems are listed and defined below. For a definition of the interfaces and interface requirements between these subsystems, refer to Appendix C. Each of these subsystems is described in detail in Sections 4-6 of this document.

- **Pivot Arm Mechanism**
  The pivot arm is the main structure that links the gimbal mechanism with the allegro dog chassis.

- **Gimbal Mechanism**
  The gimbal mechanism provides orientation in yaw, pitch, and roll. These movements are necessary in order to obtain the stabilization and pose that is desired.

- **Controls + Electronics**
  The electronics systems and control algorithms enable the active control and stabilization of the gimbal system, and provide estimates of the camera pose.

4 Pivot Arm Mechanism

The pivot arm is the main structure of our camera stabilization platform, linking the gimbal mechanism to the Allegro Dog chassis while eliminating the vibrations in heave. The pivot arm mechanism determines the overall structural integrity of the system. If designed poorly, the accuracy of the gimbal will suffer severely and camera feed will be poorly stabilized.

Figure 3. Pivot Arm Mechanism

4.1 Requirements

- The structure must support a 500 gram camera package, the gimbal mechanism, and any additional sensory packages.
- The structure must support cameras of varying sizes.
- The structure must be mountable on other robots.
- The structure must survive impulses from the base.
- The structure should be less than 2kg
- The structure should be smaller than 200 in^3
- The structure should isolate the vibrations and the translation in heave.

4.2 Design

The current design utilizes a parallel four-bar linkage, with a fixed equilibrium point, set by a spring damper system. This design is shown in Figure 3. The spring damper minimizes vibrations and dulls impulses from the base. At the base, a bracket (seen in grey) mounts to the Allegro dog through eight screw holes. Outward from this mount plate is a parallel bar linkage, which serves to stabilize heave. Through selective springs and dampers, chosen from our calculated dynamic model, this spring damper system connects in an X like pattern between the parallel pivot points.

At the end of the four-bar is mount plate bracket where one would mount the gimbal mechanism. Current links and brackets designed with 6061 T6 Aluminum;

however more exotic materials including carbon fiber, magnesium, and Titanium alloys are currently being considered to lighten the load.

4.3 Analysis Results

The Structure has been analyzed in Solidworks and NX Nastran FEA for both static and dynamic conditions.

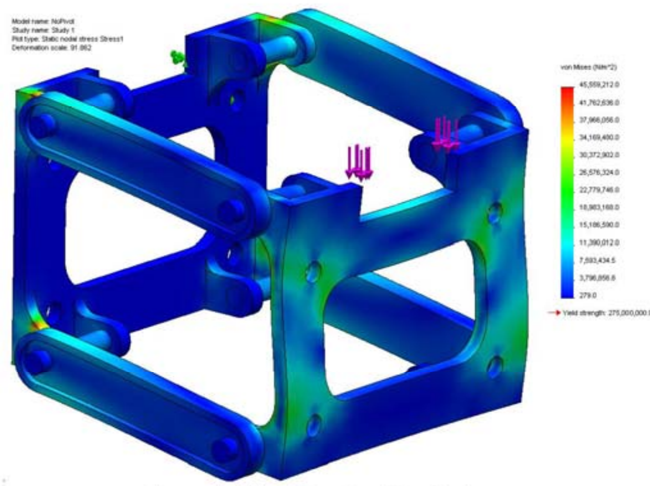


Figure 4. Pivot Structural Analysis

Conditions and results for the static analysis are listed below, and are illustrated in Figures 4 and 5.

- Fixed based plate, with 6061 T6 Aluminum Links and Structure, and 1020 Steel Pins.
- 15 KG Load on the end face, as indicated by the purple arrows.
- Maximum resultant von misses stress 45E6 N/M^2 or 6.6 KSI, compared to a yield of 275E6 N/M^2 or 39.9 KSI for 6061 T6 Aluminum.
- ISO Clipping of 3 KSI shows stress concentrates on the tops and corners of the base plates.
- Maximum deformations of 3.849e-3” occurred at the rounding of the brackets, as expected.

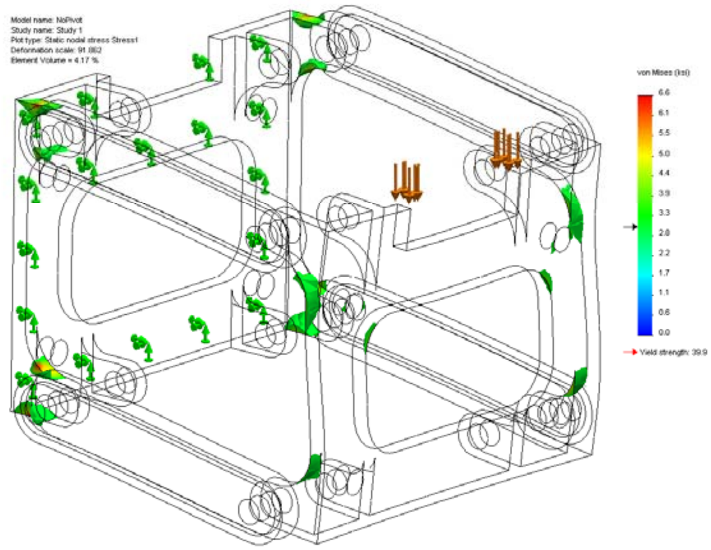


Figure 5. Analysis showing stress concentrations

From this test we can see that even with thin links, we are still well below the yield stresses of 6061 T6 Aluminum in the links which can result from the expected loading, under both impulse and controlled conditions. This demonstrates that our current design is both practical and opens us up to several different material options.

Planned analysis studies include a full system dynamic analysis and a full frequency spectrum attenuation study.

4.4 Key Requirements Fulfilled

This design is shown to support well over 500 grams, is highly modular for any size camera or robotic system, and can survive the expected dynamic impulse. The design weight is also below 2kg, smaller than the desired 200 in^3 control volume, and should isolate the desired frequencies.

4.5 Expected Cost

Table 2 summarizes the expected cost for the pivot arm mechanism.

Table 2. Expected Cost for Pivot Arm Mechanism Subsystem

Item	Number	Dims	Material	Supplier	Price/Unit	#	Total
2"x3/8" bar stock	F4382	4ft	Aluminum 6061	Metals depot	$21.2	1	$21.20
3x3x3/8" Angle	A3338	1ft	Aluminum 6061	Metals depot	$14.82	1	$14.82
Needle Thrust Bearings	5909K31	½" ID 15/16" OD	Steel	McMaster	$3.01	1	$3.01
Steel Washers	5909K44	0.032"	Steel	McMaster	$1	2	$2
Needle Roller Bearing	S99NH2-BN1610	0.5" ID 0.6875" OD	Steel	SDP/SI	$5.52	1	$5.52
Needle Roller Bearing	S99NH2-BN0808	0.25" ID 0.4375" OD	Steel	SDP/SI	$8.38	4	$32.52
Total							$82.07

5 Gimbal

The gimbal is the main mechanism for providing precise movement in yaw, pitch, and roll. It is attached near the end of the pivot arm structure to provide the largest field of view. Because the gimbal and pivot arm are interconnected it is crucial that relations are made between the two so as to provide accurate pose estimation.

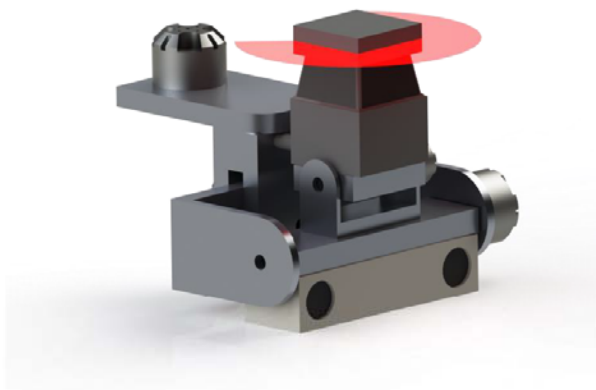


Figure 6. Gimbal Mechanism

5.1 Requirements

- The gimbal must provide +/- 140 degrees in pitch, +/- 70 degrees in yaw, and stabilized roll.
- This mechanism must provide accurate pose estimation with +/- .1 degree of accuracy
- The product produces stabilized video output with minimum attenuation of 2-60 Hz acceleration inputs from base
- The product quickly responds to control inputs with a close loop bandwidth of 2 Hz
- The product must meet the size and weight requirements of the robot
- The product is compatible with the robot's power supply

5.2 Design

The system will have actuation in pitch, yaw, and roll. This will be driven by brushless motors to provide the required speed and accuracy. Using the brushless motors in a direct drive configuration also allows direct torque control of the gimbal's degrees of freedom to achieve the required stabilization. We will use absolute magnetic encoders to produce accurate pose estimation.

5.3 Analysis Results

Dynamic modeling of the gimbal system was performed to determine the needed torque from the motors at the specified camera weight and closed loop bandwidth, in order find if available motors would meet those requirements and how big those motors needed to be.

The first attempt at modeling the system used the equation for a minimum jerk trajectory to calculate the maximum torque that would be needed to meet the performance requirements. A reasonable number was found, and we were able to find motors that provided this torque while still being small and lightweight enough to work in our system. While this was sufficient to convince us that the proposed gimbal design was feasible, we were afraid that using and ideal trajectory in our model would under-predict the actual torques that would be needed. We decided to make a second model, where we developed a simple PD controller for the yaw degree of freedom in the gimbal, and chose the gains to provide the desired performance characteristics.

Following this, we simulated a step input to the system and measured the torques that the controller requested. While the peak torques requested were somewhat higher than what the previous model had predicted, we found that when we limited the torque output of the motor in our model to a similar level to what we had predicted before we were still able to get a good response from the PD controller. This second study again showed that the gimbal design was feasible, and gave us an estimate of the torques required that would allow us to select appropriately sized motors.

5.4 Key Requirements Fulfilled

This design meets the specified needs outlined in our requirements section. Our design is within the volume and weight requirements. It also provides accurate position control and pose estimation.

5.5 Expected Cost

Table 3 summarizes the expected cost of the gimbal system.

Table 3. Expected Cost for Gimbal Subsystem

Item	Number	Dims	Material	Supplier	Price/Unit	#	Total
Brushless Motor	4008-70Kv	47mm x 21 mm		HobbyKing.com	29.58	3	88.74
Magnetic Encoder	AEAT-6012-A06			Avagotech	28.89	3	86.67
Metal			6061		30.00		30.00

			Aluminum				
Total							205.41

6 Controls and Electronics

6.1 Requirements

The requirements for the control system and electronics are summarized below:

Control System:

- The control algorithms must provide orientation control of the yaw and pitch degrees of freedom for the camera gimbal, and active stabilization of the camera system in yaw, pitch, and roll, in order to attenuate motion and vibration inputs from the base of the neck system.
- The control system must accept commands over a standard communications interface (e.g. RS232) at 200Hz, and should provide a closed-loop positioning bandwidth of 2Hz for the camera orientation while achieving an accuracy of ±0.5° for pitch and yaw.
- The sensing system also needs to provide pose estimates for the yaw, pitch, and roll of the camera with an accuracy of ±0.5°, and estimates of the heave position of the camera with an accuracy of ±0.1 in.

Electronics:

- The electronics need to be self-contained and perform all processing onboard the neck system.
- The electronics need to be able to support the communications and controls requirements.
- Only standard electrical connectors should be used in order to maintain modularity and ease of maintenance.
- The electronics also need to be compatible with the target power consumption values for the system.
- The electronics will also need to include a dedicated battery for the neck system.

6.2 Design

Several options were evaluated for the main processing unit of the control system. These options ranged from beginning with a bare microprocessor and designing a board around it to using a miniaturized Linux computer. After some evaluation and discussion with the sponsor, it was decided that designing a system from the ground up---while this would provide some advantages---was outside of the scope of this project. Available solutions were then evaluated and compared, including platforms such as Arduino, Raspberry Pi, Gumstix, Beaglebone, and LabVIEW Rio. The specifications for each of these systems are compared in Appendix G.3. After careful evaluation and further discussion with the sponsor, the Synapticon SOMANET platform was chosen. This system takes a modular and distributed approach to a control system, and while it is considerably more expensive than the other options, it was selected because it provides the following advantages:

- Low-level interfacing of components has already been done
- Modular communications interface (RS-485, CAN, EtherCAT)
- Highly integrated BLDC torque/current-control motor drivers
- Interfacing with encoders and IMU is supported
- Multi-core microprocessors allow for highly deterministic processing (e.g. control on one hardware thread and reading of encoders on a separate hardware thread)
- Support: Project liaison has working relationship with CEO, and has a former intern who worked with this system successfully over the summer
- Seems to be more aligned with the direction the NRL wants to take; would let them take advantage of this hardware more effectively in the future and be more integrated with their future projects
- Would help the project liaison to keep a good relationship with the company and CEO by showing he is still interested in using and exploring their products

A SOMANET system consists of a collection of nodes. Each node is comprised of three modules: a core module that contains the microprocessor, a COM unit that handles the inter-node and external communications, and an IFM module that handles the interfacing with motors and sensors. Each degree of freedom in a robotic system typically requires its own SOMANET node. The proposed architecture for our system is illustrated in Figure 7. Figure 8 shows an example of the hardware required to implement a typical node.

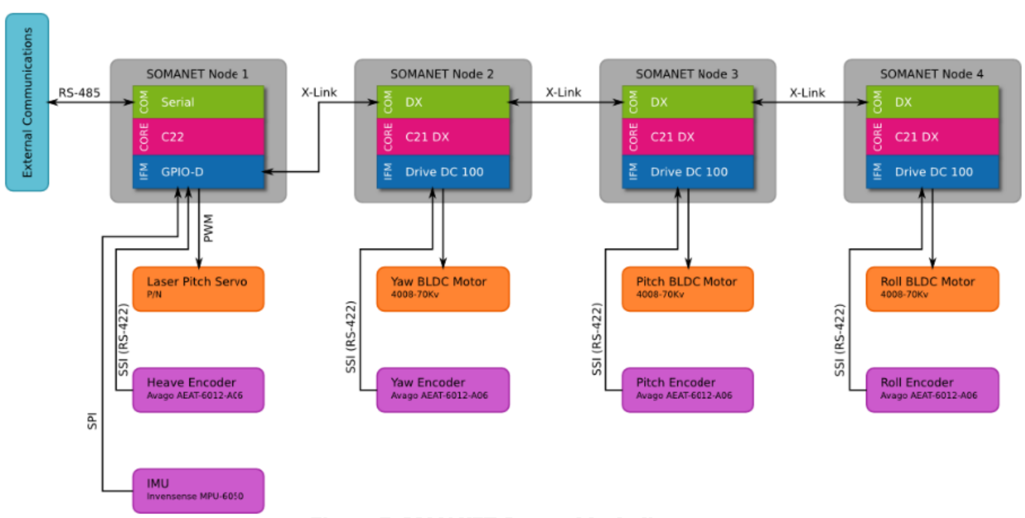


Figure 7. SOMANET System block diagram

While the control algorithms for the system are still under development, preliminary control architecture has been defined. Each degree of freedom of the gimbal will be controlled using a closed-loop PID control with an inner and outer loop. The inner loop will make use of feedback measurements from the inertial measurement unit (IMU), and will be responsible for providing inertial stabilization of the gimbal. The outer loop will use feedback inputs from the joint angle encoders, and will be responsible for holding the gimbal at the specified set-point. The different degrees of freedom (yaw, pitch, and roll) will be controlled separately, except for any joint angle information needed to transform the IMU data into the appropriate coordinate frame. This architecture is modeled on the approach followed by Ref. 1. It will permit the gimbal to control its orientation relative to the robot and maintain stability simultaneously.

Figure 8. SOMANET node hardware

Because the laser rangefinder will be mounted on the stabilized gimbal, the pitch degree of freedom for the rangefinder will not have inertial stabilization. This degree of freedom will be controlled using simple open-loop control via the servo's PWM positioning command input.

6.3 Key Requirements Fulfilled

The proposed design should fulfill all of the requirements listed in Section 6.1. The SOMANET platform will allow the control algorithms to run in a deterministic manner and quickly enough to meet the closed-loop bandwidth and accuracy performance specifications. The modular communications interface provided by the system will allow the system to receive control commands at the desired 200Hz over a variety of standard communications interfaces, including EtherCAT, CAN, and RS-485 serial communication.

6.4 Expected Cost

Using the SOMANET system makes the electronics and control system the most expensive subsystem of the proposed solution. However, because this subsystem is critical to the success and performance of the complete solution, it is believed that this expense is justified because SOMANET provides the most robust and highest performing solution. In addition, using the SOMANET platform will the make the product more useful to the customer in the long run as they are moving in this direction themselves. A summary of the expected cost for this subsystem is given in Table 4.

Table 4. Expected Cost for Electronics Subsystem

Qty.	Module	Price (Pounds)	Price (USD)	Subtotal (USD)
4	CORE C22	109	178.76	715.04
3	IFM Drive DC 100	169	277.16	831.48

3	COM DX-LVDS	39	63.96	191.88
1	COM Serial	79	129.56	129.56
1	IFM GPIO-D	19	31.16	31.16
Conversion Rate (Pounds to USD)	1.64		Total:	1899.12

7 Project Status

This section provides a summary of the project status in terms of scheduling and the development budget.

7.1 Development Milestones

According to the schedule specified in Section 2.4 and Appendix D, the project is on track to meet scheduled development milestones

7.2 Project Budget

The project is expected to meet the development budget requirements. A summary of the total cost estimates for the first fully functional prototype is given in Table 6. The total cost is estimated to be $2186.53, which is well within the $6500 budget. It is expected that costs for subsequent prototypes and additional expenses will not exceed the project budget.

Table 5. Expected Cost for Prototype 1

Sub-System	Cost
Structure	$82.00
Gimbal	$205.41
Controls	$1899.12
Total	$2186.53

8 Conclusion

Concentrated effort has produced a design that will fulfill the needs of the sponsor. Starting with a large breadth of concepts, the team successfully narrowed down the choices to the selected solution. Maintaining an open mind during the initial concept development phase fostered the research and development of a variety of solutions. Through careful deliberation, the final concept was selected.

Usage of CAD, FEA, and dynamic system modeling produced virtual models that permitted the verification of assumptions and design calculations with real numbers. These results allow the specification of parts with confidence, and will lead to fewer issues next semester.

After seeing the proposed solution and supporting analytical results, the sponsor believes the task can be accomplished with the chosen design. Next semester construction and programming of the fully functional prototype will begin.

9 References

[1] Ole C. Jacobsen and Eric N. Johnson, "Control Architecture for a UAV-Mounted Pan/Tilt/Roll Camera Gimbal," in *AIAA Infotech@Aerospace*, Arlington, VA, 2005.

Appendices

Appendix A: Definition of Terms

Having a basic understanding of the terms below will help to communicate the requirements being discussed.

- **Orientation Control** - the ability to input a command and have the sensor array position itself accurately according to the desired location.
- **Pose Estimation** - the ability to have the sensor array report where it is positioned at any given time.
- **Yaw** - moving the camera left and right. Example: looking left over one shoulder and then over the other.
- **Pitch** - rotating the sensor array up and down. Example: looking up to the sky and then down towards your feet.
- **Roll** - tilting the camera back and forth in a left or right motion.
- **Heave** - vertical translation of the camera.
- **Command Rate** – the frequency at which the system can receive and process control commands
- **Standard Communications** - our communication protocol being an industry standard protocol currently on the market.
- **Closed-loop positioning bandwidth** - the maximum frequency at which the system will track control inputs.
- **Power Requirements** - the amount of power consumed by the product at any given time.
- **Structural Integrity** - the mechanism being able to withstand an impulse from the base.
- **Convex Enclosing Volume** - the volume of space being occupied while the mechanism is in its resting position.

Appendix B: Statement of Work

Statement of Work provided by NRL Liaison:

Statement of Work
September 15, 2013

Background

The US Naval Research Laboratory (NRL) is seeking to procure a multi-purpose 3+DOF robotic joint design for positioning a camera sensor (sensor array), or tail. When the joint module is used as a neck it must be capable of isolating a 500 gram camera from mechanical vibrations experienced at the base of the neck. When acting as a tail, it will be capable of acting as a controllable counterbalanace for a highly agile walking robotic vehicle. (Tail weight of 500 grams and 70 cm in length.) This procurement is to provide a functioning prototype and report detailing the design and associated test results.

Tasks

1. Design a controllable robotic joint that meets provided specifications
2. Prototype the design
3. Evaluate the prototype's positioning and vibration isolation performance.
4. Document the design and results of the prototyping test

Specifications

1. 3+ DOF controllable positioning/orienting of the camera/tail system (at least but not limited to pitch, yaw, heave). With ranges of motion no less than +/-70 degrees (pitch), +/- 140 degrees (yaw), +/- 3 inches (heave).
2. Controller performance includes:
    a. Commanding rate of no less than 250 commands per second.
    b. While supporting a camera sensor of 500 grams (neck functionality):
        i. Positioning accuracy to within 1mm and orientation accuracy to within 6 arcminutes at steady-state.
        ii. Closed-loop positioning bandwidth of no less than 2Hz
        iii. Low-pass filtering of joint base vibrations transmitted to the camera by -20 dB (or less) in the frequency window of 2-60 Hz
    c. While supporting a counterbalance mass (300 grams and 50cm in length):
        i. Positioning accuracy to within 1cm and orientation accuracy to within 1 degree at steady-state.
        ii. Closed-loop positioning bandwidth of no less than 2Hz
3. Associated embedded electronics must accept position/orientation commands through standard communications (e.g. CAN or RS232 or EtherCAT) deterministically at rates no less than 250 Hz.
4. Total power requirements shall not exceed 8W.
5. Robust structural integrity up to 3 Gs of acceleration to the base (assuming a 500 gram camera/tail as a payload).
6. Total joint & electronics mass must be less-than-or-equal-to 1.5 kilograms and the convex enclosing volume must be less-than-or-equal-to 100 cubic inches.

Deliverables

1. Final written technical report documenting the design & test results
2. Prototype hardware

Schedule

1. Initial concept review on or before (November 1, 2013)
2. Design review on or before (December 20, 2013)
3. Prototype complete (March 30, 2014)
4. Testing complete (April 20, 2014)
5. Delivery of prototype and final report (May 1, 2014)

Appendix C: Requirements Matrix

This is the complete requirements matrix for the project, including product requirements, evaluation criteria, and marginal, ideal, and target values for those criteria.

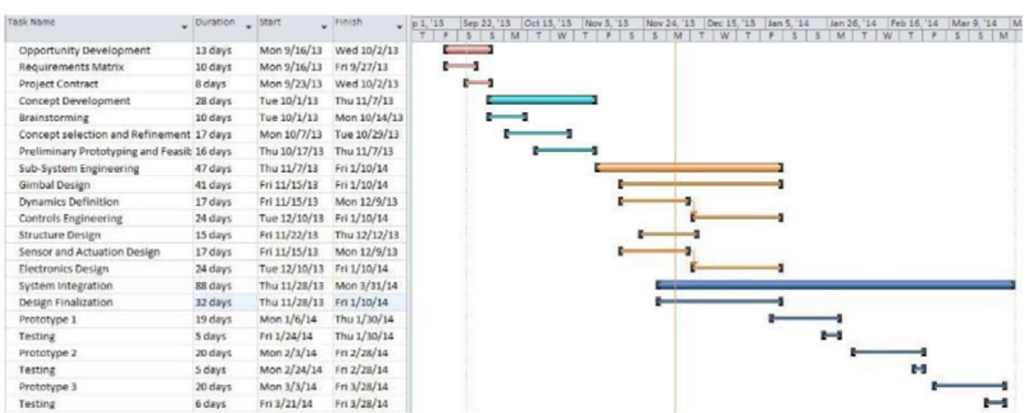
Product: Mechatronic Robotic Neck with Camera System
Subsystem: N/A
Revision: 1.2

	Surrogate Evaluation Criterion (How to measure)	Minimum attenuation of 2-60 Hz acceleration inputs from base to camer	RMS pixel jitter	Yaw range of motion	Pitch range of motion	Heave range of motion	Yaw and pitch positioning accuracy	Heave positioning accuracy	Translational pose estimate accuracy	Rotational pose estimate accuracy	Maximum closed loop positioning bandwidth for yaw, pitch, and heave	Total weight of system not including battery pack	Convex enclosing volume of product in resting configuration	The product mounts on the Allegro Dog system	Mounting bracket is interchangeable	Number of cycles product withstands a 3g base acceleration input	Electrical power consumption	The product uses a standard communications protocol	Minimum control input frequency	Data being transferred over communications link	Uses commercially available connectors	Impact resistance of the product
#	Market Requirement (What is wanted) #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	The product produces stabilized video output	●	●																			
2	The product allows control of camera pose			●	●	●	●	●	●	●	●											
3	The product provides accurate estimates of camera pose								●	●												
4	The product quickly responds to control inputs										●								●			
5	The product is within the weight constraints of the robot											●										
6	The product fits within size constraints of the robot												●									
7	The product uses a modular mounting interface													●	●							
8	The product mounts on the Allegro Dog robotic system													●	●							
9	The product supports the vision system payload										●					●	●					
10	The product withstands physical impulses from base															●						
11	The product is compatible with the robot's power supply																●					
12	The product uses a standard communications protocol																	●			●	
13	The product has a sufficient communications bandwidth for control inpu																		●			
14	The product performs all processing onboard											●	●				●			●		
15	The product uses standard electrical connections																				●	
16	The product can withstand impacts from the robot rolling over															●						●
	Unit of measurement	dB	pixels	degrees	degrees	inches	degrees	inches	inches	degrees	Hz	lbs	in^3	N/A	N/A	cycles	W	N/A	Hz	N/A	N/A	N/A
Market desired values	Marginal	-10	10	±90	±45	±0	±2.0	±0.1	±0.1	±2.0	0.5	15.4	2000	No	No	5	50	Some modifications to standard protocol	175	Additional communications for off-board processing	Some connectors are custom	Impact resistance matches that of Allegro Dog
	Ideal	-20	1	±135	±90	±3	±0.1	±0.01	±0.01	±0.1	2	3.3	100	Yes	Yes	1000	8	Uses existing standard protocol	250	Yaw, pitch, and heave control inputs and position estimates only	All connectors used are commercially available	Impact resistance exceeds that of Allegro Dog
Product performance	Target	-20	2	±135	±70	±1	±0.5	±0.04	±0.04	±0.5	2	8.8	500	Yes	Yes	10	24	Uses existing standard protocol	250	Yaw, pitch, and heave control inputs and position estimates only	All connectors used are commercially available	Impact resistance exceeds that of Allegro Dog
	Achieved																					

Appendix D: Project Schedule and Development Milestones

As the project has progressed and the design path has been defined, additional intermediate milestones were added to the project. The following table specifies our current and completed milestones as well as dates and deadlines. The schedule is also displayed in a Gantt chart format.

Task Name	Duration	Start	Finish
Opportunity Development	13 days	Mon 9/16/13	Wed 10/2/13
Requirements Matrix	10 days	Mon 9/16/13	Fri 9/27/13
Project Contract	8 days	Mon 9/23/13	Wed 10/2/13
Concept Development	28 days	Tue 10/1/13	Thu 11/7/13
Brainstorming	10 days	Tue 10/1/13	Mon 10/14/13
Concept selection and Refinement	17 days	Mon 10/7/13	Tue 10/29/13
Preliminary Prototyping and Feasibility Studies	16 days	Thu 10/17/13	Thu 11/7/13
Sub-System Engineering	47 days	Thu 11/7/13	Fri 1/10/14
Gimbal Design	41 days	Fri 11/15/13	Fri 1/10/14
Dynamics Definition	17 days	Fri 11/15/13	Mon 12/9/13
Controls Engineering	24 days	Tue 12/10/13	Fri 1/10/14
Structure Design	15 days	Fri 11/22/13	Thu 12/12/13
Sensor and Actuation Design	17 days	Fri 11/15/13	Mon 12/9/13
Electronics Design	24 days	Tue 12/10/13	Fri 1/10/14
System Integration	88 days	Thu 11/28/13	Mon 3/31/14
Design Finalization	32 days	Thu 11/28/13	Fri 1/10/14
Prototype 1	19 days	Mon 1/6/14	Thu 1/30/14
Testing	5 days	Fri 1/24/14	Thu 1/30/14
Prototype 2	20 days	Mon 2/3/14	Fri 2/28/14
Testing	5 days	Mon 2/24/14	Fri 2/28/14
Prototype 3	20 days	Mon 3/3/14	Fri 3/28/14
Testing	6 days	Fri 3/21/14	Fri 3/28/14



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Sensor and Actuation Design	17 days	Fri 11/15/13	Mon 12/9/13
Electronics Design	24 days	Tue 12/10/13	Fri 1/10/14
System Integration	88 days	Thu 11/28/13	Mon 3/31/14
Design Finalization	32 days	Thu 11/28/13	Fri 1/10/14
Prototype 1	19 days	Mon 1/6/14	Thu 1/30/14
Testing	5 days	Fri 1/24/14	Thu 1/30/14
Prototype 2	20 days	Mon 2/3/14	Fri 2/28/14
Testing	5 days	Mon 2/24/14	Fri 2/28/14
Prototype 3	20 days	Mon 3/3/14	Fri 3/28/14
Testing	6 days	Fri 3/21/14	Fri 3/28/14

Appendix E: Subsystem Definitions

This appendix defines the subsystems for the product and their interfaces.

Subsystem Definition and Interface Requirements

After the final concept decision was made, the concept was broken down into subsystems in order to identify specific areas for design work to occur and to parallelize the work of the team. Some of these subsystems were identified based on a structural decomposition of the concept, while others were identified based on a functional decomposition. The subsystems that were identified for the selected concept are:

- Pivot arm structure
- Mounting interface
- Gimbal structure
- Electronics

Additional Winter Semester Subsystems

- Roll cage
- Control Algorithm

The interfaces between these various subsystems are identified in the subsystem interface matrix, and the requirements for each of these interfaces are described in detail below.

	Mounting interface	Electronics	Control algorithm	Passive isolation	Structure	Gimbal
Gimbal		•	•		•	
Structure	•	•	•	•		
Passive isolation	•		•			
Control algorithm		•				
Electronics						
Mounting interface						

Gimbal connection to Structure and Mounting Interface

The structure needs to interface with not only a variety of robotic platforms, but also a variety of camera systems. A separable mounting bracket will need to be designed into the structure on both ends, which facilities modularity. This mounting interface at the end of the structure will need to be designed to work with the gimbal design as well.

Control Algorithm, Electronics, and Gimbal

The gimbal will need to be controlled by the system electronics, which will implement our control algorithm. This control algorithm utilizes sensory input to stabilize and orient the gimbal.

Mounting Interface

The structure needs to interface with not only a variety of robotic platforms, but also a variety of camera systems. A separable mounting bracket will need to be designed into the structure on both ends, which facilities modularity.

Appendix F: Concept Generation

This appendix outlines our concept generation and selection process. The purpose of this appendix is to demonstrate that the selected concept was chosen as a result of careful analysis and to show why we believe it is the best design.

F.1: Sticky-note Prototypes

Our initial brainstorming session generated around 120 ideas. Similar concepts were grouped into twenty-one categories: vertical movement, floaters (blimps and the like), mid-air suspension, counterbalance, tracks, UAV, eye mechanism, multi-cam, fiber-optics, fluid floats, canfield, 6-piston actuator, 3-piston platform, 6 D.O.F. fixed length, robotic arms, pivot arm/neck, linkages, linkages 4+, neck-like control, neck-like joints, & biology. The team decided that in order to refine the concepts, matrices would need to be used.

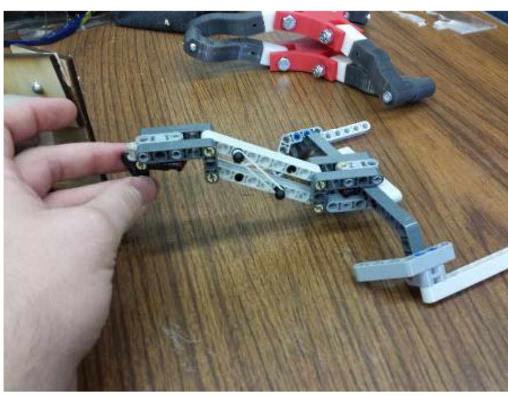
F.1.1: Large Ranking Matrix

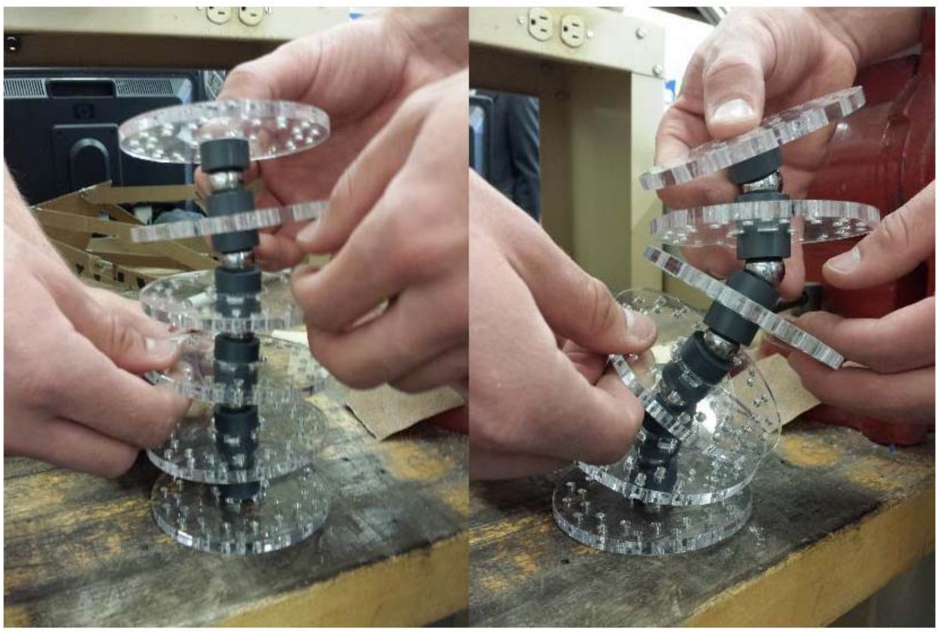
In order to filter out such a large breadth of concepts, a large ranking matrix was employed. The fourteen total evaluation criteria, used to rank each concept, were based on the market requirements. Each concept was placed in its designated category and rated with a '1' if the concept fulfilled the criteria well, a '0' if it did not fit the criteria well or poorly, and a '-1' if the concept failed to meet the criteria. The criteria used to rank were: simple, damping, produces stabilized video output, allows control of camera pose, quickly responds to control inputs, within the weight constraints of the robot, fits within size constraints of the robot, uses modular mounting interface, mounts on the Allegro Dog robotic system, supports the vision system payload, withstands physical impulses from base, compatible with the robots power supply, can withstand impact from the robot rolling over, & easy to make. Individually, each member evaluated the concepts over a weekend and then met together to discuss the results.

Through averaging individual member rankings, the matrices were combined and a number of categories were eliminated due to exceptionally low averages and low standard deviations, while others were reclassified – grouped into other categories which encompassed the concept fully. In entirety, there were eight categories eliminated from the teams direct field of view, and the team was left to focus on refining concepts from the following list of categories: Eye mechanism, canfield system, 6-piston, 3-piston, 4+ linkages, 6- DOF fixed length, mid-air suspension, pivot arm, spring isolation, UAV/security, robotic arm, neck-like mechanisms, steadicam / counterbalance.

F.2: Prototypes Stage 2

Following this refinement and concept elimination, each team member was assigned 2 ideas and became the expert advocates for these ideas. Constructing prototypes and fully exploring what designing and constructing each concept would involve. Both physical and digital prototypes were built, compared, and tested to show a hands-on approach of the capabilities of each system. These ideas were then shown to the sponsor who provided feedback on each of our highlighted concepts and prototypes.



F.2:1 Screening Matrix

Highlighting the pros and cons of these prototypes, we were able to construct a screening matrix, allowing us to eliminate some ideas, combine others, and focused the team on just a few prototypes. 6 piston and hexaparallel were pushed to research only, due to their overlap with other categories and severe weight issues. Robotic arm, steadicam, and mid-air suspension were eliminated due to impracticality. Lastly, 4+ bar was merged with pivot arm. From here we decided to focus solely on canfield, neck, pivot arm, and gimbal.

		Hexa-parallel	Stewart platform	Gimbal/UAV	Pivot arm	Robotic arm	Counter-balance	4+ bar linkage	Neck	Canfield	suspension
Orientation	Pitch	+	+	+	-	+	0	+	+	+	+
	Yaw	+	+	+	-	+	0	-	+	+	+
	Roll	+	0	+	-	+	0	-	0	-	0
Translation	x	+	+	-	+	+	-	0	+	+	0
	y	+	+	-	+	+	-	-	+	+	0
	z	+	+	-	+	+	-	+	0	+	+
Weight		-	-	+	0	-	0	+	0	+	+
Size		0	-	+	+	-	-	0	0	+	-
Structural integrity		-	0	0	+	-	0	+	+	0	+
Pose estimation		+	+	+	+	+	-	+	0	+	0
Payload		0	+	+	+	-	0	+	0	+	0
Power		-	-	+	0	-	+	0	+	0	+
Cool factor		+	+	+	0	-	-	0	+	+	-
# +'s		8	8	9	7	7	1	6	7	10	6
# 0's		2	2	1	3	0	6	4	6	2	5
# -'s		3	3	3	3	6	6	3	0	1	2
Total		5	5	6	4	1	-5	3	7	9	4
Decision		Research	Research	Keep	Keep, combine with gimbal	Discard	Discard	Merge with pivot arm	Keep	Keep, combine with gimbal	Discard
Action		Kinematic analysis	Kinematic analysis	Prototype	Prototype				Prototype	Prototype	

Once we had focused the design to 3 concepts, we utilized a weighted concept selection matrix to narrow the choice down to one – the pivot arm.

Controllability Sub-score

Specifications	Weight	Neck	Pivot Arm	Canfield	Jusificaion
Controlled pitch	5	2	3	3	Pivot Arm and Canfield have uncoupled pitch
Controlled yaw	5	2	3	2	Pivot Arm has uncoupled yaw
Controlled heave	2	3	3	1	Pivot Arm and Neck have coupled heave, Canfield has limited heave
Controlled sub-score		2.166666667	3	2.25	

Stabilization Sub-score

Specifications	Weight	Neck	Pivot Arm	Canfield	Jusificaion
Stabilized pitch	5	3	3	3	All mechanisms utilize gimbal that allows for stabilized pitch
Stabilized yaw	2	3	3	3	All mechanisms utilize gimbal that allows for stabilized yaw
Stabilized roll	3	[illegible]	3	3	Neck has passive roll stabilization in addition to active roll
Stabilized heave	5	3	3	1	Pivot Arm and Neck have great passive heave, Canfield joints can't allow heave motion
Stabilized Y	3	3	3	1	Pivot Arm and Neck have controlled Y
Stabilized X	1	3	3	5	Canfield has excellent movement in X
Stablization sub-score		3.157894737	3	2.263157895	

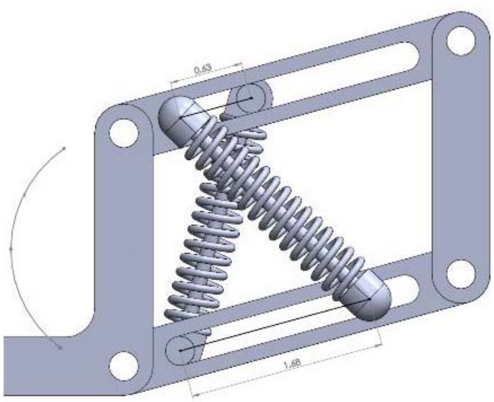
Overall Score

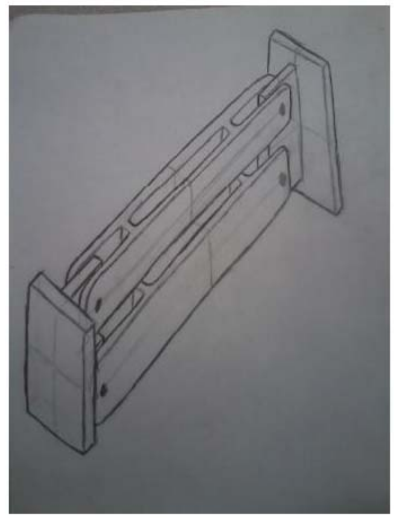
Specifications	Weight	Neck	Pivot Arm	Canfield	Jusificaion
Controlled sub-score	5	2.166666667	3	2.25	See above
Stablization sub-score	5	3.157894737	3	2.263157895	See above
Vibration isolation	5	3	3	1	Pivot Arm and Neck has integrated vibration isolation, Canfield has rigid joints
Weight	5	2	3	3	Pivot Arm and Canfield can be optimized structures with small linkages, Neck has limited optimization potential
Size	3	2	3	3	Pivot Arm and Canfield have few linkages, Neck requires multiple segments to achieve desired control
Withstands impulses from base	5	2	3	2	Pivot Arm is optimized for vertical impulse
Rollover resistance	3	3	3	4	Canfield is easiest to build a roll cage around
Pose estimation	5	1	3	3	Pivot Arm and Canfield have well defined kinematics, Neck pose estimation is uncertain and kinematics are unknown
Power	3	2	3	2	Pivot Arm does not require stalling motors to maintain heave
Feasibility	2	1	3	3	Pivot Arm and Canfield relatively straight forward designs
Response time	4	2	3	3	Pivot Arm and Canfield use gimbal to move camera around center of mass, Neck moves camera on a moment arm
Payload	3	2	3	3	Pivot Arm and Canfield are better suited for heavy loads
Camera modularity	3	4	3	3	Neck does not require full gimbal, Pivot Arm and Canfield gimbal limits camera size
Weighted Score		2.267713863	3	2.560113519	

Appendix G: Selected Design Appendix

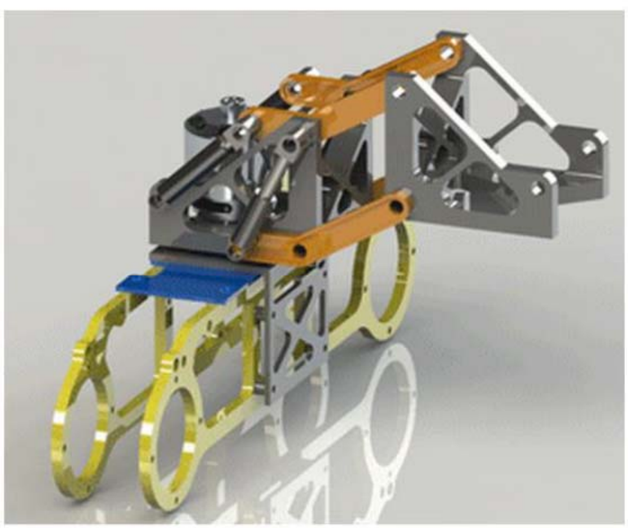
G.1: Pivot Arm Structure

Initial concept designs – with adjustable equilibrium

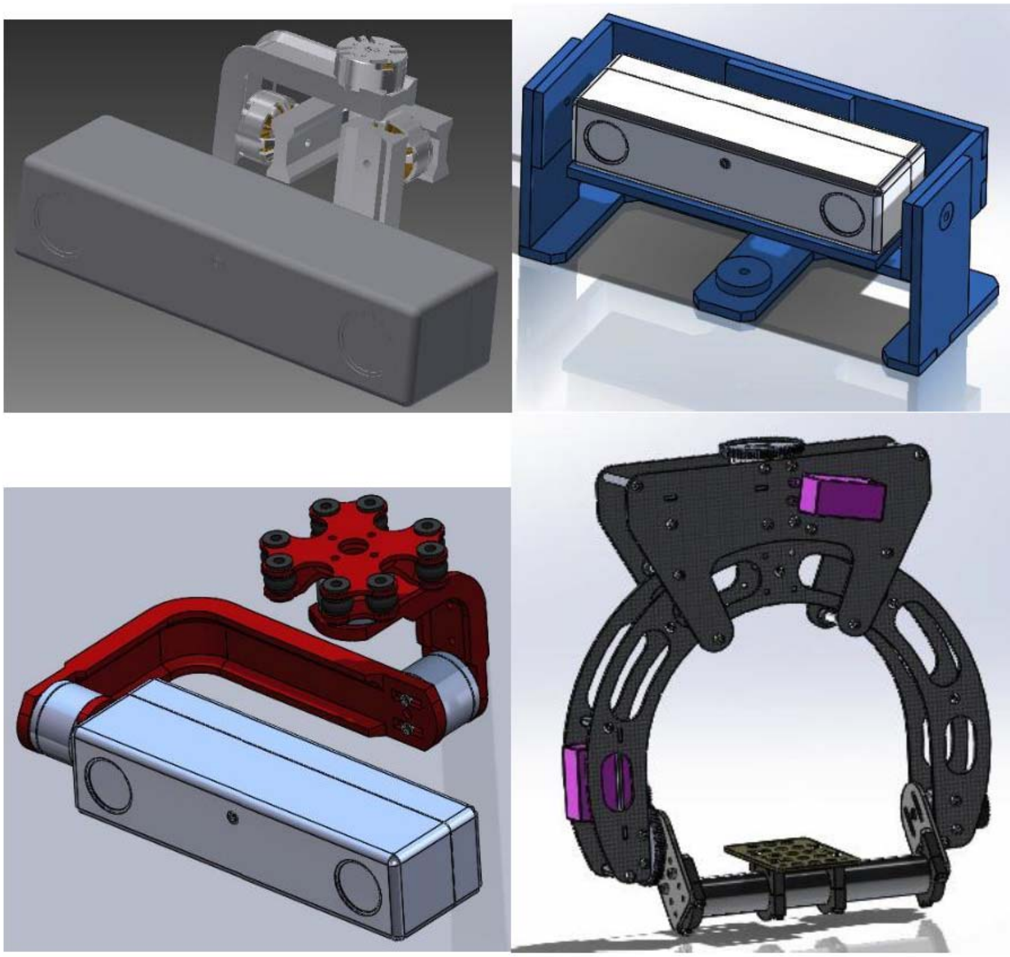




Alternate mechanism design with base pivot.



G.2: Alternate Gimbal Designs



G.3: Electronics

Microcontroller comparison chart:

	Processor	Memory			Programming Environment		Communication Protocols/Peripherals										Physical Dimensions				
Platform	CPU Speed	Program Memory	Data Memory	RAM	OS	Programming Languages	I2C	SPI	UART	SSI	GPIO	PWM	Ethernet	RS232 (serial)	USB	BLDC Drivers	Width	Length	Height	Weight	Price
Arduino	8-84Mhz	512-1Kb	1-96Kb	up to 512 Kb	Arduino? Linux?			0-1	1 to 4						Mini, micro, mini B, regular, 0-2						Variable dependent upon choices. See product comparison sheet
Raspberry Pi B	700Mhz	Not Sure, says needs SD card for long term memory		512MB	Linux		1	1	1-2?				1		has 2 (2.0) usb also has HDMI		3.4"	2.2"	.8"		35
Gumstix	1Ghz, recommend at 700Mhz	mini sd?		512MB	Linux (Ubuntu)	Linaro, yocto project	Y	Y	Y						1		67mm	118.2 mm	4.2mm		300
BeagleBone Black	1Ghz	2Gb		512MB	Angstrom, Linux, cloud9, Ubuntu, Android, and many more		2	2	4		65	8	1	3	1 with HDMI and also 2 46 pin slots					40g	45
Wandboard		N/A	N/A	512MB-2GB	Linux (Ubuntu12.04.2 or Yocto), Android (4.1.2 or 4.2.2)		2	1	1?				1	1?	1						$79-$129
fit-PC2i-Linux	1.1-1.6 GHz	N/A	N/A	1GB	Linux, Windows								2	1	4		101mm	115mm	27mm	350g	400
Synapticon SOMANET	4 x 2GHz	4Mb				C	Y	Y	Y		Y	Y	Y	Y		Y					$$$
LabVIEW Rio						LabVIEW															

Appendix H: FMEA

Failure Modes and Effects Analysis					Prepared By: Neckatronics								
For product/subsystem: Mechatronic neck System					Date: 12/3/13								
Component	**Functional purpose of component**	**Failure Mode**	**Failure Effect**	**Failure Cause**	**Current Situation**				**Assigned Action**	**Improved Situation**			
					S	L	D	RPN		S	L	D	RPN
Gimbal	Hold 500g camera array	Fails to hold camera array	Camera falls	Camera not attached properly	8	2	1	16	none	-	-	-	-
				Stucture failure	10	4	2	80	Run FEA				
	Orient camera	Motor failure	Unable to orient camera	Burnout	8	1	3	24	none	-	-	-	-
				Mechanical	10	4	5	200	Run FEA				
		IMU failure	Unable to orient camera	Disconnection	10	2	1	20	Code checks connection before running				
		Motor sensor failure	Unable to orient camera	Burnout	8	1	3	24	none	-	-	-	-
				Mechanical	10	4	5	200	Run FEA				
	Pose estimation	Encoder failure	Unable to obtain pose estimation	Disconection	10	2	1	20	Code checks connection before running				
		IMU failure	Unable to obtain pose estimation	Disconection	10	2	1	20	Code checks connection before running				
4 bar neck	Hold gimbal structure	Fails to hold gimbal	Gimbal falls	Gimbal not attached properly	8	2	1	16	none	-	-	-	-
				Stucture failure	10	5	4	200	Run FEA				
	Stablize heave	Fails to stabilze	Poor video feed	Improper damper calculation	6	7	3	126	none	-	-	-	-
				Disfunctional springs	6	7	8	336	Test springs and assembly				
	Survive impuse	System failure	System breaks	Mechanical failure	10	5	1	50	Run FEA				
				Mount failure	10	5	1	50	Run FEA & check hardware				
Controls	Controls gimbal	Failure to control	Logical error	Bad code	7	8	8	448	Debug code & peer review				
			Board failure	Improper manufacturing	8	2	5	80	none	-	-	-	-
				Elements	8	1	3	24	none	-	-	-	-
		Failure to stabilize	Logical error	Bad code	7	8	8	448	Debug code & peer review				
			Board failure	Improper manufacturing	8	2	5	80	none	-	-	-	-
				Elements	8	1	3	24	none	-	-	-	-
			Control loop runs too slow	Low Bandwidth	5	7	2	70	none				
	Pose estimation	Failure to estimate pose	Logical error	Bad code	7	8	8	448	Debug code & peer review				
			Sensor input error	Faulty wiring	6	7	3	126	none	-	-	-	-

S: Severity of Failure Effect

L: Likelihood of Occurrence

D: Ability to Detect Failure Cause Beforehand

RPN: Risk Priority Number (S*L*D)

Appendix I: Project Contract

Mechatronic Robotic Neck
Project Contract

U.S Naval Research Laboratory and BYU Capstone Team 28

James Brady, Team Member	Date
Morgan Gillespie, Team Member	Date
Christopher Graham, Team Member	Date
Daniel Koch, Team Member	Date
Jordan McDonald, Team Member	Date
Addam Roberts, Team Member	Date
Anton Bowden, Team Coach	Date
Joe Hays, Project Liaison	Date
Carl Sorenson or Christopher Mattson, Capstone Instructor	Date

This contract defines the agreement between the U.S. Naval Research Laboratory (referred to as *the sponsor*) and BYU Capstone Team 28 (referred to as *the team*) to fulfill the desired outcomes for the mechatronic robotic neck with camera system project. It provides a statement of the objective of the project, project team and sponsor information, a definition of the project scope, the product requirements, a description of the development milestones and anticipated schedule, details on the development budget, identification of market surrogates, grading criteria for the purposes of the Capstone course, and procedures for revising this contract.

1 Project Objective Statement

Design, prototype, and test a mechatronic neck capable of accepting camera orientation commands and producing stabilized video output for a legged robot by 26 March 2014 within a development budget of $6500.

2 Project Team Information

2.1 Identifying Information

Team Name: Neckatronics
BYU Capstone Team Number: 28

2.2 Team Members

- James Brady (jamesbrady0813@gmail.com)
- Morgan Gillespie (scrtcwlvl@gmail.com)
- Christopher Graham (graham.christopher18@gmail.com)
- Daniel Koch (daniel.p.koch@gmail.com)
- Jordan McDonald (jormcd@gmail.com)
- Addam Roberts (roberts.addam@gmail.com)

2.3 Team Coach

Anton E. Bowden, PhD, PE
Weidman Professor in Leadership
Director, BYU Applied Biomechanics Engineering Laboratory
Brigham Young University
Office Phone: 801-422-4760
Email: abowden@byu.edu

3 Project Owner Information

3.1 Project Sponsor

U.S. Naval Research Laboratory (NRL)

3.2 Project Liaison

Joe Hays, PhD
Roboticist
U.S. Naval Research Laboratory
Office Phone: 202-404-4281
Fax: 202-767-0365
Email: joe.hays@nrl.navy.mil

4 Project Scope

The project team will complete the opportunity development, concept development, subsystem engineering, and system integration stages of product development for the mechatronic robotic neck project. The anticipated outcome of this product development process is a tested and validated functional prototype of the final product design, along with the necessary documentation to use, maintain, and duplicate that prototype.

The team will focus primarily on developing the mechatronic neck system. Work on adapting that design for use as a robotic tail will be undertaken if time permits and if approved by both the sponsor and the team. Requirements and desired outcomes for work on the tail system will be decided upon at that time, and must be approved by the sponsor and team.

5 Product Requirements

The product requirements and associated evaluation criteria for verifying that those requirements have been met are detailed in the following requirements matrix. The marginal and ideal values in this revision are preliminary estimates only, and will be finalized at the end of concept development phase (refer to §6 for anticipated completion date). Surrogate Evaluation Criteria #13 is also preliminary and will be updated in a future revision. The positioning and range of motion requirements for also need further evaluation and review before finalizing.

Product: Mechatronic Robotic Neck with Camera System
Subsystem: N/A
Revision 1.2

#	Market Requirement (What is wanted) / Surrogate Evaluation Criterion (How to measure)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
		Minimum attenuation of 2-60 Hz acceleration inputs from base to camera (6 DOF)	RMS pixel jitter	Yaw range of motion	Pitch range of motion	Heave range of motion	Yaw and pitch positioning accuracy	Heave positioning accuracy	Translational pose estimate accuracy	Rotational pose estimate accuracy	Maximum closed loop positioning bandwidth for yaw, pitch, and heave	Total weight of system not including battery pack	Convex enclosing volume of product in resting configuration	The product mounts on the Allegro Dog system	Mounting bracket is interchangeable	Number of cycles product withstands a 3g base acceleration input	Electrical power consumption	The product uses a standard communications protocol	Minimum control input frequency	Data being transferred over communications link	Uses commercially available connectors	Impact resistance of the product
1	The product produces stabilized video output	●	●																			
2	The product allows control of camera pose			●	●	●	●	●	●	●	●											
3	The product provides accurate estimates of camera pose								●	●												
4	The product quickly responds to control inputs										●								●			
5	The product is within the weight constraints of the robot											●										
6	The product fits within size constraints of the robot												●									
7	The product uses a modular mounting interface													●	●							
8	The product mounts on the Allegro Dog robotic system													●	●							
9	The product supports the vision system payload										●					●	●					
10	The product withstands physical impulses from base															●						
11	The product is compatible with the robot's power supply																●					
12	The product uses a standard communications protocol																	●			●	
13	The product has a sufficient communications bandwidth for control inputs																		●			
14	The product performs all processing onboard											●	●				●			●		
15	The product uses standard electrical connections																				●	
16	The product can withstand impacts from the robot rolling over															●						●
	Unit of measurement	dB	pixels	degrees	degrees	inches	degrees	inches	inches	degrees	Hz	lbs	in^3	N/A	N/A	cycles	W	N/A	Hz	N/A	N/A	N/A
Market desired values	Marginal	-10	10	±90	±45	±1	±1.0	±0.1	±0.1	±0.5	0.5	5	1000	No	No	5	30	Some modifications to standard protocol	175	Additional communications for off-board processing	Some connectors are custom	Impact resistance matches that of Allegro Dog
	Ideal	-30	1	±140	±70	±3	±0.1	±0.04	±0.04	±0.1	2	≤3	100	Yes	Yes	10	8	Uses existing standard protocol	250	Yaw, pitch, and heave control inputs and position estimates only	All connectors used are commercially available	Impact resistance exceeds that of Allegro Dog
Product performance	Target																					
	Achieved																					

6 Development Milestones

Development milestones and an anticipated schedule for the project are detailed below. Boldface items are major development milestones, while other items are intermediate milestones that are likely to be modified as the project progresses.

Milestone	Date
Requirements Matrix	Fri, 27 September 2013
Project Contract	Wed, 2 October 2013
Opportunity Development Stage Complete	**Wed, 2 October 2013**
Brainstorming	Mon, 14 October 2013
Concept Selection and Refinement	Tue, 29 October 2013
Concept Development Stage Complete	**Mon, 4 November 2013**
Stabilization Engineering	Wed, 20 November 2013
Positioning Engineering	Wed, 27 November 2013
Interface Engineering	Wed, 4 December 2013
Sub-System Engineering Stage Complete	**Wed, 11 December 2013**
Design Finalization	Thu, 12 December 2013
Prototype 1 Complete	Thu, 30 January 2014
Testing on Prototype 1 Complete	Thu, 30 January 2014
Prototype 2 Complete	Thu, 27 February 2014
Testing on Prototype 2 Complete	Thu, 27 February 2014
Final Prototype Complete	**Thu, 27 March 2013**
Validation Testing Complete	**Thu, 27 March 2014**
System Integration Phase Complete	**Mon, 31 March 2014**

7 Development Budget

Expenditures by the team shall not exceed $6500 for development, prototyping, and testing of the product. The first $1500 dollars will be provided to the team as part of the standard Capstone team budget. The sponsor will be financially responsible for any expenditures exceeding $1500, up to the $6500 limit.

8 Market Surrogates

The market surrogates are those people who provide information about the product requirements and who validate the final product. The market surrogates for this project are:

- **Joe Hays**, PhD
  Roboticist
  U.S. Naval Research Laboratory
  Office Phone: 202-404-4281
  Fax: 202-767-0365
  Email: joe.hays@nrl.navy.mil
- **Team MeRLIn**
  U.S. Naval Research Laboratory
- **Mark Colton**, PhD
  Associate Professor of Mechanical Engineering
  Brigham Young University
  Office Phone: 801-422-6303
  Email: colton@byu.edu

9 Grading Criteria

These grading criteria are used for the purposes of the Capstone course to assign grades to the team members for fall and winter semesters. The numeric values in this revision of the contract are preliminary estimates only, and will be finalized at the end of the concept development phase (refer to §6 for anticipated completion date).

9.1 Fall Semester

Grading Criterion	A Criteria	B Criteria	C Criteria
Concept Generation	The sponsor is excited about the selected concept	The sponsor is satisfied with the selected concept	The sponsor has major concerns about the selected concept
Subsystem Engineering	Design of subsystems is complete and parts have been ordered	Design of subsystems is in the final stages of completion	Subsystem engineering is ongoing
Positioning Accuracy	Design allows for $\pm0.1°$orientation accuracy and ±0.04in accuracy in heave	Design allows for $\pm0.5°$orientation accuracy and ±0.07in accuracy in heave	Design allows for $\pm1.0°$orientation accuracy and ±0.1in accuracy in heave
Position Estimation Accuracy	Design should provide accuracy of $\pm0.1°$in orientation and ±0.04in in translation	Design should provide accuracy of $\pm0.3°$in orientation and ±0.07in in translation	Design should provide accuracy of $\pm0.5°$in orientation and ±0.1in in translation
Positioning Range of Motion	Design allows for $\pm140°$in yaw, $\pm70°$in pitch, and ±3in in heave	Design allows for $\pm115°$in yaw, $\pm55°$in pitch, and ±2in in heave	Design allows for $\pm90°$in yaw, $\pm45°$in pitch, and ±1in in heave
Camera Stabilization	Design should produce -20dB attenuation of base inputs at camera in 2–60 Hz range	Design should produce -18dB attenuation of base inputs at camera in 2–60 Hz range	Design should produce -10dB attenuation of base inputs at camera in 2–60 Hz range
Volume	Design fits within a 100in^3 convex volume in rest configuration	Design fits within a 500in^3 convex volume in rest configuration	Design fits within a 1000in^3 convex volume in rest configuration
Weight	Predicted weight is 3.3lbs or less not including battery	Predicted weight is 4lbs or less not including battery	Predicted weight is 5lbs or less not including battery

9.2 Winter Semester

Critical Design Requirement	A Criteria	B Criteria	C Criteria
Stabilized Video Output	-20 dB attenuation of base acceleration inputs at camera in 2–60 Hz range	-18 dB attenuation of base acceleration inputs at camera in 2–60 Hz range	-10 dB attenuation of base acceleration inputs at camera in 2–60 Hz range
Positioning Accuracy	$\pm 0.1°$orientation accuracy and ± 0.04in accuracy in heave	$\pm 0.5°$orientation accuracy and ± 0.07in accuracy in heave	$\pm 1.0°$orientation accuracy and ± 0.1in accuracy in heave
Position Estimation Accuracy	Prototype provides accuracy of $\pm 0.1°$in orientation and ± 0.04in in translation	Prototype provides accuracy of $\pm 0.3°$in orientation and ± 0.07in in translation	Prototype provides accuracy of $\pm 0.5°$in orientation and ± 0.1in in translation
Positioning Speed	Closed loop bandwidth of 2Hz	Closed loop bandwidth of 1Hz	Closed loop bandwidth of 0.5Hz
Weight	Physical prototype weighs no more than 3.3 lbs	Physical prototype weighs no more than 4 lbs	Physical prototype weighs no more than 5 lbs
Volume	Physical prototype fits within a 100in^3 convex volume in rest configuration	Physical prototype fits within a 500in^3 volume in rest configuration	Physical prototype fits within a 1000in^3 volume in rest configuration
Positioning Range of Motion	Physical prototype offers $\pm 140°$in yaw, $\pm 70°$in pitch, and ± 3in in heave	Physical prototype offers $\pm 115°$in yaw, $\pm 55°$in pitch, and ± 2in in heave	Physical prototype offers $\pm 90°$in yaw, $\pm 45°$in pitch, and ± 1in in heave
Robustness to impulses at base	Exact requirement TBD	Exact requirement TBD	Exact requirement TBD
Robustness to robot rollover	Impact resistance exceeds that of Allegro Dog	Impact resistance matches that of Allegro Dog	Impact resistance less than that of Allegro Dog
Electrical Power Requirements	The prototype requires no more than 8W during operation	The prototype requires no more than 10W during operation	The prototype requires no more than 12W during operation
Communications Protocol	250 Hz command rate	200 Hz command rate	170 Hz command rate
Electrical Interfaces	The product uses only commercially available interfaces	The product uses a mixture of custom and commercially available interfaces	The product relies heavily on custom interfaces

10 Change Management

This contract is a working document, and changes may be made to it as the project progresses. Changes to this contract may only be made with the mutual consent of the project sponsor, team members, and team coach. The changes will not be effective until signatures are obtained from the project sponsor, all members of the team, and the team coach. This contract will be placed under version control, and a revision history will be maintained along with a record of the approvals for each change.

11 Revision History

The major revision number is incremented when changes are made after the previous version of the contract has been approved and signed by all relevant parties. The minor revision number is incremented when changes are made after the contract has been reviewed by both the team and the sponsor, but before final approval and signing.

Revision No.	Description of Changes	Date
1.0	Initial draft	1 October 2013
1.1	Implemented feedback from project liaison • Added rollover requirement to requirements matrix and grading criteria • Updated volume requirement in requirements matrix and grading criteria • Added robustness to impulses and rollover, power requirements, and interfaces to winter grading criteria • Added MeRLIn team and Mark Colton as market surrogates • Updated development milestones • Noted that numeric values in requirements matrix and grading criteria are preliminary • Noted that Surrogate Evaluation Criteria #13 is preliminary	3 October 2013
1.2	Implemented feedback from Capstone instructors and project liaison • Added position estimate market requirement and evaluation criteria to requirements matrix • Removed communications from fall grading criteria • Added range of motion to fall grading criteria • Added frequency range to stabilization grading criterion • Changed fall grading criteria for weight to predicted weight • Added position estimation accuracy to fall and winter grading criteria • Updated development milestones	10 October 2013