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TEST FRAME DESIGN FOR CHARACTERIZATION OF ADDITIVE MANUFACTURING COMPLIANT MATERIALS

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Mechanical Engineering

by
Sean Taylor Fry
May 2020

Accepted by:
Dr. Cameron Turner, Committee Chair
Dr. Joshua Summers
Dr. Garrett Pataky

ABSTRACT

With the application of using surrogate models with General Purpose Graphics Processing (GPGPU) computing to meet the need for “real-time” characterization of nonlinear anisotropic material systems and the growing work of using multiaxial robotic test frames for material characterization, there has been a solution for a specific application towards additive manufacturing materials, specifically polymers. Traditional testing using uniaxial and biaxial test machines has proven insufficient in characterizing the material properties of additive manufacturing materials, therefore developing a need for a multiaxial testing machine for characterization that can dynamically excite strain states for a more in-depth look at the material properties. This design report presents the design of a multiaxial robotic test frame that incorporates a Stewart-Gough (SG) platform design to allow 6 degrees-of-freedom for multiple and combined loading applications. This solution is the next generation multiaxial machine focusing on additive manufacturing materials, specifically polymers. The problem statement is the following:

Design and fabricate a multiaxial robotic test frame that can test additive manufacturing materials, focusing on polymers and some metals, in 6 degrees-of-freedom while improving on performance and cost over the CSM design.

DEDICATION

I dedicate my thesis work to my family and friends, for they have helped and supported me throughout.

ACKNOWLEDGEMENTS

I would like to thank my family first. I would also like to thank my advisor, Dr. Turner, for allowing me to work on this project, my committee members, Dr. Summers and Dr. Pataky, for the feedback during this work. Lastly, I would like to thank my fellow CEDARians for giving me feedback and helping through the years.

TABLE OF CONTENTS

ABSTRACT.....	ii
DEDICATION.....	iii
ACKNOWLEDGEMENTS.....	iv
TABLE OF CONTENTS.....	v
LIST OF TABLES.....	ix
LIST OF FIGURES.....	xi
CHAPTER 1:	1
1.1 Motivation.....	1
1.2 Test Frame Design Problem	2
1.3 Thesis Outline.....	2
CHAPTER 2: CHARACTERIZATION THROUGH HEXAPOD DESIGN	3
2.1 Review of Robotic Manipulators.....	3
2.2 Stewart-Gough Platform.....	5
2.2.1 Kinematics of a General Stewart-Gough Platform	5
2.3 Jacobian Analysis of Stewart-Gough Platform.....	8
2.4 Review of Material Characterization Using Multiaxial Testing.....	10
2.4.1 CSM Design Solution	10
2.4.2 Naval Research Laboratory Design	15
CHAPTER 3: DESIGN SOLUTION.....	17
3.1 Requirements	17
3.1.1 Constraints	17

3.1.2 Criteria	19
3.2 Overview of Design.....	21
3.2.1 EHA Actuators	22
3.2.2 Bottom Frame	24
3.2.3 Top Frame	24
3.2.4 Grip Assembly	25
3.2.5 Camera Setup	26
3.2.6 Top Platform	27
3.3 Hexapod Workspace.....	28
3.3.1 Translation	28
3.3.2 Rotation.....	30
3.4 Component Details	34
3.4.1 Camera Assembly	34
3.4.2 Grip Assembly	34
3.4.3 Actuator Assembly.....	35
3.4.4 Data Acquisition	36
CHAPTER 4: DESIGN JUSTIFICATION	38
4.1 Constraints	38
4.2 Criteria	40
4.3 FEA Results	42
4.3.1 Top Frame FEA	42
4.3.2 Bottom Frame FEA.....	44
4.3.3 Top Plate FEA.....	45
4.4 CSM vs. 66.1 Tiger Singularity Map.....	46

4.5 Distance Measurement Analysis.....	48
CHAPTER 5: DISCUSSION AND CONCLUSION	50
5.1 Limitations of Design	50
5.2 Strengths of Design.....	51
5.3 Fabrication of Design	52
5.4 Functionality of Design	53
5.4.1 Specimen Tests	54
5.5 Future Work.....	54
5.5.1 Possible Research Questions.....	56
5.6 Conclusion	57
CHAPTER 6: REFERENCES	58
APPENDICES	64
APPENDIX A: PRODUCT DESIGN SPECIFICATION.....	65
APPENDIX B: DESIGN DRAWINGS.....	69
APPENDIX C: MATLAB CODE FOR SINGULARITY ANALYSIS.....	89
APPENDIX D: DISTANCE MEASUREMENT PACKAGE.....	97
APPENDIX E: EQUIPMENT DATASHEETS	100
APPENDIX F: BILL OF MATERIALS.....	132
APPENDIX G: TIGER 66.1 CONTROL CODE	133
APPENDIX H: CSM BILL OF MATERIALS	135
APPENDIX I: INITIAL SINGULARITY ANALYSIS	137
I.1 Overview	137
I.2 Results with Translation.....	142
I.3 Results with Orientation.....	160

LIST OF TABLES

Table 2.1: Deflection predictions for bulk materials. Material properties are from SolidWorks.	14
Table 3.1: List of Constraints.....	18
Table 3.2: List of Criteria.....	20
Table 3.3: Camera Specs.....	34
Table 3.4: Grip Specifications	35
Table 3.5: Force/Torque Sensor Specifications	35
Table 3.6: Actuator Specifications.....	36
Table 3.7: LMPMT Specifications	36
Table 3.8: Computer Specifications.....	37
Table 4.1: Constraints Status.	39
Table 4.2: Criteria that are met/not met	41
Table 4.3: Deflection results for top frame	43
Table 4.4: Deflection results for bottom frame.....	44
Table 4.5: Deflection results for top plate	45
Table 4.6: Color coding scheme.	47
Table 4.7: Positive speed PID control values for Parker EHA.	49
Table 4.8: Negative speed PID control values for Parker EHA.	49
Table I.1: Material properties of ABS-ESD7 [6].....	139

Table I.2: Results of deflection calculations of ABS-ESD7	143
Table I.3: Color coding scheme.	152

LIST OF FIGURES

Figure 2.1: Serial manipulator (left) and parallel manipulator (right) examples.....	4
Figure 2.2: Stewart-Gough platform with SPS configuration. [14].....	6
Figure 2.3: CSM hexapod design.....	11
Figure 2.4: Close up of camera (red) and actuator (grey & blue).....	15
Figure 2.5: NRL 66.3 Multiaxial robotic test frame	16
Figure 3.1: Solution	21
Figure 3.2. Actuator Assembly.	23
Figure 3.3: Bottom frame assembly	24
Figure 3.4: Top frame assembly	25
Figure 3.5: Grip assembly	26
Figure 3.6: NOGA holder.	27
Figure 3.7: Top platform assembly	27
Figure 3.8: Workspace comparison, CSM (bottom) and 66.1 Tiger (top).....	29
Figure 3.9: Rotation only comparison, 66.1 Tiger (left) and CSM (right).	31
Figure 3.10: Pure bending comparison, 66.1 Tiger (top) and CSM (bottom).	32
Figure 3.11: Difference between the traditional hexapod setup and the inverted hexapod setup.....	33
Figure 4.1: FEA of top frame (FOS = 7)	43
Figure 4.2: FEA of bottom frame (FOS = 3.6)	44
Figure 4.3: FEA of top plate (FOS = 1.7)	46

Figure 4.4: Singularity map of pure translation of the CSM (top) and 66.1 Tiger (bottom) designs.....	47
Figure 4.5: Pure rotation scenarios for the singularity map of the 66.1 Tiger (right) and the CSM (left) designs.	48
Figure 5.1: SolidWorks Image of solution (left), solution pictured in the lab (right).	53
Figure I.1: Results of increasing the bottom plate radius while keeping the top radius of 250 mm.	144
Figure I.2: Results of increasing the radius of the bottom plate. The top plate was kept at the initial 250 mm of the design.....	145
Figure I.3: Results of increasing the top plate radius while keeping the bottom radius at a default of 250 mm.	145
Figure I.4: Results of the condition number and determinant for a pure bending test. The top plate radius is kept at default while the bottom plate radius is increased.	147
Figure I.5: Results of the condition number and determinant for pure bending with increasing top plate radius and a constant default bottom plate radius.....	148
Figure I.6: Results of the condition number and determinant over the pathway of a pure torsion test with increasing bottom plate radius with a constant default top plate radius. Note that the last three legend values are close together on both charts.	150
Figure I.7: Data for “slice” of workspace at the “home” location.	151

Figure I.8: Color coding of position points based on condition number.	152
Figure I.9: Color coding scheme by changing yellow to range between 250 and 50,000 and red to range above 50,000.	154
Figure I.10 Condition number analysis at a height of 37.5 mm above the “home” position using the color scheme in table 2.	155
Figure I.11: Condition number analysis at 37.5 mm below the “home” position. Same color scheme as table 2.	156
Figure I.12: Condition number analysis at 75 mm above (top) and below (bottom) the “home” position.	157
Figure I.13: Condition number results using the color scheme in table 2, 19 mm above (top) and below (bottom).	159
Figure I.14: Condition analysis with increasing z value up to the “home” position from below.	160
Figure I.15: Specimen designs used for analysis and testing.	161
Figure I.16: Results from moments about the specimen.	162
Figure I.17: Results for orientation of rotation about “home” position (top) and the results with greater distance between data points (bottom).	163

CHAPTER 1: TOWARDS CHARACTERIZATION WITH STEWART-GOUGH PLATFORMS

The purpose of this research is to develop a 6 degree-of-freedom (6-DOF) multiaxial robotic test frame to actively characterize the constitutive material properties of additive manufacturing materials, specifically in dealing with polymers. 6-DOF supports motion in three translational directions, X, Y, and Z, and the respective rotational directions. This allows 6-axis loading to be applied to a specimen to generate the complex nonlinear responses characteristic of additively manufactured (AM) materials. In this thesis previous design is reviewed to support the application of a new design that meets the need for multiaxial testing of nonlinear, anisotropic, polymer materials.

1.1 Motivation

The motivation for a move towards multiaxial testing comes from several disadvantages of using traditional uniaxial testing for nonlinear materials. Specifically, for the case of AM materials, nonlinear and anisotropic material behavior is of concern. Work done at the Naval Research Laboratory addresses the lack of knowledge from the nonlinear domain and provides particular solutions for characterizing composite materials using a multiaxial robotic test machines [1–4]. More recent work has followed through with showing the advantages and reasoning for multiaxial testing towards nonlinear domains of material behavior [5–12]. This work contains further development of the mentioned work towards AM material characterization, while improving in some aspects of the Colorado School of Mines (CSM) design, shown in Figure 2.3 and discussed in Section 2.4.1.

1.2 Test Frame Design Problem

At the start of this research, a design solution was provided that was completed by a 2-semester senior design team named “5DOF (Designers of the Future)” at the Colorado School of Mines [13]. This is referenced to show the reasoning for a redesign of a 6-degree-of-freedom test frame for material characterization. The team provided a process and background into designing the solution. The start of the research was to determine if 5DOF’s design was suitable to go forward and fabricate. Ultimately, a decision was made to design a completely new solution as the given was not adequate due to issues outlined in section 2.1. Considering this, a problem statement is shown below:

Design and fabricate a multiaxial robotic test frame that can test additive manufacturing materials, focusing on polymers and some metals, in 6 degrees-of-freedom while improving on performance and cost over the CSM design.

1.3 Thesis Outline

Chapter 1 provides the introduction into the project with the motivation and problem statement. Chapter 2 introduces the background and previous work related to the problem. Chapter 3 includes the design solutions with its relation to the requirements. Chapter 4 summarizes the constraints and criteria and goes over the FEA, the singularity ‘map’ and work completed to see if inaccurate actuators can be made accurate with the use of PID and cheap electronics. Chapter 5 includes the discussion and conclusion of this design report. Lastly, chapter 6 includes the references.

CHAPTER 2:

CHARACTERIZATION THROUGH HEXAPOD DESIGN

Characterization is essential in understanding material behavior. Understanding AM material behavior will be beneficial in making designs that are more oriented towards structural applications. This chapter discusses characterization through hexapod design, focusing on background and analysis on a provided design, past research completed, hexapod designs, geometries, and singularities management. These topics deal with what is best suited for a hexapod design for characterization of AM materials focusing on polymers

2.1 Review of Robotic Manipulators

There are two main types of manipulators, serial and parallel, and there are several sub-categories with each type [14]. The difference in serial and parallel manipulators is the architecture. Serial manipulators consist of a fixed base and an end effector that is free to move. Parallel manipulators are classified as a robot that has a moving platform and is connected to a fixed platform by several “limbs or legs”. Robot in this context means a machine that can carry out complex actions through a computer. Parallel manipulators are also known as platform manipulators [14]. Examples of each are provided in Figure 2.1. This research uses parallel manipulator due to the superior rigidity, accuracy, and control that is possible with closed loop manipulators as compared to serial manipulators that are opened ended [14].

Figure 2.1: Serial manipulator (left) and parallel manipulator (right) examples.

Parallel manipulators are classified into three main categories, planar, spherical, or spatial manipulators. Planar manipulators consist of planar movement, excluding any change in orientation except movement about the axis perpendicular of the plane. Spherical manipulators consist only of spherical movement, meaning movement around a central virtual point. Spatial manipulators consist of movement in any direction in which it is not only spherical or planar but can contain both types of movement. In the case of this research, translational and rotational movement is needed. Classification can also be determined by using equations 2.1 and 2.2,

$$\sum_{k=1}^m C_k = (\lambda + 1)F - \lambda = 7F - 6 \quad 2.1$$

$$\lambda \geq C_k \geq F \quad 2.2$$

where C_k is the connectivity of the k th limb, λ is a motion parameter the manipulator within the workspace, F is the degrees of freedom of the manipulator, and m is the number of limbs. It must be noted that $m = F = 6$ in the case of a Stewart-Gough (SG) platform. In

the case of this research it is desired to have 6-DOF, therefore λ is equal to 6 and the equation is shortened to the far right side of equation 2.1 [14]. This results in $C_{1...6} = 6$, with the sum of all joint freedoms being 36. Degrees of freedom of the joints depend on the classification of joints which includes: Prismatic (P), Spherical (S), Universal (U), Cylindrical (C), and Revolute (R). The associated limbs that have 6-DOF are SPS, SCS, UPS, and SSR while keeping in mind that P, C, and R joints have 1-DOF. S joints have 3-DOF and U joints have 2-DOF.

2.2 Stewart-Gough Platform

An example of a parallel manipulator that is ideal for material characterization is the Stewart-Gough (SG) platform. To test materials accurately, precision and rigidity are key in designing a machine that can apply the proper loading to a specimen. It has already been discussed in Section 2.1 that parallel manipulators are more accurate and rigid than serial manipulators. Of the types of parallel manipulators, SG platforms provide the accuracy and strength needed.

2.2.1 Kinematics of a General Stewart-Gough Platform

A SG platform is classified as a spatial manipulator using a combination of limbs such that 6 degrees of freedom are achieved for the moving platform. A generic SG platform consists of a SPS or SPU configuration. Figure 2.2 shows a basic SG platform, whereas the variables labeled are referenced in later equations. The joints labeled are for each limb.

Figure 2.2: Stewart-Gough platform with SPS configuration. [14]

The kinematics are analyzed using vector loop equations, orthogonal conditions, and a rotation matrix. The moving platform consists of the reference frame B , with unit vectors of u , v , and w , and the fixed platform consists of the fixed frame A . The variables, A_i and B_i represent the bottom and top platforms respectively, where $i = 1, 2, \dots, 6$. The variables O and P are the bottom and top platform origin points respectively. The vectors a_i and b_i are the vectors originating from the origin points to the associated limb. The vector loop equation results in the equation below,

$$\overline{A_i B_i} = p + R_B^A b_i - a_i \quad 2.3$$

Where $\overline{A_i B_i}$ consists of each line going from the bottom joint of link i to the top joint of link i in Figure 1.2, p is the vector from the origin of the fixed frame to the origin of the moving frame, and R_B^A is the rotation matrix of the moving platform, which is shown below.

$$R_B^A = \begin{bmatrix} u_x & v_x & w_x \\ u_y & v_y & w_y \\ u_z & v_z & w_z \end{bmatrix} \quad 2.4$$

The variables within the matrix are unit vectors of the moving frame B in respect to x , y , and z of the fixed frame A . The variable u represents the new x-axis, v represents the new y-axis, and w represents the new z-axis. The variable u_x represents the reflection of the new x-axis on the original x-axis, and v_x represents the reflection of the new y-axis with respect to the original x-axis and so on. Since Cartesian frames are orthogonal there are a set of equations that must hold true for any rotation, indicated in equations 1.6-1.11. To find the length of a limb, equation 2.3 is used by taking the dot product of itself to obtain the equation below, where d_i represents the length of the associated limb.

$$d_i^2 = [p + R_B^A b_i - a_i]^T [p + R_B^A b_i - a_i] \quad 2.5$$

For the inverse kinematics, the unknown variable is d_i is unknown and the vector p and the rotation matrix are the input variables, resulting in 6 unknowns. It should be noted that the positive value is taken as the actual limb length as a negative limb length is not logical. The direct kinematics problem involves solving for p and the rotation matrix, which follows the orthogonal conditions shown below and accounts for 6 of the 12 equations:

$$u_x^2 + u_y^2 + u_z^2 = 1 \quad 2.6$$

$$v_x^2 + v_y^2 + v_z^2 = 1 \quad 2.7$$

$$w_x^2 + w_y^2 + w_z^2 = 1 \quad 2.8$$

$$v_x w_x + v_y w_y + v_z w_z = 0 \quad 2.9$$

$$u_x v_x + u_y v_y + u_z v_z = 0 \quad 2.10$$

$$u_x w_x + u_y w_y + u_z w_z = 0 \quad 2.11$$

Since the direct kinematic equations are highly nonlinear, there are multiple solutions, specifically 4,096 solutions, if the equations are solved using the equations below for $i =$

2, ... 6 (equations 2.12 and 2.13), assuming the origin for the moving frame is located at A_1 and the origin of the fixed frame is at B_1 , resulting in the values, a_{iz} , b_{iw} , a_{ix} , a_{iy} , a_{iz} , b_{iu} , b_{iv} , and b_{iw} being equal to zero. The variables p_x , p_y , and p_z are the scalar values of vector $\mathbf{p}$. Raghavan, [15], reduced the number of solutions to 40 solutions.

$$d_i^2 = p_x^2 + p_y^2 + p_z^2 \quad 2.12$$

$$\begin{aligned} & b_{iu}(p_x u_x + p_y u_y + p_z u_z) + b_{iv}(p_x v_x + p_y v_y + p_z v_z) + b_{iw}(p_x w_x + p_y w_y + p_z w_z) \quad 2.13 \\ & - a_{ix}p_x - a_{iy}p_y - a_{iz}p_z - b_{iu}(a_{ix}u_x + a_{iy}u_y + a_{iz}u_z) \\ & - b_{iv}(a_{ix}v_x + a_{iy}v_y + a_{iz}v_z) - b_{iw}(a_{iw}w_x + a_{iy}w_y + a_{iz}w_z) \\ & + \frac{(a_{ix}^2 + a_{iy}^2 + a_{iz}^2 + b_{iu}^2 + b_{iv}^2 + b_{iw}^2 + d_1^2 + d_i^2)}{2} = 0 \end{aligned}$$

2.3 Jacobian Analysis of Stewart-Gough Platform

A major disadvantage of parallel manipulators is the existence of singularities within the workspace. Singularities are defined as the manipulator gaining or losing 1 or more degrees of freedom, in other words the control of the manipulator is lost. The authors of [16,17] analyze the Jacobian matrix for inverse and direct kinematic singularities. According to Tsai [14], there are three types of singularities, inverse kinematic, direct kinematic, and combined singularities. Inverse kinematic singularities cause the manipulator to not move infinitesimally in some directions and direct kinematic singularities cause the actuators to lock while the manipulator is able to move infinitesimally in some directions. Combined singularities occur when both inverse and direct kinematic singularities occur and are rare.

The Jacobian is calculated by analyzing the velocity vector loop equations in which the velocities are shown in Equations 2.14 and 2.15,

$$\dot{\mathbf{q}} = [\dot{d}_1, \dot{d}_2, \dots, \dot{d}_6] \quad 2.14$$

$$\dot{\mathbf{x}} = \begin{bmatrix} \mathbf{v}_p \\ \boldsymbol{\omega}_B \end{bmatrix} \quad 2.15$$

where $\dot{\mathbf{q}}$ contains the velocity of each of the limbs, and $\dot{\mathbf{x}}$ contains the velocity of the point P in Figure 2.2 and the angular velocity of the moving platform. By writing the vector loop equation for velocity, differentiating with respect to time, and multiplying both sides of the equation with $\mathbf{s}_i$ results in equation 1.16.

$$\mathbf{s}_i \cdot \mathbf{v}_p + (\mathbf{b}_i \times \mathbf{s}_i) \cdot \boldsymbol{\omega}_B = \dot{d}_i \quad 2.16$$

The above equation can be written for each limb and equations 1.14 and 1.15 can be taken out to result equation 2.17 in which J_x is the direct kinematic Jacobian and J_q is the inverse kinematic Jacobian.

$$J_x \dot{\mathbf{x}} = J_q \dot{\mathbf{q}} \quad 2.17$$

For the above equation, J_q is an identity matrix and J_x is defined by Equation 1.18.

$$J_x = \begin{bmatrix} \mathbf{s}_1^T & (\mathbf{b}_1 \times \mathbf{s}_1)^T \\ \vdots & \vdots \\ \mathbf{s}_6^T & (\mathbf{b}_6 \times \mathbf{s}_6)^T \end{bmatrix} \quad 2.18$$

One of the most important aspects of parallel manipulators is the analysis of singularities as singularities can greatly affect the performance of the hexapod. The Jacobian matrix is used to evaluate the controllability of a hexapod [14]. Several researchers have looked and provided several ways of evaluating singularities within the workspace, but singularities within the workspace are still widely not understood. It is also impossible to find all the possible singularities besides the basic types. These basic types include the inverse kinematic, direct kinematic, and combined singularities.

Inverse kinematic singularities occur at the workspace boundary and do not occur within the workspace of the hexapod. This is since the Jacobian matrix for the leg (actuator) velocities, J_q is an identity matrix shown in equation 2.17. Direct kinematics are the most difficult to find with a few exceptions by analyzing the Jacobian matrix, J_x , and the following conditions: (1) the top and bottom platform geometry is the same, (2) when all limb lengths are equal, (3) and all limbs are parallel. Lastly combined singularities do not occur with SG platforms due to the identity matrix, J_q [14].

2.4 Review of Material Characterization Using Multiaxial Testing

Since material characterization includes a significant amount of subject areas and information, focus is taken on characterization of mechanical properties. Discussion into the background of material characterization will shed light onto the reasoning for characterization through multiaxial testing machines. Material characterization has grown because of the capabilities of additive manufacturing with creating shapes and material properties that are not available through other traditional methods. The issue at hand are designs that allow engineers and scientists to study these properties. In some cases, activating these material properties require testing in multiple directions and multiaxial testing allows this.

2.4.1 CSM Design Solution

A senior design team at the Colorado School of Mines over the course of two semesters designed a solution for a hexapod design for characterization of AM materials

shown in Figure 2.3. This design is 0.5s meter wide and 0.47 meters tall and consists of a LVDT, spherical joints, cameras, grips, and a 6-axis force sensor.

Figure 2.3: CSM hexapod design.

At the start of this work, this solution was provided, and an analysis was conducted to determine the validity of the design. Initial validation was completed by Dr. John Stueben of the Naval Research Laboratory (NRL) and resulted in the following, taken from email [18]:

- 1. The monolithic platens in the original design are extremely heavy and far too compliant to permit testing of metallic or composite materials. We have developed a better design which is far more rigid and weighs less.*

2. *The kinematic singularities of Stewart-Gough platforms are very badly understood. The "home" pose of the current design is nearly singular and presents control problems.*
3. *The forces and displacements applied to the test specimens are extremely, and I mean extremely, sensitive to variations in the as-built geometry of the test frame. This implies that either the machine must be built with superlative tolerances, or we need to monitor the relative displacement of the grips using an optical technique (instead of using LVDTs on the actuators and propagating those measurements through the forward kinematic transforms).*
4. *I think that the grips selected in the original design are inadequate to support bending and torsional loads. We should give some thought to finding or designing a better option.*

Note that the “home” pose is the position of the hexapod in Figure 2.3, in which no stresses are applied to the specimen and represents the starting position for any material testing. To clarify on the points addressed, the first point states that the top and bottom platform design is too compliant and heavy, and heavy in this case means heavy compared to the load capabilities of the actuators. The second point states that the CSM design is highly uncontrollable due to the ‘home’ pose being a singularity.

After the initial evaluation, another analysis was completed at the start of this research to identify other possible issues. Several issues were identified. The undergraduate design team chose a PC40 precision linear actuator from Thomson Linear. This model of the series has a max stroke of 1200 mm. Looking at [19] and using the length of the actuator chosen, the stroke the team chose is 60 mm, which provides very little movement for testing more compliant materials. Using the original specimen design of a thickness of 5 mm, height of 50 mm, and a width of 50 mm, shown in the figure below. Tests for specimen deflection were done assuming a full rectangular specimen without defects to see if this design can reach the deflection limits of the specimen. Table 1 shows the deflection results for pure

$$\theta = \frac{Fl^2}{2EI} \quad 2.19$$

$$y_{max} = -\frac{Fl^3}{3EI} \quad 2.20$$

bending using cantilever beam Equations 2.19 and 2.20 in [20].

Based on the values in Table 2.1, and the limited range of the chosen actuators, shown in, this part of the CSM design is not suitable and suggests that specimen redesign and larger actuator stroke is desired. It also suggests that a boundary singularity will be reached well before the max deflection points are reached. Another issue with the actuator assembly is the use of spherical joints on both ends of the actuator. This causes the actuators to gain a degree of freedom and be able to rotate along the axis of the cylinder rod. A quick fix for this is to use a universal joint at one end of the actuator.

Table 2.1: Deflection predictions for bulk materials. Material properties are from SolidWorks.

Material	Max Deflection [mm]	Angle [°]
ABS-ESD7	-42.36	-72.81
PLA	-38.10	-57.30
PC	-75.36	-135.43
6061-T6	-10.34	-17.77

Another issue is the choice of spherical joint which has an inadequate load rating. The CSM team chose the SRJ024C model with a static load rating of 3920 N. As noted in [21], the static load should not exceed 80% of the static load rating for long periods, and the load should not be applied for long periods if the shaft of the joint is not concentric with the body. Initial tensile test calculations suggest that a greater load rating is needed considering results show forces of 17000 N up to 30000 N and each leg would take 1/6th of the load or greater depending on the location and orientation. Looking at Figure 2.4, there is only roughly 16 mm between the camera and the actuator, suggesting that movement associated with more compliant materials is not likely, especially with the bending results in Table 2.1.

Figure 2.4: Close up of camera (red) and actuator (grey & blue).

Upon the analysis of the given design, with the errors outlined by the NRL review, and the analysis done within the scope of this research, a choice was made to completely redesign the platform to address issues outlined in this section as well as to improve in other aspects. Past research, other platform designs, geometry, and singularities are looked at in detail to show the process leading to the final design.

2.4.2 Naval Research Laboratory Design

This work follows the past work completed by NRL with using robotic manipulators in characterizing the constitutive properties of materials with complex behavior. The work completed focused on characterizing composite materials using a current generation multi-axial robotic test frame, shown in [1,7,9,10,22–26]. The SG test frame allowed for 6

dimensional movements with four cameras to capture the strain states in “real” time. A

Figure 2.5: NRL 66.3 Multiaxial robotic test frame

robotic arm places the specimen in the grips and applies loading in 6-DOF. This design focuses on composite materials and for the sake of this work, the full field strain measurement system, and the SG configuration are of importance. The full field strain measurement system uses 4 cameras to measure the distance between dots placed on the specimen surface and uses that to capture the strain states and calculate the material properties using a surrogate model. The advancement in surrogate modeling has allowed ‘real’ time characterization with modeling occurring in less than 0.5 seconds [27].

CHAPTER 3: DESIGN SOLUTION

With the underlying relationships to the kinematic performance of the hexapod defined, different architectures of the top and bottom platform were evaluated (see Section I.1). A geometry was chosen based on the results of Appendix I:. The design solution aligns with the requirements.

3.1 Requirements

To reiterate, the problem statement is as follows:

Design and fabricate a multiaxial robotic test frame that can test additive manufacturing materials, focusing on polymers and some metals, in 6 degrees-of-freedom while improving on performance and cost over the CSM design.

This section goes over the requirements for this design problem.

3.1.1 Constraints

Table 3.1 shows the list of constraints set out to determine a successful design according to the problem statement. The constraints were generated with the goal to make sure that the design could break a specimen, improving over the CSM design, and containing the basics for complete material characterization in the future. A full PDS is included in Appendix A:.

Table 3.1: List of Constraints

1.

No.	Requirement	Justification	Target
5	Must allow for adjustments in stationary grip placement	allowing more room for adjustment adds versatility	1 set of removable grips
6	Design platform to have extra degrees of freedom	to test materials that compliant such that the hexapod cannot reach the point where the specimen breaks	≥ 1 DOF
7	Design platform to test 3D printed metal specimens	additive manufacturing (not considering composite) does consist of metal materials	≥ 1 designed specimen
10	The platform shall be able to break samples in all loading conditions	if it cannot do this, then the hexapod cannot perform as it is meant to	6DOF
12	Platform must be able to test multiple sized specimens	variability allows testing of the varying designs of the additive manufacturing world	> 1 specimen
14.1	Hexapod must fit through the lab door frame	goes against transporting easily	80"x60"
17	Design must be based on a Stewart-Gough platform	serial manipulators lack stiffness and accuracy needed, other parallel manipulators provide issues in degrees of freedom and mechanics	1 SG platform
18	The platform must be able to perform standard tests	would not function as intended if this is not met	≥ 3 DOF
18.1	hexapod must perform a standard tensile test	would not function as intended if this is not met	1 tensile test
18.2	hexapod must perform a standard torsion test	would not function as intended if this is not met	1 torsion test
18.3	hexapod must perform a standard bending test	would not function as intended if this is not met	1 bending test
18.4	hexapod must perform a combination of two or more of the mentioned standard tests	would not function as intended if this is not met	> 1 standard tests
19	The gripping system must not interfere with full field strain measurements	hexapod would not work as intended otherwise	1 specimen in 360 deg view
20	Device must perform repeatable tests	Would not function as intended	> 2 tests
21	Must have a greater workspace than the CSM design	CSM design does not have have the capability to do tests on the specimen size indicated	
22	Must provide a way to measure actuator stroke	To control the design	1 measuring device

3.1.2 Criteria

This section shows a list of criteria set out for the problem statement. The goal here is to improve on the design further in a way that does not prevent a successful design if the requirement(s) are not met. Weights are applied to show the importance with 1 meaning the least important, 3 is the median, and 9 means a high desirability.

Table 3.2: List of Criteria

No.	Requirement	Weight	Justification	Target
1	Design Stewart platform for low cost	1	the lower the cost, while not losing functionality, the better it looks for companies to use	< \$36,000
2	Platform design should be sufficient size based on singularity analysis	9	minimize singularities to make sure performance does not degrade on a pathway after the specimen breaks	top platform smaller than bottom platform
3	Should allow platform to change kinematics	9	if singularity is in the path, this method can provide a way to where there is no singularity	> 1 geometry setup
4	Should allow the ability to change grips	3	for special testing of unique specimens	1 set of removable grips
8	Platform should be easy to maintain	3	minimal maintenance means more time towards testing and in a manufacturing, environment means less downtime	
8.1	platform should have easy access to electronics	3	Testing can be done efficiently	
8.2	Should minimize needed maintenance for components of the platform	3	See 8	
9	Loading specimen should be easy as just placing it in the grips	3	more time spent setting up the specimen takes time away from testing, saves time in a manufacturing environment	3 steps
11	Platform should be ergonomic such that human use is accounted for	9	the easier to use, the less time it takes for new people to learn or experience users to test	no extraneous activity needed
13	Device should be easy to transport	3	In case machine needs to be moved	2 people minimum
14	Parts should not exceed 30 lbs. individually	3	easy transport to the lab and easy transport in the future	30 lbs.
15	Device should be able to function with at least one user	3	less manpower if only one person can use it	1 user
16	Device should be designed for minimum construction difficulty	9	easy to take apart for maintenance, transporting, easy for machinists	

3.2 Overview of Design

This section provides the details of the final design. The design is split into assembly sections: actuator, camera, top frame, bottom frame, and top platform. Figure 3.1 shows the solution.

Figure 3.1: Solution

Looking at Figure 3.1, one noticeable difference between this solution and that of the CSM design is that the location of the specimen is above the moving platform rather than in between the moving platform and the bottom platform. Inverting the location allows a greater workspace when doing pure bending scenarios. The bottom spherical joint that the CSM design contains has been replaced with a universal joint to eliminate the extra degree of freedom. This extra degree of freedom allows the actuators to rotate about the cylinder rod. This improves on the performance as compared to the CSM design (requirement 21). Electrohydraulic actuators (EHA) were chosen and were a significant improvement over the CSM actuators (requirements 18-18.4 & 21). Adaptability refers to the ability to move the location of the universal joints, pertaining to requirement 3.

3.2.1 EHA Actuators

New actuators needed to be chosen as the original choice of CSM design did not have enough stroke to account for the compliance of polymers of AM materials. While the PC series of linear actuators of Thomson Linear, the compact EHA (Electro-hydraulic actuator) model from Parker was chosen due to the load capacity being four times the value of the PC 40 [28]. It was also chosen because the motor is included and there is no need for a setup of hydraulic hoses. All of this improves on the performance and increases the workspace (requirements 18-18.4 & 21).

Figure 3.2. Actuator Assembly.

The actuator assembly, Figure 3.2 consists of the spherical ball joint, the aluminum plates, the spherical joint adapter, the string potentiometer, the drawer slide, the universal joint adapter, and the universal joint. The aluminum plates' purpose is to keep the cylinder rod of the EHA actuator from rotating along the cylinder rod axis. The plates are clamped to the actuator with the LMPMT attached on the middle plate so the actuator stroke can be measured (requirement 22). The LMPMT has a stroke of 12.5 in (317.5 mm) which accounts for the 203 mm stroke of the actuators. The load capacity of the chosen ball joint is 10,250 lbs. in the static radial direction, and it has a max swivel angle of 50°.

3.2.2 Bottom Frame

The bottom frame assembly, shown in Figure 3.3, consists of the tubing frame, the actuator adapter, and the leveling mounts. Additional mounting holes were implemented to change the workspace and therefore the singularity map to accommodate for the path planning for the specimen.

Figure 3.3: Bottom frame assembly

3.2.3 Top Frame

In-plane bending, and in-plane shear was determined to be the testing scenarios with the highest loads. To account for this, the I-beam design was used with the addition of gussets. The angled plate at the end of the I-beam was removed and the original straight portion of the I-beam was kept as strength is lost in the I-beam if an angled cut was implemented and welded.

Figure 3.4: Top frame assembly

3.2.4 Grip Assembly

The grip assembly consists of the top frame adapter, the grip adapters, the grips, 6-DOF sensor (bottom black), and the adapter from the sensor to the top frame. Figure 3.5 shows the grip assembly. This setup bolts to the top frame and the moving platform via bolts. This allows new grips to be designed and allows adapters to be designed that allow testing of non-traditional test specimens (requirements 4, 5, 12).

Figure 3.5: Grip assembly

3.2.5 Camera Setup

The camera assembly involves a NOGA heavy duty holder with a magnetic base to attach to the grips or the adapters, 3D printed adapters, and the Chameleon3 cameras. Initially, 4 cameras will be used until more are needed. More may be needed to address camera singularities with the full field strain measurements involved with compliant materials. The adapters allow two cameras to be mounted and adjusted via the 2 NOGA holders to adjust the angle at which the camera is oriented to the face of the specimen. This setup allows the cameras to be attached to any position and to be adjusted accordingly. The camera system has not been implemented and will not be until the future work (Section 5.5). Figure 3.6 shows the NOGA holder.

Figure 3.6: NOGA holder.

3.2.6 Top Platform

Shown in Figure 3.7, the top platform assembly consists of two parts, the actuator adapters (prism) and the tubing. The actuator adapter attaches to the spherical ball joint and the top platform connects to the adapter underneath the 6-axis force sensor. FEA results are shown in Section 4.7.

Figure 3.7: Top platform assembly

3.3 Hexapod Workspace

The start of this research involved an analysis on the validity of the previously developed design (see Section 2.4.1). The analysis determined that the workspace of the CSM design was not large enough for testing of compliant materials and a new design was needed with a greater workspace (requirement 21). Note that the data shown on the graphs are data points and not continuous lines.

3.3.1 Translation

While it is unknown what the specimen designs will be and the failure behavior of tests with different additive manufacturing materials, especially polymers, a constraint was set in which the new design must have an increased workspace volume. As a reminder, workspace in this case is defined as the volumetric space in which the centroid of the hexapod can reach.

Figure 3.8: Workspace comparison, CSM (bottom) and 66.1 Tiger (top)

Figure 3.8 shows the difference between the reachable workspace of the CSM design versus the new design, the 66.1 Tiger. The 66.1 Tiger has a much wider range with translation in the x, y, and z directions.

3.3.2 Rotation

Figure 3.9 shows the rotation only comparison between the two designs with the clear indication of improvement with the new design. There is a drastic difference between the purely rotational workspace. Purely rotation in this case means rotation about the origin point of the top platform of the hexapod.

Figure 3.9: Rotation only comparison, 66.1 Tiger (left) and CSM (right).

One other comparison to look at with the reachable workspace involves pure bending loading tests as shown in Figure 3.9. The max angles the 66.1 Tiger can reach are roughly 50 degrees in the Z direction and 28 degrees in the X and Y direction. It can be noted that in torsion tests, the hexapod can reach a total of 100° by pre-loading in the negative direction (or positive) and starting the test from there.

Figure 3.10: Pure bending comparison, 66.1 Tiger (top) and CSM (bottom).

Figure 3.11 shows the difference of the reachable workspace in a pure bending scenario (requirement 23) of a tradition hexapod material characterization setup like that of the NRL 66.3 in Figure 2.5. The tradition setup results in a max of 85 mm in the x direction and 72 mm in the y direction. The inverted setup, which is shown in Figure 3.1, has a max of 116 mm in the x direction and 131 in the y direction.

Figure 3.11: Difference between the traditional hexapod setup and the inverted hexapod setup.

3.4 Component Details

While the major sub-assemblies have been identified in the previous sections, this section goes over the components of the major assemblies that contain sensors and other electronics. These directly relate to the performance requirements (requirements 10, 12, 15, 18-18.4, 20, 22).

3.4.1 Camera Assembly

Going from top to bottom, the first component are the cameras. The camera chosen is the Chameleon3 model. Table 3.3 shows the specifications of the camera along with the specific model number.

Table 3.3: Camera Specs

Model #	CM3-U3-13Y3C-CS
Type	Color
MP	1.3
Sensor Description	ON Semi PYTHON 1300 CMOS, ½”, 4.8 µm
Shutter	Global Shutter
Max Resolution	1280 x 1024
Max FPS	149

3.4.2 Grip Assembly

Included in the components of the grip assembly are the grips and the 6-axis force/torque sensor, in which the grips are from ADMET and Sunrise Instruments respectively. The ADMET grips are of the GV-50T model with the specifications in Table 3.4.

Table 3.4: Grip Specifications

Tensile Force	50 kN
Opening	0-30 mm
Clamping Surface Size	60 x 66 mm
Clamping Surface	Plain/Flat

The 6-axis force/torque sensor chosen includes the specs in Table 3.5. This sensor was chosen due to the load capacity, pricing, and size. The data sheet for the sensor is in Appendix E.

Table 3.5: Force/Torque Sensor Specifications

Capacity			
F_x, F_y	F_z	M_x, M_y	M_z
16.2 kN	32.4 kN	660 Nm	530 Nm

3.4.3 Actuator Assembly

The actuator assembly includes two total components: actuator and linear transducer. Specific models include Compact EHA (Electro-Hydraulic Actuator), and the LMPMT (Linear Motion Position-Measuring Transmitters). The actuators were chosen due to the load rating, compact size, and the stroke availability. The LMPMT was chosen due to the price and the avoidance of an actuator-like transducer. Mounting a linear transducer on the actuator required a more complex design for mounting clamps. Data for the actuator and transmitter are shown in Table 3.6 and Table 3.7 respectively. The datasheet for the actuators can be found in Appendix E.

Table 3.6: Actuator Specifications

Force	Max Stroke	Max Speed
21.3 kN	203 mm	85 mm/s

3.

Table 3.7: LMPMT Specifications

Stroke	Accuracy Range	Repeatability	Resolution	Cable Material
12.5 in	$\pm 0.25\%$	$\pm 0.05\%$	0.0001 mV	Nylon-coated Stainless Steel

3.4.4 Data Acquisition

Included in the data acquisition is the DAQ card, motor controller, Arduino Due, and the specs of the computer that will be used to control and collect the data. The motor controller chosen is the RoboteQ FDL3260 and the datasheet is in Appendix E. This controller can control three brushless DC motors or in this case, three actuators. This requires two controllers total. Both controllers are connected to an Arduino Due to be controlled using Arduino coding and an Intel NUC with the specifications in Table 3.8.

Table 3.8: Computer Specifications

Processor	RAM	Memory Speed	Hard Drive	Graphics Card
Intel Core i7	32 GB	3.1 GHz	128 GB SSD	AMD Radeon RX Vega M GH

The DAQ system consists of an Arduino Due where each string potentiometer will be connected to two ADS1115's since one can only read for sensors at a time. The data sheet of the Arduino Due and ADS1115 are in Appendix E and Appendix F respectively. The string potentiometers need 30 volts to have enough power for more accurate results. The Arduino 5-volt supply is not enough. Since the ADS1115 can only except up to 5 volts due to the power it receives from the Arduino Due, a voltage divider is provided between the output of the string potentiometers and the ADS1115. The code to control the hexapod is shown in Appendix G:.

CHAPTER 4: DESIGN JUSTIFICATION

This chapter focuses on the justification for design choices for the detailed design of the robotic test frame. The constraints and criteria are laid out and discussed on what was met, what will be verified in future work, and what requirements were not met. The actuators, FEA results, workspace results, the singularity analysis, sensors, and data collection all contribute to the satisfaction of the set requirements, see PDS in Appendix A. Table 4.1 shows the specific constraints that were met, and Table 4.2 shows the results of the criteria. In summation, this section discusses the requirements and how the driving requirements were met.

4.1 Constraints

This section goes over the constraints, or the needs, of the design. The constraints that were met are presented in Table 4.1, and the full requirement format is presented in Appendix A.

Table 4.1: Constraints Status.

No.	Requirement	
5	Must allow for adjustments in stationary grip placement	
6	Design platform to have extra degrees of freedom	
7	Design platform to test 3D printed metal specimens	
10	The platform shall be able to break samples in all loading conditions	
12	Platform must be able to test multiple sized specimens	
14.1	Hexapod must fit through the lab door frame	
17	Design must be based on a Stewart-Gough platform	
18	The platform must be able to perform standard tests	
18.1	hexapod must perform a standard tensile test	
18.2	hexapod must perform a standard torsion test	
18.3	hexapod must perform a standard bending test	
18.4	hexapod must perform a combination of two or more of the mentioned standard tests	
19	The gripping system must not interfere with full field strain measurements	
20	Device must perform repeatable tests	
21	Must have a greater workspace than the CSM design	
22	Must provide a way to measure actuator stroke	

Requirement 5 was met with the ability to change the location of the universal joints, or the bottom joints of the actuator assemblies. Requirement 6 was determined by the uniqueness that additive manufacturing to designs. Allowing the possibility of adding more degrees of freedom down the road will allow testing of significantly compliant materials

that the hexapod could not test with the given workspace. This is possible with having the grip assemblies to be taken apart or taken off. Requirement 7 deals with the possibility of testing metal AM parts. While the focus of this design is for polymers, AM deals with metals as well and it is becoming more and more popular. This was determined to be a constraint and has been met by the FEA of the design (Section 4.3) and testing (Section 5.4). Requirements 10, 12, 14.1, 17-18.4, 19, 20, and 21 all deal with simply testing if the requirement is met or not. Requirements 12, 17-18.4 all deal with basic functionality and research conducted at the start of this work. Requirement 19 is meant to make sure the full field strain measurement with the 4 cameras can be completed without obstruction and has been met.

The requirements presented in this section are those that allow for a successful testing machine. This work includes up to the ability of the platform to move and be cable of coordinated movement shown by simple tests. Section 5.4.1 provides more detail.

4.2 Criteria

This section discusses the criteria or wants of the design. Table 4.2 presents the criteria that are met, not met, and the criteria that require validation before it is determined if it is met or not. Requirements that were met are labeled green, and the requirements that were not met are labeled in red.

Table 4.2: Criteria that are met/not met

No.	Requirement	Weight	
1	Design Stewart platform for low cost	1	
2	Platform design should be sufficient size based on singularity analysis	9	
3	Should allow platform to change kinematics	9	
4	Should allow the ability to change grips	3	
8	Platform should be easy to maintain	3	
8.1	platform should have easy access to electronics	3	
8.2	Should minimize needed maintenance for components of the platform	3	
9	Loading specimen should be easy as just placing it in the grips	3	
11	Platform should be ergonomic such that human use is accounted for	9	
13	Device should be easy to transport	3	
14	Parts should not exceed 30 lbs. individually	3	
15	Device should be able to function with at least one user	3	
16	Device should be designed for minimum construction difficulty	9	

Requirement 1 was met by the significant price drop of developing a hexapod. The CSM design was estimated at \$36,000 while this design falls around \$25,000. Requirement 2 was met by the singularity analysis in Appendix I:. It was determined that a top platform that has a bigger radius performs better and with the singularity analysis of the normalized Jacobian, the ratio of top platform vs bottom platform was determined. Requirement 3 was met by adding the ability to move the universal joints on the designated bolt locations on the bottom frame in Figure 3.1.

4.3 FEA Results

This section presents the deflection and FEA results of the top frame and the bottom frame of the SG platform design. The directions of the forces are indicated by the purple arrows shown in the respective figures and the fixed geometries are indicated by green and orange arrows. All FEA results were conducted using with the force values found in Section 3.3 for 6061-T6. For each analysis, an h-adaptive method was used with a target accuracy of 98%, accuracy bias in the middle, and a maximum number of loops of 5 for the mesh adaptation. The factor of safety (FOS) for the frame analyses are taken as the yield strength over the maximum load in which all analyses have the FOS well above a reasonable amount.

4.3.1 Top Frame FEA

The final top frame FEA results are depicted in Figure 4.1. It can be noted that there are no stress concentrations and the stresses stay well below the yield stress of the material used, which is 4130 steel, and results in a safety factor of 7. The gussets were added to reduce the deflection and avoid stress concentrations around the connection of the legs and I-beams and the bottom portion of the legs connecting to the bottom frame. To account for the cylinder and grips, a straight cylinder was extruded from the bottom of the I-beams. For bending and torsion scenarios, a reference axis is added so that the bottom of the cylinder can rotate about the axis. Table 4.3 shows the deflection results of the final design.

Table 4.3: Deflection results for top frame

Scenario	Deflection (mm)	Force/Moment
Shear	0.3453	3000 N
Tensile	0.3305	30000 N
Moment (Z)	0.001335	30 Nm
Moment (X)	0.007857	100 Nm
Moment (Y)	N/A	25 Nm

Figure 4.1: FEA of top frame (FOS = 7)

4.3.2 Bottom Frame FEA

The final bottom frame FEA is shown in Figure 4.2. Most of the stress is located around the joint locations and the area where the top frame connects. The adapters to the actuators are included so that the forces acting on the actuators can be applied to the correct direction. The actuator forces required are calculated using the force equation for a general SG platform [14]. The high deflection is in the bottom frame for the shear loading scenario in Table 4.4: Deflection results for bottom frame.

Table 4.4: Deflection results for bottom frame

Scenario	Deflection (mm)	Force/Moment
Shear	3.671	3000 N
Tensile	0.502	30000 N
Moment (Z)	N/A	30 Nm
Moment (X)	0.00905	100 Nm
Moment (Y)	N/A	25 Nm

Figure 4.2: FEA of bottom frame (FOS = 3.6)

4.3.3 Top Plate FEA

The final top plate FEA is shown in Figure 4.3: FEA of top plate (FOS = 1.7) in which the factor of safety is 1.7, and the maximum deflections are indicated in Table 4.5. For results that were significantly small, the result was given N/A. The same procedure applied in Section 4.3.2 also was used for the top plate FEA in this section. The forces for each actuator were determined as well as the direction in which the force is applied.

Table 4.5: Deflection results for top plate

Scenario	Deflection (mm)	Force/Moment
Shear	0.3517	3000 N
Tensile	0.1798	30000 N
Moment (Z)	N/A	30 Nm
Moment (X)	N/A	100 Nm
Moment (Y)	N/A	25 Nm

4.

Figure 4.3: FEA of top plate (FOS = 1.7)

4.4 CSM vs. 66.1 Tiger Singularity Map

Based on the work done in Appendix I:, the singularity map was applied to the CSM design and the 66.1 Tiger. Pure translation (Figure 4.4), and pure rotation (Figure 4.5) were looked at for comparison. There is a significant difference between the two designs. For the CSM design, the condition numbers for pure translation were all considerably higher than the 66.1 Tiger with values in 10^{18} and above. The values for the 66.1 Tiger all fall below 1,100. The MATLAB results for the CSM design also gave warnings that the Jacobian matrices were often close to being singular. This correlates with the review from NRL in Section 2.1 and the statement from the authors of [14] about singularities caused by similar geometries for the top and bottom plate. Table 4.6 shows the color-coded scheme.

Table 4.6: Color coding scheme.

Color	Condition Number Range
Green	≤ 50
Black	$> 50 \text{ \& } \leq 100$
Blue	$> 100 \text{ \& } \leq 250$
Yellow	$> 250 \text{ \& } \leq 500$
Red	$> 500 \text{ \& } \leq 100000$
Cyan	> 100000

Figure 4.4: Singularity map of pure translation of the CSM (top) and 66.1 Tiger (bottom) designs.

The results for Figure 4.5 are similar to that of Figure 4.4 in that the CSM design has condition numbers on the order of 10^{18} and the 66.1 Tiger has condition numbers on the order of 10^3 . The reduction in the magnitude of the condition number translates into a significant improvement in system controllability. As for the singularity map, it shows the relative change based on the min and max condition number on the workspace that is evaluated. While there is a lot of green in the top of Figure 4.5, the relative condition numbers are much higher in the CSM design than the 66.1 Tiger. It should be noted that

the high condition numbers (shown as cyan) are dispersed towards the outside regions of the workspace rather than near the “home” position of the hexapod ($R_x = 0, R_y = 0$).

Figure 4.5: Pure rotation scenarios for the singularity map of the 66.1 Tiger (right) and the CSM (left) designs.

4.5 Distance Measurement Analysis

Work was completed during an internship at NRL to determine if an inaccurate actuator could be controlled with a PID such that the actuator can be accurate in combination with a string potentiometer to measure the stroke. Several Arduino IDE libraries from www.github.com were used to develop a code to control the electrohydraulic actuators.

The results from Table 4.7 and Table 4.8 show that the proportional, integral, and derivative terms of the PID controller vary based on the speed of the actuator. It was initially believed that the smallest distance that could be measured was 50 microns, but with the work completed, the code (Appendix D:) was able to bring the smallest displacement to roughly 5 microns and the lowest speed to 1 micron per second. These results give an option for slower and more accurate material testing. A circular buffer in

included with the code to showcase steadier results while running. For the sake of determining the slowest speed and displacement, the moving average was disabled.

Table 4.7: Positive speed PID control values for Parker EHA.

Moving Average Value	Speed (um/s)	Kp	Ki	Kd
1	1	70	40	10
	3	90	40	10
	6	90	40	10
	24	90	30	10
	48	90	30	30
	100	90	30	30
	500	90	30	30
	Speed (mm/s)	Kp	Ki	Kd
	1	50	50	10
	5	50	50	10
	15	50	50	10

Table 4.8: Negative speed PID control values for Parker EHA.

Moving Average Value	Speed (-um/s)	Kp	Ki	Kd
1	1	280	50	10
	3	280	50	10
	6	280	50	10
	24	280	50	10
	48	280	50	50
	100	280	50	50
	250	180	50	10
	500	180	50	10
	Speed (-mm/s)	Kp	Ki	Kd
	1	70	10	10
	5	70	10	10
	15	70	10	10

CHAPTER 5: DISCUSSION AND CONCLUSION

Chapter 5 includes the discussion and conclusion of this thesis and more specifically the hexapod design. The limitations of the design, the strengths of the design as compared to the CSM design, the fabrication and functionality of the design, and the future work are discussed moving forward.

5.1 Limitations of Design

The 66.1 Tiger includes a few limitations of note. For one, the specimen design is limited if metal AM materials are studied, and composite materials cannot be tested due to the way the hexapod is designed with the inverted style as compared to the CSM design and that composite materials have significantly higher yield strengths and large loads needed for failure. The inverted style introduces more deflection than that of the traditional design and reduces the amount of force the hexapod frame can withstand without excessive deflections.

Another limitation is the uncertainty of the singularities within the hexapod workspace, although a method to ‘map’ the singularities is provided, further research will need to be conducted to determine the correlation of the maps with the controllability of the hexapod.

Two more limitations involve requirements 9 and 14 (Appendix A:), both of which were criteria. Requirement 9 (loading the specimen should be easy) was not satisfied but does not limit the design in its performance. The specimen can be inserted by hand rather than by a 6-DOF robotic hand. If this design was to be used in an industrial setting, a 6-DOF robotic hand can be implemented to decrease the time required to do it manually. It

also takes time to adjust and align both grips so that no load is applied before testing. Requirement 14, stating that the design should not have components exceeding 30 lbs., was not satisfied, but the components of the hexapod can be transported easily with a pallet jack.

5.2 Strengths of Design

There are several aspects about the 66.1 Tiger that improve it upon the sense of a traditional design than that of the CSM design. For one, the inverted design allows the hexapod to have a larger workspace than if it was designed like the other two other designs.

The ability to move the bottom frame joints to several locations allows the user to change the singularity ‘map’ to their choosing. For example, if it is known that a singularity exists at the end of test when the specimen breaks, one or more joint(s) can be moved to change the singularity ‘map’ such that there is no singularity at that point. This is a good capability considering the consequences of the hexapod reaching a singularity near a failure point and the possible loss of control as a result which may lead to possible damage to the machine and the user having to move the machine out of the singularity. Another strength of the design is its modularity, several of the key components of the design are bolted together which allows for modular replacement components to be fabricated. For example, to test a unique specimen that the chosen grips cannot secure, the user can either design an attachment or install a different style of grips. Another example is the location of the 6-axis force sensor, the hexapod was designed so that the sensor can either be inserted with the top grip or the bottom grip. Considering it is unknown currently which spot is better

(or even if using two sensors is better), this allows an easy configuration of the system to maximize resolution or performance. The implications of the different locations will be determined in future work during system calibration.

5.3 Fabrication of Design

During fabrication of the design, some changes were made based on the feedback from the machinist at Machining and Technical Services (MTS) on the Clemson University campus. The slanted metal pieces at the ends of the I-beams in Figure 3.1 were removed because it was noted by the machinists that it would be easier to fabricate the top frame without it. It was also noted that it would increase the strength in that area due to the reduction in welding that would be needed if this aspect was kept. Another change was removing the design of the cameral adapter ring originally shown in Figure 3.1, this design was bolted in the top frame and presented an issue with deflection that can occur in the area. To resolve this issue, NOGA holders (Figure 3.6) were implemented and are a much better solution since the holders can be placed anywhere on the frame and eliminate any deflection that would occur. The only issue with this decision is that deflection in the frame would move the camera, but this can be accounted for in the calculation for material properties. These design changes can be seen in Figure 5.1.

Figure 5.1: SolidWorks Image of solution (left), solution pictured in the lab (right).

5.4 Functionality of Design

Considering the end goal of this thesis to show that the hexapod can perform tests repeatedly and in variation, this section includes the discussion on the functionality. It must be noted that the software that uses the cameras to calculate strain states to get the material properties has already been proven to work and is provided by NRL. This leaves the end goal of the hexapod breaking specimens in general and breaking them in various loading conditions.

The code, shown in Appendix G:, uses Arduino IDE to control the 66.1 Tiger and there are several points to address and conclude on. To start, the PID control included in the code has some issues that do not affect the end goal of this thesis but do affect future work with

testing certain specimens or materials. A variable PID control would be needed as it was discovered with the work in Section 4.5 that different PID gain values are needed based on the speed. It is unknown at this time if tests will be conducted with varying or constant speed, but for the sake of showing that the hexapod works, the PID gain values can be manually changed and further testing during the calibration portion of the future work will need to be conducted.

5.4.1 Specimen Tests

Testing was completed to satisfy requirements 18.1 – 18.4. These tests were done to show that the hexapod can move in 6-DOF and break specimens. They were also done to test the grips and to see if slippage will be a problem in the future work. Videos were produced to show each test, with the tensile test having the most difficulty. This difficulty was due to an inaccurate print job. The initial specimen for the tensile test produced significant slippage which required adjusting the grip strength repeatedly until a test was successful. Another specimen was printed in which there were less deformities and the testing proved to be successful without slippage. The testing suggests that different grip pads should be used, or rubber paint should be applied on less uniform specimens for tensile testing. The other tests satisfying requirements 18.1 – 18.4 showed no issues. The code controlling the Tiger 66.1 is shown in Appendix G:.

5.5 Future Work

A continuation of the work included in this thesis includes implementation of the full strain field measurement program using the camera system described in Section 3.2.5.

Researchers at NRL have already developed a system to complete full field measurements, and this system will be implemented to the Tiger 66.1. Initial testing of the program will be conducted showing that bulk material properties are indeed different than that of the AM material properties using the same materials. Once this is completed, then calibration of the hexapod will need to be conducted to ensure accurate results and full testing can be completed.

Full testing will be possible after the accuracy of the system is determined with the error and uncertainty analysis. Random error and systematic error will need to be reduced as much as possible. There is already some evidence of systematic error with the hexapod returning to the 'home' position. There are some inaccuracies with the PID controller as the actuators behave differently when extending vs. extracting. Calibration of the PID values will need to be conducted to eliminate this error. The uncertainty analysis would consider the error of the string potentiometers, actuators, cameras, and the 6-axis force sensor. Some factors that will be considered to affect measurements are noise, non-linearity, non-uniformity, and random error. Ultimately the 6-axis force sensor will be used to control the actuators during testing as the direction and magnitude of the force(s) on the specimen is the end goal, but the actuator measurement control will need to be used to reset the machine or to place it in the desired position before testing starts.

A sensitivity analysis will need to be conducted as well to determine how the hexapod calculations are affected by the different measurements discussed. There are three possible types in which one or more may be used and include numerical, experimental, and mathematical. An example of the experimental method would be to do repeated tests on

bulk materials to determine the change in output. The mathematical determination can be found through the SG platform mathematics. Another step includes addressing the issue of singularities with the full field strain measurement system. Even with the addition of two (total of 6) cameras, there may still be singularities where the cameras will lose track of the dots placed on the specimen.

Once the hexapod has been properly calibrated then research can be conducted on specific AM methods with polymers. First testing will be conducted on FDM printed specimens to study the effect 3D printing versus bulk material properties. Next would be to conduct and study specimens made from other methods such as SLA (stereolithography), DLP (digital light processing), SLS (selective laser sintering), SLM (selective laser melting), EBM (electronic beam melting), LOM (laminated object manufacturing), and others.

5.5.1 Possible Research Questions

Once the 66.1 Tiger is calibrated and can perform full characterization tests, there are some research questions that can be looked at.

1. In what ways do the bulk material properties differ from the printed material properties for an FDM printed specimen?
2. In what ways do different infill patterns for FDM printed specimens affect the material properties?
3. In what ways can singularities with the camera setup be addressed for more compliant materials?

4. How can topology optimization be used as an infill pattern generator to increase the desired properties of a FDM printed specimen?
5. How do other printing methods differ to bulk material properties?

5.6 Conclusion

Going back to Section 1.2, the design statement states the following:

Design and fabricate a multiaxial robotic test frame that can test additive manufacturing materials, focusing on polymers and some metals, in 6 degrees-of-freedom while improving on performance and cost over the CSM design.

This design statement has been satisfied by the completion of the requirements set out by the PDS. The major requirements involving completed successful tests showing the range and degrees-of-freedom of the hexapod (Req 18.1-18.4). It has been shown in Section 3.3 that the Tiger 66.1 has a significantly greater workspace than that of the CSM design. Section 4.4 shows that the singularity “map” of the Tiger 66.1 has much lower condition number values than the CSM design showing an improvement on the controllability. Comparing the cost of the CSM design, Appendix H:, and the cost of the Tiger 66.1, Appendix F:, there is a difference of roughly \$10,000 with the Tiger 66.1 costing less. With these main points, it can be said the design statement has been satisfied.

CHAPTER 6: REFERENCES

- [1] Mast P. W., Nash G. E., Michopoulos J. G., Thomas R., Badalian R., and Wolock I., 1995, “Characterization of strain-induced damage in composites based on the dissipated energy density part I. Basic scheme and formulation,” *Theor. Appl. Fract. Mech.*, **22**(2), pp. 71–96.
- [2] Mast P. W., Nash G. E., Michopoulos J. G., Thomas R., Badalian R., and Wolock I., 1995, “Characterization of strain-induced damage in composites based on the dissipated energy density Part III. General material constitutive relation,” *Theor. Appl. Fract. Mech.*, **22**(2), pp. 115–125.
- [3] Mast P. W., Nash G. E., Michopoulos J. G., Thomas R., Badalian R., and Wolock I., 1995, “Characterization of strain-induced damage in composites based on the dissipated energy density part II. Composite specimens and naval structures,” *Theor. Appl. Fract. Mech.*, **22**(2), pp. 97–114.
- [4] Mast P. W., Beaubien L. A., Clifford M., Mulville D. R., Sutton S. A., Thomas R. W., Tirosh J., and Wolock I., 1983, “A semi-automated in-plane loader for materials testing,” *Exp. Mech.*, **23**(2), pp. 236–241.
- [5] Michopoulos J. G., and Furukawa T., 2008, “Towards hierarchical design optimization for simultaneous composite material characterization and adjustment of the corresponding physical experiments,” *Inverse Problems in Science and*

Engineering, pp. 763–775.

- [6] Michopoulos J., 2003, *Recent Advances in Composite Materials*, Springer Netherlands, Dordrecht.
- [7] Michopoulos J., 2004, “Mechatronically Automated Characterization of Material Constitutive Response,” *Proc. 6th World Congr. Comput. Mech.*, (January 2004), pp. 486–491.
- [8] Michopoulos J. G., Hermanson J. G., and De W., 2011, “On the Constitutive Response Characterization for Composite Materials Via Data-Driven Design Optimization,” *Proc. ASME 2011 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf.*, pp. 1–13.
- [9] Michopoulos J., Hermanson J., and Iliopoulos A., 2012, “First industrial strength multi-axial Robotic testing campaign for composite material characterization,” *Notes*, pp. 1–11.
- [10] Iliopoulos A., and Michopoulos J. G., 2016, “On the feasibility of crack propagation tracking and full field strain imaging via a strain compatibility functional and the Direct Strain Imaging method,” *Int. J. Impact Eng.*, **87**(May), pp. 186–197.
- [11] Michopoulos J. G., and Iliopoulos A., 2012, “Complete High Dimensional Inverse Characterization of Fractal Surfaces and Volumes,” *J. Comput. Inf. Sci. Eng.*, **13**(1), p. 011001.
- [12] Michopoulos J., Iliopoulos A., and Hermanson J. C., 2012, “Preliminary Validation

of Composite Material Constitutive Characterization,” *Proc. ASME 2012 Int. Des. Eng. Tech. Conf. Comput. Inf. Eng. Conf. IDETC/CIE*, August 12-15, 2012, Chicago, IL, USA, pp. 1–10.

- [13] Allen J., Hentges B., Hulse A., Parsons T., and Tillery S., 2014, “6DOF Material Test Frame,” p. 95.
- [14] Tsai L., 1999, “Robot analysis: the mechanics of serial and parallel manipulators,” *Mech. Ser. Parallel Manip.*, p. 520.
- [15] Raghavan M., 1993, “The Stewart Platform of General Geometry Has 40 Configurations,” *J. Mech. Des.*, **115**(2), pp. 277–282.
- [16] Gosselin C., and Angeles J., 1990, “Singularity Analysis of Closed Kinematic Chains,” *J. Mech. Des.*, **6**(3), pp. 281–290.
- [17] Zlatanov D., 1994, “Singularity Analysis of Mechanisms and Robots via a Motion-Space Model of the Instantaneous Kinematics,” *IEEE International Conference on Robotics & Automation*, pp. 986–991.
- [18] Steuben J., “AM 6DOF Testing System ‘Email.’”
- [19] “PC Series TM Precision Linear Actuators Unmatched Power Density , Speed and Stroke Length,” *Thomas Linear* [Online]. Available: https://www.thomsonlinear.com/downloads/actuators/PC_Series_Precision_Linear_Actuators_bren.pdf. [Accessed: 12-Apr-2017].

- [20] Budynas R. G., and Nisbett J. K., 2015, *Mechanical Engineering Design*.
- [21] 2008, "Spherical Rolling Joints," *Myostat*, pp. 2–3 [Online]. Available: [http://www.myostat.ca/cmCart_files/repo/download/SR Joint Brochure.pdf](http://www.myostat.ca/cmCart_files/repo/download/SR_Joint_Brochure.pdf). [Accessed: 12-Apr-2017].
- [22] Iliopoulos A., and Michopoulos J., 2012, "Direct Strain Imaging For Full Field Measurements," *ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE, August 13-15, 2012, Chicago, IL, USA*, pp. 1–11.
- [23] Michopoulos J. G., Hermanson J. C., Iliopoulos A., Lambrakos S. G., and Furukawa T., 2011, "Data-driven design optimization for composite material characterization," *J. Comput. Inf. Sci. Eng.*, **11**(2).
- [24] Iliopoulos A. P., and Michopoulos J. G., 2014, "Meshless methods for full field displacement and strain measurement," *Adv. Comput. Inf. Eng. Res.*, **1**(February), pp. 97–124.
- [25] Michopoulos J. G., Hermanson J. C., and Furukawa T., 2008, "Towards the robotic characterization of the constitutive response of composite materials," *Compos. Struct.*, **86**(1–3), pp. 154–164.
- [26] Michopoulos J. G., Hermanson J. C., and Iliopoulos A., 2010, "Towards a recursive hexapod for the multidimensional mechanical testing of composites," *Proceedings of the ASME 2010 International Design Engineering Technical Conferences &*

Computers and Information in Engineering Conference IDETC/CIE 2010, pp. 91–99.

- [27] Steuben J., Michopoulos J., Iliopoulos A., and Turner C., 2015, “Inverse characterization of composite materials via surrogate modeling,” *Compos. Struct.*, **132**, pp. 694–708.
- [28] 2018, “Compact Electro-Hydraulic Actuator (EHA)” [Online]. Available: <http://ph.parker.com/us/17560/en/compact-electro-hydraulic-actuator>. [Accessed: 02-Dec-2018].
- [29] Stratasys, 2017, “ABS-ESD7: Production-Grade Thermoplastic for Fortus 3D Production Systems” [Online]. Available: <http://www.stratasys.com/materials/fdm/abs-esd7>. [Accessed: 01-Feb-2017].
- [30] Shigley J. E., Mischke C. R., and Budynas R. G., 2002, *Mechanical Engineering Design*.
- [31] Bonev I., and Zlatanov D., 2001, “The Mystery of the Singular SNU Translational Parallel Robot.”
- [32] Ma O., and Angeles J., 1991, “Optimum architecture design of platform manipulators,” *Fifth International Conference on Advanced Robotics 'Robots in Unstructured Environments*.
- [33] Fattah a., and Hasan Ghasemi A. M., 2002, “Isotropic Design of Spatial Parallel Manipulators,” *Int. J. Rob. Res.*, **21**, pp. 811–824.

- [34] Ropponen T., and Arai T., “Accuracy analysis of a modified Stewart platform manipulator,” *Proceedings of 1995 IEEE International Conference on Robotics and Automation*, IEEE, pp. 521–525.
- [35] Merlet J. P., 2006, “Jacobian, Manipulability, Condition Number, and Accuracy of Parallel Robots,” *J. Mech. Des.*
- [36] Fry S. T., and Turner C. J., 2016, “Design of a Stewart-Gough Platform for Engineering Material Characterization,” *Proceedings of the ASME 2016 International Mechanical Engineering Congress & Exposition, IMECE 2016, November 11-17, 2016, Phoenix, Arizona, USA*, pp. 1–9.

APPENDICES

Appendix A: Product Design Specification

No.	Req.	Constraint	Crit. Wt. (1,3,9)	Justification	Value	Verification	Checked On
1	Design Stewart platform for low cost		1	the lower the cost, while not losing functionality, the better it looks for companies to use	< \$70,000	BOM	
2	Platform design should be a sufficient size based on singularity analysis		9	minimize singularities to make sure performance does not degrade on a pathway after the specimen breaks	top platform smaller than bottom platform	SolidWorks measurements/Matlab program	
3	Should allow platform to change kinematics		9	if singularity is in the path, this method can provide a way to where there is no singularity	> 1 geometry setup	test	
4	Should allow the ability to change grips		3	for special testing of unique specimens	1 set of removable grips	sight check	
5	Must allow for adjustments in stationary grip placement	YES		allowing more room for adjustment adds versatility	bolt setup	sight check	
No.	Req.	Constraint	Crit. Wt. (1,3,9)	Justification	Value	Verification	Checked On
6	Design platform to have extra degrees of freedom	YES		to test materials that compliant such that the hexapod cannot reach the point where the specimen breaks	>= 1 DOF	sight check	
7	Design platform to test 3D printed metal specimens	YES		additive manufacturing (not considering composite) does consist of metal materials	>= 1 designed specimen	test	
8	Platform should be easy to maintain		3	minimal maintenance means more time towards testing and in a manufacturing environment means less downtime	N/A	Multiple tests	
8.1	platform should have easy access to electronics			for maintenance, see above		sight check	

No.	Req.	Constraint	Crit. Wt. (1,3,9)	Justification	Value	Verification	Checked On
8.2	Should minimize needed maintenance for components of the platform			see above	all components require no maintenance	test over one semester	
9	Loading specimen should be easy as just placing it in the grips		3	more time spent setting up the specimen takes time away from testing, saves time in a manufacturing environment	1 step	test	
10	The platform shall be able to break samples in all loading conditions	YES		if it cannot do this, then the hexapod cannot perform as it is meant to	6DOF	test	
11	Platform should be ergonomic such that human use is accounted for		9	the easier to use, the less time it takes for new people to learn or experience users to test	no strenuous activity needed	test	
No.	Req.	Constraint	Crit. Wt. (1,3,9)	Justification	Value	Verification	Checked On
12	Platform must be able to test multiple sized specimens	YES		variability allows testing of the varying designs of the additive manufacturing world	> 1 specimen	test	
13	Device should be easy to transport		3		2 people minimum	test	
14	Parts should not exceed 30 lbs. individually		3	easy transport to the lab and easy transport in the future	30 lbs	test	
14.1	Hexapod must fit through the lab door frame	YES		goes against transporting easily	80"x60"	test	
15	Device should be able to function with at least one user		3	less manpower if only one person can use it	1 user	test	

16	Device should be designed for minimum construction difficulty		9	easy to take apart for maintenance, transporting, easy for machinists	N/A	fabrication test	
No.	Req.	Constraint	Crit. Wt. (1,3,9)	Justification	Value	Verification	Checked On
17	Design must be based on a Stewart-Gough platform	YES		serial manipulators lack stiffness and accuracy needed, other parallel manipulators provide issues in degrees of freedom and mechanics	1 SG platform	sight check	
18	The platform must be able to perform standard tests	YES		would not function as intended if this is not met	>= 3 DOF	test	
18.1	hexapod must perform a standard tensile test	YES		would not function as intended if this is not met	1 tensile test	test	
18.2	hexapod must perform a standard torsion test	YES		would not function as intended if this is not met	1 torsion test	test	
18.3	hexapod must perform a standard bending test	YES		would not function as intended if this is not met	1 bending test	test	
18.4	hexapod must perform a combination of two or more of the mentioned standard tests	YES		goes along with req. 19	1 standard tests	test	
19	The gripping system must not interfere with full field strain measurements	YES		hexapod would not work as intended otherwise	1 specimen in 360 deg view	sight check	
No.	Req.	Constraint	Crit. Wt. (1,3,9)	Justification	Value	Verification	Checked On
20	Device must perform repeatable tests	YES		hexapod would not work as intended otherwise	> 3 repeatable tests	test	

21	Must have a greater workspace than the CSM design	YES		CSM design does not have have the capability to do tests on the specimen size indicated		Matlab Graphs	
22	Must provide a way to measure actuator stroke	YES		To control the actuators	1 measurement device		
23	Must have the specimen located above the moving platform	YES		Greater workspace can be achieved			

Appendix B: Design drawings

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		DIMENSIONS ARE IN MM TOLERANCES: FRACTIONAL: ± ANGULAR: MACH ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	NAME	DATE				
			DRAWN	STF				
			CHECKED					
			ENG APPR.					
			MFG APPR.					
		MATERIAL	Q.A.		COMMENTS:			
		6061						
		FINISH						
NEXT ASSY	USED ON							
APPLICATION		DO NOT SCALE DRAWING						

SIZE	DWG. NO.	REV.
A	LVDT Slide Panel	
SCALE: 1:5		WEDGE:
		SHEET 1 OF 1

SHEET NO. **A** DWG. NO. **LVDT Slide Panel** REV.
 SCALE: 1:5 WIDTH: SHEET 1 OF 1

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		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		DIMENSIONS ARE IN INCHES	DRAWN	STF	
		TOLERANCES:	CHECKED		
		FRACTIONAL: $\pm$	ENG APPR.		
		ANGULAR: MATCH $\pm$ BEND $\pm$	MFG APPR.		
		TWO PLACE DECIMAL $\pm$	G.A.		
		THREE PLACE DECIMAL $\pm$	COMMENTS:		
		INTERPRET GEOMETRIC TOLERANCING PER:			
		MATERIAL:			
		4130 Normalized			
		FINISH			
NEXT ASSY	USED ON				
APPLICATION		DO NOT SCALE DRAWING			
			TITLE:		
			Bottom Frame Plate		
SIZE	DWG. NO.	REV			
B					
SCALE: 1:5	WEIGHT:	SHEET 1 OF 1

		UNLESS OTHERWISE SPECIFIED:	NAME	DATE	TITLE: <h1>Bottom Actuator Conneter L</h1>	
		DIMENSIONS ARE IN mm TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	STF		
			CHECKED			
			ENG APPR.			
			MFG APPR.			
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.			
		MATERIAL 4130 Normalized	COMMENTS:			
		FINISH				SIZE DWG. NO. REV
NEXT ASSY USED ON					B	
APPLICATION		DO NOT SCALE DRAWING				SCALE: 1:2 WEIGHT: SHEET 1 OF 1

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	V2.1BAC L V2		1
2	V2.1BAC LC V2		1

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		UNLESS OTHERWISE SPECIFIED:	NAME	DATE	TITLE: V2.1 Bottom Actuator Connector		
		DIMENSIONS ARE IN mm	DRAWN	STF			
		TOLERANCES:	CHECKED				
		FRACTIONAL: ±	ENG APPR.				
		ANGULAR: MACH ± BEND ±	MFG APPR.				
		TWO PLACE DECIMAL ±	Q.A.				
		THREE PLACE DECIMAL ±	COMMENTS:				
		INTERPRET GEOMETRIC TOLERANCING PER:					
		MATERIAL					
		4130 Normalized					
		FINISH			SIZE B	DWG. NO.	REV
NEXT ASSY		USED ON					
APPLICATION		DO NOT SCALE DRAWING			SCALE: 1:2 WEIGHT: SHEET 1 OF 1		

D

TITLE:		
Bottom Frame Assembly		
SIZE D	DWG. NO.	REV
SCALE: 1:10 WEIGHT:		SHEET 1 OF 1

_____ D
_____ C
_____ B
_____ A

84

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	2V2.1Top Plate F		3

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UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN mm		SIP	
TOLERANCES		CHECKED	
FRACTIONAL ±		ENG APPR.	
ANGULAR MATCH ± BEND ±		MFG APPR.	
TWO PLACE DECIMAL ±		G.A.	
THREE PLACE DECIMAL ±		COMMENTS:	
INTERPRET GEOMETRIC TOLERANCING PER:			
NATURAL			
4130 Normalized			
FINISH			
NEXT ASSY	USED ON		
APPLICATION	DO NOT SCALE DRAWING		

TITLE: Top Plate	
SIZE DWG. NO.	REV
C	
SCALE: 1:5	WEIGHT: SHEET 1 OF 1

Appendix C: Matlab Code for Singularity analysis

Main File:

```
clear
clc
close all
format longEng

% Optimal d -> 22
% d = 18;
% d = [-d d -d d -d d];
% ThetaT = [55,65,175,185,295,305] + d;
% ThetaB = [115,125,235,245,355,5]+ d;

% ThetaT = [66.43, 114.02, 186.16, 233.6, 306, 353.77];
% ThetaB = [53.51, 126.49, 173.51, 246.49, 293.51, 6.49];

ThetaT2 = [345, 15, 105, 135, 225, 255];
ThetaB2 = [45, 75, 165, 195, 285, 315];

% [P,J] = NormalizeJacobianP1(238,490,ThetaT,ThetaB,497,203);
% [P,J] = NormalizeJacobianP2(238,490,ThetaT,ThetaB,497,203);
% [P,J] = NormalizeJacobianP3(238,490,ThetaT,ThetaB,497,203);
[P,J] = NormalizeJacobianP1(247,247,ThetaT2,ThetaB2,413,60);
% [P,J] = NormalizeJacobianP2(247,247,ThetaT2,ThetaB2,413,60);
% [P,J] = NormalizeJacobianP3(247,247,ThetaT2,ThetaB2,413,60);

% figure
% scatter(P(:,1),P(:,2),20,P(:,4),'filled')
% colorbar
%%

figure
P1 = P(any(P(:,4) <= 50,2),:);
P2 = P(any(P(:,4) > 50 & P(:,4) <= 100,2),:);
P3 = P(any(P(:,4) > 100 & P(:,4) <= 250,2),:);
P4 = P(any(P(:,4) > 250 & P(:,4) <= 500,2),:);
% P5 = P(any(P(:,4) > 500,2),:);

P5 = P(any(P(:,4) > 500 & P(:,4) <= 100000,2),:);
P6 = P(any(P(:,4) > 100000,2),:);
scatter(P1(:,1),P1(:,2),3,'g','filled')
hold on; scatter(P2(:,1),P2(:,2),3,'k','filled')
hold on; scatter(P3(:,1),P3(:,2),3,'b','filled')
hold on; scatter(P4(:,1),P4(:,2),3,'y','filled')
hold on; scatter(P5(:,1),P5(:,2),3,'r','filled')
hold on; scatter(P6(:,1),P6(:,2),10,'c','filled')
```

```

xlabel('Rx( \theta )')
ylabel('Ry( \phi )')
% xlabel('X [mm]')
% ylabel('Y [mm]')
set(gca, 'fontsize',12)

```

Second File: NormalizeJacobianP2

```

function [P1, JNorm] =
NormalizeJacobianP2(radiusT,radiusB,thetaT,thetaB,homeheight,stroke)

a1 = [radiusB*cosd(thetaB(6)); radiusB*sind(thetaB(6)); 0];
a2 = [radiusB*cosd(thetaB(1)); radiusB*sind(thetaB(1)); 0];
a3 = [radiusB*cosd(thetaB(2)); radiusB*sind(thetaB(2)); 0];
a4 = [radiusB*cosd(thetaB(3)); radiusB*sind(thetaB(3)); 0];
a5 = [radiusB*cosd(thetaB(4)); radiusB*sind(thetaB(4)); 0];
a6 = [radiusB*cosd(thetaB(5)); radiusB*sind(thetaB(5)); 0];

b1 = [radiusT*cosd(thetaT(6)); radiusT*sind(thetaT(6)); 0];
b2 = [radiusT*cosd(thetaT(1)); radiusT*sind(thetaT(1)); 0];
b3 = [radiusT*cosd(thetaT(2)); radiusT*sind(thetaT(2)); 0];
b4 = [radiusT*cosd(thetaT(3)); radiusT*sind(thetaT(3)); 0];
b5 = [radiusT*cosd(thetaT(4)); radiusT*sind(thetaT(4)); 0];
b6 = [radiusT*cosd(thetaT(5)); radiusT*sind(thetaT(5)); 0];

k = 0;
w = 0;
q = 0;

t = 0;
Ry = [cosd(t) 0 sind(t); 0 1 0; -sind(t) 0 cosd(t)];

% position of the center of the top plate referenced to the center
of the bottom plate
p = [0; 0;homeheight];

% leg lengths
A1B1 = p + Ry*b1 - a1;

d11 = sqrt(transpose(A1B1)*A1B1);

dmax = d11 + stroke/2;
dmin = d11 - stroke/2;

for x = -300:.5:300
for y = -300:.5:300

% Rotation matrix of the top plate
R = [1 0 0; 0 1 0; 0 0 1];

```

```

    % position of the center of the top plate referenced to the center
of the bottom plate
    pc2 = [x; y; homeheight];

    % leg lengths
    A1B1 = pc2 + R*b1 - a1;
    A2B2 = pc2 + R*b2 - a2;
    A3B3 = pc2 + R*b3 - a3;
    A4B4 = pc2 + R*b4 - a4;
    A5B5 = pc2 + R*b5 - a5;
    A6B6 = pc2 + R*b6 - a6;

    d1 = sqrt(transpose(A1B1)*A1B1);
    d2 = sqrt(transpose(A2B2)*A2B2);
    d3 = sqrt(transpose(A3B3)*A3B3);
    d4 = sqrt(transpose(A4B4)*A4B4);
    d5 = sqrt(transpose(A5B5)*A5B5);
    d6 = sqrt(transpose(A6B6)*A6B6);

    % Unit vectors of each leg
    s1 = A1B1/norm(A1B1);
    s2 = A2B2/norm(A2B2);
    s3 = A3B3/norm(A3B3);
    s4 = A4B4/norm(A4B4);
    s5 = A5B5/norm(A5B5);
    s6 = A6B6/norm(A6B6);

    % Jacobian of the Stewart Gough Platform
    Jx = [transpose(s1) transpose(cross(b1,s1)); transpose(s2)
transpose(cross(b2,s2)); transpose(s3) transpose(cross(b3,s3));
transpose(s4) transpose(cross(b4,s4)); transpose(s5)
transpose(cross(b5,s5)); transpose(s6) transpose(cross(b6,s6))];

    % Checks to make sure leg lengths do not exceed max length with
the max
    % stroke
    if (d1 <= dmax && d2 <= dmax && d3 <= dmax && d4 <= dmax && d5 <=
dmax && d6 <= dmax) && (d1 >= dmin && d2 >= dmin && d3 >= dmin && d4 >=
dmin && d5 >= dmin && d6 >= dmin)

        K(q+1,1:3) = [x, y, cond(Jx)];
        JxAll(q*6+1:q*6+6,1:6) = Jx;

        q = q + 1;
    % break
end

end
end

[CondMax, locmax] = max(K(:,3));

```

```

[CondMin,locmin] = min(K(:,3));

JrMax = JxAll((locmax-1)*6+1:(locmax-1)*6+6,:);
JrMin = JxAll((locmin-1)*6+1:(locmin-1)*6+6,:);

o = 1;
for x1 = -300:.5:300
    y = 1;
    for y1 = -300:.5:300

% Rotation matrix of the top plate

        % position of the center of the top plate referenced to the center
        of the bottom plate
        pc1 = [x1; y1;homeheight];

        % leg lengths
        A1B1 = pc1 + (R)*b1 - a1;
        A2B2 = pc1 + (R)*b2 - a2;
        A3B3 = pc1 + (R)*b3 - a3;
        A4B4 = pc1 + (R)*b4 - a4;
        A5B5 = pc1 + (R)*b5 - a5;
        A6B6 = pc1 + (R)*b6 - a6;

        d1 = sqrt(transpose(A1B1)*A1B1);
        d2 = sqrt(transpose(A2B2)*A2B2);
        d3 = sqrt(transpose(A3B3)*A3B3);
        d4 = sqrt(transpose(A4B4)*A4B4);
        d5 = sqrt(transpose(A5B5)*A5B5);
        d6 = sqrt(transpose(A6B6)*A6B6);

        % Unit vectors of each leg
        s1 = A1B1/norm(A1B1);
        s2 = A2B2/norm(A2B2);
        s3 = A3B3/norm(A3B3);
        s4 = A4B4/norm(A4B4);
        s5 = A5B5/norm(A5B5);
        s6 = A6B6/norm(A6B6);

        if d1 <= dmax && d2 <= dmax && d3 <= dmax && d4 <= dmax && d5 <=
dmax && d6 <= dmax && d1 >= dmin && d2 >= dmin && d3 >= dmin && d4 >=
dmin && d5 >= dmin && d6 >= dmin

            % Jacobian of the Stewart Gough Platform
            Jx = [transpose(s1) transpose(cross(b1,s1)); transpose(s2)
transpose(cross(b2,s2)); transpose(s3) transpose(cross(b3,s3));
transpose(s4) transpose(cross(b4,s4)); transpose(s5)
transpose(cross(b5,s5)); transpose(s6) transpose(cross(b6,s6))];

```

```

JNorm = (JrMax - Jx)/(JrMax - JrMin);

P1(o+1,1:4) = [x1, y1, homeheight, cond(JNorm)];
y = 0;
o = o + 1;

end

end

if y == 0
    k = k + 1;
end
% end
end

end

```

Third File: NormalizeJacobianP1

```

function [P1, JNorm] =
NormalizeJacobianP1(radiusT,radiusB,thetaT,thetaB,homeheight,stroke)

a1 = [radiusB*cosd(thetaB(6)); radiusB*sind(thetaB(6)); 0];
a2 = [radiusB*cosd(thetaB(1)); radiusB*sind(thetaB(1)); 0];
a3 = [radiusB*cosd(thetaB(2)); radiusB*sind(thetaB(2)); 0];
a4 = [radiusB*cosd(thetaB(3)); radiusB*sind(thetaB(3)); 0];
a5 = [radiusB*cosd(thetaB(4)); radiusB*sind(thetaB(4)); 0];
a6 = [radiusB*cosd(thetaB(5)); radiusB*sind(thetaB(5)); 0];

b1 = [radiusT*cosd(thetaT(6)); radiusT*sind(thetaT(6)); 0];
b2 = [radiusT*cosd(thetaT(1)); radiusT*sind(thetaT(1)); 0];
b3 = [radiusT*cosd(thetaT(2)); radiusT*sind(thetaT(2)); 0];
b4 = [radiusT*cosd(thetaT(3)); radiusT*sind(thetaT(3)); 0];
b5 = [radiusT*cosd(thetaT(4)); radiusT*sind(thetaT(4)); 0];
b6 = [radiusT*cosd(thetaT(5)); radiusT*sind(thetaT(5)); 0];

k = 0;
w = 0;
q = 0;

t = 0;
Ry = [cosd(t) 0 sind(t); 0 1 0; -sind(t) 0 cosd(t)];

% position of the center of the top plate referenced to the center
of the bottom plate
p = [0; 0;homeheight];

% leg lengths
A1B1 = p + Ry*b1 - a1;

```

```

d11 = sqrt(transpose(A1B1)*A1B1);

dmax = d11 + stroke/2;
dmin = d11 - stroke/2;

for t2 = -90:.1:90
for theta2 = -90:.1:90

    % Rotation matrix of the top plate
    Rx = [1 0 0; 0 cosd(theta2) -sind(theta2); 0 sind(theta2)
cosd(theta2)];
    Ry = [cosd(t2) 0 sind(t2); 0 1 0; -sind(t2) 0 cosd(t2)];

    % position of the center of the top plate referenced to the center
of the bottom plate
    pc2 = [0; 0;homeheight];

    % leg lengths
    A1B1 = pc2 + Rx*Ry*b1 - a1;
    A2B2 = pc2 + Rx*Ry*b2 - a2;
    A3B3 = pc2 + Rx*Ry*b3 - a3;
    A4B4 = pc2 + Rx*Ry*b4 - a4;
    A5B5 = pc2 + Rx*Ry*b5 - a5;
    A6B6 = pc2 + Rx*Ry*b6 - a6;

    d1 = sqrt(transpose(A1B1)*A1B1);
    d2 = sqrt(transpose(A2B2)*A2B2);
    d3 = sqrt(transpose(A3B3)*A3B3);
    d4 = sqrt(transpose(A4B4)*A4B4);
    d5 = sqrt(transpose(A5B5)*A5B5);
    d6 = sqrt(transpose(A6B6)*A6B6);

    % Unit vectors of each leg
    s1 = A1B1/norm(A1B1);
    s2 = A2B2/norm(A2B2);
    s3 = A3B3/norm(A3B3);
    s4 = A4B4/norm(A4B4);
    s5 = A5B5/norm(A5B5);
    s6 = A6B6/norm(A6B6);

    % Jacobian of the Stewart Gough Platform
    Jx = [transpose(s1) transpose(cross(b1,s1)); transpose(s2)
transpose(cross(b2,s2)); transpose(s3) transpose(cross(b3,s3));
transpose(s4) transpose(cross(b4,s4)); transpose(s5)
transpose(cross(b5,s5)); transpose(s6) transpose(cross(b6,s6))];

    % Checks to make sure leg lengths do not exceed max length with
the max
    % stroke
    if (d1 <= dmax && d2 <= dmax && d3 <= dmax && d4 <= dmax && d5 <=
dmax && d6 <= dmax) && (d1 >= dmin && d2 >= dmin && d3 >= dmin && d4 >=
dmin && d5 >= dmin && d6 >= dmin)

```

```

K(q+1,1:3) = [t2, theta2, cond(Jx)];
JxAll(q*6+1:q*6+6,1:6) = Jx;

q = q + 1;
end

end
end

[CondMax,locmax] = max(K(:,3));
[CondMin,locmin] = min(K(:,3));

JrMax = JxAll((locmax-1)*6+1:(locmax-1)*6+6,1:6);
JrMin = JxAll((locmin-1)*6+1:(locmin-1)*6+6,1:6);

o = 1;
for t = -90:.1:90
    y = 1;
    for theta1 = -90:.1:90

% Rotation matrix of the top plate
        Rx = [1 0 0; 0 cosd(theta1) -sind(theta1); 0 sind(theta1)
cosd(theta1)];
        Ry = [cosd(t) 0 sind(t); 0 1 0; -sind(t) 0 cosd(t)];

% position of the center of the top plate referenced to the center
of the bottom plate
        pc1 = [0; 0;homeheight];

% leg lengths
        A1B1 = pc1 + (Rx*Ry)*b1 - a1;
        A2B2 = pc1 + (Rx*Ry)*b2 - a2;
        A3B3 = pc1 + (Rx*Ry)*b3 - a3;
        A4B4 = pc1 + (Rx*Ry)*b4 - a4;
        A5B5 = pc1 + (Rx*Ry)*b5 - a5;
        A6B6 = pc1 + (Rx*Ry)*b6 - a6;

        d1 = sqrt(transpose(A1B1)*A1B1);
        d2 = sqrt(transpose(A2B2)*A2B2);
        d3 = sqrt(transpose(A3B3)*A3B3);
        d4 = sqrt(transpose(A4B4)*A4B4);
        d5 = sqrt(transpose(A5B5)*A5B5);
        d6 = sqrt(transpose(A6B6)*A6B6);

% Unit vectors of each leg
        s1 = A1B1/norm(A1B1);
        s2 = A2B2/norm(A2B2);
        s3 = A3B3/norm(A3B3);
        s4 = A4B4/norm(A4B4);

```



```

s5 = A5B5/norm(A5B5);
s6 = A6B6/norm(A6B6);

if d1 <= dmax && d2 <= dmax && d3 <= dmax && d4 <= dmax && d5 <=
dmax && d6 <= dmax && d1 >= dmin && d2 >= dmin && d3 >= dmin && d4 >=
dmin && d5 >= dmin && d6 >= dmin

    % Jacobian of the Stewart Gough Platform
    Jx = [transpose(s1) transpose(cross(b1,s1)); transpose(s2)
transpose(cross(b2,s2)); transpose(s3) transpose(cross(b3,s3));
transpose(s4) transpose(cross(b4,s4)); transpose(s5)
transpose(cross(b5,s5)); transpose(s6) transpose(cross(b6,s6))];

    JNorm = (JrMax - Jx)/(JrMax - JrMin);

    P1(o+1,1:4) = [t, theta1, homeheight, cond(JNorm)];

    y = 0;
    o = o + 1;

end

end
if y == 0
    k = k + 1;
end

end

end

```

Appendix D: Distance Measurement Package

The code in Appendix A simply contains a PID library taken from Github (<https://github.com/br3ttb/Arduino-PID-Library>), a circular buffer (<https://www.megunolink.com/documentation/arduino-libraries/circular-buffer/>), and the standard Adafruit ads and wire libraries for Arduino IDE. Table 1 and 2 show the PID values to get optimal control for a certain speed. These values are a result of the moving average turned off. The next steps would be to implement these known values into a nonlinear control algorithm so that accurate control can be achieved as the speed changes. Hardware includes a RoboteQ FDC3260 motor controller, Arduino Due, ADS1115, an NRL based circuit board, Parker electrohydraulic actuators (EHA), and a TE SP2 string potentiometer (<https://www.te.com/usa-en/product-CAT-CAPS0068.html?q=&d=484864%20484868%20484872&type=products&samples=N#mdp-tabs-content>) with a separate power source (12 V).

CODE:

```
#include <PID_v1.h>
#include <CircularBuffer.h>
#include <Adafruit_ADS1015.h>
#include <Wire.h>

Adafruit_ADS1115 ads(0x48);

template <int WindowSize>

class movingAverage
{
public:
    double append( const unsigned int v)
    {
        if ( data.CountStored() < WindowSize )
        {
            sum += v;
            data.Add(v);
            return ads.readADC_SingleEnded(0);
        }
    }
};
```

```

    }

    auto h = data.Tail();
    sum = sum + v - h;
    data.Add(v);
    return getAverage();
}

double getAverage()
{
    return (double) sum / WindowSize;
}

private:
    typedef CircularBuffer< unsigned int, WindowSize > dataBuffer;
    dataBuffer data;

    unsigned long sum = 0;
};

double Setpoint, Input, Output, dYmicro, Lengthmicro, Min = -1000, Max =
1000;

double Kp = 280, Ki = 50, Kd = 10;

PID myPID(&Input, &Output, &Setpoint, Kp, Ki, Kd, P_ON_E, DIRECT);

void setup() {

    Serial1.begin(115200);
    while (!Serial);
    Serial.begin(115200);
    ads.begin();
    ads.setGain(GAIN_TWOTHIRDS);
    ads.setSPS(ADS1115_DR_64SPS);
    delay(20);
    myPID.SetMode(AUTOMATIC);
    myPID.SetOutputLimits(Min, Max);

}

// Initializer
movingAverage<1> ma;
int count = 0;
double EHA1 = 0, EHA2 = 0, dY = 0, dY1 = 0;
int i = 0, y = 0;

void loop() {

    auto val = ads.readADC_SingleEnded(0);
    delay(20);
    auto average = ma.append( val );
    auto Voltage = average * 0.1875 / 1000.0;
    auto Length = (317.5 / (12.2 - 0.033)) * (Voltage - 0.033);

```

```

while (dY == 0) {
    dY = Length - 0.1;
}

dY1 = -0.000003 * millis() + dY; // Input for controller; determine
speed by slope; results in mm

Setpoint = dY1;
Input = Length;
myPID.Compute();
EHA2 = Output;

// Software limit switches
while (Length > 130 || Length < 40) {
    EHA2 = 0;
    Serial1.println("!g 2 " + String(EHA2));
}

Serial1.println("!g 2 " + String(EHA2));

Serial.print(dY1 * 1000, 1);
Serial.print(' ');
Serial.println(Length * 1000, 1);

delay(20);
}

```

Appendix E: Equipment Datasheets

SP SERIES, STRING POTS

MEAS | MEAS SP

TE Model # SP2

TE Internal #: CAT-CAPS0068

[View on TE.com >](#)

Sensors > Position Sensors > Potentiometric Sensors > Cable Actuated Position Sensors

The SP2 string pot is a compact, economical and water resistant device that utilizes a flexible cable, a spring-loaded spool and a potentiometer to detect and measure linear position.

Product Type: SP Series, String Pots

Full Stroke Ranges: 101.6 - 1270 mm

Output Signal: Voltage Divider (Potentiometric)

Accuracy: .25 % of FS

Repeatability: .02 % of FS

The SP2 string pot is identical to the SP1 except for an added 40-inch electrical cable with a watertight rubber strain relief.

The SP2 has been compactly designed for tight spaces and high cycle applications and generously allows for measuring cable misalignment. With 4 different ranges and a handy mounting bracket, the SP2 is a perfect solution for many applications from light industrial to OEM.

Benefits

- Encoder
- Linear Position to 50 inches (1270 mm)
- Low-Cost, Long Life
- Rugged Polycarbonate Enclosure
- 40-in. Electrical Cable
- Free-Release Tolerant
- In Stock for Quick Delivery!

Features

Product Type Features

Product Type	SP Series, String Pots
--------------	------------------------

Signal Characteristics

Output Signal	Voltage Divider (Potentiometric)
---------------	----------------------------------

Body Features

Housing Material	Polycarbonate + Stainless Mounting Bracket
------------------	--

GV-50T

50kN Manual Vise grip

These high capacity vise grips are ideal for tensile testing of components and metal samples. Grips do not come with tightening bolts, only hex head bolts (26mm). An impact gun is recommended for tightening the inserts.

Item number	GV-50T
Tensile force	50 kN
Temperature range	0°C - +180°C Other temperature ranges on request
Body	Steel, manganese phosphate coating
Weight	12 kg each grip (without jaws)
Scope of delivery	1 pair of grips (can also be ordered separately (0.5 pair)).

Jaws for GV-50T: Scope of delivery: 1 set = 4 jaws

Item No.	Surface	Clamping surface H x W	Opening	Weight per pair
GV-50T-B	Blank (smooth) jaws	60 x 66 mm	0 - 30 mm	1.2 kg
GV-50T-BP	Pyramid jaws (serrated)	60 x 66 mm	0 - 30 mm	1.1 kg
GV-50T-BV	V-jaws	60 x 66 mm	5 - 30 mm Ø	1.1 kg
GV-50T-BW	Wave jaws	60 x 66 mm	0 - 30 mm	1.1 kg
GV-50T-BD	Diamond jaws	60 x 66 mm	0 - 30 mm	1.1 kg
GV-50T-B210	Blank (smooth) jaws	70 x 210 mm	0 - 10 mm	6.6 kg
GV-50T-BP210	Pyramid jaws (serrated)	70 x 210 mm	0 - 10 mm	6.6 kg
GV-50T-BW210	Wave jaws	70 x 210 mm	0 - 10 mm	6.4 kg

Jaws with other dimensions and surface coatings available on request

Blank jaws <ul style="list-style-type: none"> Suitable for further treatments Steel-blanks without coating
Pyramid jaws <ul style="list-style-type: none"> Pyramids 1.2x45° Hardened steel 58HRC manganese phosphated
V-jaws <ul style="list-style-type: none"> For all kinds of round samples Tooth pitch 1.2 mm Hardened steel 58HRC manganese phosphated
Wave jaws <ul style="list-style-type: none"> For flexible materials Wave 5 mm Hardened steel 58HRC manganese phosphated
Diamond jaws <ul style="list-style-type: none"> Clamping surface coated with synthetic diamonds Nickel-plated

GV-50T

FLIR CHAMELEON[®]3

P/N: CM3-U3-13Y3, USB3 VISION

FLEXIBLE FORM FACTOR + USB3 VISION

The Chameleon3 camera line combines the ease-of-use of USB 3.0, the small size and flexibility of board-level, and the most popular CCD and CMOS image sensors into an affordable package. Available in a compact 44 x 35 x 19.5 mm case or as a 40 x 31 mm board stack. The lightweight metal case is designed for reliability and offers multiple mounting points and a locking USB 3.0 connection. Includes on-camera frame buffer for image retransmission, opto-isolated GPIO with locking connection, and a hassle-free 3-year warranty.

KEY FEATURES

- Boxed and board level available
- On-camera image processing: color interpolation, gamma, and LUT
- 16 MByte frame buffer; LED status indicator

Board Level

With Case

www.flir.com/mv

The World's Sixth Sense[®]

Specifications

	CM3-U3-13Y3M	CM3-U3-13Y3C
Firmware	1.9.3.0	1.9.3.0
Resolution	1280 x 1024	1280 x 1024
Frame Rate	149 FPS	149 FPS
Megapixels	1.3 MP	1.3 MP
Chroma	Mono	Color
Sensor	On Semi P1300, CMOS, 1/2"	On Semi P1300, CMOS, 1/2"
Readout Method	Global shutter	Global shutter
Pixel Size	4.8 µm	4.8 µm
Lens Mount	CS-mount (case) / (S-mount board level)	CS-mount (case) / (S-mount board level)
ADC	10-bit	10-bit
Gain Range	0 dB to 18 dB	0 dB to 18 dB
Exposure Range	0.006 ms to 999.240 ms	0.006 ms to 999.240 ms
Trigger Modes	Standard, bulb, multi-shot	Standard, bulb, multi-shot
Partial Image Modes	Pixel binning, ROI	Pixel binning, ROI
Image Processing	Gamma, lookup table, and sharpness	Gamma, lookup table, hue, saturation, and sharpness
HDR Sequencing	Not supported	Not supported
Image Buffer	16 MB	16 MB
User Sets	2 memory channels for custom camera settings	2 memory channels for custom camera settings
Flash Memory	1 MB non-volatile memory	1 MB non-volatile memory
Opto-isolated I/O Ports	1 input, 1 output	1 input, 1 output
Non-isolated I/O	2 bi-directional	2 bi-directional
Auxiliary Output	3.3 V, 150 mA maximum	3.3 V, 150 mA maximum
Interface	USB 3.0	USB 3.0
Power Requirements	5 - 24 V via GPIO or 5 V via USB 3.0 interface	5 - 24 V via GPIO or 5 V via USB 3.0 interface
Power Consumption	<3 W maximum	<3 W maximum
Dimensions/Mass	44 mm x 35 mm x 19.5 mm (case enclosed); 40 mm x 31 mm (board level) / 54.9 g (case) / 27.9 g (board level)	44 mm x 35 mm x 19.5 mm (case enclosed); 40 mm x 31 mm (board level) / 54.9 g (case) / 27.9 g (board level)
Machine Vision Standard	USB3 Vision v1.0	USB3 Vision v1.0
Compliance	CE, FCC, KCC, RoHS. The ECCN for this product is: EAR099.	CE, FCC, KCC, RoHS. The ECCN for this product is: EAR099.
Temperature	Operating: 0° to 45°C Storage: -30° to 60°C	Operating: 0° to 45°C Storage: -30° to 60°C
Humidity	Operating: 20% to 80% (no condensation) Storage: 20% to 95% (no condensation)	Operating: 20% to 80% (no condensation) Storage: 20% to 95% (no condensation)
Warranty	3 years	3 years

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The World's **Sixth Sense**®

Bulletin HY22-3200A/US

Instruction Manual

Effective: April 01, 2011

Parker Compact Electro-Hydraulic Actuator (EHA)

416179

Table of Contents	Page
Introduction	3
Explanation of Warning Labels	3
Description	3
Preparation for Use	3
Installation	5
Start-Up Procedures	5
Special Tools	6
Safe Operating Procedures	6
Operation	6
Maintenance	6
Troubleshooting	9
Declaration of Incorporation	10

How to read the label on your EHA:

1 Name & address of manufacturer	8 Unique identifier/serial number
2 WARNING - see page 3	9 Maximum extend force
3 WARNING - see page 3	10 Maximum retract force
4 CE Mark	11 Motor voltage
5 Year of product manufacture	12 Motor watts
6 Product type	13 Motor horsepower
7 Part number	14 Maximum Amperage draw

WARNING – USER RESPONSIBILITY

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Introduction and Specification

Introduction

This manual provides descriptive operation and maintenance instructions for the Parker Compact EHA (Electro-Hydraulic Actuator) manufactured by the Parker Hannifin Corporation, Oildyne Division. Any additional information may be obtained from Parker by referencing the unit's part number printed on the nameplate or by contacting your local authorized Parker Distributor.

Some of the Information in this manual may not apply to your EHA. Information about custom units may require service and application information from other sources.

Warning

This Instruction Manual should be read in its entirety and understood prior to installing and operating the Parker Compact EHA.

It is imperative that personnel involved in the installation, service, and operation of the Oildyne units should be familiar with how the equipment is to be used. They should be aware of the limitations of the system and its component parts and have knowledge of good hydraulic practices in terms of safety, installation, and maintenance.

Explanation of Warning Labels

The following labels will be used in this Instruction Manual and on all applicable Oildyne products.

Be careful; take precautions; examine instructions before operation.

There may be hydraulic liquid under pressure. Do not open unit or break pipe connections until hydraulic pressure has been released.

Description

The Parker Compact Electro-Hydraulic Actuator (EHA) is a self-contained, bi-directional DC motor driven gear or gerotor pump with an integral hydraulic cylinder.

See Figures 1, 2, and 3 for dimensional drawings. The internal components are determined by the specifications provided by customers for each specific application.

Instruction Manual Compact EHA

See Figure 4 for a hydraulic schematic.

The life expectancy of Parker Oildyne units is directly tied to the frequency of use, the product in which they are incorporated and the application.

Unit weight will fall into a range from 3.6 kg (8.0 lbs) to 5.5 kg (11.9 lbs) based on stroke length and motor size. See below:

Base unit by stroke length:

102 mm (4 in)	2.1 kg (4.7 lbs)
152 mm (6 in)	2.8 kg (6.5 lbs)
203 mm (8 in)	3.5 kg (7.6 lbs)

Add for motor:

12 VDC or 24 VDC 245W	+1.5 kg (3.3 lb)
12 VDC or 24 VDC 560W	+2.0 kg (4.3 lb)

EHA is intended to be used for specific applications requiring actuation defined by the customer. Listed below are the acceptable operation parameters:

Maximum forces for actuator extend:

21,350 Nf (4,800 lbf) with gear pump

Maximum forces for actuator retract:

16,000 Nf (3,600 lbf)

Note: The maximum forces listed above are the highest forces available for an EHA unit. The maximum forces listed on your unit label will match the specific unit configured for your application.

Power range for intermittent duty:

12 or 24 VDC
.25 kW to .56 kW (.33 to .75 hp)

Operating temperature: -34°C to +65°C (-30°F to +150°F)

Storage temperature: -34°C to +93°C (-30°F to +200°F)

Maximum rate: 84 mm/sec (3.3 in/sec) at no load

EHA is intended for intermittent use only. It is not designed for continuous operation.

Parker Hannifin Corporation takes no responsibility for safety of any unit if it is not used for the intended purposes detailed in this Instruction Manual.

Examples of Abnormal Use:

- Use of unit with pressure other than that for which it was intended
- Use with a higher or more frequent duty cycle other than that for which it was intended
- Use with higher or lower Voltage than required for optimal use
- Use in a different mounting orientation other than that for which it was intended
- Use of fluids other than those recommended

Preparation for Use

Unpacking and Checking

All units were carefully packed in boxes, and may or may not be on skids. In any case, do not remove anything from the skid or any packaging until it has been carefully checked for damage that may have occurred in transit. Report all damage immediately to the carrier and send a copy to the vendor.

Storage

If the unit is not going to be installed immediately, it should be stored indoors, covered with a waterproof sheet.

Installation

Locating EHA

The unit should preferably be installed indoors in a clean, dry environment with an ambient temperature of 16° to 37°C (60°F to 100°F).

Parker Oildyne products should not be installed where they are at risk of objects falling from overhead or where there is any risk of impact with external objects.

Mounting the Unit

Each Parker Compact EHA is designed to be mounted and connected in a specific way. Be sure to use the proper size mounting hardware to match the mate end on the rod or base end of the EHA.

Connect one end of the EHA unit to its corresponding mount on the machine.

The load must be supported by its own guidance system. The axis of the cylinder and that of the load should not be unduly displaced to ensure that there are no imposed side loads following installation or significant reaction forces of the cylinder. It is the user's responsibility to properly position the unit to keep the load in axial alignment with the center line of the EHA rod. The degree of accuracy needed will vary from unit to unit based on the configuration so every effort should be made to be as accurate as possible.

The unit should be positioned in the machine to ensure good ventilation.

For environmental protection a rubber gaiter or boot may be placed round the piston shaft. This serves to prevent access to the moving piston shaft but this is only an option. The provision of a rubber gaiter or boot for safety purposes is not mandatory. However it is recommended that a gaiter or boot might be fitted if the end user does not intend to provide any alternative form of protection such as guarding. The piston shaft is stainless steel and is resistant against wear. But, if a dusty environment is involved a gaiter or boot may still be used to protect seals.

If the unit has a yellow sticker designating "THIS SIDE UP" or "THIS END UP", make sure that the unit is mounted with that sticker up, or on top of the unit.

If the unit is mounted to the machine using bolts (user supplied), make sure to use the correct tightening torque to ensure a secure mounting and no damage to the hardware.

Electrical Service Connections

Connect the motor to the power source following good practices as outlined in the National Electric Codes and any local codes which may apply. Verify that the available Voltage is the same as the Voltage identified on the label. A **suggested** example for wiring is illustrated in **Figure 5**.

The blue lead (positive) extends the unit and green lead (positive) retracts the unit. Refer to **Figure 6** for wire colors and corresponding operation.

Once the motor is connected, extend or retract the unit to align the pin connection or specified mounting at the free end of the EHA with the machine mounting. Attach to the machine using appropriate mounting hardware.

The machine in which the EHA is incorporated should be bonded to earth. Each EHA unit must be bolted to the frame of the machinery in which it is incorporated. Therefore, if lightning strikes, this will immediately be returned to ground potential.

Figure 5

Function	Positive	Ground
Extend	Blue	Green
Retract	Green	Blue

Figure 6

Start-Up Procedures

Fuse protection can be added to the wiring circuit if desired. Use a slow blow fuse so it will not be tripped from the inrush current. Make sure the fuse is sized above the maximum requirement for the application and below the maximum available from the power supply. See **Figure 7** for approximations of maximum amperage based on basic configurations.

The following is the standard operation of the Parker Compact EHA and can be considered as a functional test for unit at the completion of installation or at any time during usage:

1. With the unit fully installed, actuate the extend switch for 2 seconds and release. The rod should stop and lock in position.
2. Press and hold the extend switch until the rod reaches the end of the stroke. When rod stops, release switch. The motor should turn off and the rod should lock in place.
3. Actuate the retract switch for 2 seconds and release. The rod should stop and lock in position.
4. Actuate the retract switch until the rod fully retracts into the cylinder. When rod stops, release switch. The motor should turn off and the rod should lock in place.

If required, any tests for radiated and conducted emissions should be performed in accordance with the Electromagnetic Compatibility (EMC) Generic Emission standards for environments appropriate to the end use product to confirm compliance with the EMC Directive.

If required, any tests for radiated and conducted immunity should be performed in accordance with the Electromagnetic Compatibility (EMC) Generic Immunity standard for environments appropriate to the end use product to confirm compliance with the EMC Directive.

Special Tools

No dismantling, service or maintenance is recommended for EHA so no special tools are required.

Safe Operating Procedures

Should a failure of the electrical power supply occur, power should not be returned to these power units without a conscious action by the operator.

The power switch must be de-activated once the rod reaches either end of stroke. If not, the pressure will build and run over the relief valve which may cause the motor to trip the thermal overload and shut down.

In the unlikely event of sound levels exceeding 70 dBA it is recommended that hearing protection should be worn. If sound levels exceed 80 dBA it is necessary to take measures to reduce sound levels. This is normally achieved by placing machinery in an acoustically lined enclosure.

Motor Voltages for EHA will be 12 VDC or 24 VDC. If these motors are operated at Voltages other than those specified, the life expectancy and safety of these units cannot be guaranteed.

Operating temperature requirements:
-34°C to +65°C (-30°F to +150°F)

The EHA unit must not be operated on a duty cycle or stroke frequency that exceeds those identified in Operation instructions. When necessary, cooling must be provided to ensure that the temperature of the internal fluids used never exceed suitable temperatures for operation.

The Parker Compact EHA can support a load for a finite time determined by the loads and operating conditions of the application. There is no guarantee that an EHA will hold a load indefinitely and some creep should be anticipated.

Removal From Service

If for some reason, the EHA must be removed from service, follow these instructions:

1. Wear protective eye gear.
2. Remove electrical power from the motor.
3. Mechanically hold or block the load held by the actuator should there be any movement once pressure is relieved.
4. Only after the load is mechanically held in place, remove the EHA.
5. When reinstalling the EHA, follow all the procedures and startup instructions given previously.

Operation

Suitable lighting requirements for operation of this unit are the responsibility of the machine manufacturer.

See **Figure 7** for performance curves to identify parameters of operation and **Figure 8** to identify motor duty cycle characteristics.

Operation of Manual Release Option

Manual release functionality is provided as an option for the Parker Compact EHA. This feature is intended for infrequent emergency use only. It is NOT intended to provide functionality for regular operation.

To engage the manual release, turn the assembly in a counter-clockwise direction using the slot on the end of the assembly. Turn the release until it cannot turn any more. This will release the pressure in the unit so that the actuator rod can be manually moved in and out.

To disengage the manual release and continue regular operation, turn the assembly in a clockwise direction until it won't go any further. Provide power to the motor, pressure will rebuild and the unit will operate as usual.

**THE PARKER COMPACT EHA
SHOULD NOT BE DISMANTLED.**

**Dismantling the Parker Compact EHA
will void any warranty.**

Maintenance

Maintenance should only be conducted when units are disconnected from their power supply.

Maintaining Proper Oil Temperature

Hot oil in your equipment's hydraulic system is one of the primary causes of poor operation, component failure and downtime. Here are some pointers on maintaining proper oil temperature.

1. The oil in your hydraulic system was designed for operation within a specified temperature range. You may be able to run it at hotter temperatures for short periods of time, intermittently, without adverse effects.
2. "Hot oil" is a relative term. In most cases, 49°C (120°F) at the reservoir is considered an ideal operating temperature.
3. Keep your equipment clean. A thick layer of dirt acts as insulation. It will prevent the hydraulic system from getting rid of heat.

Measuring Oil Temperature

Because your machine does not have a reservoir thermometer, use the "palm test". The reservoir is located adjacent to the motor. First check the reservoir with your fingertip; if it's not too hot to touch, place your palm on the reservoir. You'll be able to hold it there without discomfort if the oil temperature is about 55°C (130°F) or below.

The maximum force and speed available and Amperage draw on rod extend for different combinations of motor, pump and cylinder bore can be determined from the tables below:

Figure 7

Current draw for Motor C (24VDC, 245 W) and Motor D (24VDC, 560 W) will be approximately ½ of Amp draw shown above.

Retract Forces: The maximum force available on **rod retract** is lower than on extend due to the presence of the piston rod which reduces the effective surface area of the piston. When the force required to retract the piston rod approaches that required for extend, please contact the factory.

Note: Performance data is based on **rod extend**, not retract, and is for reference only.

Standard Motor Duty Cycle Characteristics

Recommended Spare Parts

There are no recommended spare parts for the EHA as it is a sealed unit. Any warranty repair would be done at the Oildyne Division.

Troubleshooting

The information provided in this section will provide some ideas on how to resume normal operation given certain conditions.

Do not attempt to open the EHA unit to make internal adjustments or repairs; it will void the warranty on the unit.

The Parker Compact EHA is NOT field servicable.

Troubleshooting Areas**Unit fails to operate**

1. Power source is not charged – recharge.
2. Amperage from power source is not sufficient to operate unit – use power supply with adequate Amperage to operate EHA.
3. Wiring harness from EHA motor is not securely fastened to power source or wiring – tighten connections to power source.
4. Motor has failed due to higher or more frequent duty cycle than the unit was intended for – replace unit.
5. Motor has run for an extended time and the internal thermal breaker tripped.

Unit slows during operation

1. Voltage from power source has changed – examine power supply for source of varying Voltage.
2. Unit is stalling due to high loads– reduce load against unit to the forces prescribed in the specifications.
3. Unit is mis-aligned and is causing side loading – cease operation until alignment is corrected.
4. The load is increased on the unit – this is to be expected.

Unit makes excessive noise

1. Operating temperature too low – operate EHA above -34°C (-30°F).
2. Unit is mounted in the wrong orientation – cease operation. Contact the factory.

Speed of unit varies during operation

Unit is being used with higher or lower Voltage than for which it is designed (12 VDC or 24 VDC) – cease operation. Use unit with power source of appropriate Voltage.

Rod stops moving

1. Power source has become disconnected – reconnect power source.
2. Motor thermal breaker has been tripped due to high temperature in the motor, causing motor to stop – allow motor to return to ambient temperature and restart operation.

Overheating of unit

Warning: If motor stops due to thermal overload, de-actuate the power switch. Otherwise, when the motor cools, it will start up again.

1. Continuous operation at relief setting – cease operation. Allow the unit to return to ambient temperature before resuming operation.
2. Stalling under load – cease operation. Ensure loads being moved are within the prescribed specifications outlined in this manual.
3. Improper air circulation around reservoir – relocate unit to area in assembly that will provide adequate air circulation to maintain the operating temperature range of -34°C to +65°C (-30°F to 150°F).
4. EHA operating in direct sunlight or ambient temperature is too high – move unit to location that will be lower than the specified maximum operating temperature of +65°C (+150°F).
5. EHA operating at a continuous duty cycle – cease operation. Discontinue use until required operation of the unit will fall within the duty cycle characteristics illustrated in **Figure 7**.

Should the user encounter any other conditions, please contact your local authorized Parker Oildyne distributor or the Oildyne Division directly for further information or to arrange for warranty replacement/repair if within the warranty period.

Conclusive Unit Failure

If the operation of the unit cannot be restored after attempts at the troubleshooting suggestions listed previously, please contact your local authorized Parker Oildyne distributor or the Oildyne Division directly to arrange for warranty replacement/repair if within the warranty period.

EC Declaration of Incorporation.

Manufacturer's Name: Parker Hannifin Corporation
Manufacturer's Address: Oildyne Division
5520 Highway 169 North
New Hope, MN 55428 USA

Declare that the partially complete machinery described below conforms to applicable health and safety requirements of Part 1 of Annex 1 of Machinery Directive 2006/42/EC taking full account of requirements for pressure equipment. This partly completed machinery must not be put into service until the machinery into which it is to be incorporated has been declared in conformity with the provisions of the Machinery Directive. Confidential technical documentation has been compiled as described in Part B of Annex VII of Machinery Directive 2006/42/EC and is available to European national authorities on written request. If a request is received documentation will be transmitted either electronically or by post.

Description: Compact Electro-Hydraulic Actuator (EHA)
Model Number: All
Sizes: All
Serial Number: All

The following standards have either been referred to or complied with in part or in full as relevant:

ENISO 12100 – 2 Machinery Safety	-	Basic concepts, general principles for design – Part 2: Technical principles and specifications.
EN13849 Machinery Safety	-	Safety Related Parts of Control Systems – Part 1: General Principles for Design.
EN 982:1996Machinery Safety	-	Safety requirements for fluid power systems and their components – Hydraulics.

Full Name of responsible person Van Mancuso

Place of signing:

Parker Hannifin Corporation
Oildyne Division
5520 Highway 169 North
New Hope, MN 55428 USA

Position General Manager

Signature

Date March 17, 2011

Full Name of Authorized European Representative Stephen Fryer

Place of signing:

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Date March 17, 2011

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Bulletin HY22-3200A/US
.25M, 11/11 BG

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Your local authorized Parker distributor

Advanced Features Triple Channel 60A Brushed DC Motor Controller with USB and CAN

Roboteq's FDC3260 is a feature-packed, high-current, triple channel controller for brushed DC motors. The controller features a high-performance 32-bit microcomputer and quadrature encoder inputs to perform advanced motion control algorithms. The motors may be operated in open or closed loop speed mode, position mode or in torque mode.

The FDC3260 features several Analog, Pulse and Digital I/Os which can be remapped as command or feedback inputs, limit switches, or many other functions. The FDC3260 accepts commands received from an RC radio, Analog Joystick, wireless modem, PLC, or microcomputer. For mobile robot applications, two of the controller's three motor channels can either be operated independently or mixed to move and steer a vehicle. Using CAN bus, up to 127 controllers can be networked at up to 1Mbit/s on a single twisted pair.

Numerous safety features are incorporated into the controller to ensure reliable and safe operation. The controller's operation can be extensively automated and customized using Basic Language scripts. The controller can be configured, monitored and tuned in realtime using a Roboteq's free PC utility. The controller can also be reprogrammed in the field with the latest features by downloading new operating software from Roboteq.

Applications

- Motion simulators
- XYZ platforms
- Underwater Robotic Vehicles
- Stabilization Gimbals
- Machine tools
- Industrial automation
- Telepresence Systems
- Animatronics

Key Features

- USB, RS323, RS485, 0-5V Analog, or Pulse (RC radio) command modes
- CAN bus interface up to 1Mbit/s with multiple protocol support
- Auto switch between Serial, USB, CAN, Analog, or Pulse based on user-defined priority
- Built-in dual 3-phase high-power drivers for three brushed DC motor at up to 60A each
- Full forward & reverse motor control. Four quadrant operation. Supports regeneration
- Operates from a single 10V-60V power source
- Programmable current limit up to 60A per motor for protecting controller, motor, wiring and battery
- Dedicated connector for three quadrature encoders
- Up to eight Analog Inputs for use as command and/or feedback
- Up to eight Pulse Length, Duty Cycle or Frequency Inputs for use as command and/or feedback
- Up to 10 Digital Inputs for use as Deadman Switch, Limit Switch, Emergency stop or user inputs
- Four general purpose 24V, 1.5A output for brake release or accessories
- Selectable min, max, center and deadband in Pulse and Analog modes
- Selectable exponentiation factors for each command inputs
- Trigger action if Analog, Pulse or Encoder counter capture are outside user selectable range (soft limit switches)
- Open loop or closed loop speed control operation
- Closed loop position control with encoder, analog or pulse/frequency feedback
- Torque mode

- PID control loop
- Built-in Battery Voltage and Temperature sensors
- Optional backup power input for powering safely the controller if the main motor batteries are discharged
- Power Control wire for turning On or Off the controller from external microcomputer or switch
- No consumption by output stage when motors stopped
- Regulated 5V output for powering RC radio, RF Modem, sensors or microcomputer
- Separate Programmable acceleration and deceleration for each motor
- Ultra-efficient 2.0 mOhm ON resistance MOSFETs
- Selectable triggered action if Amps is outside user-selected range
- Short circuit protection
- Overvoltage and Undervoltage protection
- Watchdog for automatic motor shutdown in case of command loss
- Overtemperature protection
- Diagnostic LED
- ABS plastic enclosure with heat conducting bottom plate
- Efficient heat sinking. Operates without a fan in most applications.
- Dustproof and weather resistant. IP51 NEMA rating
- Power wiring 0.25" Faston tabs
- 5.5" (139.7mm) L, 5.5" W (139.7mm), 1.0" (25mm) H
- -40° to +85° C operating environment
- 0.5 lbs (250g)
- Easy configuration, tuning and monitor using provided PC utility
- Field upgradeable software for installing latest features via the Internet Orderable Product References

Orderable Product References

Reference	Number of Channels	Amps/Channel	Volts	Ethernet	Resolver
FDC3260	3	60	60	No	No

Important Safety Disclaimer

Dangerous uncontrolled motor runaway condition can occur for a number of reasons, including, but not limited to: command or feedback wiring failure, configuration error, faulty firmware, errors in user script or user program, or controller hardware failure.

The user must assume that such failures can occur and must make their system safe in all conditions. Roboteq will not be liable in case of damage or injury as a result of product misuse or failure.

Power Wires Identifications and Connection

Power connections are made by means of faston tabs located at the back of the controller.

FIGURE 1. FDC3260 Front View

FIGURE 2. FDC3260 Rear View

Figure 3, below, shows how to wire the controller and how to turn power On and Off.

FIGURE 3. Powering the Controller. Thick lines identify MANDATORY connections

Important Warning

Carefully follow the wiring instructions provided in the Power Connection section of the User Manual. The information on this datasheet is only a summary.

Mandatory Connections

It is imperative that the controller is connected as shown in Figure 3 in order to ensure a safe and trouble-free operation. All connections shown as thick black lines are mandatory. The controller must be powered On/Off using switch SW1 on the Pwr Ctrl tab. Use a suitable high-current fuse F1 as a safety measure to prevent damage to the wiring in case of major controller malfunction.

Emergency Switch or Contactor

The battery must be connected in permanence to the controller's VMot tabs via a high-power emergency switch or contactor SW2 as additional safety measure. The user must be able to deactivate the switch or contactor at any time, independently of the controller state.

Electrostatic Discharge Protection

In accordance with IEC 61000-6-4, Roboteq Motor Controllers are designed to withstand ESD up to 4kV touch and 8kV air gap. This protection is implemented without any additional external connections required.

Some specifications, such as EN12895, require a higher level of protection. To maximize ESD protection, up to 8kV touch and 15kV air gap, you may connect the metallic heatsink of the controller to your battery negative terminal. [See App Note 062918 for example connections.](#)

Precautions and Optional Connections

Note 1: Backup battery to ensure motor operation with weak or discharged batteries, connect a second battery to the Power Control wire/terminal via the SW1 switch.

Note 2: Use precharge 1K, 0.5W Resistor to prevent switch arcing.

Note 3: Insert a high-current diode to ensure a return path to the battery during regeneration in case the fuse is blown.

Note 4: Optionally ground the VMot tabs when the controller is Off if there is any concern that the motors could be made to spin and generate voltage in excess of 60V.

Note 5: Connect the controller's bottom plate to a wire connected to the Earth while the charger is plugged in the AC main, or if the controller is powered by an AC power supply.

Note 6: Be sure not to create a path from the ground pins on the I/O connector and the battery minus terminal.

Use of Safety Contactor for Critical Applications

An external safety contactor must be used in any application where damage to property or injury to person can occur because of uncontrolled motor operation resulting from failure in the controller's power output stage.

FIGURE 4. Contactor Wiring Diagram

The contactor coil must be connected to a digital output configured to activate when "No MOSFET Failure". The controller will automatically deactivate the coil if the output is expected to be off and battery current of 1A or more is measured for more than 0.5s. This circuit will not protect against other sources of failure such as those described in the "Important Safety Disclaimer" on page 3.

Controller Mounting

During motor operation, the controller will generate heat that must be dissipated. The published amps rating can only be fully achieved if adequate cooling is provided. Good conduction cooling can be achieved by mounting the controller to a metallic surface, such as the chassis, cabinet, etc.

Encoder Connection

Connection to the Encoders is done using a special connector on the front side of the controller. The connector is a 10-pin Molex Microfit 3.0, ref. 43025-1000. Pin assignments are in Table 1, below.

FIGURE 5. Encoder Connector

TABLE 1.

Pin Number	1	2	3	4	5
Row Ch1	5V	Enc3 A	Enc1 B	Enc1 A	Ground
Row Ch2	5V	Enc3 B	Enc2 B	Enc2 A	Ground

Commands and I/O Connections

Connection to RC Radio, Microcomputer, Joystick and other low current sensors and actuators is done via the 25 connector. The functions of many pins vary depending on controller model and user configuration. Pin assignments are found in Table 2, below.

FIGURE 6. Main Connector Pin Locations

TABLE 2.

Connector Pin	Power	Dout	Com	Pulse	Ana	Dinput	Default Config
1	GND						
14	5VOut						
2			RS TxD				RS232Tx
15				RC1	ANA1	DIN1	RCRadio1
3			RS RxD				RS232Rx
16				RC2	ANA2	DIN2	RCRadio2
4				RC3	ANA3	DIN3	AnaCmd1 (1)
17				RC4	ANA4	DIN4	AnaCmd2 (1)
5	GND						
18		DOUT1					Motor Brake 1
6		DOUT2					Motor Brake 2
19		DOUT3					Contactor
7		DOUT4					Unused
20			CANH				Unused
8			CANL				Unused
21				RC5	ANA5	DIN5	Unused
9						DIN9	Unused
22				RC6	ANA6	DIN6	Unused
10						DIN10	Unused
23			RS485+				RS485
11			RS485-				RS485
24				RC7	ANA7	DIN7	Unused
12				RC8	ANA8	DIN8	Unused
25	5VOut						
13	GND						

Note 1: Analog command is disabled in factory default configuration.

Default I/O Configuration

While the controller can be configured so that practically any Digital, Analog and RC pin can be used for any purpose, the controller's factory default configuration provides an assignment that is suitable for most applications. Figure 7, below shows how to wire the controller to two analog potentiometers, an RC radio, and the RS232 port. It also shows how to connect two outputs to motor brake solenoids and another output to an external status LED. You may omit any connection that is not required in your application. The controller automatically arbitrates the command priorities depending on the presence of a val-

id command signal in the following order: 1-RS232, 2-RC Pulse, 3-None. If needed, use the Roborun+ PC Utility to change the pin assignments and the command priority order.

FIGURE 7. Factory Default Pins Assignment

Enabling Analog Commands

For safety reasons, the Analog command mode is disabled by default. To enable the Analog mode, use the PC utility and set Analog in Command Priority 2 or 3 (leave Serial as priority 1). Note that by default the additional securities are enabled and will prevent the motor from starting unless the potentiometer is centered, or if the voltage is below 0.25V or above 4.75V. The drawing shows suggested assignment of Pot 1 to ANA1 and Pot 2 to ANA4. Use the PC utility to enable and assign analog inputs.

USB communication

Use USB only for configuration, monitoring and troubleshooting. USB is not a reliable communication method when used in an electrically noisy environment. Communication will not always recover after it is lost without unplugging and replugging the connector, or restarting the controller. RS232 is the preferred method of communication when interfacing to a computer. USB and CAN can operate at the same time on the FDC3260. Plugging USB to a computer will not disable the CAN interface.

Status LED Flashing Patterns

After the controller is powered on, the Power LED will turn on, indicating that the controller is On. The Status LED will be flashing at a 2 seconds interval. The flashing pattern provides operating or exception status information.

FIGURE 8. Normal Operation Flashing Patterns

FIGURE 9. Exception or Fault Flashing Patterns

Additional status information may be obtained by monitoring the controller with the PC utility.

Battery Backed Clock and RAM

The controller includes a real-time clock/calendar and RAM storage for user variables. Both the clock and the RAM storage require a battery to continue running and for the stored data not to be lost while the controller is powered down. The battery is not installed by Roboteq. Users who wish to use the clock and/or battery backed RAM variables must install a battery themselves. The battery socket can be reached by removing the 6 screws that are holding the cover. Lift the cover to reach the board and insert a 3V, 12.5mm coin-style battery. Use battery type CR1225 or equivalent.

Measured and Calculated Amps

The controller includes Amps sensor in line with the motor terminals. Motor Amps are therefore measured with precision. Battery Amps is estimated using the formula $\text{Battery Amps} = \text{Motor Amps} * \text{PWM}$. This formula produces accurate results as long as the motor is well tuned, ie Hall Sensors correctly aligned in Trapezoidal mode, and $I_d = 0$ in Sinusoidal mode.

Secure Connection to AMP FASTON™ Tabs

Power Motor and Battery connections are made via standard 250mils (6.35mm) AMP FASTON Tabs. FASTON connectors provide a high current and very secure connection, proven over decades of use in the automotive industry. For maximum current handling, use connectors for AWG10 wires recognizable by their yellow plastic insulator.

FASTON connectors have an extremely tight fit and will not come off on their own. It is recommended, nevertheless, that the wiring is made so that the cables are never pulling the connector outward.

Frequent disconnects and reconnects will eventually loosen the connector's grip on the tab. If frequent disconnection is required, consider using Positive Lock connectors from TE Connectivity or their equivalent. These connectors have a spring loaded tab latch pin that will lock into the hole of the male tab.

Electrical Specifications

Absolute Maximum Values

The values in Table 3, below, should never be exceeded. Permanent damage to the controller may result.

TABLE 3.

Parameter	Measure point	Min	Typical	Max	Units
Battery Leads Voltage	Ground to VBat			63	Volts
Reverse Voltage on Battery Leads	Ground to VBat	-1			Volts
Power Control Voltage	Ground to Pwr Control wire			63	Volts
Motor Leads Voltage	Ground to M+ and M- wires			63 (1)	Volts
Digital Output Voltage	Ground to Output pins			30	Volts
Analog and Digital Inputs Voltage	Ground to any signal pin on 15-pin & Hall inputs			15	Volts
RS232 I/O pins Voltage	External voltage applied to Rx/Tx pins			15	Volts
Case Temperature	Case	-40		85	°C
Humidity	Case			100 (2)	%
Note 1: Maximum regeneration voltage in normal operation. Never inject a DC voltage from a battery or other fixed source					
Note 2: Non-condensing					

Power Stage Electrical Specifications (at 25°C ambient)

TABLE 4.

Continuous Max Current per channel	Measure point	Min	Typical	Max	Units
Battery Leads Voltage	Ground to VMot	0 (1)		63	Volts
Motor Leads Voltage	Ground to M+ and M- wires	0 (1)		63 (2)	Volts
Power Control Voltage	Ground to Power Control wire	0 (1)		65	Volts
Minimum Operating Voltage	VMot or Pwr Ctrl wires	9 (3)			Volts
Over Voltage protection range	Ground to VMot	5	60 (4)	63	Volts
Under Voltage protection range	Ground to VMot	0	5 (4)	63	Volts
Idle Current Consumption	VMot or Pwr Ctrl wires	50	100 (5)	150	mA
ON Resistance (Excluding wire resistance)	VMot to M+/- . Ground to M+/-		2.5		mOhm
Max Current for 30s	Motor current			60	Amps
Continuous Max Current per channel	Motor current			40(6)	Amps
Current Limit range	Motor current	10	50 (7)	60	Amps
Stall Detection Amps range	Motor current	10	60 (7)	60	Amps

TABLE 4.

Continuous Max Current per channel	Measure point	Min	Typical	Max	Units
Stall Detection timeout range	Motor current	1	500 (8)	65000	milli-seconds
Short Circuit Detection threshold (9)	Between Motor wires or Between Motor wires and Ground			500 (10)	Amps
Short Circuit Detection threshold	Between Motor wires and VBat	No Protection. Permanent damage will result			
Motor Acceleration/Deceleration range	Motor Output	100	500 (11)	65000	milli-seconds
Note 1: Negative voltage will cause a large surge current. Protection fuse needed if battery polarity inversion is possible					
Note 2: Maximum regeneration voltage in normal operation. Never inject DC voltage from a battery or other fixed source					
Note 3: Minimum voltage must be present on VBat or Power Control wire					
Note 4: Factory default value. Adjustable in 0.1V increments					
Note 5: Current consumption is lower when higher voltage is applied to the controller's VBat or PwrCtrl wires					
Note 6: Estimate. Limited by case temperature. Current may be higher with better cooling					
Note 7: Factory default value. Adjustable in 0.1A increments					
Note 8: Factory default value. Time in ms that Stall current must be exceeded for detection					
Note 9: Controller will stop until restarted in case of short circuit detection					
Note 10: Approximate value					
Note 11: Factory default value. Time in ms for power to go from 0 to 100%					

Command, I/O and Sensor Signals Specifications

TABLE 5.

Parameter	Measure point	Min	Typical	Max	Units
Main 5V Output Voltage	Ground to 5V pins on	4.6	4.75	4.9	Volts
5V Output Current	5V pins on RJ45 and DSub15			200 (1)	mA
Digital Output Voltage	Ground to Output pins			30	Volts
Output On resistance	Output pin to ground		0.25	0.5	Ohm
Output Short circuit threshold	Output pin	1.7		3.5	Amps
Digital Output Current	Output pins, sink current			1.5	Amps
Input Impedances	AIN/DIN Input to Ground		53		kOhm
Digital Input 0 Level	Ground to Input pins	-1		1	Volts
Digital Input 1 Level	Ground to Input pins	3		15	Volts
Analog Input Range	Ground to Input pins	0		5.1	Volts
Analog Input Precision	Ground to Input pins		0.5		%
Analog Input Resolution	Ground to Input pins		1		mV
Encoder Frequency				500	kHz

TABLE 5.

Parameter	Measure point	Min	Typical	Max	Units
Pulse durations	Pulse inputs	20000		10	us
Pulse repeat rate	Pulse inputs	50		250	Hz
Pulse Capture Resolution	Pulse inputs		1		us
Frequency Capture	Pulse inputs	100		1000	Hz

Note 1: Sum of all 5VOut outputs

Operating & Timing Specifications

TABLE 6.

Parameter	Measure Point	Min	Typical	Max	Units
Command Latency	Command to output change	1	0.5	1	ms
PWM Frequency	Motor Output	10	18	20	kHz
Closed Loop update rate	Internal		1000		Hz
RS232 baud rate	Rx & Tx pins		115200 (1)		Bits/s
RS232 Watchdog timeout	Rx pin	1 (2)		65000	ms

Note 1: 115200, 8-bit, no parity, 1 stop bit, no flow control

Note 2: May be disabled with value 0

Scripting

TABLE 7.

Parameter	Measure Point	Min	Typical	Max	Units
Scripting Flash Memory	Internal		32000		Bytes
Max Basic Language programs	Internal	1000		3000	Lines
Integer Variables	Internal		4096		Words (1)
Boolean Variables	Internal		8192		Symbols
Execution Speed	Internal	50 000	100 000		Lines/s

Note 1: 32-bit words

Thermal Specifications

TABLE 8.

Parameter	Measure Point	Min	Typical	Max	Units
Case Temperature	Case	-40		85 (1)	°C
Thermal Protection range	Case	80		90 (2)	°C
Power Dissipation	Case			70	Watts
Thermal resistance	Power MOSFETs to case			0.6	°C/W
Humidity	Case			100(3)	%

Note 1: Thermal protection will protect the controller power

Note 2: Max allowed power out starts lowering at minimum of range, down to 0 at max of range

Mechanical Specifications

Weight	Board		452 (0.99)		g (lbs)
Power Connectors width	Terminal tab		0.25		Inches

FIGURE 10. FDC3260 Side View and Dimensions

FIGURE 11. Top View and Dimensions

Appendix F: Bill of Materials

Group	Model Number	Company	Part Number	Price	Qty	Total
Actuator Assembly	EHA Actuator	MSC	92667997	\$ 616.82	6	\$ 3,700.92
Measurement	6-Axis Force Sensor	Sunrise Instruments	M3943	\$ 5,350.00	1	\$ 5,350.00
Hexapod	Ball Joint	McMaster-Carr	60745K651	\$ 26.22	6	\$ 157.32
Measurement	Cameras	Flir	CM3-U3-13Y3C-CS	\$ 350.00	6	\$ 2,100.00
Camera	Camera Lens	Flir	LENS-15F5-250C	\$ 170.00	6	\$ 1,020.00
Measurement	Linear Motion Position-Measuring Transmitters	McMaster-Carr	6863K2	\$ 213.38	6	\$ 1,280.28
Camera	Cables	Flir	ACC-01-2301	\$ 15.00	6	\$ 90.00
Camera	Host Adapter	FLIR	ACC-01-1203	\$ 155.00	1	\$ 155.00
Power & Control	Arduino Due	Arduino	1050-1049-ND	\$ 38.68	1	\$ 38.68
Power & Control	Brushed DC Motor Controller	Roboteq	FDC3260	\$ 595.00	2	\$ 1,190.00
Power & Control	Emergency Stop Button	Amazon		\$ 6.78	1	\$ 6.78
Power & Control	Optima Batteries	Amazon	8016-103 D34M	\$ 190.36	2	\$ 380.72
Power & Control	Powermax 40 Amp, 24V charger	PPL	PM3-40-24LK	\$ 170.28	2	\$ 340.56
Actuator Assembly	Universal Joints	McMaster-Carr	2456K17	\$ 79.68	6	\$ 478.08
Actuator Assembly	Partial-Extension Lock-Open Drawer Slides	McMaster-Carr	63835A31	\$ 53.03	6	\$ 318.18
Actuator Assembly	Plastic Corner Bracket	McMaster-Carr	13135A59	\$ 0.33	12	\$ 3.96
Hexapod	Ultra-High Capacity Leveling Mount	McMaster-Carr	3757K39	\$ 49.57	3	\$ 148.71
Fabrication Cost	3rd Party Fabrication	MTS (Clemson Campus)		\$ 11,331.16	1	\$ 11,331.16
					TOTAL:	\$ 28,090.35

Appendix G: Tiger 66.1 Control Code

```
#include <PID_v1.h>
#include <CircularBuffer.h>
#include <Adafruit_ADS1015.h>
#include <Wire.h>

Adafruit_ADS1115 ads(0x48);

template <int WindowSize>

class movingAverage
{
public:
    double append( const unsigned int v)
    {
        if ( data.CountStored() < WindowSize )
        {
            sum += v;
            data.Add(v);
            return ads.readADC_SingleEnded(0);
        }

        auto h = data.Tail();
        sum = sum + v - h;
        data.Add(v);
        return getAverage();
    }

    double getAverage()
    {
        return (double) sum / WindowSize;
    }

private:
    typedef CircularBuffer< unsigned int, WindowSize > dataBuffer;
    dataBuffer data;

    unsigned long sum = 0;
};

double Setpoint, Input, Output, dYmicro, Lengthmicro, Min = -1000, Max =
1000;

double Kp = 280, Ki = 50, Kd = 10;

PID myPID(&Input, &Output, &Setpoint, Kp, Ki, Kd, P_ON_E, DIRECT);

void setup() {

    Serial1.begin(115200);
    while (!Serial);
    Serial.begin(115200);
```

```

ads.begin();
ads.setGain(GAIN_TWOTHIRDS);
ads.setSPS(ADS1115_DR_64SPS);
delay(20);
myPID.SetMode(AUTOMATIC);
myPID.SetOutputLimits(Min, Max);

}

// Initializer
movingAverage<1> ma;
int count = 0;
double EHA1 = 0, EHA2 = 0, dY = 0, dY1 = 0;
int i = 0, y = 0;

void loop() {

    auto val = ads.readADC_SingleEnded(0);
    delay(20);
    auto average = ma.append( val );
    auto Voltage = average * 0.1875 / 1000.0;
    auto Length = (317.5 / (12.2 - 0.033)) * (Voltage - 0.033);
    while (dY == 0) {
        dY = Length - 0.1;
    }

    dY1 = -0.000003 * millis() + dY; // Input for controller; determine
    speed by slope; results in mm

    Setpoint = dY1;
    Input = Length;
    myPID.Compute();
    EHA2 = Output;

    // Software limit switches
    while (Length > 130 || Length < 40) {
        EHA2 = 0;
        Serial1.println("!g 2 " + String(EHA2));
    }

    Serial1.println("!g 2 " + String(EHA2));

    Serial.print(dY1 * 1000, 1);
    Serial.print(' ');
    Serial.println(Length * 1000, 1);

    delay(20);
}

```

Appendix H: CSM Bill of Materials

	ALL ITEMS					
	Item	Company	Model Number	Price	Qty	Total
Hexapod	Top/Bottom plate	Metals Depot	1-1/2in Al plate, 4x8ft	\$ 3,072.00	1	\$ 3,072.00
	Linear Actuators	Thomson Linear	PC40PA999B05-0060XM1	\$ 1,319.00	6	\$ 7,914.00
	Motors	Applied Motion Products	HT34-496	\$ 579.00	6	\$ 3,474.00
	Globe Joint	Myostat	SRJ024C	\$ 380.00	12	\$ 4,560.00
Grips	Grips (Set of 2)	ADMET	GV-20T	\$ 2,048.00	1	\$ 2,048.00
	Grip Adapter	Metals Depot	5x5in C1018 steel square, 1ft	\$ 421.42	1	\$ 421.42
Sensors	6-Axis Force Sensor	Sunrise Instruments	M3943	\$ 5,350.00	1	\$ 5,350.00
	LVDT	Macro Sensors	SE-750-4000-006	\$ 497.00	6	\$ 2,982.00
	LVDT Core Rod Kit	Macro Sensors	CCR3M-0650-1	\$ 67.00	6	\$ 402.00
Optics	Camera	Point Grey	FL3-U3-88S2C-C (Flea 3)	\$ 895.00	4	\$ 3,580.00
	Lens	Tamron	23FM16SP	\$ 245.00	4	\$ 980.00
	Tripod Adaptor	Point Grey	ACC-01-0003	included	4	\$ -
	USB Hub	Point Grey	ACC-01-600	\$ 110.00	1	\$ 110.00
	USB Cable	Point Grey	ACC-01-2301	\$ 15.00	1	\$ 15.00
	Camera Mount	Metals Depot	1/4in thick 3003-H14 Al 1x1ft	\$ 23.52	1	\$ 23.52
Safety	Brackets	Sick	C4000 Select	\$ 82.00	4	\$ 328.00
	Fence	RapidWire	4x8 ft Fence + 2 posts	\$ 289.00	2	\$ 578.00
	Light Curtain	Sick	C40E-1203CD010	\$ 793.00	1	\$ 793.00
Electronics	DAQ Card			\$ 2,000.00	1	\$ 2,000.00

	Hard Drive	Seagate	STCL4000400	\$ 225.00	1	\$ 225.00
	TOTAL					\$ 35,783.9 4

Appendix I: Initial Singularity Analysis

I.1 Overview

While some of the geometry has been explained for a general SG platform in previous sections, this section will discuss the steps taken to analyze the Jacobian and using the results to determine a suitable geometry for an SG platform. The chosen parameters are outlined in Figure 2.2. The variables $\mathbf{a}_i$ and $\mathbf{b}_i$ are found for the SolidWorks model by using a specified coordinate system and using the measure tool in SolidWorks. The leg lengths, $\overline{A_i B_i}$ where $i = 1, 2, \dots, 6$, are found by using a vector loop equation shown in Equation 2.3. The vectors $\mathbf{a}_i = [a_{ix}, a_{iy}, a_{iz}]^T$ and ${}^B\mathbf{b}_i = [b_{iu}, b_{iv}, b_{iw}]^T$ are with respect to the coordinate systems of the top and bottom plates respectively. For each case, a_{iz} and b_{iw} are equal to zero. The variable ${}^A\mathbf{R}_B$, shown in Equation 2.4, is the rotation matrix of the top platform [5]. In the case where the top platform is level, the rotation matrix is simply an identity matrix.

With the model of the Stewart Platform established, the Jacobian matrix can be calculated in Equation 6.1 such that,

$$J = \begin{bmatrix} \mathbf{s}_1^T & (\mathbf{b}_1 \times \mathbf{s}_1)^T \\ \vdots & \vdots \\ \mathbf{s}_6^T & (\mathbf{b}_6 \times \mathbf{s}_6)^T \end{bmatrix} \quad 6.1$$

where $\mathbf{s}_i$ is the unit vector of the leg length calculated in Equation 2.5 [14]. With the Jacobian formulated, there is now a way to find the condition number and determinant of the Jacobian.

Next, pathways are designated so that the singularities can be detected along it. For simplicity, pure tensile, bending, and torsion tests were used to analyze possible singularities. In order to determine the amount of movement needed for each test, a deflection prediction was completed on a specified material, ABS-ESD7 [29]. The tensile test is the simplest case. The goal is to use an iteration to calculate the Jacobian matrix with input of $\mathbf{p}$ and the rotation matrix. Since it is a pure tensile test, only the z value of the $\mathbf{p}$ vector needs to be used, x and y are equal to zero. The rotation matrix is simply an identity matrix considering there is no rotation about the x , y , or z axis. For the pure bending test, only the x (or y depending on orientation) values are changed or the $\mathbf{p}$ position, along with the specified result of the rotation matrix. In the case of revolution about the y -axis for the bending test, the rotation matrix is given in Equation 6.2,

$${}^A R_B = \begin{bmatrix} \cos(\theta) & 0 & \sin(\theta) \\ 0 & 1 & 0 \\ -\sin(\theta) & 0 & \cos(\theta) \end{bmatrix} \quad 6.3$$

where θ is the angle at which the coordinate system rotates about the y -axis. For the deflection value of the bending test, it was assumed that the material specimen is loaded as a cantilever beam with a concentrated loading scenario in which the maximum deflection occurs at the maximum bending moment needed to cause failure. Lastly, for the torsion test, the top plate is rotated about the z -axis such that the rotation matrix, given in Equation 6.4, is,

$${}^A R_B = \begin{bmatrix} \cos(\gamma) & -\sin(\gamma) & 0 \\ \sin(\gamma) & \cos(\gamma) & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad 6.5$$

where γ is the angle at which the top plate coordinate system revolves about its z-axis. Maximum deflection was calculated with the torsion equation with a solid rectangular cross-section (maximum deflection was calculated assuming the specimen was completely solid). In this case, x and y are equal to zero and z is equal to the “home” height of the Stewart-Gough platform in the $\mathbf{p}$ vector. The only variable that changes in the torsion case is the angle, γ .

Applying the equations for the motion of SG platform, we calculate the deflection of ABS-ESD7 for each of the tests using the material properties outlined in the table below.

Table I.1: Material properties of ABS-ESD7 [6].

Tensile Elongation	3.000	%
Elastic Modulus	2400	MPa
Tensile Strength	36.00	MPa
Flexural Strength	61.00	MPa
Flexural Modulus	2400	MPa

Using the properties in Table I.1, one can calculate the resulting deflections in which the material fails. First, the tensile deflection is calculated by simply multiplying the tensile elongation in Table 1 with the height of the specimen, 50 mm. The deflection of the bending test is calculated Equation 6.6,

$$\theta = \frac{T_{max}l}{JG} \quad 6.7$$

where T_{max} is the maximum torque needed to cause failure, l is the length of the material, in this case the height of the specimen, J is the polar moment of inertia of a solid rectangular

bar, and G is the shear modulus, which is calculated using the equation $G = E/2(1 + \nu)$. For the deflection of the pure bending test, it was assumed that the scenario is like a cantilever beam with a concentrated loading such that,

$$y_{max} = \frac{F_{max}l^3}{3EI} \quad 6.8$$

where F_{max} is the maximum force needed to deflect the specimen till failure, and I is the second moment of area of a rectangle in which,

$$I = \frac{lt^3}{12} \quad 6.9$$

where t is the thickness of the specimen. To determine the angle at which the top platform should be at, we simply find the maximum slope of the bar with Equation 6.10. Where *Slope* is the angle at which the top plate will orientate when maximum deflection has occurred [30]. Specifically, for the $\mathbf{p}$ vector, the change in x position is the value y_{max} , and the change in the angle of the coordinate system of the top plate is the value *Slope*.

$$Slope = \frac{F_{max}l^2}{2EI} \quad 6.10$$

With the equations above, graphs can be made in which singularities can be identified at certain points along the path. An iteration loop can be used in MATLAB to produce values of the determinant and condition number over the movement of the manipulator. To go further, the data from several geometries can be analyzed to see which design is more suitable for additively manufactured material characterization.

Even with analyzing the condition number with various material testing scenarios, certain singularities cannot be determined using the methods above. Tsai, as well as Bonev

and Zlatanov, mention singularities that occur based on architecture that cannot be determined using kinematic methods [14], [31]. The design shown in Figure 2.3 is not suitable, and a different geometry was used for further testing. The first issue at hand is that the top platform geometry is very similar to the bottom platform geometry. Section 2.6 explains in more detail, but in sum, having the top platform smaller than the bottom platform results in lower condition numbers which results in better controllability and performance.

Upon initial testing, the condition number and determinant values varied by the units used, which corresponds with the fact that the Jacobian matrix is inhomogeneous when considering the units of the elements. To better organize the results, the Jacobian is normalized along the x , y , and z axes by using Equation 6.11 below,

$$J_N = \frac{J - J_{Min}}{J_{Max} - J_{Min}} \quad 6.11$$

where J_N is the normalized Jacobian, and J is the Jacobian of the current position. The center or zero of the normalization is the “home” position of the platform. The variable J_{Min} is the Jacobian at the min radius in the direct opposite direction of the max radius of J_{Max} . J_{Max} is the Jacobian at the max value, or where one of the legs of the platform reaches max length, causing a singularity. The results of this method are in the next section. Ma and Angeles, as well as Fattah and Ghasemi, took a similar approach in which they defined a homogenous Jacobian matrix by dividing the orientation side (left side) of the matrix in equation 6.1 by a characteristic length [32,33]. The left side is shown in Equation 6.12.

$$J_s = \begin{bmatrix} \mathbf{s}_1^T \\ \vdots \\ \mathbf{s}_6^T \end{bmatrix} \quad 6.12$$

To produce the desired “map” in which singularities within the workspace are visible, MATLAB was used to create a boundary space in which the Jacobian could be normalized to. For feasibility, spherical coordinates were used. The radius, r , was increased to the max value for each x-y plane angle, θ , at each angle from the z-axis, γ , ranging from -90 to 90 degrees. An architecture similar to Ma’s and Angeles’ was used in which they determined triangular top and bottom platforms to be suitably conditioned [32]. A “slice” was taken from the workspace at the “home” position height and analyzed based on the condition number. Consequently, a “map” was developed by color coding the data points based on the condition number values. This process was repeated at different heights to see the change in condition number values over a vertical distance.

I.2 Results with Translation

Calculations of deflections for pure tensile, bending, and torsion were conducted of a 50 x 50 mm and 5 mm thick specimen. The material ABS-ESD7 was chosen to establish the pathways the manipulator needed to follow till failure of the material. Using the equations in the previous section, the results are depicted in Table I.2. For simplicity and for maximum estimation, it was assumed the specimen was a solid rectangular bar.

Table I.2: Results of deflection calculations of ABS-ESD7

Tensile Test	1.500 mm
Bending Test	25.00 mm
Torsion Test	11.68 deg

After applying the methodology outlined, simulations were completed with a pure tensile test. It is also noted that all graphs are shown with the deflection of the specimen till failure. Figure I.1 shows the results, note that the results of 500 mm, 550 mm, and 600 mm are close in value.

It was found that increasing the radius of the bottom plate reduces the condition number of the Jacobian, which follows the conclusion of Tsai that similar geometries of the top and bottom plate results in a singularity or that the manipulator is in closer proximity of a singularity [14]. It is also noted that while the condition number is reduced, the Stewart-Gough platform becomes more controllable in such that the accuracy and dexterity increases as the condition number gets closer to 1 [34,35]. To further analyze the manipulator, the determinant of the Jacobian was calculated throughout the path. While the results did not indicate that there are any singularities in the path, the determinant of the top and bottom plates of 250 mm diameter indicated that this geometry is closer to a singularity throughout the path than the other geometries. Note that the graphs in Figure I.1-Figure I.6 were used as a way to visualize how the condition number and determinant

changed with certain changes in geometry. The desire is to have lower condition numbers and high determinants.

Figure I.1: Results of increasing the bottom plate radius while keeping the top radius of 250 mm.

Next, the condition number and the determinant were calculated while keeping the bottom radius the default of 250 mm and increasing the radius of the top plate. Looking at Figure I.2, the top plate radius to be bigger than the bottom plate radius causes the condition number to rise further away from the value 1, indicating that this style of design becomes significantly less accurate as the ratio of the top and bottom plate grows. It follows that increasing the top plate radius also adds more weight that the linear actuators must control, putting more stress on the system. As for the determinant of this scenario, the results are the same as in Figure I.3.

Figure I.2: Results of increasing the radius of the bottom plate. The top plate was kept at the initial 250 mm of the design.

Figure I.3: Results of increasing the top plate radius while keeping the bottom radius at a default of 250 mm.

After the tensile test, a scenario of a pure bending test was looked at. The path of the Stewart-Gough platform was calculated by using simple geometry to find the distance of x traveled of point $\mathbf{p}$ and the equivalent angle at which the top plate finalizes at, which in this

case is the angle of deflection of the specimen. Figure I.4 depicts the results of the determinant and condition number over the path. Like the tensile test results, increasing the bottom plate radius reduces the condition number and increases the determinant. It can be noted that at a certain ratio of the size of the top and bottom plates, the condition number and determinant only have minimal changes compared to the changes of plate sizes with lower ratios. This suggests that at a certain point, there is no need to make the bottom plate larger. It is also noted that the slope of the curves for the larger radii starts decreasing at a faster rate than smaller radii. The decrease in slope for the determinant suggests that the manipulator is approaching a singularity.

Figure I.4: Results of the condition number and determinant for a pure bending test. The top plate radius is kept at default while the bottom plate radius is increased.

The condition number and determinant were calculated while increasing the top plate radius and following the path of the manipulator such that the material specimen would fail in a pure bending test. Considering the results of the tensile test, it was concluded that for the positions between the singularities, increasing the top radius would cause larger condition numbers than keeping the geometry at default as shown in Figure I.5. The slopes

of the graphs also suggest that the manipulator is approaching a singularity, and it approaches the singularity at a faster rate than that of only increasing the bottom plate radius.

Figure I.5: Results of the condition number and determinant for pure bending with increasing top plate radius and a constant default bottom plate radius.

Finally, the condition number and determinant were calculated over the pathway for a pure torsion test. In this case, the graphs are presented for the change in angle starting from

the negative x-axis going counterclockwise towards the z-axis. Looking at the results of the pure torsion test, one can see that the condition number for each case does not change significantly over the change in position. Increasing the radius of the top plate, though, decreases the condition number and increases the determinant, following previous observations that once past a certain ratio, the change in the condition number and determinant decreases significantly.

Figure I.6: Results of the condition number and determinant over the pathway of a pure torsion test with increasing bottom plate radius with a constant default top plate radius. Note that the last three legend values are close together on both charts.

Concluding the results for the initial performance analysis, the last test was completed by only increasing the top radius again. For the pure torsion application, there is a clear increase in overall condition numbers while the determinant values remain the same. This

correlates with the results of the pure tensile test in that similar geometries brings the manipulator closer to a singularity. It should be noted that the results of the condition number and determinant are similar for the pure tensile and pure torsion tests.

For the normalized condition number analysis, a MATLAB program determined the data points within a “slice” of the workspace of the platform. The max Jacobian is located at the farthest point from the p origin (see Figure 2.2) located on the plane of the z value of the “home” position. The minimum Jacobian was taken at the origin p . The results depict a platform with a top radius of 62.5 mm, a bottom radius of 250 mm, and a “home” position height of 300 mm. Figure I.7 shows the result.

Figure I.7: Data for “slice” of workspace at the “home” location.

It can be seen from the graph that the “slice” of the workspace resembles a shield. The max Jacobian was if the next iteration of increasing the radius, r , caused the stroke of one of the actuators to exceed its limit, and it must be noted that the orientation of the top

platform is kept horizontal throughout the process. Once the “slice” was created, the points were color coded based on the condition number values to show a specific “map” of where possible singularities can be located, which is shown in the figure below. Table I.3: Color coding scheme. shows the color-coding scheme.

Table I.3: Color coding scheme.

Color	Condition Number Range
≤ 50
$> 50 \text{ \& } \leq 100$
$> 100 \text{ \& } \leq 250$
$> 250 \text{ \& } \leq 500$
> 500

Figure I.8: Color coding of position points based on condition number.

Looking Figure I.8, a “map” can be seen of the condition number ranges. General areas can be located that would be suitable for low condition numbers as well as areas to avoid due to higher condition numbers. The green area is the most suitable. It can also be seen

that using the right side of the platform is desirable as it can reach farther than the left side. It can also be seen that the condition number fluctuates at certain areas. For example, near the x value of 0 and the y value of -50 the condition number fluctuates due to the multiple colors present in a small area.

Depending on the ranges desired, some areas can be seen in which they should be avoided. In this case, condition numbers of greater than 500, or the red area in Figure I.8, should be avoided. If that number increases to a higher value, for example 50,000, and the platform can be controlled with values less than that, then the result is Figure I.9: Color coding scheme by changing yellow to range between 250 and 50,000 and red to range above 50,000.. This shows that the range of condition numbers can be chosen based on the user's choice. Specific areas can be isolated to plan a path, decide if a certain geometry is sufficient, or identify the specific points where singularities are.

Figure I.9: Color coding scheme by changing yellow to range between 250 and 50,000 and red to range above 50,000.

An ideal method would be to analyze the condition numbers in the 3D workspace. While it is important to analyze the horizontal movement for shear and bending tests, tensile tests and compression tests rely on movements on the z-axis and therefore the change in condition numbers along the z-axis is important.

Figure I.10 Condition number analysis at a height of 37.5 mm above the “home” position using the color scheme in table 2.

The graph above indicates that most of the workspace in the “slice” contains sufficient condition numbers while thin portions of it containing other colors shows less sufficient condition numbers. Considering the amount of red depicted in Figure I.10, this area of the workspace is sufficient. It can also be noted that there is a red zone in the center suggesting that the controllability becomes difficult in the -z direction.

Figure I.11: Condition number analysis at 37.5 mm below the “home” position. Same color scheme as table 2.

Figure I.12: Condition number analysis at 75 mm above (top) and below (bottom) the “home” position.

As the platform reaches the outermost limits of the z-axis, according to Figure I.12, there is less space for the platform to move horizontally on the x-y plane. It also can be noted that areas of higher condition numbers are “thinned out” with a few significantly small red areas. There are also red areas around the origin p located 75 mm above the “home” position.

Since the results at 75 mm above and below suggests the areas of higher condition numbers reduce in size as the platform moves away from the “home” position, an analysis was conducted at 19 mm above and below the starting position. Figure I.12 correlates with the observation that the higher condition number areas reduce in size moving away from the starting position. The figure also shows the reduction in the size of the horizontal workspace. The graph at the top slightly reduces in size while still resembling a shield and the bottom graph starts to take the form of Figure I.10 and the bottom graph of Figure I.11.

Figure I.13: Condition number results using the color scheme in table 2, 19 mm above (top) and below (bottom).

While there is a clear pattern above and below the “home” position of the platform, there is significant difference between the condition analysis at the starting height and the analyses above and below. A 3D depiction of “slices” that are close to the starting position was created to see if there is a quick change that is not noticed at the z positions chosen in

the above results. Figure I.14 shows that there is no gradual change between the similar

results of Figure I.10,

Figure I.11,

Figure I.12, Figure I.13 and the result of Figure I.8. It is unclear for the reason of this. The large amount of higher condition numbers at the “home” position suggests that the current design should not be used at that height.

Figure I.14: Condition analysis with increasing z value up to the “home” position from below.

I.3 Results with Orientation

Additional work was completed following the work of [36] on “mapping” singularities within the workspace involving translation at a given height of the top platform. This additional work included singularities with respect to the orientation of the SG platform. Two scenarios were tested using a normalization of the Jacobian matrix. These scenarios included moments about the origin point of the top plate reference frame, and the second included moments about the center point or the intersection point of axes 3 and 4 on Figure I.15. Note that these are just used as reference and as test specimens to test that the 66.1 Tiger can apply the loading conditions set by requirements 18-18.4. The moments about the axes of the specimen were done to simulate a pure bending scenario.

Type 1

Type 2

Figure I.15: Specimen designs used for analysis and testing.

Figure I.16 shows the results of the second scenario and the top of Figure I.17 shows the results of the pure bending scenario. The axes represent the angle of the platform relative to the x-axis for θ and the y-axis for ϕ using a common rotation matrix.

Figure I.16: Results from moments about the specimen.

Figure I.17: Results for orientation of rotation about “home” position (top) and the results with greater distance between data points (bottom).

A different process was used to normalize the Jacobian than that of the previous work. The condition number was found for each Jacobian at each point within the “slice” of the workspace. The largest and smallest condition number were found, and their respective Jacobians were set as the maximum and minimum Jacobians. From there the Jacobian was normalized and new Jacobians were found for each point following a calculation of the

condition number. To be consistent the color code scheme consists of the values in Table I.3, which is the same as the work in [36].

It must be noted that while there are significant points that are cyan, not all cyan values indicate singularities, it may just indicate an elevated level of uncontrollability within the area. Also, one data point in the plot in Figure I.17 does result in a condition number of infinity. This point is at values of $\theta = -37.6$ and $\phi = -0.2$ at a specific SG platform geometry. There may be more singularities within these “slices” as the distance between data points affects the results.

These maps of the controllability of a specific geometry of a SG platform were used as a basis for choosing an ideal geometry. Iterations of geometry were compared until results showed all green, but only for the translation portion of [36] as the work for Figure I.16 and Figure I.17 was done after the final design. Figure I.16 shows higher values of condition numbers but rotations about the center of the top plate at the “home” position does not represent any loading scenarios that would be used for testing. It must also be noted while the “maps” were used to find an ideal geometry, it is not known how much the values of the condition number affect the controllability of the SG platform. In other words, the scale of affect is not known except for the cases in which the condition number is infinity. While the new work on singularities and controllability with respect to the orientation was completed after the final design of the test frame, this method of obtaining an optimized geometry can be used for future designs of multiaxial test frames to provide optimal designs where singularities can be avoided.