# 6-Degree of Freedom Flight Table Design

# Final Report

4/29/2019

**Sponsor**
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# Background

Acutronic supplies multi-axis motion simulators used in laboratory testing of missile seekers. The laboratory environment creates simulations of missile-to-target engagement scenarios with the actual missile seeker hardware involved in the simulations. These multi-axis motion simulators are typically 3-DOF gimballed motion systems, called flight tables. Figure 1 shows a new concept 6-DOF flight table.

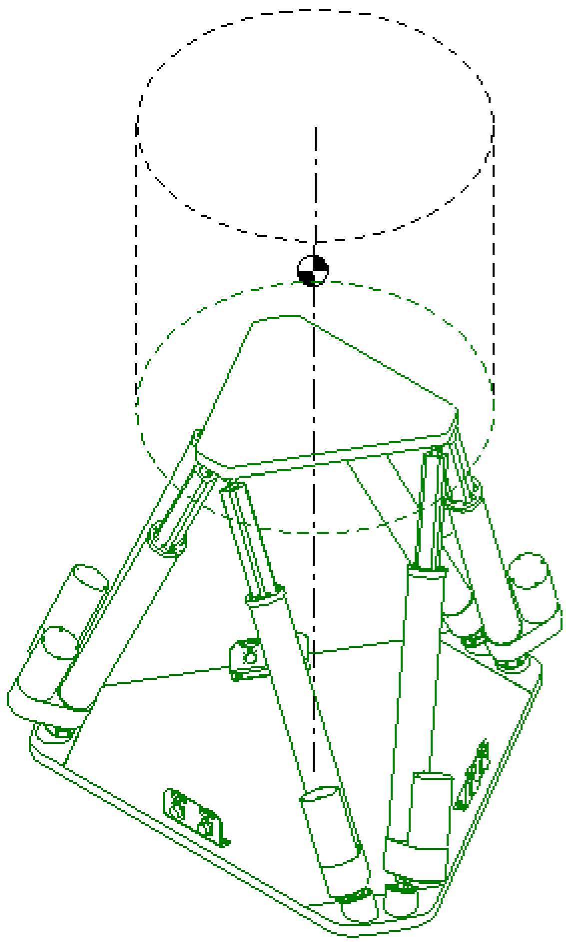

*Figure 1. New Concept Hexapod Flight Table with Six- Degrees- of- Freedom*

Six identical, linear, link actuators connect the upper and lower platforms of the hexapod. The connecting joints between the links and the platforms use U-Joints. The hexapod can provide active control in all six degrees-of-freedom.

The typical, Acutronic 3-DOF flight table configuration is shown in Figure 2.

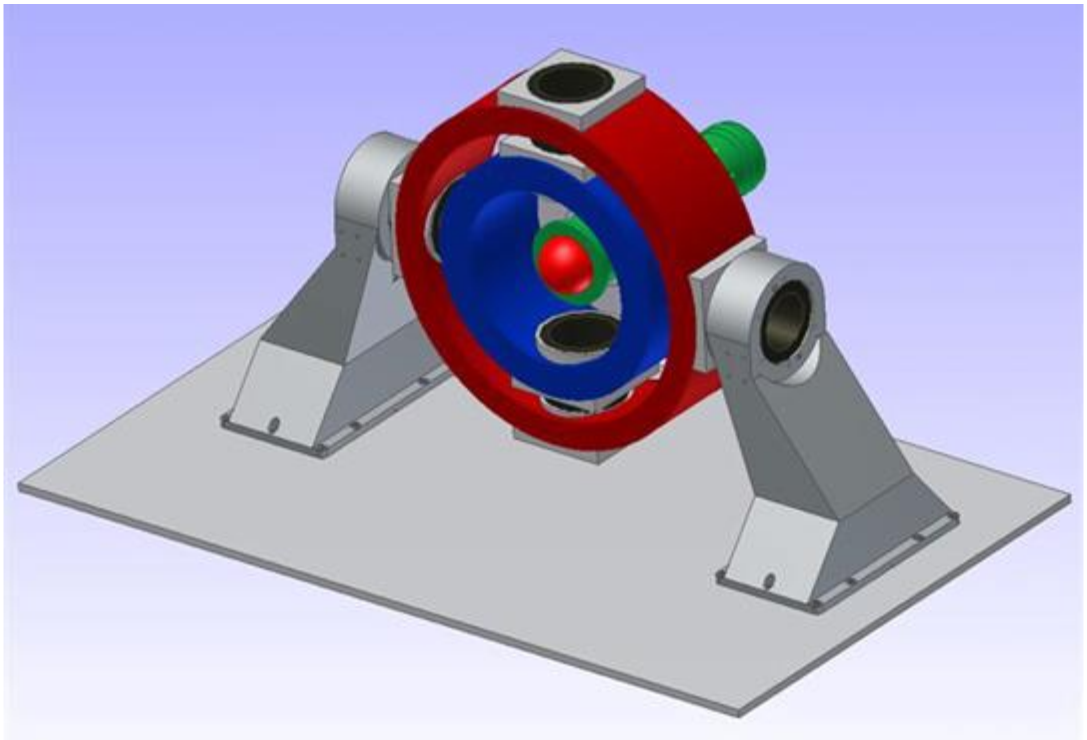

*Figure 2. Typical Three-Axis, Gimballed Flight Table Configuration with Three Angular Degrees-of-Freedom*

Acutronic constructs these flight tables with aluminum gimbals powered by hydraulic actuators. The 3-axis flight table, shown in Figure 2, contains a missile seeker attached to the inner-most gimbal (green) with the outer (red) gimbal and middle (blue) gimbal; this gimbal arrangement produces the three angular degrees of freedom: yaw, pitch and roll. One of the drawbacks of this gimbaled configuration is that the missile seeker is surrounded by metal. The metal can cause RF interference errors during a simulation with an RF missile seeker. The new 6-DOF configuration, shown in Figure 1, eliminates the potential RF interference by placing the seeker ahead of the flight table.

Acutronic wanted to continue with the concept design of the hexapod flight table. The conceptual design, performance specifications, has been completed and the structural resonances has been predicted.

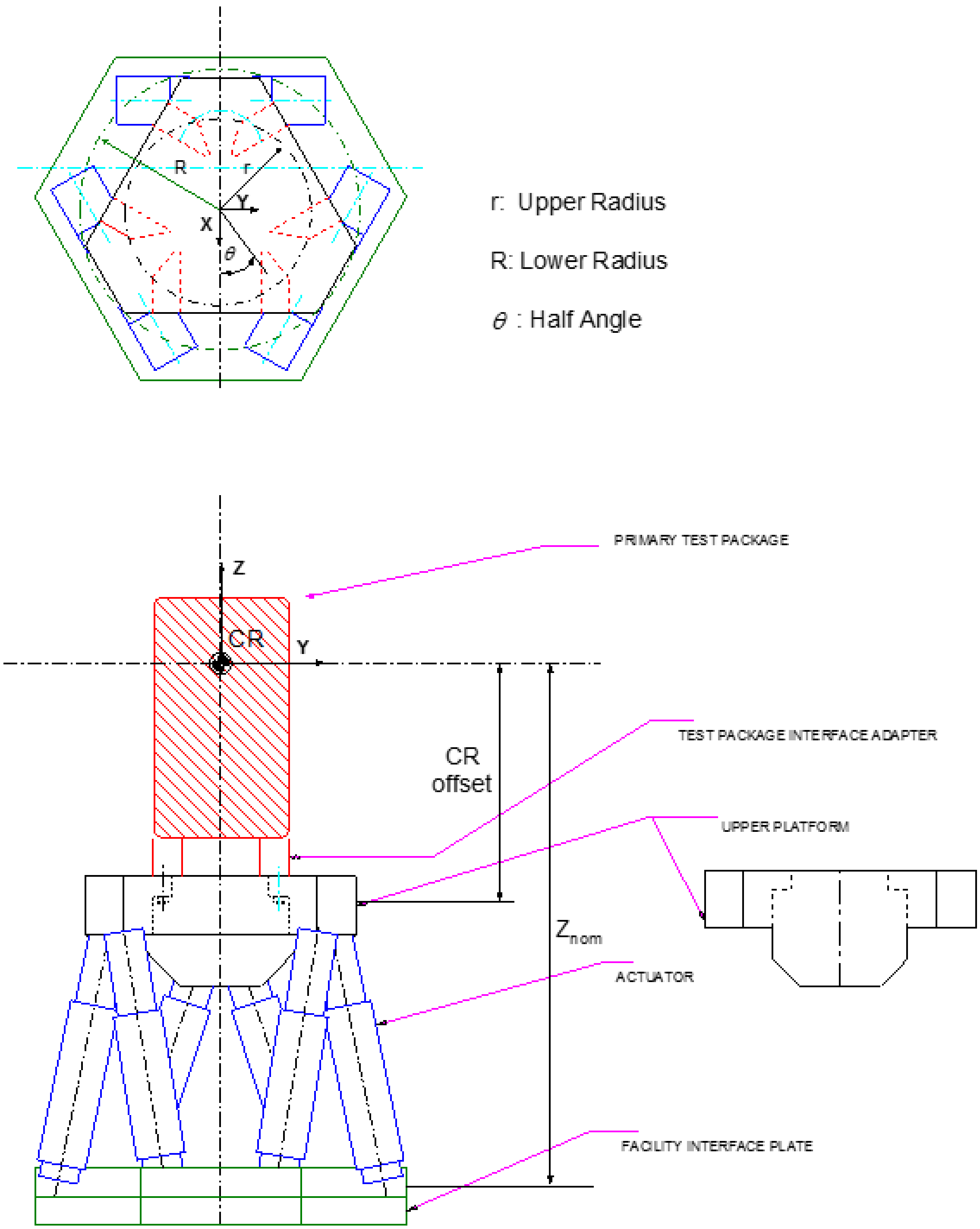


*Figure 3. General Arrangement of Hexapod Flight Table Showing Size and Interfaces*

The configuration in Figure 3 shows many of the specific parameters that define a hexapod flight table. Among these are Center of Rotation, CR offset, Upper and Lower radii, Half Angle and nominal Z distance.

Table 1 lists a set of strawman values.

*Table 1 Initial Strawman Model Parameters*

| Parameter | Inertia X and Y axis | Inertia Z axis | Mass | Znom | CR offset | Upper Radius, r | Upper half Angle,Θ | Lower Radius, R | Lower half Angle, Θ |
|---|---|---|---|---|---|---|---|---|---|
| Units | In-lb-sec2 | In-lb-sec2 | slugs | inches | inches | inches | degrees | inches | degrees |
| Value | 27 | 4.5 | 3.5 | 32 | -12 | 7.97 | 15 | 10.87 | 15 |

Mass and inertia include the test package and the upper platform. Inertia is the moment of inertia about the x,y and z axes through the center of rotation; inertia about the x and y axes is the same. Znom is the initial distance from the lower platform joint surface to the center of rotation. The CR offset is the distance from the center of rotation to the upper platform joint surface. The upper and lower radii are the distances from the platform center to the joint connections. The upper and lower half angle is the half angle subtended by the vectors from the platform center to the joint connections.

Figure 4 shows two kinematic moves of the hexapod flight table that demonstrate how the flight table can produce angular travel.

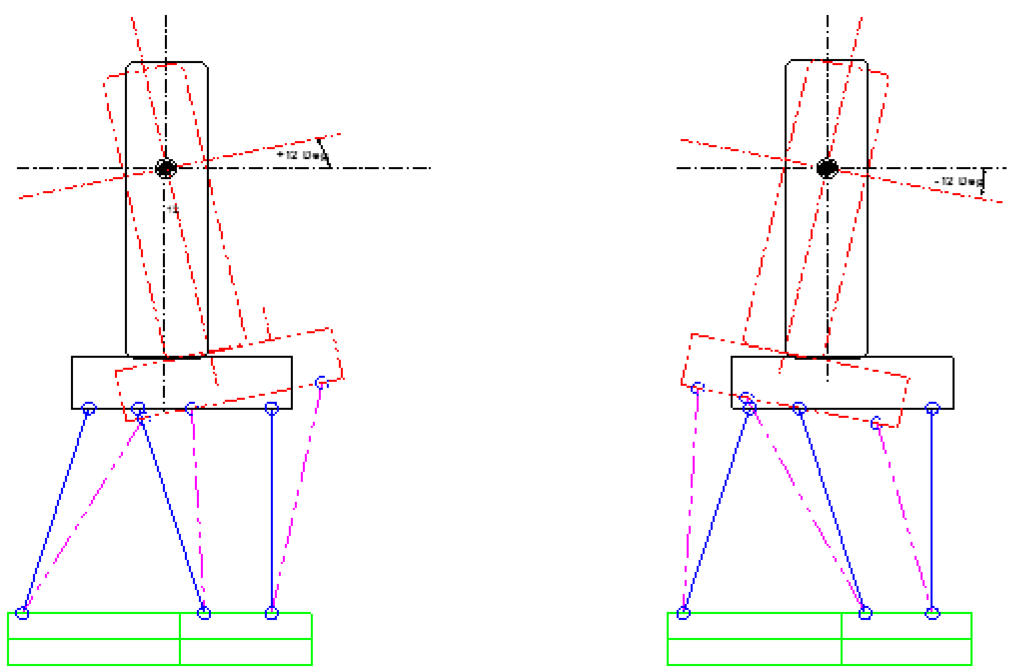


*Figure 4. Hexapod Rotation About X-Axis (Pitch) of 12 Degrees at the Test Package Center of Gravity Showing Leg Length Motions from the Nominal Position*

The figure demonstrates a pitch and/or yaw rotation about the designated center of rotation. Unlike the gimballed configuration shown in Figure 2, the center of rotation is not fixed by the mechanical design. Rather, the center of rotation is a virtual point in space that is set by the hexapod control system. During the rotation, the center of rotation, which locates the seeker's entrance hole for light known as a seeker entrance pupil, is always out in front of the metallic upper platform of the hexapod. In all such moves a practical hexapod design would limit the plus or minus leg length motions from the nominal leg lengths to about ±50% of the nominal leg lengths.

# Work

The student engineering team consists of two Mechanical Engineering students from Point Park University, Jacob Pasternak and Rakan Almughrabi, who are in their senior year. The engineering team had not taken a class in Finite Element Analysis, however they are confident in their abilities to successfully complete the proposed work. The engineering team met up during designated hours, and in their free time to work on the project. The first design of the hexapod was created in the student version of Creo Pro E provided in the University's labs. There was some difficulty modeling rod ends, so we decided to create U-Joints. Figure 5 shows the design of the static hexapod with U-Joints. We figured out that in order to create a hexapod capable of motion we needed a Creo extension software known as "Creo Parametric". We contacted the makers of Creo, Parametric Technology Corporation (PTC), in an attempt to get the program for our school's computers. However, PTC did not respond to our request and we had to download a student version on our personal computers.

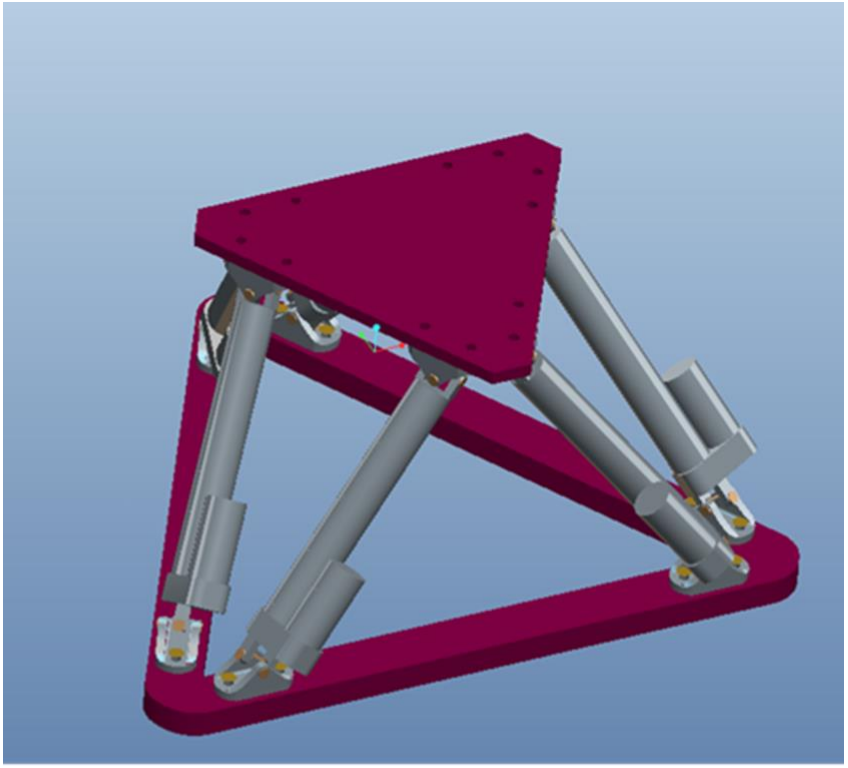

*Figure 5. First 3D design model created by engineering team*

After familiarizing ourselves with the new program, we successfully designed a hexapod with a top plate capable of 40 deg movement. The dynamic hexapod is shown in Figure 6. We experimented with modeling different joints, such as rod ends and ball joints, and figured out that U-Joints provided more desirable results. Although we missed our milestone of completing the kinematics of the hexapod, we made substantial progress towards finding the resonant frequency.

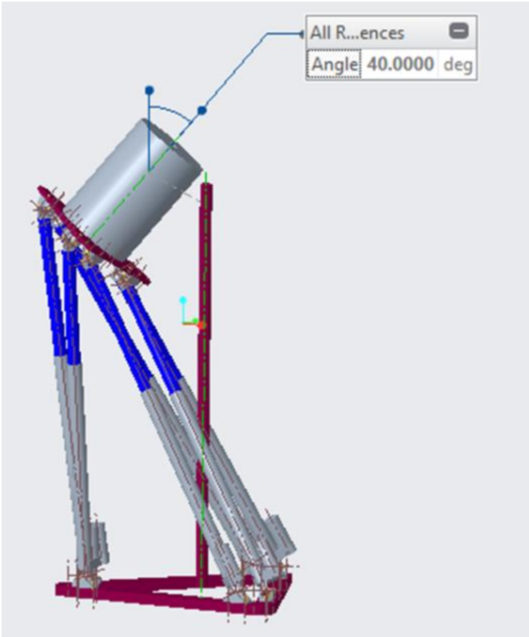

*Figure 6. Dynamic hexapod capable of 40 deg movement*

We asked the university's Finite Element Analysis instructor to aid us in using the program ANSYS 19.2 to find the resonant frequency of the hexapod. We started to test for the resonant frequency. We conducted two tests, we tested the hexapod as a whole and we tested only the top plate. We changed the material of the plate to test which material provided the best results. The materials we tested were Al6061, structural steel, stainless steel, iron, and titanium. We also tested a new design idea for the top plate. The idea should have provided better frequency results, but it only provided better results when testing the entire hexapod. The results from our frequency tests are listed under “Acceptance Testing”. We decided to continue with our snowflake design for the top plate, as it provided a higher frequency when testing the entire hexapod compared to the regular plate. We suspect that the reason for this is because the plate had a similar stiffness, however was much lighter making the hexapods overall resonance higher.

With our frequency designs completed, we began searching for an optimal set of motors and ball screws to use. We decided to use a 600W servo motor, and 24 inch length ball screws. We calculated that the actuators will be able to fully extend in 1.0 second(s). The actuators will have an accuracy of 0.00008 inch. Without reply from the motor manufacturer

Parameters for designed hexapod. We are unable to calculate the inertia of the top plate and test package because a mass(m) for the test package on its own was never given.

*Table 2. Model Parameters*

| Parameter | Inertia X and Y axis | Inertia Z axis | Mass | $Z_{nom}$ | CR offset | Upper Radius, r | Upper half Angle,Θ | Lower Radius, R | Lower half Angle, Θ |
|---|---|---|---|---|---|---|---|---|---|
| Units | In-lb-sec2 | In-lb-sec2 | slugs | inches | inches | inches | degrees | inches | degrees |
| Value | ? | ? | 0.2+m | 33 | -12 | 5.7 | 14 | 12 | 53 |

To predict the leg lengths it is necessary to use the inverse kinematics because the requirements given were set by the top plate's displacements. In other words, using inverse kinematics we were able to find the leg lengths from the top plate. We did run confirm the results using the measure tool from Creo's Parametric software to double check that the computer generated leg lengths matched. The computer generated leg lengths did not make sense when we would plug in the easiest displacement, which was movement in the z direction only. The computer generated leg displacements were consistently smaller than the z direction, which initially did not make sense, however the measure tool confirmed the answers are correct. We thought it would make sense that dZ would always be smaller than dS (which is the change in leg length), however doing simple hand calculation proved otherwise, in addition to the two programs being in agreement.

Example Calculation using computer aided software (mathcad)
For dZ=1in

| | |
|---|---|
| s(dX,d Y,dZ,dRx,dRy,dRz)=T^-1dm | (0.97,<br>0.97,<br>0.97,<br>0.97,<br>0.97,<br>0.97,)in |

Using Creo measure tool, moving the top plate up one inch, we measured the same result of 0.9662 which rounds up to 0.97 in.

Using the formulas we were able to solve for leg lengths at nominal height (z=33in), and for required motion.

*Table 3. Leg Length Predictions*

| Range | ±12deg | ±20deg | ±40deg |
|---|---|---|---|
| S1in | 1.314 | 2.19 | 4.379 |
| S2in | -1.314 | -2.19 | -4.379 |
| S3in | -1.819 | -3.032 | -6.064 |
| S4in | -0.505 | -0.842 | -1.685 |
| S5in | 0.505 | 0.842 | 1.685 |
| S6in | 1.819 | 3.032 | 6.064 |

# Acceptance Testing

Data from changing only the material of the top plate (3/4 inch plate thickness)

*Note hexapod's material is structural steel, leg lengths are at the mid leg lengths

| Modes | Structrual Steel | Titanum Alloy | Aluminium Alloy | Gray Cast Iron | Stainless Steel | |
|---|---|---|---|---|---|---|
| 1 | 73.313 Hz | 69.698 Hz | 68.877 Hz | 69.189 Hz | 73.072 Hz | |
| 2 | 73.974 Hz | 70.473 Hz | 69.697 Hz | 69.919 Hz | 73.739 Hz | |
| 3 | 113.96 Hz | 110.24 Hz | 108.67 Hz | 110.45 Hz | 113.78 Hz | <-Torsional Frequency |
| 4 | 157.97 Hz | 154.85 Hz | 153.1 Hz | 155.2 Hz | 157.85 Hz | |
| 5 | 158.3 Hz | 156.34 Hz | 155.45 Hz | 156.72 Hz | 158.2 Hz | |
| 6 | 158.96 Hz | 156.82 Hz | 155.88 Hz | 157.21 Hz | 158.85 Hz | |
| 7 | 161.32 Hz | 160.68 Hz | 160.33 Hz | 160.81 Hz | 161.3 Hz | |
| 8 | 161.89 Hz | 161.22 Hz | 160.84 Hz | 161.34 Hz | 161.86 Hz | |
| 9 | 162.39 Hz | 161.84 Hz | 161.56 Hz | 161.96 Hz | 162.37 Hz | |
| 10 | 162.73 Hz | 162.21 Hz | 161.94 Hz | 162.33 Hz | 162.71 Hz | |

*Figure 7. ¾ in normal plate (testing full hexapod)*

Data from changing only the material of the top plate (3/4 inch plate thickness with snowflake)

*Note hexapod's material is structural steel, leg lengths are at the mid leg lengths

| Modes | Structrual Steel | Titanum Alloy | Aluminium Alloy | Gray Cast Iron | Stainless Steel | |
|---|---|---|---|---|---|---|
| 1 | 69.539 | 70.804 | 71.702 | 69.12 | 69.563 | |
| 2 | 70.329 | 71.425 | 72.137 | 70.248 | 70.354 | |
| 3 | 112.13 | 113.46 | 114.84 | 110.69 | 112.12 | <-Torsional Frequency |
| 4 | 156.52 | 156.67 | 156.77 | 144.42 | 156.45 | |
| 5 | 157.47 | 157.89 | 158.61 | 148.34 | 157.37 | |
| 6 | 158.01 | 158.68 | 159.55 | 156.85 | 157.86 | |
| 7 | 160.95 | 160.97 | 160.99 | 159.32 | 160.94 | |
| 8 | 161.43 | 161.44 | 161.44 | 160.26 | 161.43 | |
| 9 | 162.14 | 162.16 | 162.18 | 161.02 | 162.12 | |
| 10 | 162.5 | 162.5 | 162.5 | 161.45 | 162.36 | |

*Figure 8. ¾ in snowflake design (testing full hexapod)*

| Data from hexapod's plate testing, the top plate only. (3/4 inch plate) | | | | | | |
|---|---|---|---|---|---|---|
| | 3/4 inch plate | | | | | |
| Modes | Structrual Steel | Titanum Alloy | Aluminium Alloy | Gray Cast Iron | Stainless Steel | |
| 1 | 1638.4 | 1495.1 | 1651.3 | 1265.1 | 1622.3 | |
| 2 | 1701.5 | 1542.8 | 1709.5 | 1316.6 | 1683 | |
| 3 | 1723.3 | 1563.6 | 1732 | 1333.2 | 1704.8 | |
| 4 | 2511.7 | 2267.5 | 2518 | 1946.3 | 2482.6 | <- Torsional Frequency |
| 5 | 2587.2 | 2339.5 | 2596.1 | 2003.4 | 2558.1 | |
| 6 | 2598.6 | 2350.1 | 2607.7 | 2012.2 | 2569.4 | |
| 7 | 3946.9 | 3557.1 | 3953.6 | 3060 | 3900.2 | |
| 8 | 4335.6 | 3922.7 | 4351.8 | 3356.4 | 4287.3 | |
| 9 | 4347.6 | 3938 | 4366.2 | 3364.5 | 4299.9 | |
| 10 | 4363.3 | 3952.3 | 4381.1 | 3377.9 | 4314.9 | |

*Figure 9. ¾ in normal plate (testing only top plate)*

| Data from hexapod's plate testing, the top plate only. (3/4 inch plate with partial snowflake) | | | | | | |
|---|---|---|---|---|---|---|
| | 3/4 inch plate with partial snowflake | | | | | |
| Modes | Structrual Steel | Titanum Alloy | Aluminium Alloy | Gray Cast Iron | Stainless Steel | |
| 1 | 1606.2 Hz | 1457.7 Hz | 1614.5 Hz | 1242.4 Hz | 1589 Hz | |
| 2 | 1738.9 Hz | 1576.2 Hz | 1746.8 Hz | 1345.6 Hz | 1719.9 Hz | |
| 3 | 1740 Hz | 1577.2 Hz | 1747.9 Hz | 1346.6 Hz | 1721 Hz | |
| 4 | 2490.2 Hz | 2252.1 Hz | 2498.6 Hz | 1928.6 Hz | 2462.1 Hz | <- Torsional Frequency |
| 5 | 2567.9 Hz | 2322.1 Hz | 2576.7 Hz | 1988.5 Hz | 2539 Hz | |
| 6 | 2569.2 Hz | 2323.3 Hz | 2578 Hz | 1989.5 Hz | 2540.3 Hz | |
| 7 | 3669.1 Hz | 3302.5 Hz | 3673.2 Hz | 2845.5 Hz | 3625.1 Hz | |
| 8 | 4245.6 Hz | 3845.2 Hz | 4263 Hz | 3286.5 Hz | 4198.7 Hz | |
| 9 | 4249.4 Hz | 3849 Hz | 4267 Hz | 3289.3 Hz | 4202.5 Hz | |
| 10 | 4314.3 Hz | 3903.3 Hz | 4329.8 Hz | 3340.6 Hz | 4265.9 Hz | |

*Figure 10. ¾ in snowflake design (testing only top plate)*

*Kinematics were double checked in an open source inverse kinematics solver (example motion: dRy=40deg)*

$$\begin{bmatrix} dX \\ dY \\ dZ \\ dRx \\ dRy \\ dRz \end{bmatrix} = T \cdot \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{bmatrix}$$

$$T = \begin{pmatrix} 1.762086 & -1.762086 & 0.612663 & 2.374748 & -2.374748 & -0.612663 \\ -1.724782 & -1.724782 & 2.388402 & -0.66362 & -0.66362 & 2.388402 \\ 0.171784 & 0.171784 & 0.171784 & 0.171784 & 0.171784 & 0.171784 \\ -2.568073 & -2.568073 & 1.744356 & 0.823717 & 0.823717 & 1.744356 \\ -0.531531 & 0.531531 & -1.958251 & -2.489782 & 2.489782 & 1.958251 \\ 5.251349 & -5.251349 & 5.251349 & -5.251349 & 5.251349 & -5.251349 \end{pmatrix}$$

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \\ s_5 \\ s_6 \end{bmatrix} = T^{-1} \cdot \begin{bmatrix} dX \\ dY \\ dZ \\ dRx \\ dRy \\ dRz \end{bmatrix}$$

$$T^{-1} = \begin{pmatrix} 0.237232 & 0.049101 & 0.970211 & -0.162777 & 0.159331 & 0.031738 \\ -0.237232 & 0.049101 & 0.970211 & -0.162777 & -0.159331 & -0.031738 \\ -0.161139 & 0.180898 & 0.970211 & -0.056596 & -0.220634 & 0.031738 \\ 0.076093 & -0.229999 & 0.970211 & 0.219373 & -0.061303 & -0.031738 \\ -0.076093 & -0.229999 & 0.970211 & 0.219373 & 0.061303 & 0.031738 \\ 0.161139 & 0.180898 & 0.970211 & -0.056596 & 0.220634 & -0.031738 \end{pmatrix}$$

<u>Actuator displacements for example motion</u>

$$s(dX, dY, dZ, dRx, dRy, dRz) = \begin{pmatrix} 4.379 \\ -4.379 \\ -6.064 \\ -1.685 \\ 1.685 \\ 6.064 \end{pmatrix} \text{in}$$

# Project Hardware and Software Deliverables

The engineering team did not have enough time to complete the scale model of the hexapod flight table.

# Product Documentation Deliverables

The engineering project team will deliver a final report, presenting the results, analyses, acceptance testings, budget, deliverables and the conclusion of the project. The final report will contain; the predicted leg range of travel for yaw/pitch maneuvers, the predicted lowest torsional resonant frequency, and a set of design and performance specifications.

The engineering team will also provide a set of drawings on a USB drive. The USB will contain; 3-D top level drawings, layout, assembly drawings, and parts list.

# Budget and Timeline

The engineering project team did not produce a scale model of the hexapod as intended due to a lack of time. The project team spent the majority of the time solving the Finite Element Analysis. The team expected to spend the majority of the time on the FEA, as neither of the team members had taken FEA yet. The second most time consuming resource was modeling the parts in a CAD software. There were some indecision on what joints to use, which costed more time than we expected.

# Conclusion

The engineering project team successfully achieved their goals for the project. The lowest torsional resonant frequency requirement was met, the nominal leg length and leg length changes were also calculated. The team provided schematics for their parts, along with a parts list, and provided a three dimensional CAD drawing of the hexapod. Although it was an optional goal, the engineering team did not have enough time to produce a scale model of hexapod. Other issues due to the time constraint include; being able to complete a more indepth stress analysis, more research on motors, more designs tested specifically for FEA, and a more finished model overall. We believe that our work has a strong foundation, and realistically requires polishing before we would consider it a product ready to sell to customers. The polishing work we are referring to are things like motor efficiency, wire routing, and additional parts such as a 360 degree turntable, and of course real world testing and prototypes.

# Appendices

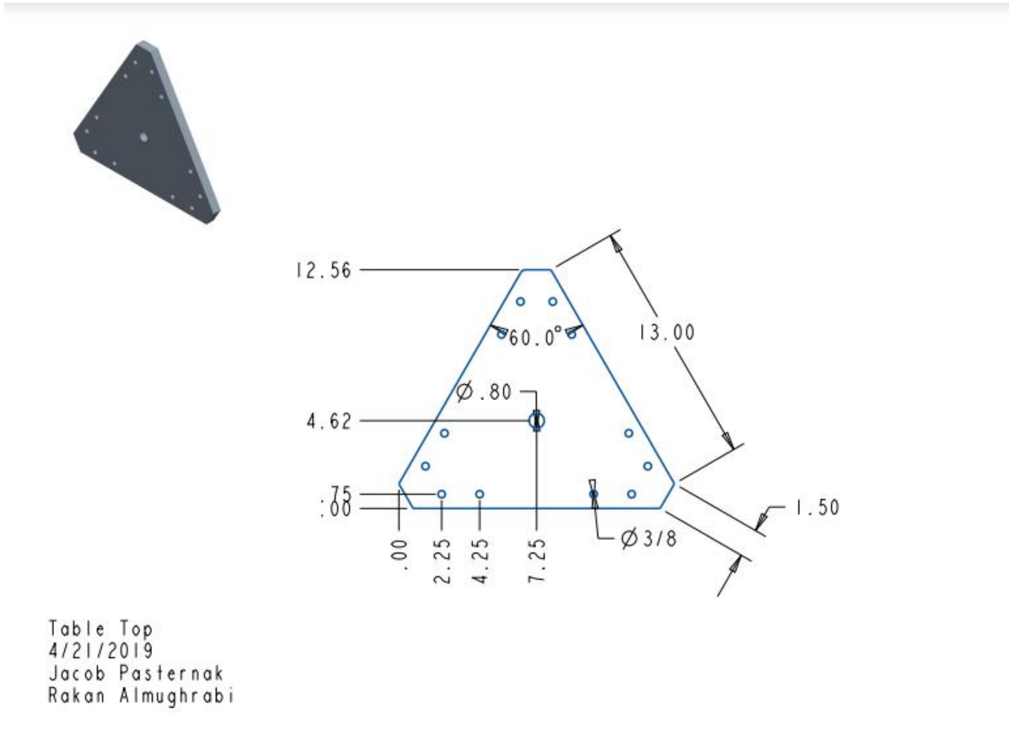
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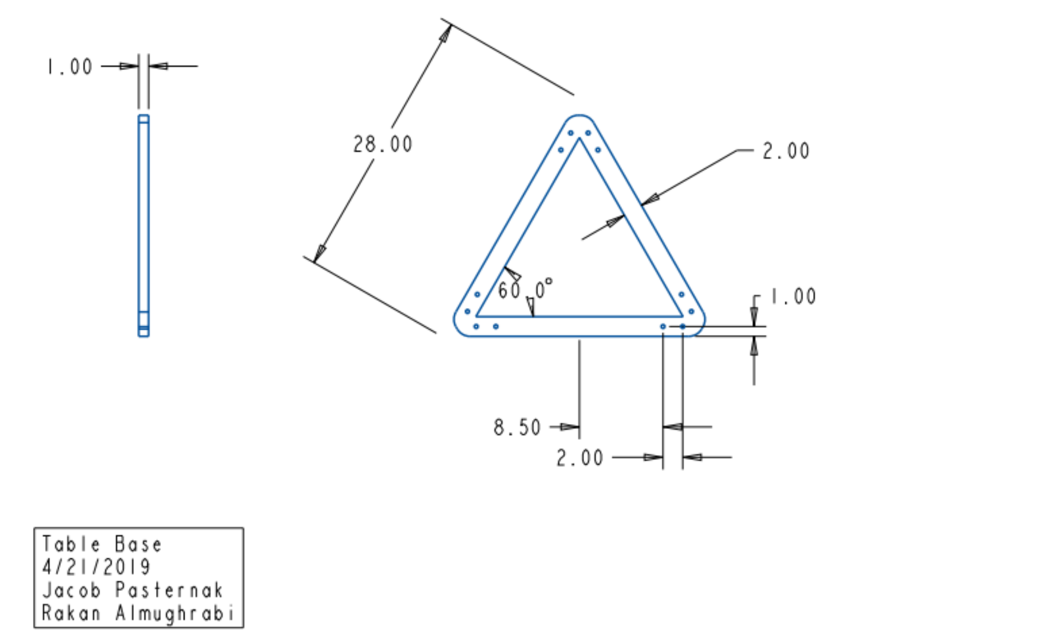
Table Top
4/21/2019
Jacob Pasternak
Rakan Almughrabi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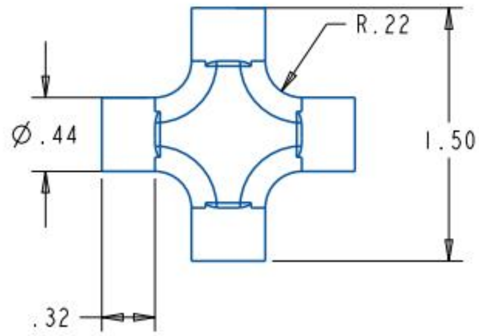


U-Joint
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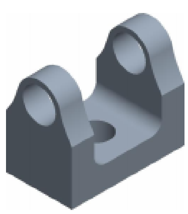

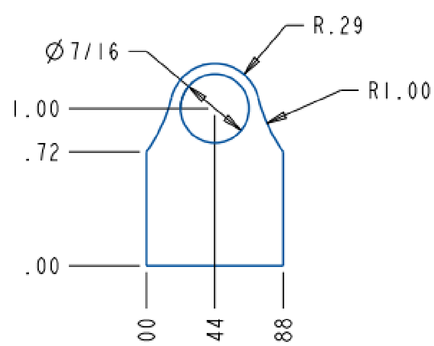


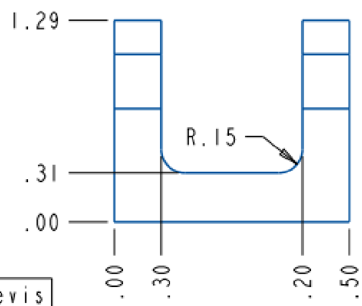


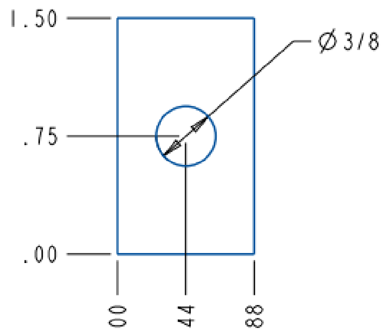


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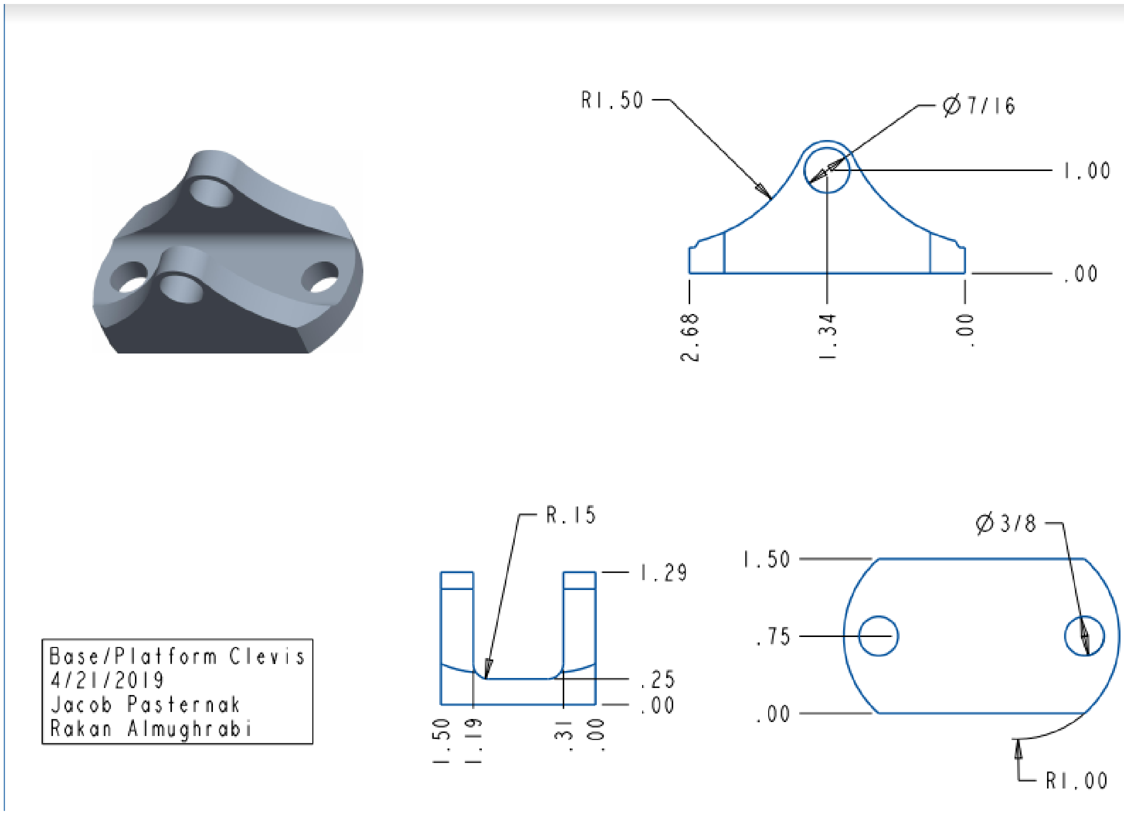
Rakan Almughrab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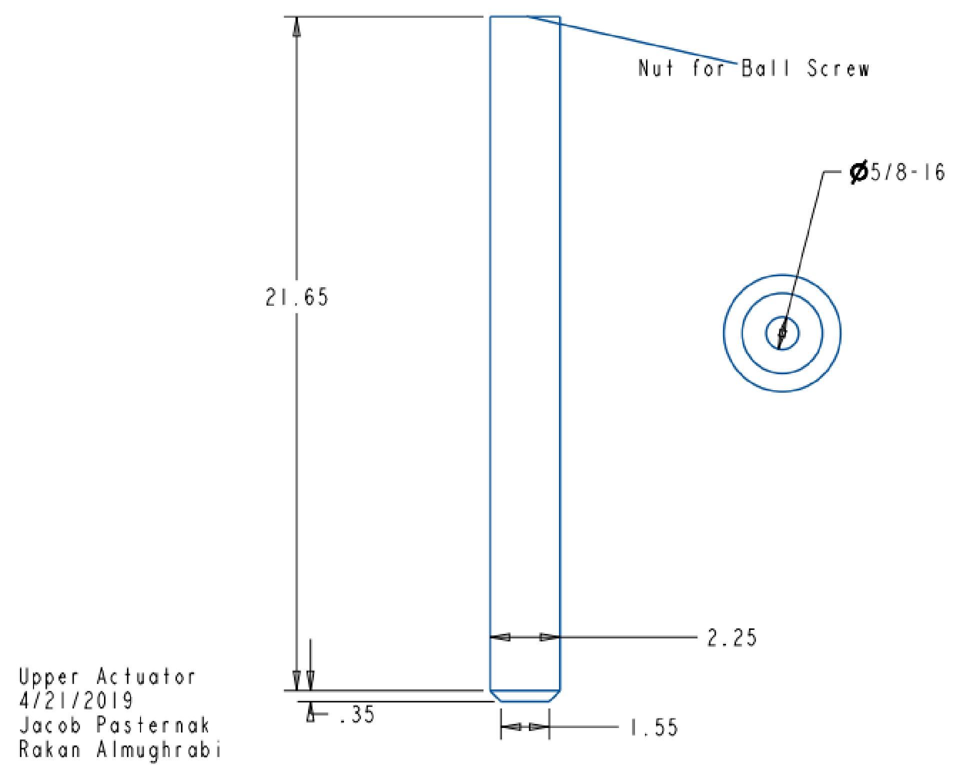
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4/21/2019
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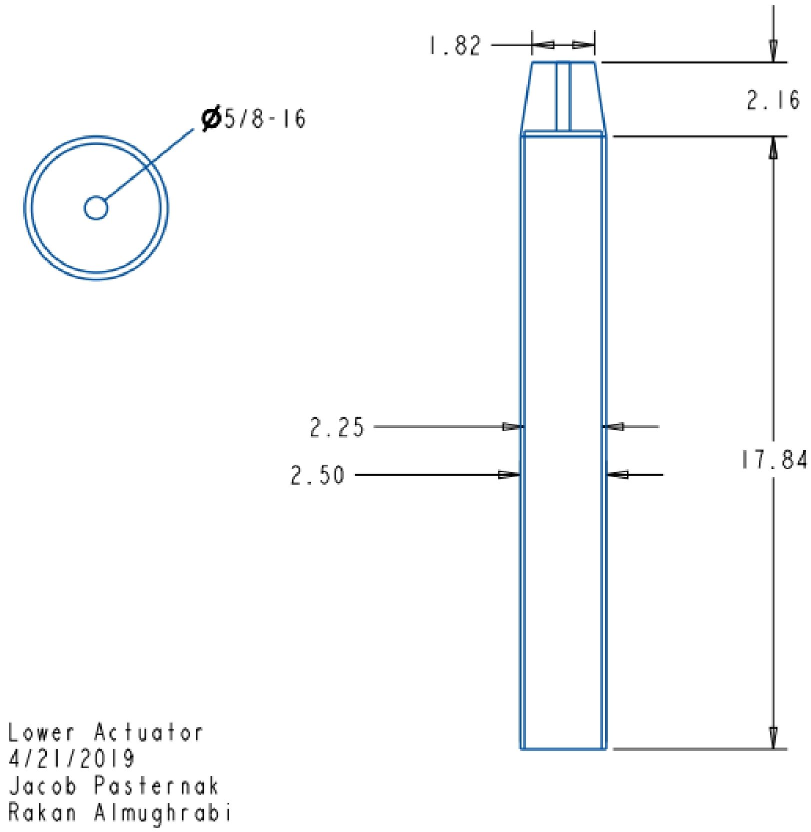
Rakan Almughrabi




PART LIST:

6x Linear Actuators
6x 600W 3000RPM High Torque AC Servo Motor
6x 24 In Length, Steel Ball Screw, 0.631 In Dia
6x Ball Nut, designed for Ball Screw
1x ¾ In Alu-6061 Snowflake Design Top Plate
1x Bottom Plate
12x U-Joints
36x ⅜ - 16x1½ Screws

*Table 4. Performance*

| | Pitch(Y) | Roll(X) | Yaw(Z) |
|---|---|---|---|
| Ang range | ±40Deg | ±40Deg | ±90deg |
| Repeatability | ± | ± | ± |
| Max rate | 24deg/s | 24deg/sec | |
| Linear range | ±25in | ±25in | ±5in |
| Repeatability | ± | ± | ± |
| Max rate | ±7in /sec | ±7in /sec | ±10in /sec |