Individual Component Analysis

# Linkage Arm

Anteater Dynamics – 7DOF Robotic Arm

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## Project Overview and Component Justification

Anteater Dynamics is working with industry sponsor ROBOTIS to develop a 7 degree of freedom (DOF) robotic arm to be used for machine learning data collection and by at home robotics enthusiasts. The arm is to use Robotis' proprietary Dynamixel-X servos motors for actuation, and will have a completed bill of materials of roughly $1000. The arm should be easy to assemble, and any parts that are not purchased like the servos or Robotis' frames used to join the servos should be able to be both injection molded or 3D-printed, making the project open source for robotics enthusiasts.

The robotic arm is a mechanical linkage with a total of 6 servos and 3 links. The Linkage Arms are the connection from one servo to another in the linkage, and as such, are subject to dynamic loads imposing both torsional and bending stresses on the linkage arms. To ensure proper functionality, the Linkage Arms must be strong enough to resist these forces. As such, various cross sections of these linkage arms are to be analyzed using finite element analysis (FEA) simulations allowing the optimal cross section to be determined for the application. Cross sections to be analyzed include typical engineering beam cross-sections (I/H-beam, hollow/solid rectangular, hollow/solid tubular, channels, etc), along with a few other atypical cross sections.

Beam cross sections, in general, have different advantages and disadvantages depending on the application. The two main types of stresses the linkage arms will be exposed to are bending moments and torsion. A beam's resistance to bending moments is related to the amount of cross-sectional area of the beam and its location from the cross section's neutral axis - the axis in the cross section of a beam (a member resisting bending) along which there are no longitudinal stresses or strains. More mass concentrated further from the neutral axis increases the beams resistance to bending and as such, H and I beams are often used in situation where bending stresses are present. However, H and I beams are typically much stronger when a force is applied in one direction than another, so they are typically used in static scenarios where the load directions are not changing directions, as they will in the robotic arm. A beam's resistance to torsional stresses is related more to the actual geometry of the beam. Typically, shapes that have a closed cross section, such as a tube, pipe, or rectangle, are more resistant to bending than those that do not, such as the I and H beam.

For the application in the 7-degree-of-freedom robotic arm, these types of stresses both need to be accounted for. In general, bending stresses will be more common in this application, especially in the first linkage arm, as the linkage arm must resist bending from the mass of any object lifted and the weight of all the links that follow it. The servos themselves will also provide significant amounts of torque to the linkage arms, meaning that resistance to torsion is also desirable. Several different shapes will be analyzed to ultimately decide on the final linkage arm shape. It is important to also ensure that the shape of these linkage arms should be easily manufactured, via both 3D-printing and injection molding. The goal of this analysis is to find the linkage arm cross section that best resists bending and torsional deformation, accounting for ease of assembly and total material usage. The results of the engineering analysis will be analyzed in a decision matrix to dictate which cross section best suits the application.

## Linkage Functional Requirements

FRB-1: The arm linkage shall provide the reach to pick objects at a distance of 500 mm away

FRB-2: The servos in the arm linkage shall support the load of 400 g at the end effector

FRB-3 The arm linkage shall articulate to move around obstructions

## Analysis Methodology

For testing, the same forces were applied in a static FEA simulation to six different beam cross sections. The Linkage Arm was modeled as solid acrylonitrile butadiene styrene (ABS) as the method of manufacturing desired by the project sponsor is injection molded ABS. A 16 Newton force was applied across the faces shown in figures 1 and 2 with the bottom face of the linkage arm fixed.

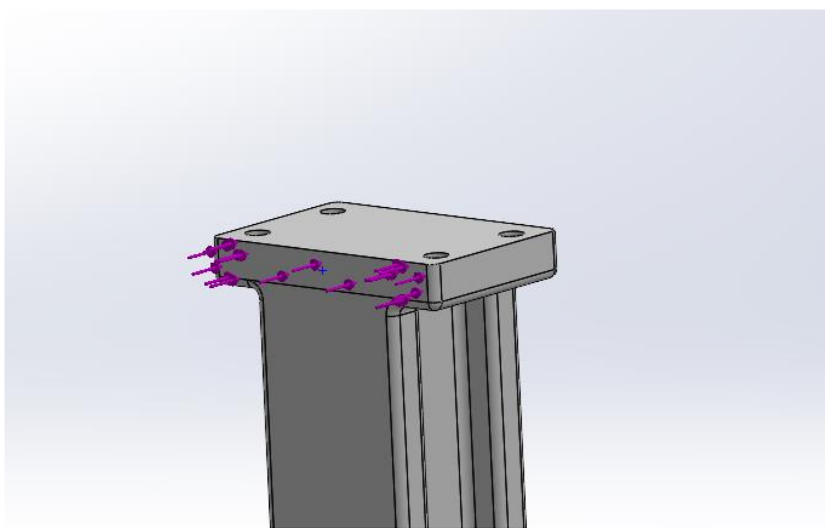


*Figure 1 Force Application Location*

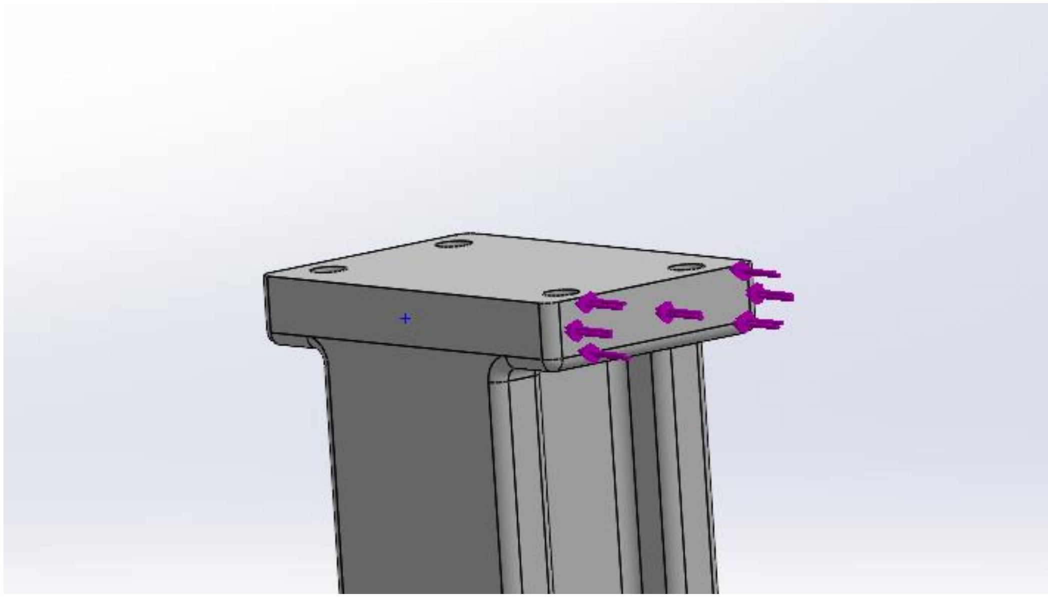


*Figure 2 Force Application Location*

The 16 N force was chosen as the weight of the entire linkage that exists beyond the first linkage arm (see figure 2) arms is roughly 0.400 kg, as estimated from the CAD model of the linkage.

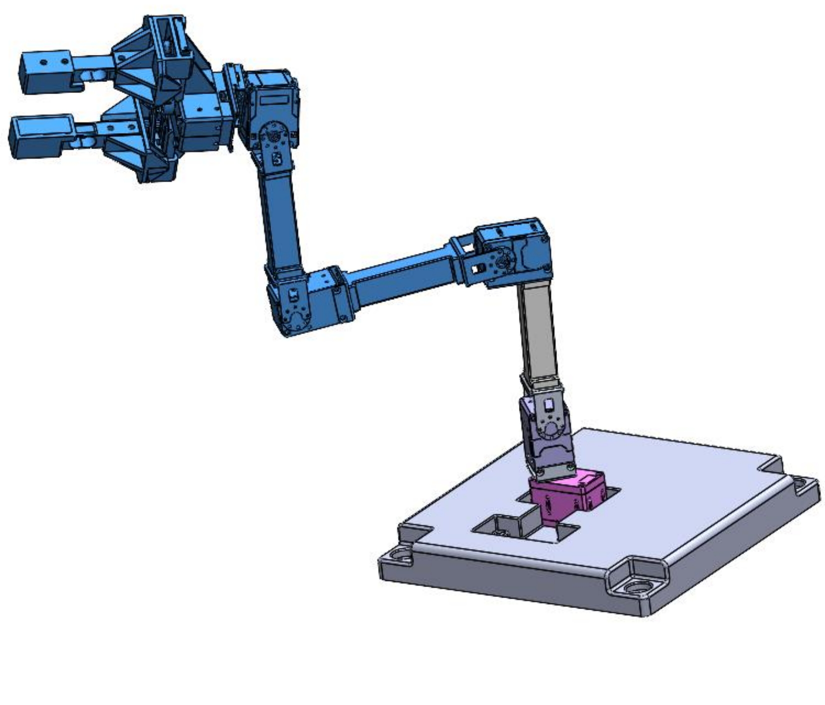


*Figure 3 Linkage Beyond First Linkage Arm*

Adding a 400 g object that can be grasped by the end effector, the resulting total mass is 0.800 kg. The weight of this entire portion of the arm would then be 0.850kg*9.8m/s$^2$ = 7.84 N. Multiplying by a safety factor of 2 arrives at a 15.68 N force, which was then rounded to 16 N to represent a worst-case bending scenario experienced by the first linkage arm. The force was applied over the shown surfaces as opposed to a point force as when initial simulation was completed the highest deformation point of the component occurred locally at the point of application, not providing characteristic results for the simulation.

For torsional analysis the largest torsional force that will be applied to the first linkage will come from the inertial forces stopping the rotation of the entire arm. To simulate this force, it is assumed that the arm is spinning at 20 RPM at the base, and then decelerates to 0 RPM over a quarter of a second, resulting in an angular acceleration of $-8\pi/3$ rad/s$^2$ or -480 deg/s$^2$. Using the relationship between torque, moment of inertia, and angular acceleration we can arrive at a reasonable torque to be applied for this simulation. Principal moment of inertia about center of mass of the arm remaining after the first linkage (see figure 4) was calculated in SolidWorks to be Pz = 8327341.62 g*mm$^2$. Using the parallel axis theorem to translate this moment of inertia around the centroid to the axis of rotation for the arm ($I=I_o+Md^2$), located roughly 270mm from the linkage centroid, we arrive at the moment of inertia of this remaining portion of the linkage about its axis of rotation of ~37487341 g*mm$^2$ = 0.0375 kg*m$^2$ (see figures 4 and 5 for reference).

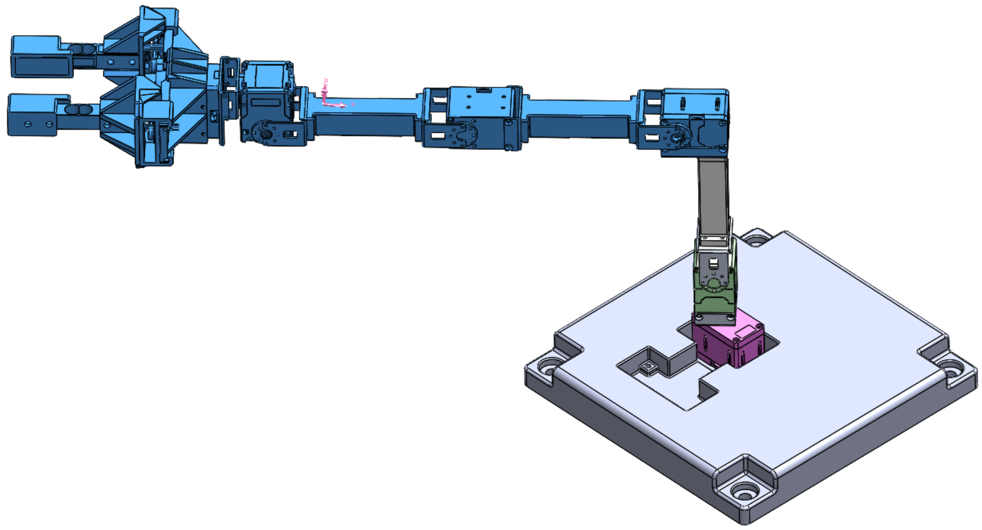


*Figure 4 Center of Mass of Remaining Linkage*

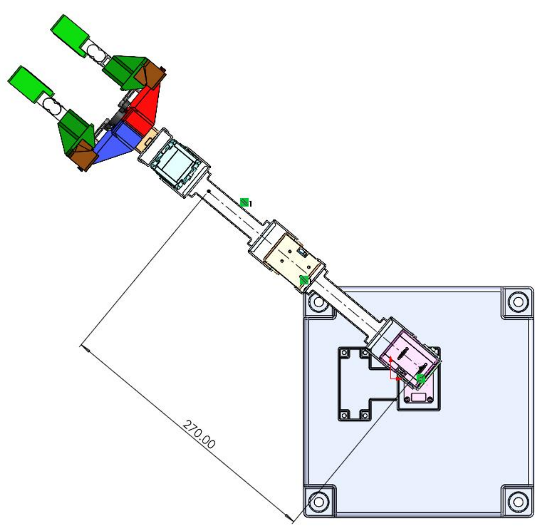



*Figure 5 Distance Between Center of Mass of Arm Portion and Rotation Axis*

Since $T=I*\alpha$ from the values calculated above, we arrive at a torque of $T = 0.0375*(8\pi/3) = 0.157$ Nm. To include a factor of safety, and for simplicity, torsional simulation was done with a 1 Nm torque applied axially, centered on the top face of the beam (see figure 6 for reference).

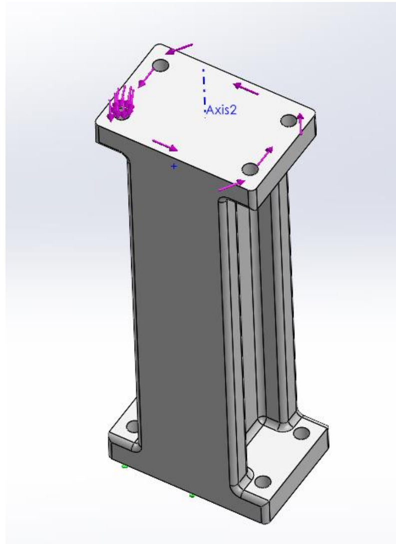



*Figure 6 Point of Application of 1Nm Torque*

Three FEA simulations are to be conducted on each beam cross section: two with 16 N forces on the two major faces of the beam inducing bending moments, and one with the 1 Nm torque applied to the top face of the beam. Results are to be analyzed based on the maximum displacement in each of these three simulations. Results for each of the FEA simulations will then be compared to deciding the final cross-sectional area for the linkage arm. Results for these three simulations for a rectangular cross sectioned beam are shown in figures 7, 8, and 9 below.

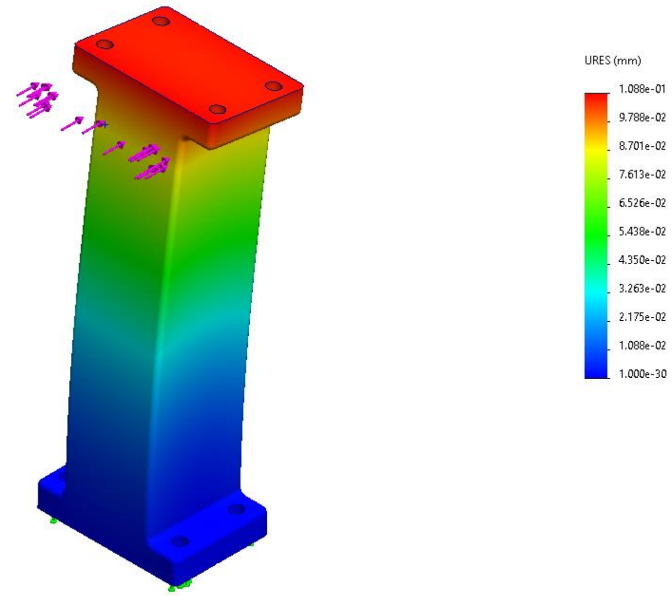



*Figure 7 Face 1 FEA Result*

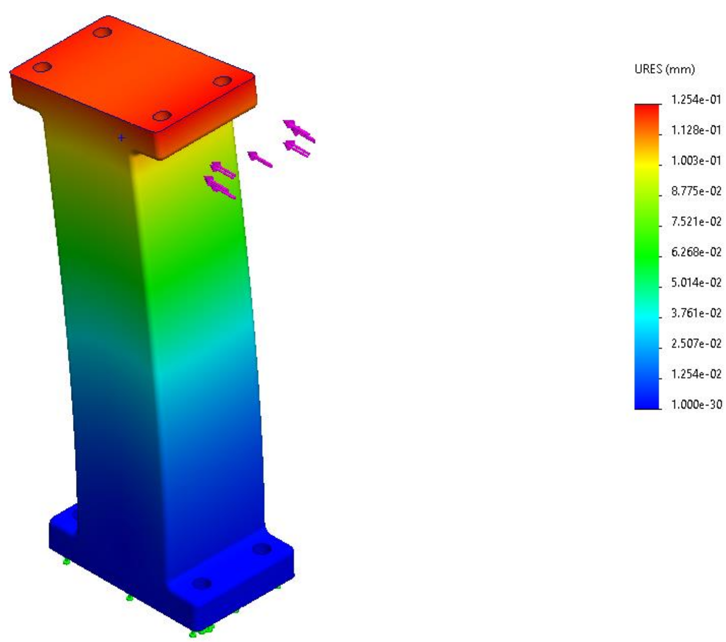



*Figure 8 Face 2 FEA Result*

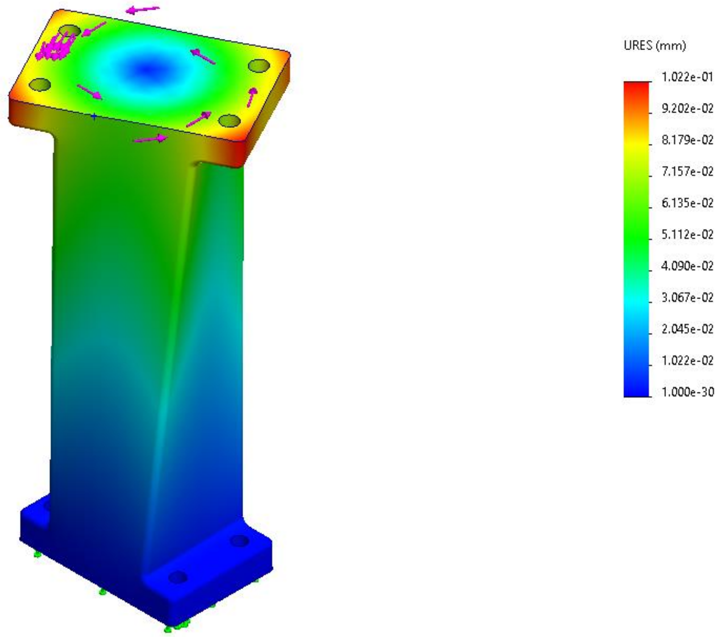



*Figure 9 Torsional FEA Results*

## Results and Analysis

Six different beam cross-sections were analyzed. The selected beam cross sections are shown in table 1 below.

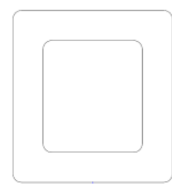
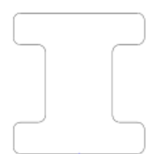
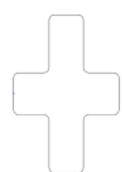
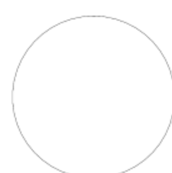
| Beam Cross Section | |
|---|---|
| **Rectangle** |  |
| **Hollow Rectangle** |  |
| **H/I Beam** |  |
| **Plus** |  |
| **Cylinder** |  |
| **Tube** |  |

*Table 1 Beam Cross Sections*

Table 2 below summarizes the results of the FEA simulations

| Beam Cross Section | Total Cross Sectional Area (mm^2) | Max Displacement Face 1 (mm) | Max Displacement Face 2 (mm) | Max Displacement Torsion (mm) |
|---|---|---|---|---|
| **Rectangle** | 369.14 | 0.108758 | 0.125352 | 0.102243 |
| **Hollow Rectangle** | 220.50 | 0.141146 | 0.158717 | 0.119934 |
| **H/I Beam** | 270.14 | 0.123223 | 0.236985 | 0.299817 |
| **Plus** | 302.14 | 0.223128 | 0.092971 | 0.274458 |
| **Cylinder** | 314.16 | 0.163073 | 0.162685 | 0.123071 |
| **Tube** | 201.50 | 0.194030 | 0.193307 | 0.136744 |

*Table 2 FEA Simulation Results*

The table shows the maximum displacements caused by the loads described in the previous section. Ideally, this test would have been able to be conducted with cross sections of the same total area but differing shapes. This was not possible as the linkage arm shape is constrained by the mounting holes on ROBOTIS frames.

To decide on a final linkage shape, a weighted decision matrix is used to consider additional factors beyond just the simulation results. Bending resistance, quantified by max displacement on face one and face two are weighed the highest, at 25% each. Next torsional resistance, quantified by maximum displacement in the torsional test, is important, but not to the same level as bending and as such is weighted at 20%. To consider cost, total cross-sectional area is included in the decision matrix, weighing 10%. Since the part is to be additively manufactured, all the cross sections are similar in terms of tooling and manufacturing processes. Therefore, the cost of the part can be quantified simply by the amount of material necessary to manufacture it – a larger cross-sectional area requires more material. Finally, ease of assembly is considered as the final factor of the decision matrix. Ease of assembly is related to how simple routing cables around these various cross sections will be to allow for connection of the servo motors. Hollow cross sections make cable routes easy, as they provide a channel for cables to run through, removing the need for any external cable routing clips or other solutions. Proper cable routing solutions significantly decreases the risk of cables between servos snapping or getting disconnected, and as such, this category is weighed relatively heavily at 20%. The resulting decision matrix is shown below.

| **Rating 1 - 6** | | | **Bending Face 1** | **Bending Face 2** | **Torsion** | **Total Cross Section** | **Ease of Assembly** | ***SCORES*** |
|---|---|---|---|---|---|---|---|---|
| | | **Category Weight** | **25.00%** | **25.00%** | **20.00%** | **10.00%** | **20.00%** | **100.00%** |
| **Cross Section** | **Rectangle** | **Rating** | 6 | 5 | 6 | 1 | 2 | 4 |
| | | **Weighted Score** | 25% | 21% | 20% | 2% | 7% | 74% |
| | **Hollow Rectangle** | **Rating** | 4 | 4 | 5 | 5 | 5 | 4.6 |
| | | **Weighted Score** | 17% | 17% | 17% | 8% | 17% | 75% |
| | **H/I Beam** | **Rating** | 5 | 1 | 1 | 4 | 3 | 2.8 |
| | | **Weighted Score** | 21% | 4% | 3% | 7% | 10% | 45% |
| | **Plus** | **Rating** | 1 | 6 | 2 | 3 | 4 | 3.2 |
| | | **Weighted Score** | 4% | 25% | 7% | 5% | 13% | 54% |
| | **Cylinder** | **Rating** | 3 | 3 | 4 | 2 | 1 | 2.6 |
| | | **Weighted Score** | 13% | 13% | 13% | 3% | 3% | 45% |
| | **Tube** | **Rating** | 2 | 2 | 3 | 6 | 6 | 3.8 |
| | | **Weighted Score** | 8% | 8% | 10% | 10% | 20% | 57% |

*Table 3 Weighted Decision Matrix*

Based on the weighted decision matrix and FEA results, the final cross section of the beam will be hollow rectangular. Looking at the results outlined in Table 1, we can see that in this case the beam that performed best is the rectangular beam, but when considering other factors like ease of assembly and total cross section, the hollow rectangular beam is the best choice. See Appendix A for an engineering drawing that fully specifies the final shape of the Linkage Arm.

## References

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*ASME Y14 | Y14 Standards - ASME*. https://www.asme.org/codes-standards/y14-standards. Accessed 26 Feb. 2025.

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Liang, Zoe. *Benefits of Different Steel Sections | SkyCiv Engineering*. 17 May 2019, https://skyciv.com/technical/benefits-of-different-steel-sections/.

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# Appendix A – CAD Drawing of Final Beam