Project OpaNoid: A modular, variable form humanoid platform

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***Abstract*-**This paper describes a 3D-printed robotics platform (Fig. 1) which is capable of greatly varying its form and mass distribution within the confines of the humanoid form. It owes these abilities to its modularity and bespoke rail mounting system, which will be further explored below.

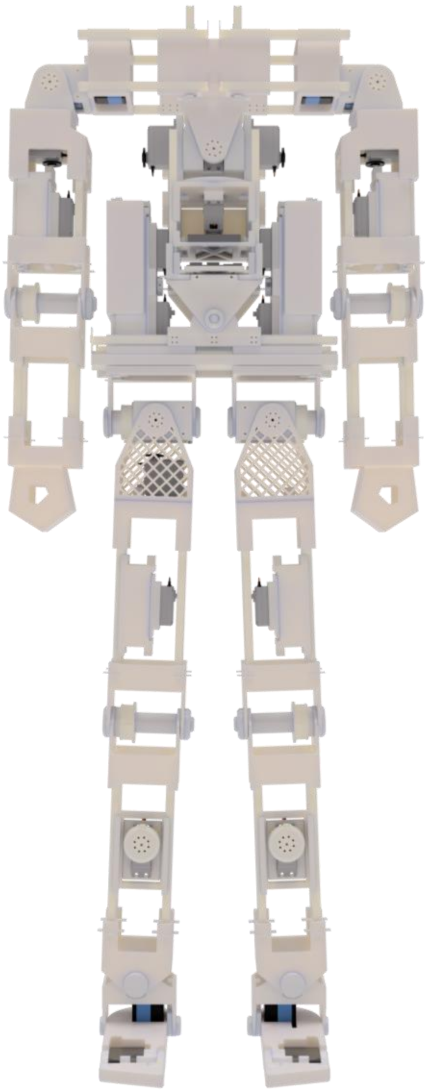


Fig. 1: Project OpaNoid

I. INTRODUCTION

Although modular humanoid robots exist, they are largely incapable of significant changes in form and mass distribution without the addition or replacement of parts. Project OpaNoid's frame is designed from the outset to be modified using only a hex-head screwdriver; no additional parts beyond those that already exist on the robot are required. In addition, the parts are engineered for fused-deposition modeling (FDM) printing, making OpaNoid accessible to even amateur roboticists.

II. RESULTS

<u>Variable mass distribution</u>

OpaNoid's mass distribution can be adjusted by varying the position of modules containing servos, electronics or other functionality of the user's choice within its frame. The potential of this system is illustrated below.

The moments about a thigh of ≈ 25cm length can increase by up to ≈ 55% due to a shift in internal mass (Fig. 2).

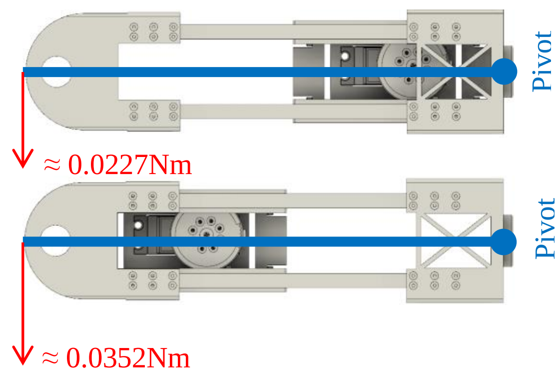


Fig. 2: Change in mass distribution caused by repositioning of servo module

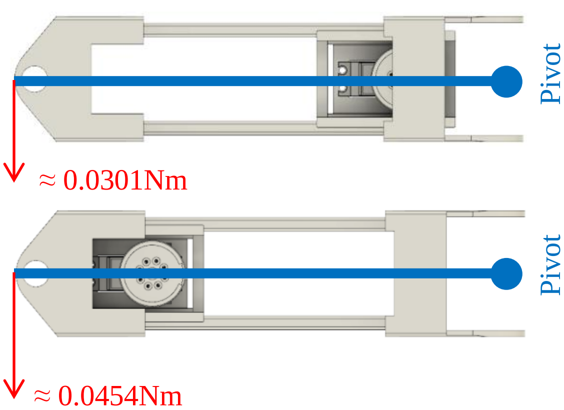


Fig. 3: Change in mass distribution caused by repositioning of servo module

Meanwhile, the moments about a calf ≈ 29cm in length increases by up to ≈ 50.8% due to a shift in internal mass (Fig. 3).

Dimensional variability

OpaNoid's dimensions can be altered by changing the positions of key brackets such as knees, ankles etc. The designs of the brackets involved allow for significant changes in dimensions without impairment of function, while using the same set of rails.

The calves are designed for changes in length of up to ≈ 77mm (Fig. 4).

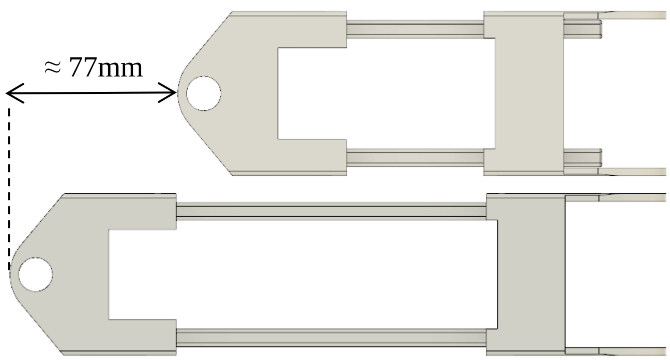


Fig. 4: Dimensional variability of calf

The thighs are designed for changes in length of up to ≈ 70mm (Fig. 5).

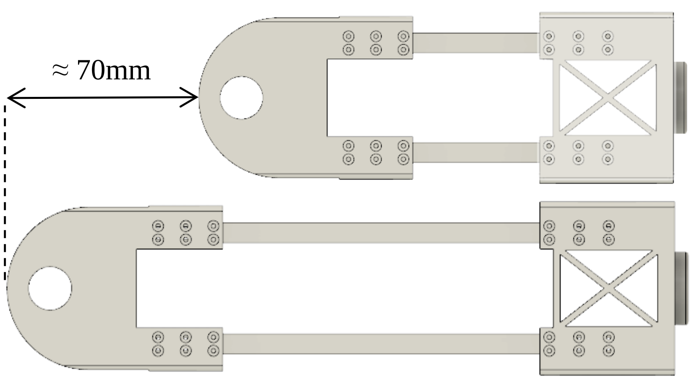


Fig. 5: Dimensional variability of thigh

Arm length can be varied by around 66.5mm (Fig. 6), and shoulder width can be varied by around 130mm (Fig. 7).

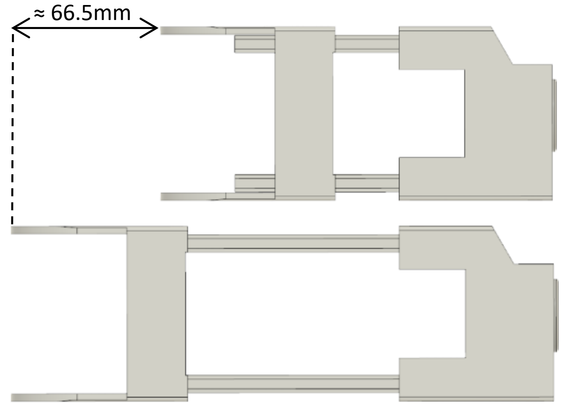


Fig. 6: Dimensional variability of arm

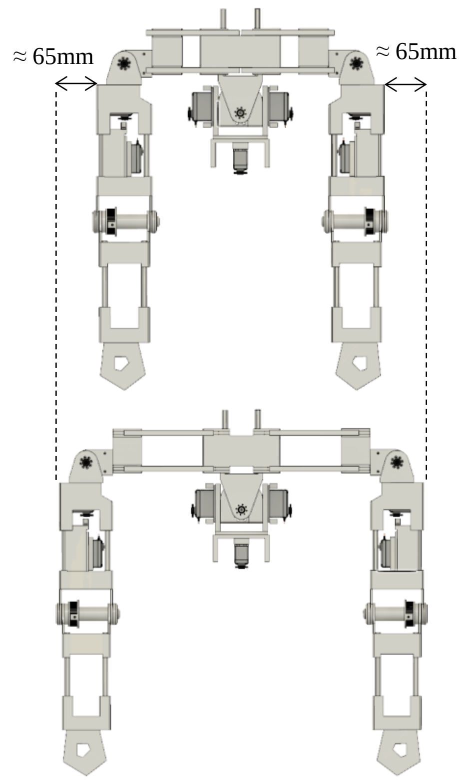


Fig. 7: Dimensional variability of shoulders

III. DISCUSSION

An aspect of the platform's design which could have been pushed even further is the module system. A greater percentage of servos could have been incorporated into the system, enabling even greater control over the robot's mass distribution and increased torque expandability.

IV. MATERIALS AND METHODS

Rail mounting system

The basis of OpaNoid's adjustability is its rail mounting system. OpaRail is designed to mount objects on two sides, and has a relatively thick central spine which enhances its multi-directional rigidity (Fig. 8).

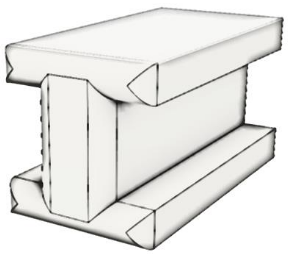


Fig. 8: Final rail design

The key design aims for OpaRail are rigidity, simplicity (for 3D printing), mounting ability, and low density (the frame would thus occupy a smaller percentage of overall mass, allowing for greater authority in mass distribution control through the movement of modules around the frame).

The inherent rigidity of the rail can also be augmented organically through the mounting of modules to the frame, or artificially through specialized reinforcing brackets (Fig. 9).

Besides enabling dimensional variability, the rail system also allows electronic components to be mounted onto the structure at highly variable locations, modifying the robot's mass distribution.

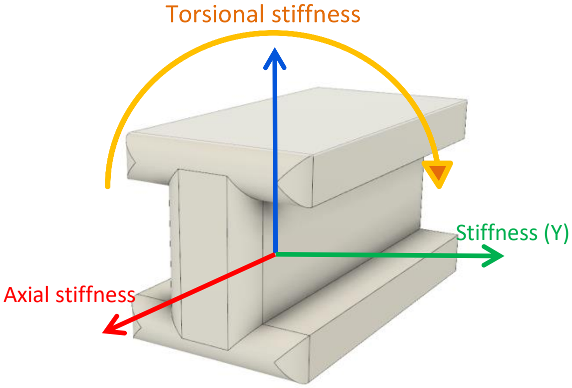


Fig. 11: 4 axes of stiffness

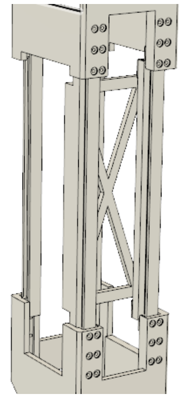


Fig. 9: Reinforcing bracket mounted to frame

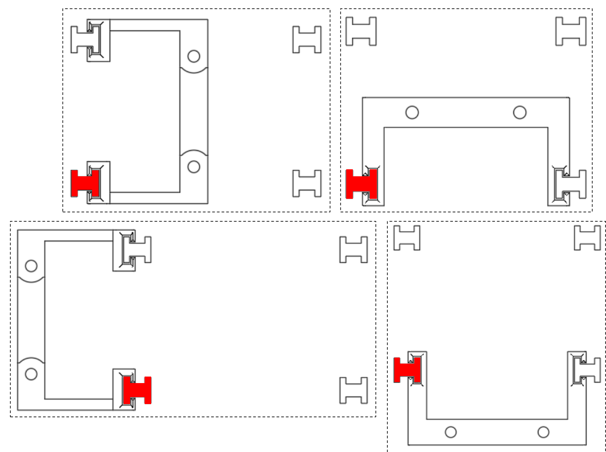


Fig. 10: Quad-directional mounting about a single rail (highlighted in red)

3 different rail profiles were considered based on their rigidity, mounting ability (comprising number of items that can be mounted and the robustness of the mount) (Table 1). Finite element analyses (see Appendix A) were conducted to determine the stiffness of the rails along 4 axes (Fig. 11) and the robustness of their mounting systems (Fig. 12).

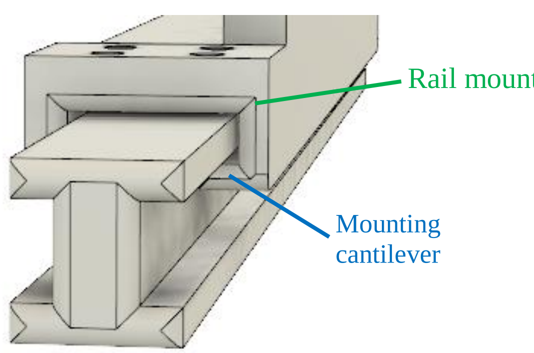


Fig. 12: Rail mount

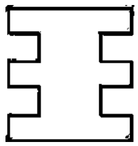
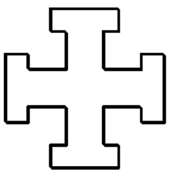
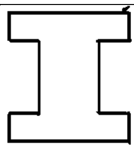
No.	Rail profile	L x H (mm)	Density, assuming PLA material (g/cm)	Print duration /mm (min) (5s.f.)	No. of possible mounts	Stiffness of 150mm rail, assuming ABS material (5s.f.)				Stiffness of mounting cantilever (Nmm^{-1}) (5.s.f.)
						Torsional ($Nrad^{-1}$)	Y (Nmm^{-1})	Z (Nmm^{-1})	Axial (Nmm^{-1})	
1		7.5x8	0.566 (1.76678)	0.77333	2	716.20	223.51	290.70	7023.5	4595.6
2		8x8	0.466 (2.14592)	0.89333	4	286.48	146.37	146.37	5393.7	3684.6
3		7.5x8	0.533 (1.87617)	0.66333	2	716.20	199.60	323.62	6432.5	4725.9

Table 1: Comparison of rail profiles

The results were then normalised and used in the computation of a weighted average. The justifications for the weights are as follows:

- Density was given a high weightage as low mass is a priority
- Print duration was given a high weightage as the print duration of the rails constitutes a significant proportion of total print time
- The number of possible mounts per rail was given a lower weightage as it was found that a 2-sided rail would still enable mountings on 4 sides if 4 rails are arranged in parallel to form the structure of a component (Fig. 10).
- Torsional stiffness was given a low weightage due to their lower significance in a parallel 4-rail setup (Fig. 10).
- As can be seen, certain values were weighted unexpectedly low due to the realization that rails would most often be arranged in arrays of at least 4 parallel rails in practice, while single-rail use cases would be scarce.
- Y and Z stiffness were given high weightages due to their relevance even in a parallel 4-rail setup, and the relative fragility of the rails along these axes.
- Axial stiffness was given a very low weightage as all 3 rail types were found to be extremely robust along the axial plane, rendering differences in axial stiffness within the same order of magnitude imperceptible in practice.
- The stiffness of mounting cantilever (Fig. 12) was given a relatively high weightage as it affects how well critical components such as servos are secured to the frame, where even slight movements could have implications on the dynamics of the robot's motion

Parameter	Weight
$Density^{-1}$	0.19
Print $duration^{-1}$	0.2
Mount no.	0.05
Torsional	0.05
Y	0.2
Z	0.2
Axial	0.01
Stiffness of mounting cantilever	0.1

Table 2: Weights used in computation of weighted average

Data normalization									
No.	$Density^{-1}$	Print $duration^{-1}$	No. of possible mounts	Torsional	Y	Z	Axial	Stiffness of mounting cantilever	Weighted average
1	82.3	85.7	50	100	100	89.8	100	97.2	89.0
2	100	74.3	100	40	65.5	45.2	76.8	78.0	74.6
3	87.4	100	50	100	89.3	100	91.6	100	92.9

Table 3: Normalised rail profile data

The weighted average of profile 3 was found to be the highest, and it was thus selected as the main rail design for Project OpaNoid.

Module system

Actuators comprise a large percentage of the mass of most robots. Consequently, it was essential for OpaNoid to be capable of varying the position of its servos if it was to be capable of controlling its mass distribution to a significant degree.

The module system allows servos to actuate joints through a belt drive, removing the need for the servo shaft to be aligned with the axis of rotation of the joints. This enables servos to be positioned almost anywhere along the limbs that they actuate.

Consequently, “adjustable internal mass", or the mass that can be repositioned without compromising the robot's dimensions or function, comprises approximately 28% of the basic platform's mass (the percentage differs based on the length of rails used). Meanwhile, the total adjustable mass, or mass that can be repositioned if dimensional integrity is not preserved, comprises around 80% of the basic platform's mass.

Designed for FDM

- Certain parts have had a portion of their bases raised to reduce base area, and thus facilitate their removal from build plates.
- Parts are designed such that the support material required to print them is minimized.
- Most rail guides and joints/pins are designed to be printed vertically for increased accuracy.
- Tolerances are largely rather generous to accomodate printers which are incapable of high levels of refinement.
- Parts are engineered with the material limits of 3D printed PLA in mind.
- Certain parts with very small bases (such as the rails) are designed with flaps on the bottom in order to increase base area for better adhesion to build plates-these flaps can be cleanly broken off the main part without tools.
- As far as possible, parts are designed to be symmetrical along the vertical and horizontal axes in order to increase reusability.
- Parts are designed to be slab-sided with few contours to increase printing speed, with the exception of areas where contouring would be functional, such as the feet.
- The thickness of the part walls are minimised (while taking into consideration the frailties of the fabrication process and material) in order to minimise mass and print duration, such that the mass of the robot's frame constitutes as small a component of the overall mass as possible.
    - This would allow the mass distribution of the robot to be controlled with greater authority through the positioning of servos and electronics within its frame.

APPENDIX A

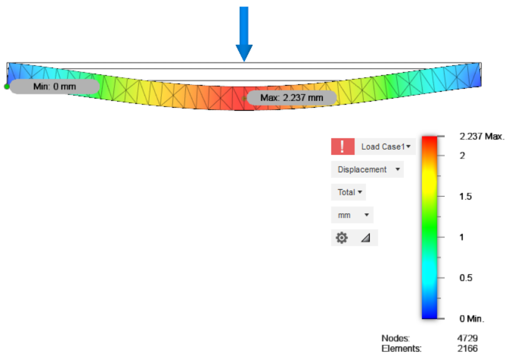


Figure A: Y-axis stiffness of rail 1

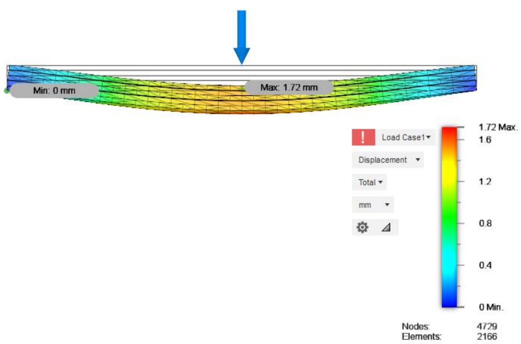


Figure B: Z-axis stiffness of rail 1

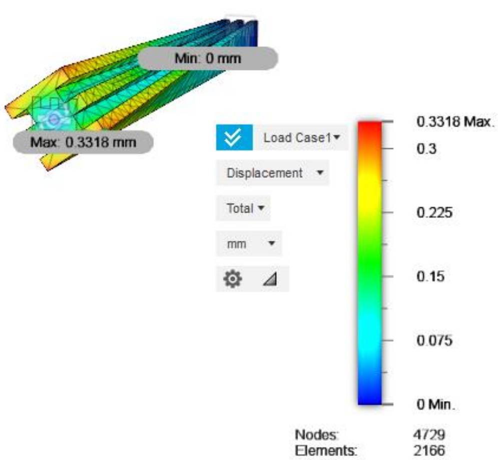


Figure C: Torsional stiffness of rail 1

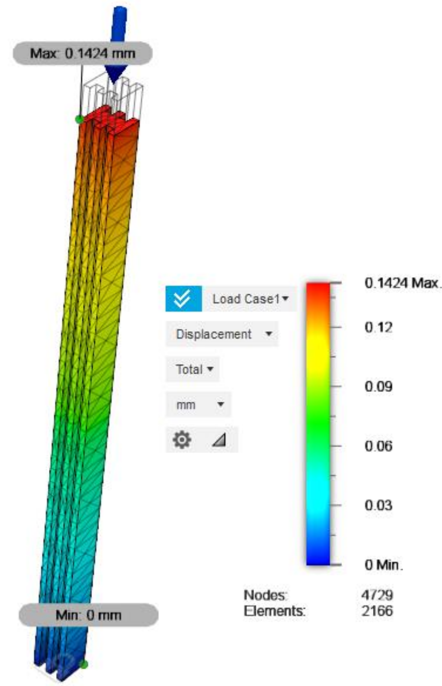


Figure D: Axial stiffness of rail 1

Figure E: YZ-axis stiffness of rail

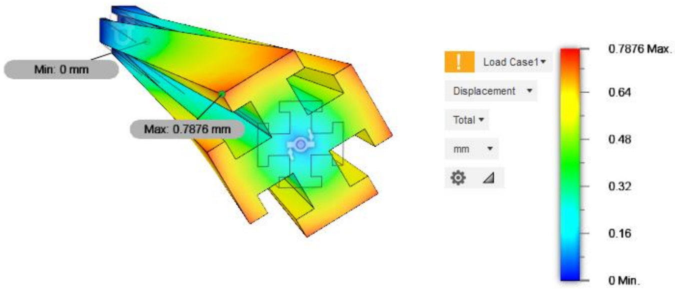


Figure F: Torsional stiffness of rail 2

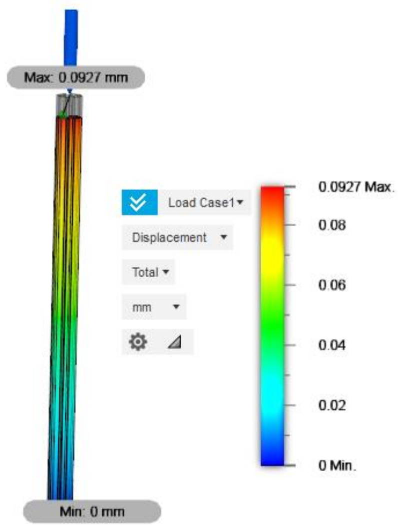


Figure G: Axial stiffness of rail 2

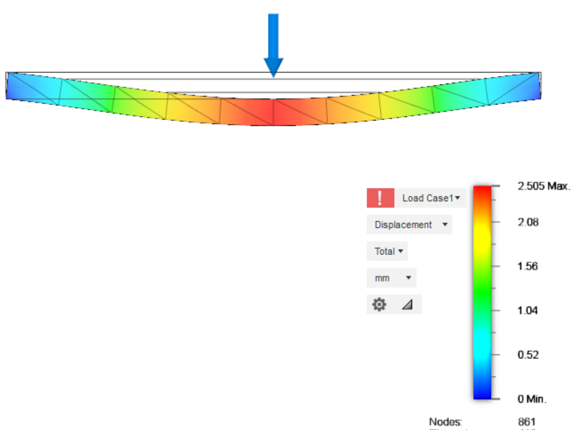


Figure H: Y-axis stiffness of rail 3

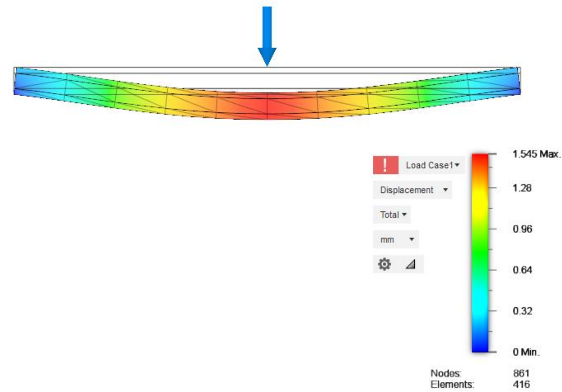


Figure I: Z-axis stiffness of rail 3

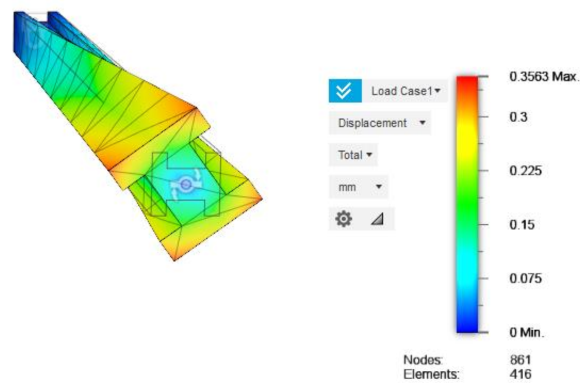


Figure J: Torsional stiffness of rail 3

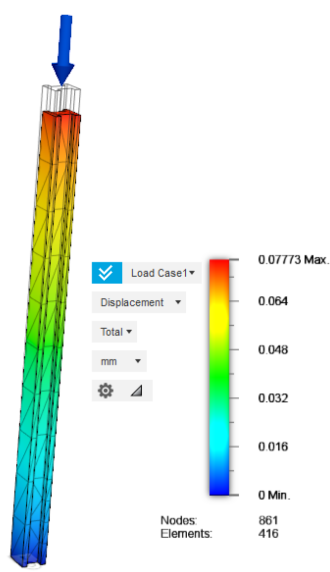


Figure K: Axial stiffness of rail 3

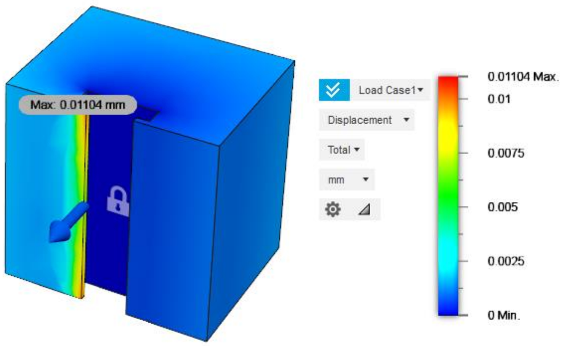


Figure L: Rail 1 mounting cantilever stiffness

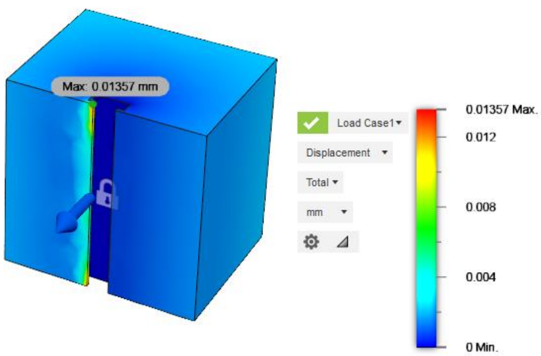


Figure M: Rail 2 mounting cantilever stiffness

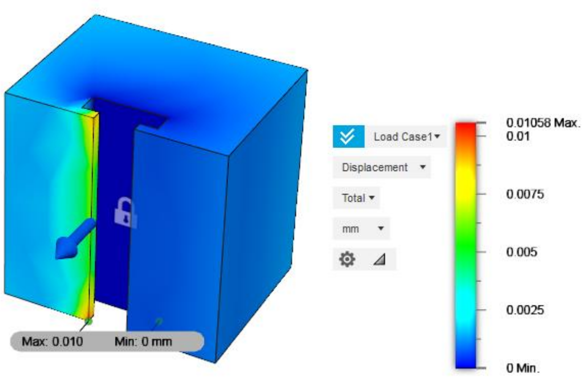


Figure N: Rail 3 mounting cantilever stiffness