

# Evolution of a Triad Twisted String Actuator for Controlling a Two Degrees of Freedom Joint to Improve Performance and Allow for Active Transmission Adjustment

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**Abstract—**

**Index Terms**—Flexible Robots, Force Control, Tendon/Wire Mechanism, Twisted String Actuator.

## I. INTRODUCTION

## II. IMPROVEMENTS TO ORIGINAL DESIGN

### A. Increasing AUJ Angle Range

The AUJ angle tracking experiments in [1] only had a range of  $\pm 14.5^\circ$  in a single axis, and  $\pm 6^\circ$  for both axes. This was because one or more twisted string actuator (TSA) would completely “unwind” near that limit and be unable to lengthen further. This limits the practicality of such a mechanism, for example a multi-segment design would have a very large minimum curvature. Increasing  $f_{\min}$  does increase the angle range marginally by increasing the TSA motor angle at  $\theta = [0 \ 0]^\top$ , as shown by experiments conducted on the original design in figure 1. These experiments were able to achieve modest increases of  $4.004^\circ N^{-1}$  for the positive (upper) limit of the universal joint roll  $\theta_1$ , and  $-6.062^\circ N^{-1}$  for the negative (lower) limit, within the  $f_{\min}$  interval [3, 3.5]. However, further attempts to increase  $f_{\min}$ , or attempts to perform the same experiment on the pitch axis resulted in premature string failure. It was also clear to achieve significant increases in AUJ angle range, a different approach would be needed that would require modifications to the design.

The most effective modification to improve AUJ angle range is to reduce the value of  $r$  in (??), as shown in figure 2. This decreases the stroke length required for each TSA to achieve the same AUJ angle range, which also reduces the TSA motor angle accordingly, allowing a greater AUJ angle to be reached before one or more TSA unwind. This can be done by using smaller motors, or by using the same size or larger motors with offset shafts

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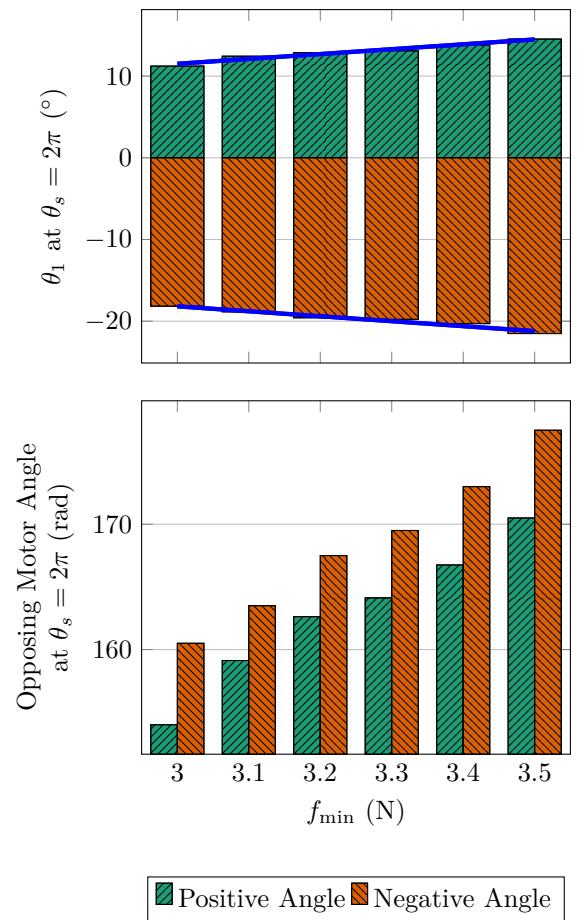


Fig. 1: AUJ roll angle ( $\theta_1$ ) of the original design when the smallest TSA motor angle is equal to  $2\pi$ , and motor angle of the “opposing” TSA (the TSA with the largest motor angle) at the same position.

connected by spur gears. Smaller motors were chosen, with a cross section of only  $120\text{ mm}^2$  compared to  $227\text{ mm}^2$  for the existing design. These were Guangdong Kingly Gear Co. Micro Metal Gearmotors (50:1), [2] which were low cost so could be easily replaced if damaged, were lighter than the existing motors, 18 g compared to 27 g, and the mechanism would be less complex. These motors have a  $\theta_{\max}$  lower than the existing motors of

only  $44 \text{ rad s}^{-1}$  compared to  $442 \text{ rad s}^{-1}$  [3], but since the original experiments limited the motor velocity to  $\text{rad s}^{-1}$  to ensure mechanism stability, this is not a concern. This change of motors allowed  $r$  to be reduced from 13 mm to 7.25 mm, as shown in figure ??.

In order to facilitate this reduction, other alterations to the design were required. The distance between the TSA strings was now too small to have a central shaft in the middle, as was the case in the original design. Instead of having a central shaft for the universal joint, the universal joint was constructed around the TSA with a “hollow spider” arrangement, where the TSA strings pass through a hole in the middle of the universal joint, as illustrated in figure 3. This also meant there was enough space to allow the installation of AUJ angle sensors directly onto the universal joint, which are discussed in section II-B.

### B. Improving AUJ Angle Measurement Accuracy

The original design used a Bosch Sensortec BNO080 9 degree of freedom (DOF) inertial measurement unit (IMU) [4] to measure the AUJ orientation. Originally it was planned for a pair of these IMU to be used, one on the base segment and one on the follower segment, and the orientation of the AUJ to be calculated from the difference between them in any orientation. However, the magnetometer measurements proved to be unreliable inside the laboratory, so only a single IMU was used and the base segment was orientated with the gravity vector parallel to the  $z$  axis. This allowed the AUJ orientation to be calculated from only the accelerometer readings, but meant the mechanism could only be controlled when orientated in the vertical axis.

There was also an issue with the IMU resolution as shown in figure ??, which is only only accurate to within  $0^\circ$ . A Savitsky-Golay filter was applied to the results in [1] for data presentation purposes and to more accurately represent the true AUJ angles at that point in time.

In order to allow the mechanism to be controllable for any orientation with respect to gravity, a solution that could directly measure the mechanical angular displacement of the universal joint was needed. Two options were considered, potentiometers and hall effect sensors. A potentiometer would couple a shaft of each universal joint spider axes to a resistive track, changing its resistance depending on AUJ orientation and providing an analog voltage signal to the controller. A hall effect sensor would be similar to the potentiometer solution, but would use a radially bipolar magnet on the end of the shaft with a hall effect sensor beneath it, which would also provide an analog voltage signal or digital data for the axial orientation of the magnet, and therefore the shaft [5]. The potentiometer solution was chosen for easy availability of components and simplicity of control integration, since no programming of the sensor would be required. The potentiometer also has mechanical stops, which make it easier to assure the required AUJ angle range will be able to be measured during assembly. The hall effect sensor is

continuous, and the measured voltage overflows every  $180^\circ$  [5], so it would be very important to ensure the magnet was initially oriented at a value that would encompass both the maximum and minimum joint limit for each AUJ axis. The Bourns PDB08 was selected as the potentiometer due to its small size and internally threaded shaft, which would allow a captive bolt to be inserted as the spider shaft [6]. As a voltage divider at  $+5 \text{ V}$ , the PDB08 would have a resolution of approximately  $40^\circ \text{ V}^{-1}$ . With the 12-bit resolution of the onboard analog to digital converter (ADC) for myRIO analog inputs, this gives a theoretical resolution of  $\approx 0.048^\circ$ . The potentiometer sliding noise (max. 100 mV) will reduce this during AUJ motion, however this can be partially mitigated with filtering.

### C. Preventing String Failure

One reoccurring issue with the original experiments were the TSA strings breaking at high values of  $\theta_s$ , which became more common after a number of twisting and untwisting cycles. Occasionally this was caused by the mechanism operating beyond expected limits for  $\theta_s$  and  $f$  due to a failure of limit monitoring within the control system, but failure would also occur within normal operating conditions.

Analysis of the design and the location of the string failures identified “pinch points” and “bite points”, as shown in figure 4a, which could potentially damage the string under high tension, causing it to thin out and lose integrity. By removing these points, by rounding off sharp edges and using an alternative method to secure the string, tying it into a loop instead of using grub screws, eliminated these potential sources of string damage, as shown in figure 4b. However, nylon monofilament, as was used for the TSA string, is still susceptible to torsion fatigue [7], [8] which reduces tensile strength [9]. This means the monofilament string will be increasingly susceptible to failure with more twisting and untwisting cycles. Therefore, the SeaKnight BLADE 0.2 mm nylon monofilament was exchanged for 0.2 mm Dyneema<sup>®</sup> polyfilament string, as used in [10]. Changes to the design of the string clamp allowed for easier installation of string filament, making polyfilament string a practical option.

### D. Final Improved Design

Figure 5 shows an annotated schematic of the improved design, and figure 6 shows a photograph with the AUJ axes annotated. The load cells were kept the same as the original design, and the universal joints below the load cells were altered. The hollow spider was connected to the base and follower bodies with machine precision bearings and bushings to allow for smooth motion. The control system remained broadly the same as the original design, except the Faulhaber MCDC3002 motor controllers [11] were exchanged for a single Pimoroni Motor 2040 which could handle up to four Micro Metal Gearmotors with Micro Metal Motor Encoders attached. This was programmed with a velocity controller similar to the example given in

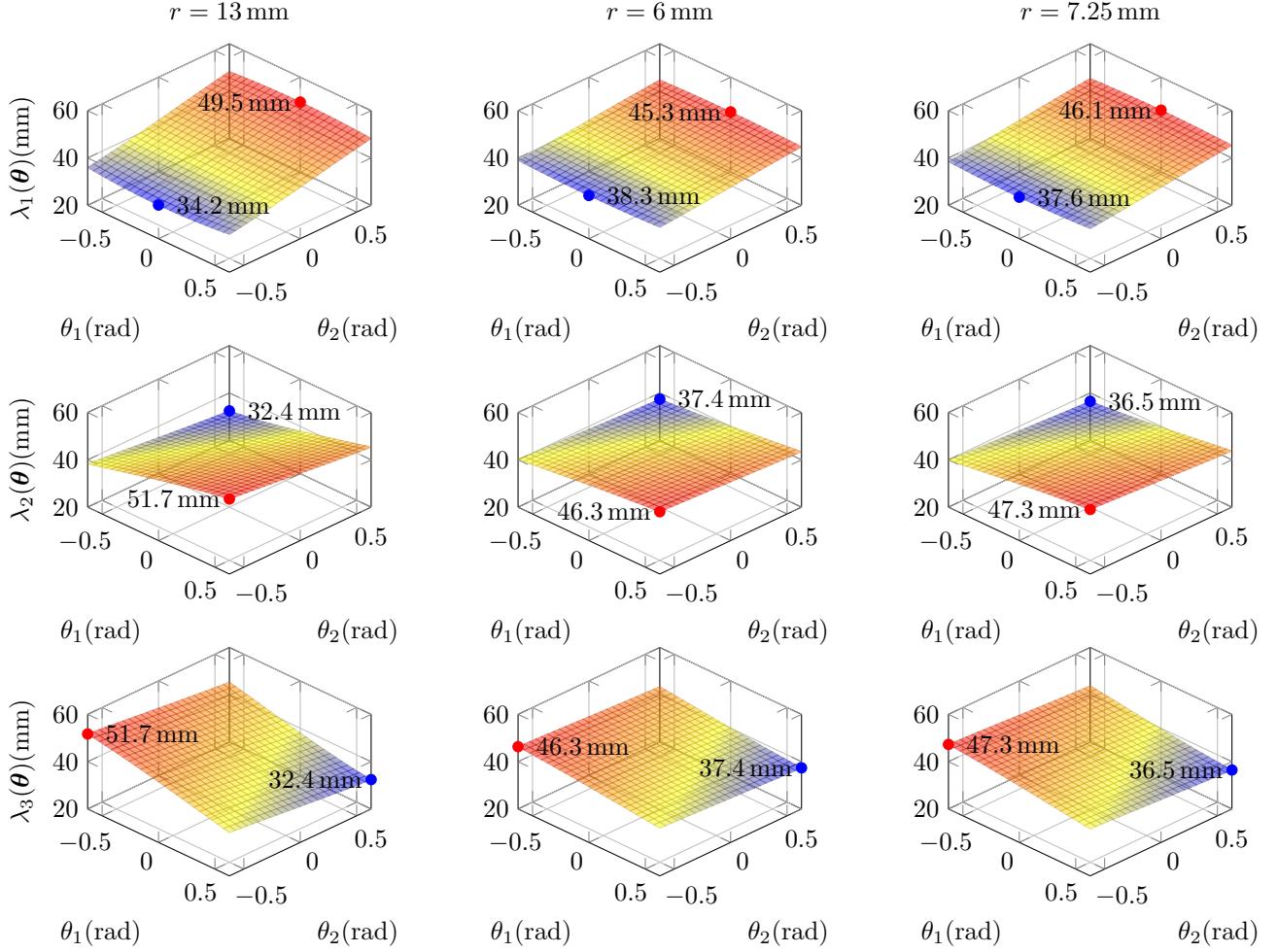


Fig. 2: Surface plots, minima and maxima for the lengths of  $\lambda_{1,2,3}$  at  $r = 13 \text{ mm}$ ,  $r = 10 \text{ mm}$  and  $r = 5 \text{ mm}$  in the range  $[-\frac{\pi}{5}, \frac{\pi}{5}]$ . As  $r$  decreases, the difference between the minima and maxima also decreases. This means that a lower value of  $r$  requires a smaller stroke range of the TSA for a given AUJ angle range.

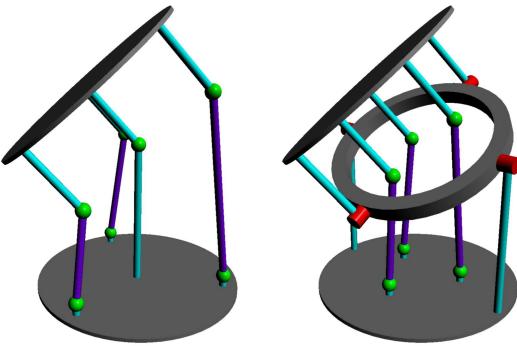


Fig. 3: An AUJ with a central universal joint, and one with a hollow spider. The hollow spider allows  $r$  to be decreased as space is no longer required for a central universal joint.

the `pimoroni-pico` library. The deadband compensation threshold was also reduced to  $\pm 0.5 \text{ rad s}^{-1}$  as the motors had a much smaller deadband region.

### III. EXPERIMENTAL RESULTS

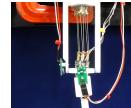
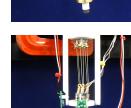
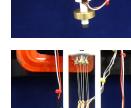
#### A. AUJ Angle Tracking

Figure 7 plots the tracking response of both the simulation and experiments for both version 1 and version 2. Three trajectories were created to test the capabilities of the mechanism. Two were only in one axis of the AUJ, and the third was in both axes. The angle range of the AUJ was limited to  $\pm 0.45 \text{ rad}$  due to mechanical limitations, namely the hollow spider colliding with the TSA universal joints in the pitch axis and the follower body in the roll axis. The angle range was also limited to  $\pm 0.35 \text{ rad}$  for the dual axis trajectory, or the trajectory would be aborted prematurely, due to a load cell exceeding a safety limit of  $9 \text{ N}$  (the load cell full scale is  $9.8 \text{ N}$  [12]).

#### B. The Effect of Follower Mass on AUJ Angle Tracking

Figure 8 shows the response for a roll trajectory with different amounts of mass added to the follower body, namely  $20 \text{ g}$ ,  $50 \text{ g}$  and  $80 \text{ g}$ . Larger masses could not be used as the trajectory would be aborted prematurely, due

TABLE I: Table of all the follower mass configurations, with the parameters for follower mass  $m$  and follower COM z offset  $\rho_3$ .

Configuration	$m$ [g]	$\rho_3$ [mm]	$I$ [kg m $^{-2}$ ]	Image
No Mass	62	3.1	$\begin{bmatrix} 3.3 \times 10^{-5} & 0 & 0 \\ 0 & 3.1 \times 10^{-5} & 0 \\ 0 & 0 & 1.4 \times 10^{-5} \end{bmatrix}$	
+20.0 g	160	35	$\begin{bmatrix} 1.3 \times 10^{-4} & 0 & 0 \\ 0 & 1.3 \times 10^{-4} & 0 \\ 0 & 0 & 4.6 \times 10^{-5} \end{bmatrix}$	
+50.0 g	260	43	$\begin{bmatrix} 1.7 \times 10^{-4} & 0 & 0 \\ 0 & 1.7 \times 10^{-4} & 0 \\ 0 & 0 & 7.7 \times 10^{-5} \end{bmatrix}$	
+80.0 g	360	46	$\begin{bmatrix} 2.0 \times 10^{-4} & 0 & 0 \\ 0 & 2.0 \times 10^{-4} & 0 \\ 0 & 0 & 1.1 \times 10^{-4} \end{bmatrix}$	

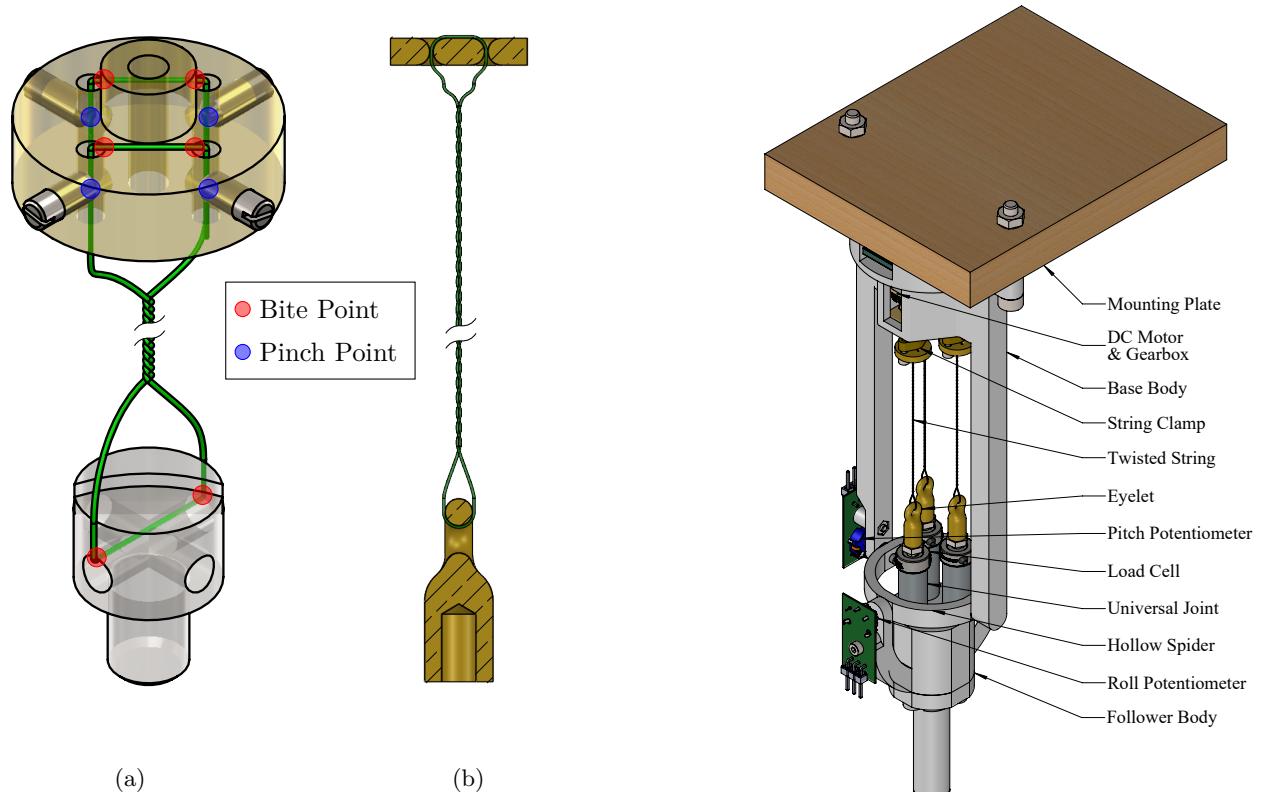


Fig. 4: (a) The original TSA string loop between the string clamp and capstan bolt, with “pinch” and “bite” points indicated, where premature string failure may occur. (b) Section view of the new TSA string loop showing how there pinch and bite points have been eliminated.

Fig. 5: Schematic of the improved design with labelled components.

to a load cell exceeding a safety limit of 9 N. Initially,

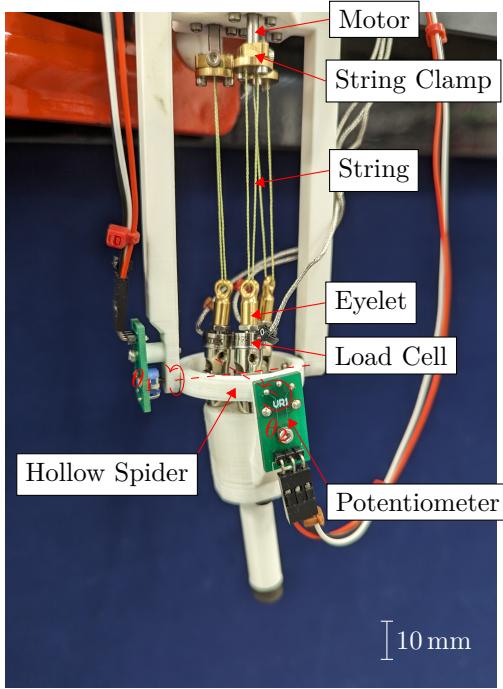


Fig. 6: Annotated photograph of the single segment physical prototype antagonistic triad, with the roll  $\theta_1$  and pitch  $\theta_2$  axes marked.

$k_p$  was set to the same value as in table ??, however the system was unable to reach a steady state in any configuration other than “No Mass”. Reducing  $k_p$  to 1000 in the weighted configurations solved the steady state issue and resulted in an average maximum tracking error of  $0^\circ$  over all configurations with added mass, similar to the result from the initial experiments. However, for the “No Mass” configuration,  $k_p = 8000$  resulted in a very poor tracking response, whereas  $k_p$  from table ?? resulted in a maximum tracking error of  $0^\circ$ , once again similar to the result from the initial experiments. In future implementations gain scheduling can be employed to select the most optimal  $k_p$  for a given follower mass, that allows for the smallest tracking error while being able to reach a steady state.

### C. The Effect of AUJ Angular Velocity on AUJ Angle Tracking

To verify the performance of the AUJ at higher angular velocities, the single axis experiments from section III-A, with a reduced angle range of  $\pm 0.4$  rad in case of overshoot, were repeated with a trapezoidal “chirp” signal, with the maximum angular velocity increasing by  $\omega_0 + (2(n-1)\omega_0)$  each cycle, where  $n$  is the cycle number, and  $\omega_0$  is the initial maximum angular velocity, and the angular acceleration increasing by  $\alpha_0 + (16(n-1)\alpha_0)$  each cycle, where  $\alpha_0$  is the initial angular acceleration. A total of four cycles were performed, with the maximum velocity and acceleration values shown in table II. Figure 9 shows the results of these experiments, which shows the tracking error increasing marginally as maximum angular

TABLE II: Trapezoidal trajectory sequence parameters.

Cycle	Max./Min. Angle [rad]	Max. Velocity [ $\text{rad s}^{-1}$ ]	Acceleration [ $\text{rad s}^{-2}$ ]
1	0.4	0.4	0.01
2	0.4	0.44	0.011
3	0.4	0.484	0.0121
4	0.4	0.5324	0.01331

velocity and acceleration increases. The pitch experiment was unable to be completed as the maximum load cell force went above the safety limit of 9 N, as can be seen in the figure.

## IV. DISCUSSION

### A. Active Transmission Adjustment (ATA)

One interesting property of the TSA mechanism is the non-linear transmission ratio that is dependant on  $\theta_s$ , as shown in figure 10. This means that the performance characteristics of the TSA, specifically the maximum stroke velocity  $\dot{p}_{\max}$  and maximum tensile force  $f_{\max}$ . These characteristics have an inverse relationship as  $\theta_s$  increases, with  $f_{\max}$  decreasing and  $\dot{p}_{\max}$  increasing.

Using the jacobian from [13],  $f_{\max}$  and  $\dot{p}_{\max}$  are found as

$$\begin{aligned}\mathcal{J} &= \frac{\theta_s r_s^2}{l_u - p} \\ \mathcal{J}^{-1} &= \frac{l_u - p}{\theta_s r_s^2} \\ f_{\max} &= \mathcal{J}^{-1} \tau_{\max} \\ \dot{p}_{\max} &= \mathcal{J} \dot{\theta}_{\max}.\end{aligned}\quad (1)$$

Therefore, for the same stroke  $p$ , increasing  $\theta_s$  will decrease  $f_{\max}$  and increase  $\dot{p}_{\max}$ . The effect is even greater if  $p$  increases.

In order to change  $f_{\min}$ , the minimum value of  $\theta_s$  has to be increased for each TSA, since  $f$  will always be the same value when the TSA are fully unwound ( $p = 0$ ). This means that by changing  $f_{\min}$ , the performance of the TSA, and therefore AUJ, can be altered in real time during operation. The maximum AUJ joint velocity can be reduced in favour or increased maximum AUJ joint torque, or vice versa. This has applications where performance characteristics need to be altered temporarily to perform a specific action, such as a mobile snake robot lifting up segments off the ground, or a prosthesis that needs to be ready to perform a faster motion while unencumbered.

In the original design, the stroke length required to reach both AUJ angle limits was too large for  $f_{\min}$  to be adjusted significantly, the TSA would either unwind or over twist. But by reducing  $r$ , the stroke length is significantly smaller as shown in figure 2, so  $f_{\min}$  could be adjusted within a much larger interval.

It may be noticed that  $\lim_{p \rightarrow 0} f(p) = \pm\infty$  and  $\lim_{p \rightarrow l_u} \dot{p}(\dot{\theta}, p) = \pm\infty$ . This is a result due to the assumption of an infinite material stiffness for the strings, which would not be possible outside simulation and is a

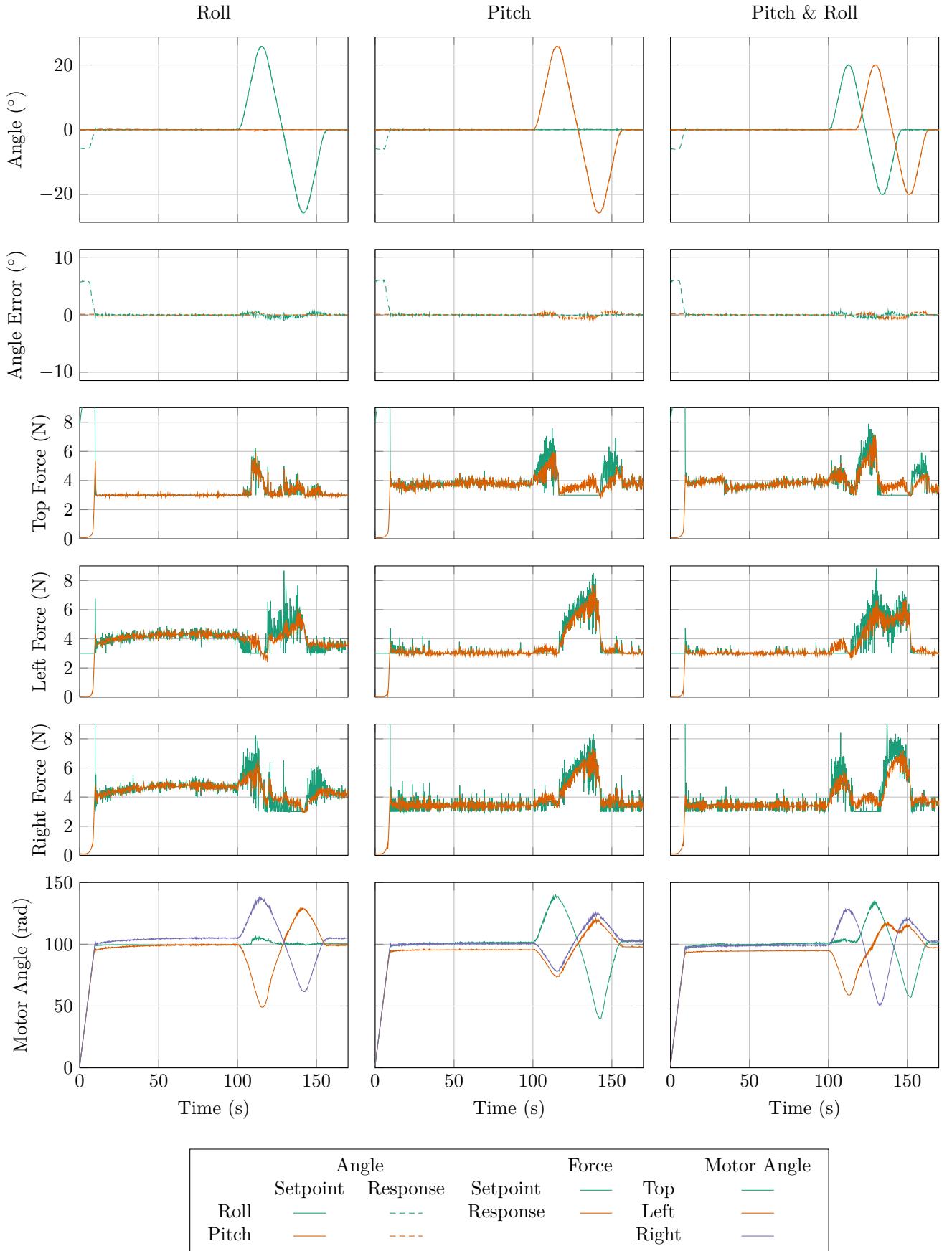
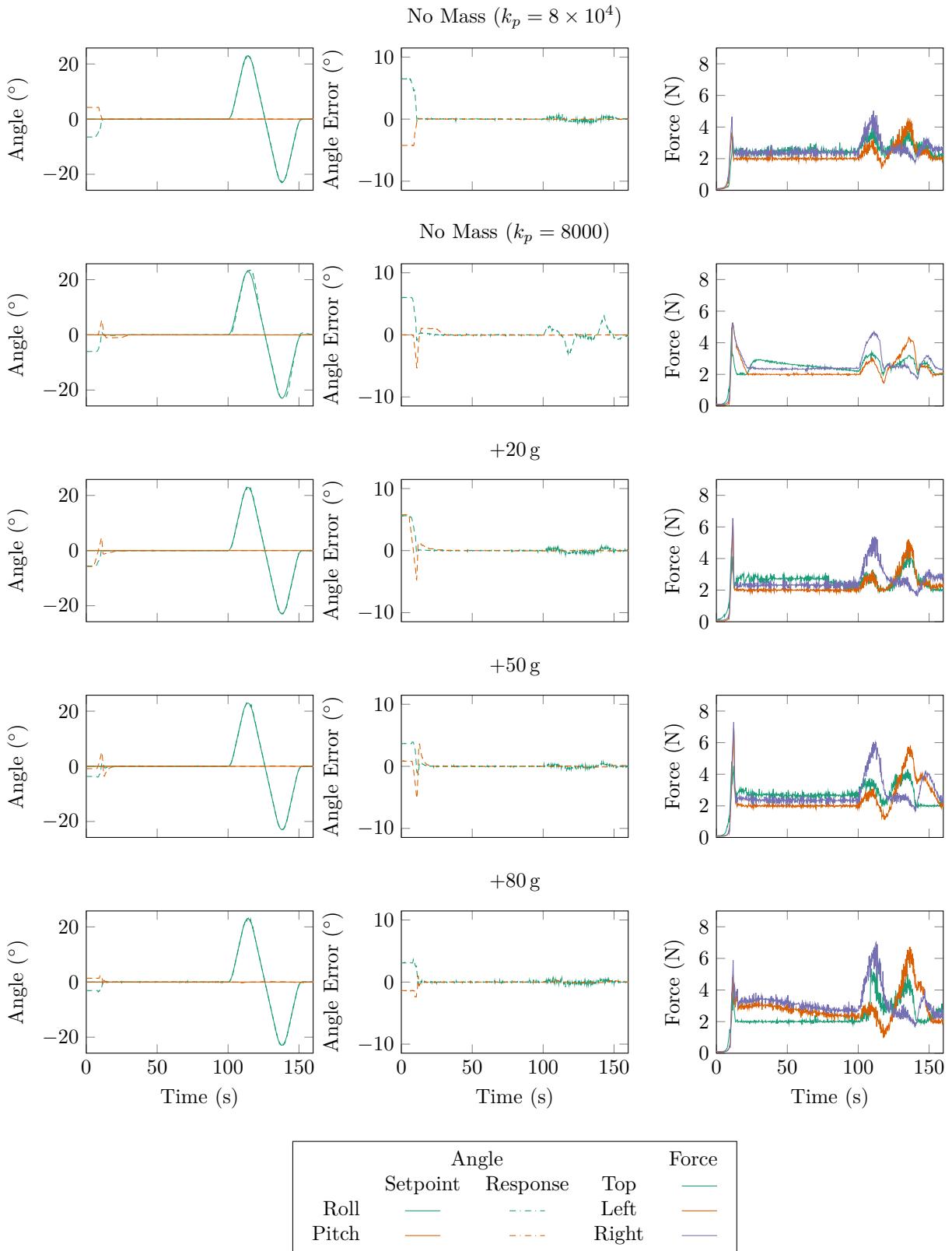


Fig. 7: Plots of the response for three different trajectories, one on only the roll axis  $\theta_1$  (column 1), one on only the pitch axis  $\theta_2$  (column 2), and one on both axes  $\theta_1$  and  $\theta_2$  (column 3). Plots include AUV orientation, forces at the top, left and right TSA, and the motor positions.

Fig. 8: AUJ roll tracking with increasing follower mass from table I, plus with no mass at  $k_p = 8000$  and  $k_p = 8 \times 10^4$ .

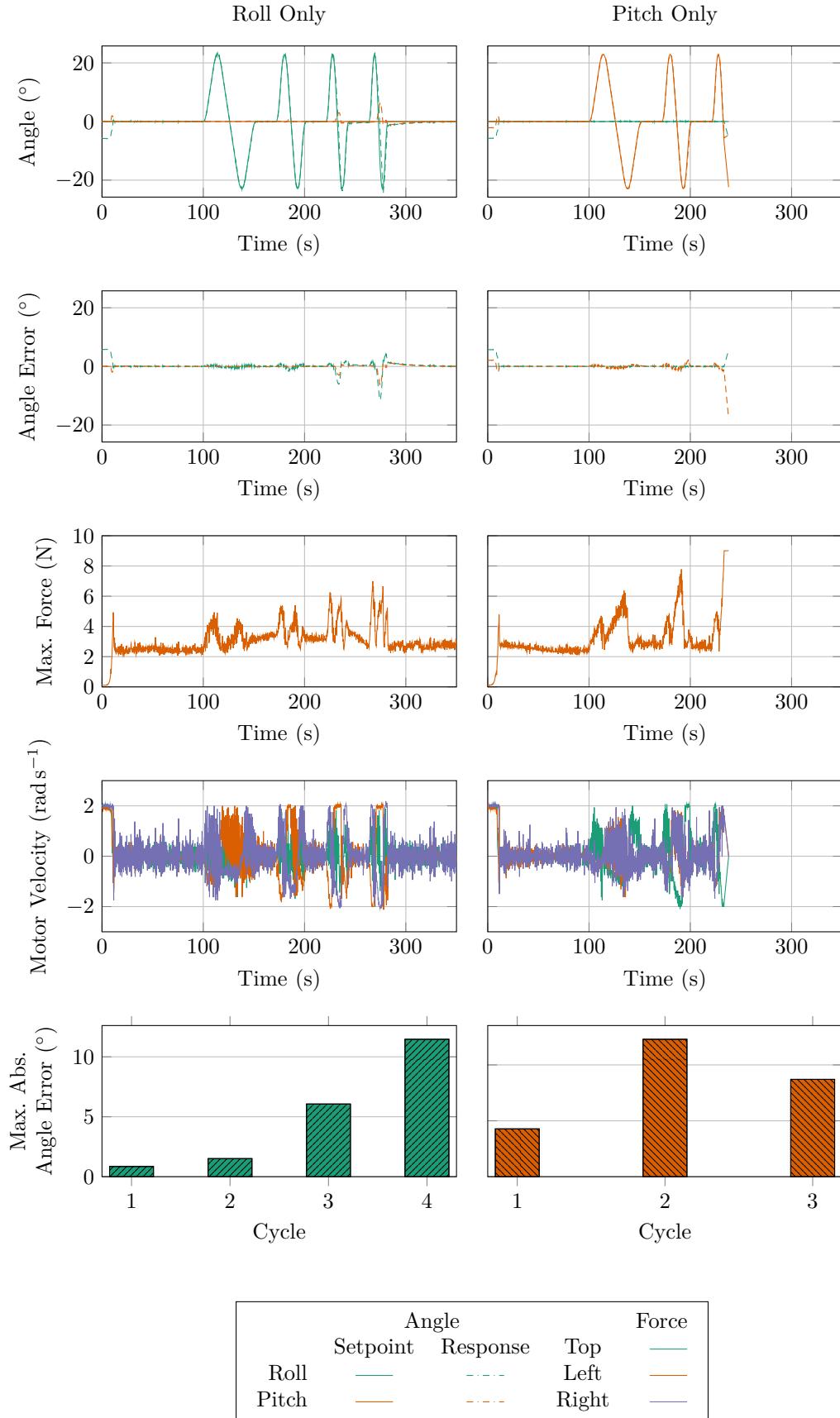


Fig. 9: Results of the trapezoidal velocity trajectory from table II for both AUJ pitch and roll trajectories, including the maximum absolute angle error for each cycle.

significant issue for high force applications as detailed in [13].

Experiments were conducted to try and verify this concept by executing the same AUJ trajectory with increasing values of  $f_{\min}$ . By measuring the current consumption of all of the motors, it was hoped at an increase in current consumption would be noticed as  $f_{\min}$ , and therefore the minimum value of  $\theta_s$ , increased, since this also increases the motor torque required to maintain that value of  $\theta_s$  if stroke  $p$  remains constant [13], which would be the case for the same AUJ angle position for different values of  $f_{\min}$  as shown by (??). However, due to the properties of the low cost brushed DC motors, such as backlash in the gearbox, and the nature of PWM control, it was not possible to determine this relationship. Future work would include better analysis methods, or possibly changing the motors for brushless DC motors, to see if this relationship can be verified experimentally.

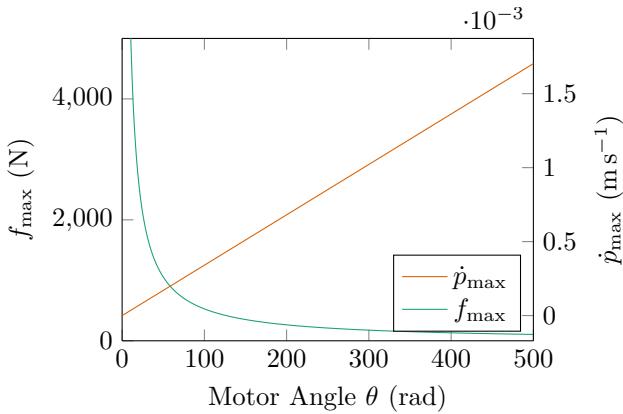


Fig. 10: By adjusting  $f_{\min}$ , the transmission ratio of the TSA can be altered. Reducing  $f_{\min}$  increases the maximum TSA force  $f_{\max}$  while reducing the maximum TSA stroke velocity  $\dot{p}_{\max}$ . Conversely, increasing  $f_{\min}$  reduces  $f_{\max}$  and increases  $\dot{p}_{\max}$ . This can be used to actively modify the dynamic properties of the AUJ during operation. In this graph,  $p = 0$ .

### B. Dynamics Gravity Vector

In the experiments, the gravity vector  $\mathbf{g}$  was assumed to be parallel to the  $z$  axis ( $[0 \ 0 \ -9.81]$ ) since the experiments were conducted in a vertical orientation. To operate in any other orientation, the gravity vector would need to be calculated using an IMU (gyroscopes would be required to compensate for forces generated using motion).

### C. Load Cell Limitation

As noted in sections III-A, III-B and III-C, the load on each TSA being limited to 9 N meant that the AUJ angle range limited both with an increased follower mass, increased velocity, and dual axis operation. Using load cells with a larger full scale would increase the AUJ angle range in all cases.

### D. Multi-Segment Design

A distributed embedded control system in each segment, as shown in figure 11, could receive AUJ angle position setpoint commands from a “primary” controller. This would allow for complex trajectories to be executed while allowing the segments to share a common power and communication bus, reducing wiring complexity and allowing for a modular design.

## V. CONCLUSION

### VI. ACKNOWLEDGEMENT

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## REFERENCES

- [1] D. Crosby, J. Carrasco, W. Heath, and A. Weightman, “A novel triad twisted string actuator for controlling a two degrees of freedom joint: Design and experimental validation,” in *2022 International Conference on Robotics and Automation (ICRA)*, IEEE, 2022, pp. 11 388–11 394.
- [2] *Jl-12fn20-50-06420*, Guangdong Kingly Gear Co.
- [3] *Dc micromotors - precious metal commutation*, Dr. Fritz Fauhaber GmbH & Co. KG, Feb. 2020.
- [4] *Bno080 data sheet*, 1.3, Hillcrest Laboratories, Inc., Oct. 2017.
- [5] K. Bienczyk, “Angle measurement using a miniature hall effect position sensor,” in *2009 2nd International Students Conference on Electrodynamics and Mechatronics*, IEEE, 2009, pp. 21–22.
- [6] *Pdb08 - 8 mm micro rotary potentiometer*, Bourns, Mar. 2021.
- [7] B. Goswami and J. Hearle, “A comparative study of nylon fiber fracture,” *Textile Research Journal*, vol. 46, no. 1, pp. 55–70, 1976.
- [8] M. Toney and P. Schwartz, “Bending and torsional fatigue of nylon 66 monofilaments,” *Journal of applied polymer science*, vol. 46, no. 11, pp. 2023–2032, 1992.
- [9] D. Hennessey, E. Carey, C. Simms, A. Hanly, and D. Winter, “Torsion of monofilament and polyfilament sutures under tension decreases suture strength and increases risk of suture fracture,” *Journal of the Mechanical Behavior of Biomedical Materials*, vol. 12, pp. 168–173, 2012.
- [10] G. Palli, C. Natale, C. May, C. Melchiorri, and T. Wurtz, “Modeling and control of the twisted string actuation system,” *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 2, pp. 664–673, 2012.
- [11] *Motion controllers - series mcde 3002 s*, 6th ed., Dr. Fritz Fauhaber GmbH & Co. KG, Nov. 2018.
- [12] *Lcm100 miniature in line load cell*, FUTEK Advanced Sensor Technology Inc.

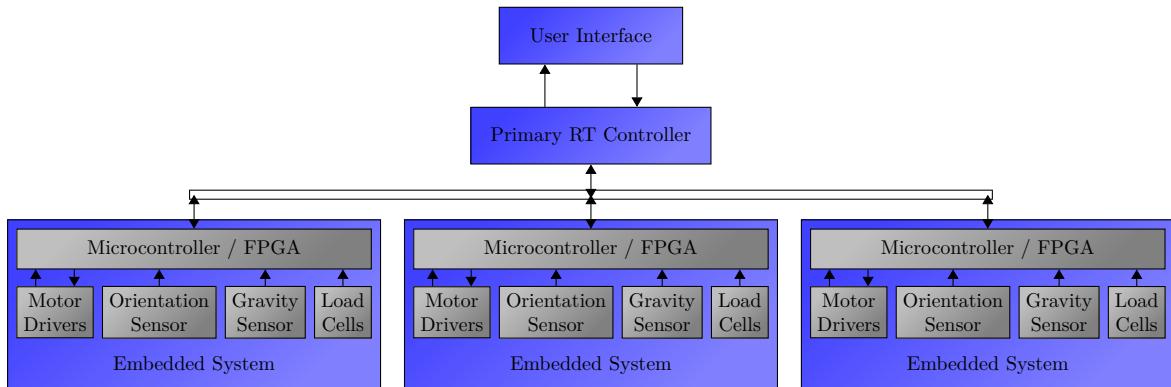
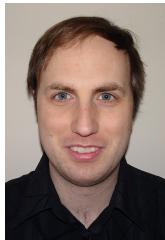


Fig. 11: Proposed system architecture for a future multi-segment system. Each segment has an embedded controller programmed with the cascaded control loop in section ???. The controller interfaces with the load cells for each TSA, the orientation sensors for the AUJ, an accelerometer to provide the local gravity vector for dynamics calculations, and the drivers for the TSA motors. A primary controller then uses a common control bus to interface with the embedded controllers, reading and writing data to registers to issue motion commands and get status updates.

- [13] S. Nedelchev, I. Gaponov, and J. Ryu, “Accurate dynamic modeling of twisted string actuators accounting for string compliance and friction,” *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 3438–3443, 2020. DOI: 10.1109/LRA.2020.2970651.



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