

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 θ_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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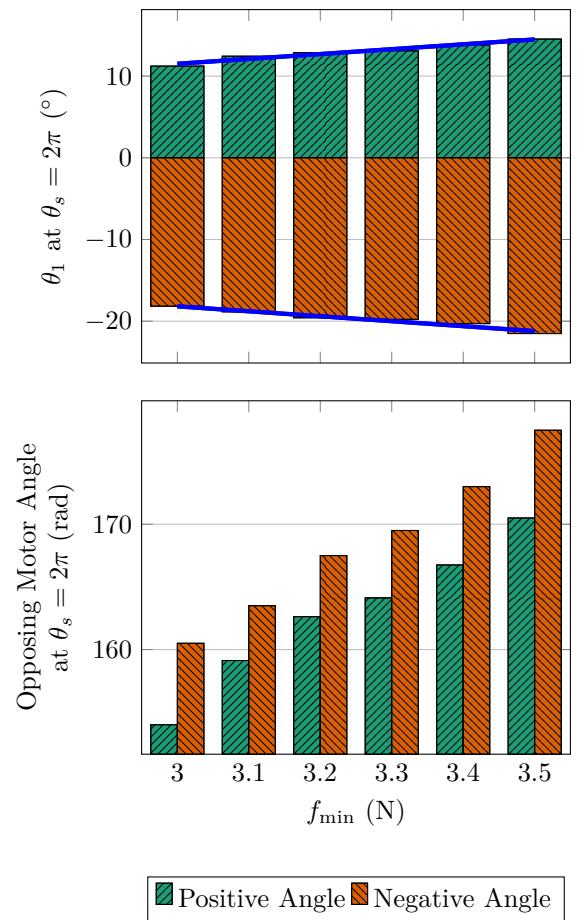


Fig. 1: AUJ roll angle (θ_1) of the original design when the smallest TSA motor angle is equal to 2π , and motor angle of the “opposing” TSA (the TSA with the largest motor angle) at the same position.

connected by spur gears. Smaller motors were chosen, with a cross section of only 120 mm^2 compared to 227 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 θ_{\max} lower than the existing motors of

only 44 rad s^{-1} compared to 442 rad s^{-1} [3], but since the original experiments limited the motor velocity to 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° . 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° [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° 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 θ_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 θ_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[®] 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 ?? 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

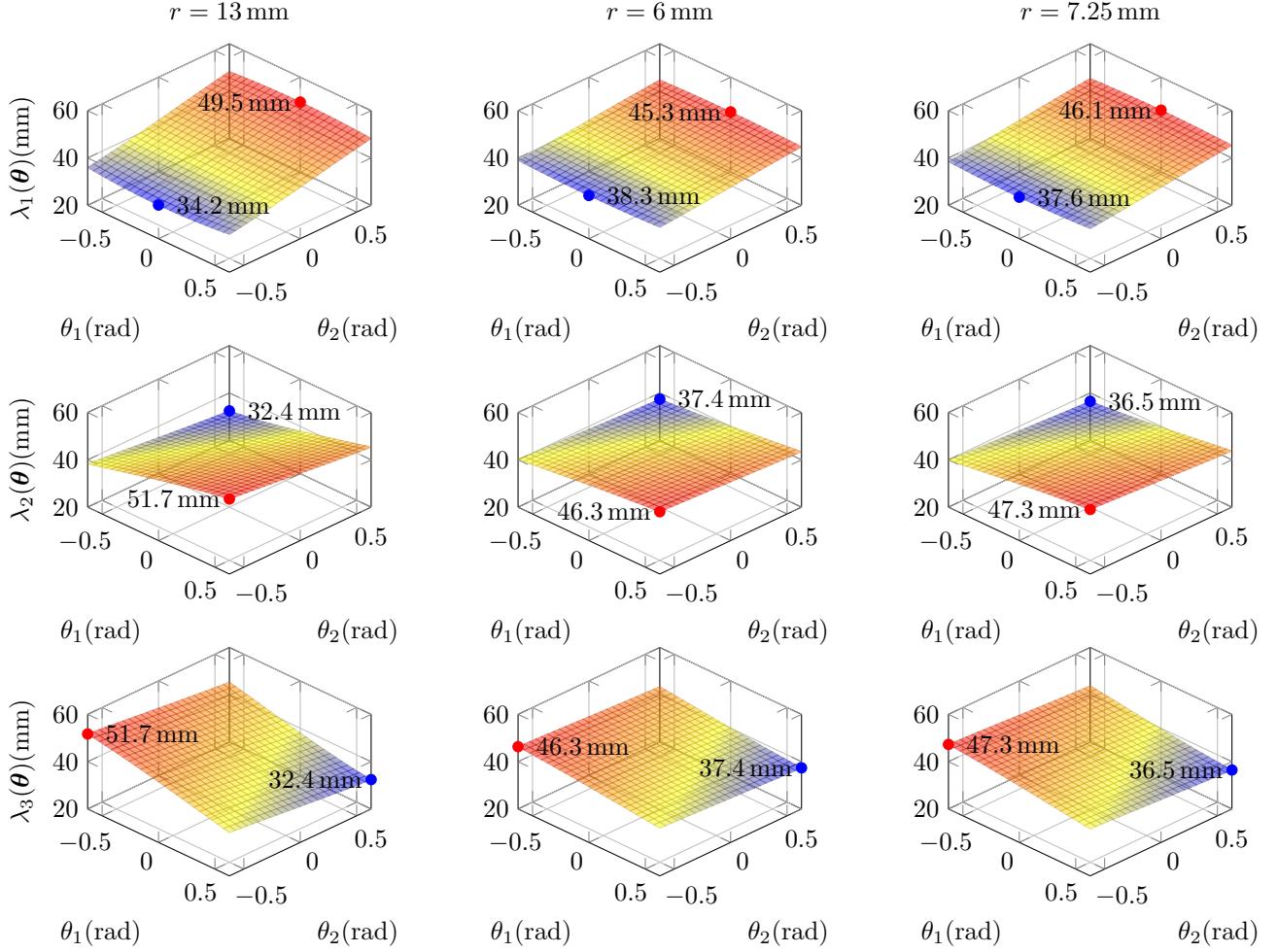


Fig. 2: Surface plots, minima and maxima for the lengths of $\lambda_{1,2,3}$ at $r = 13 \text{ mm}$, $r = 10 \text{ mm}$ and $r = 5 \text{ mm}$ in the range $[-\frac{\pi}{5}, \frac{\pi}{5}]$. As r decreases, the difference between the minima and maxima also decreases. This means that a lower value of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

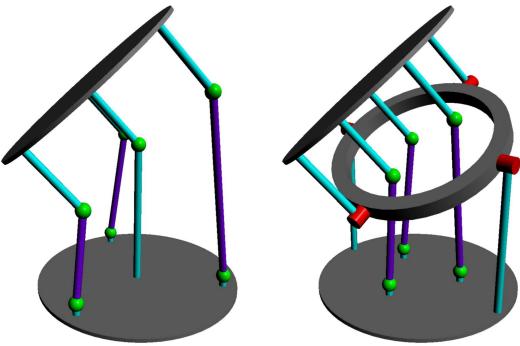


Fig. 3: An AUJ with a central universal joint, and one with a hollow spider. The hollow spider allows r to be decreased as space is no longer required for a central universal joint.

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

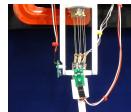
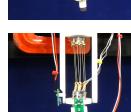
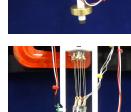
A. AUJ Angle Tracking

The angle range of the AUJ was limited to [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.

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 20g, 50g and 80g. Larger masses could not be used as the trajectory would abort prematurely, due to a load cell exceeding a safety limit of 9 N, the full scale being 9.8 N [12]. Initially, 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° over all configurations with added mass, similar to the result from the initial experiments. However, for

TABLE I: Table of all the follower mass configurations, with the parameters for follower mass m and follower COM z offset ρ_3 .

Configuration	m [g]	ρ_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	$\begin{bmatrix} 2.0 \times 10^{-4} & 0 & 0 \\ 0 & 2.0 \times 10^{-4} & 0 \\ 0 & 0 & 1.1 \times 10^{-4} \end{bmatrix}$	

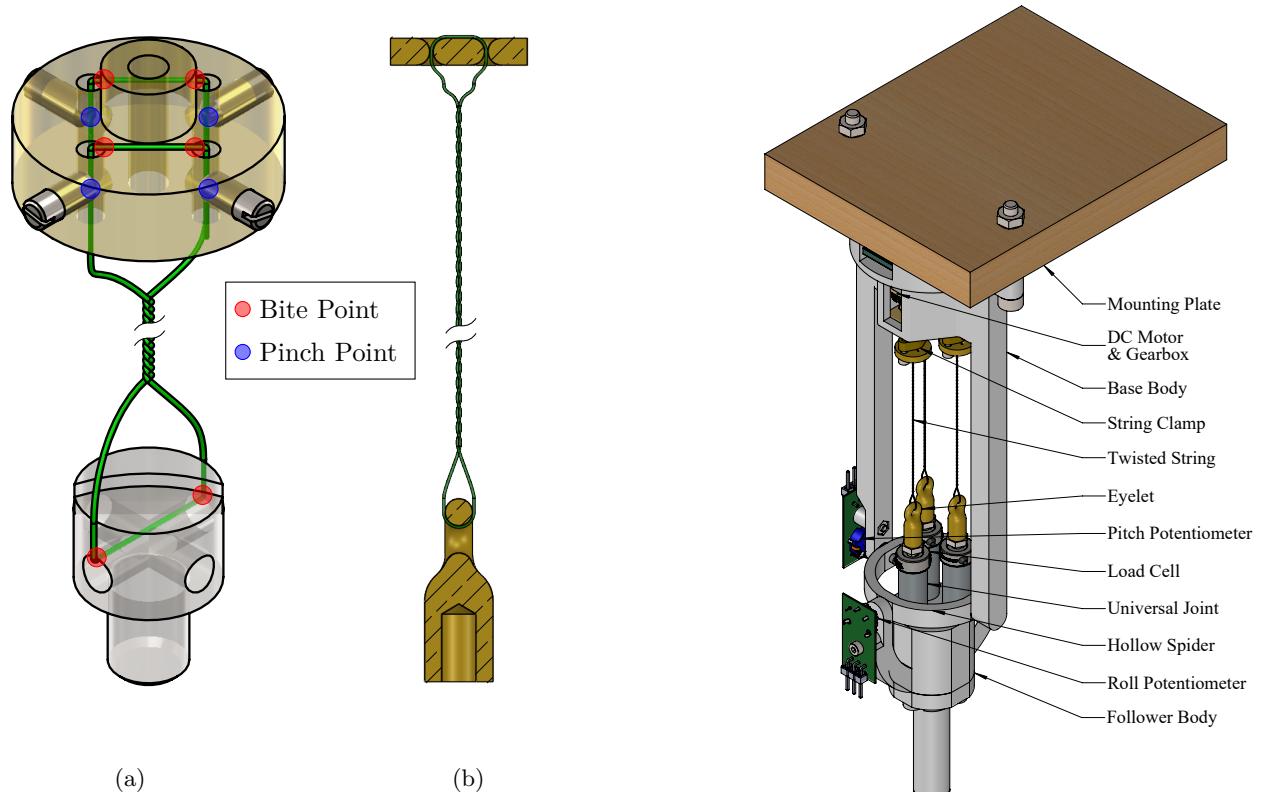


Fig. 4: (a) The original TSA string loop between the string clamp and capstan bolt, with “pinch” and “bite” points indicated, where premature string failure may occur. (b) Section view of the new TSA string loop showing how there pinch and bite points have been eliminated.

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

the “No Mass” configuration, $k_p = 8000$ resulted in a

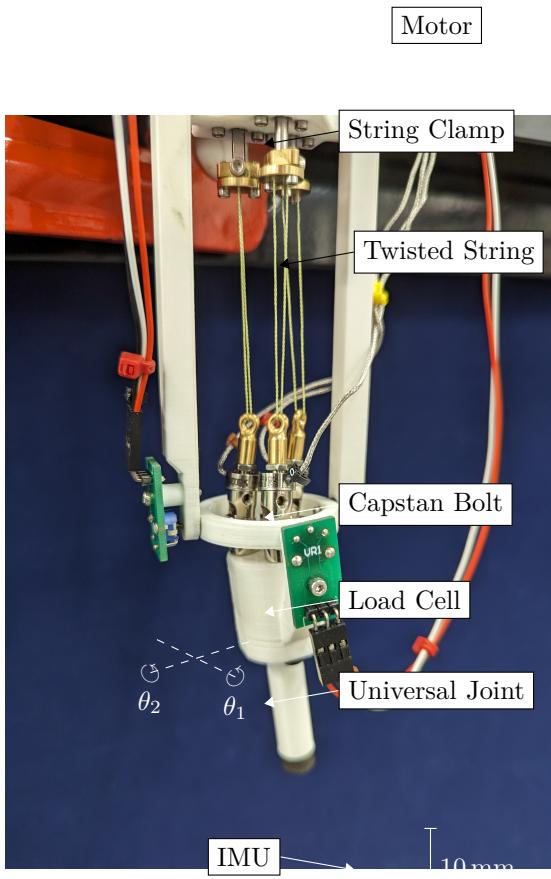


Fig. 6: Annotated photograph of the single segment physical prototype antagonistic triad, with the roll θ_1 and pitch θ_2 axes marked.

TABLE II: Trapezoidal trajectory sequence parameters.

Cycle	Max./Min. Angle [rad]	Max. Velocity [rad s ⁻¹]	Acceleration [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

very poor tracking response, whereas k_p from table ?? resulted in a maximum tracking error of 0° , 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.

1) The Effect of AUJ Angular Velocity on AUJ Angle Tracking:

IV. DISCUSSION

A. Active Transmission Adjustment (ATA)

One interesting property of the TSA mechanism is the non-linear transmission ratio that is dependant on θ_s , as shown in figure ???. 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 θ_s increases, with f_{\max} decreasing and \dot{p}_{\max} increasing, as shown in figure ???. Equation ?? shows that tensile force f increases with θ_s , so it follows that increasing f_{\min} will also increase the minimum value of θ_s for all TSA on the AUJ for a given AUJ angle pair.

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.

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 θ_s , increased, since this also increases the motor torque required to maintain that value of θ_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.

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 seen in section ?? and ??, the load on each TSA being limited to 9 N meant that the AUJ angle range limited both with an increased follower mass and dual axis. Using load cells with a larger full scale would increase the AUJ angle range in both cases.

D. Multi-Segment Design

A distributed embedded control system in each segment, as shown in figure ??, 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.

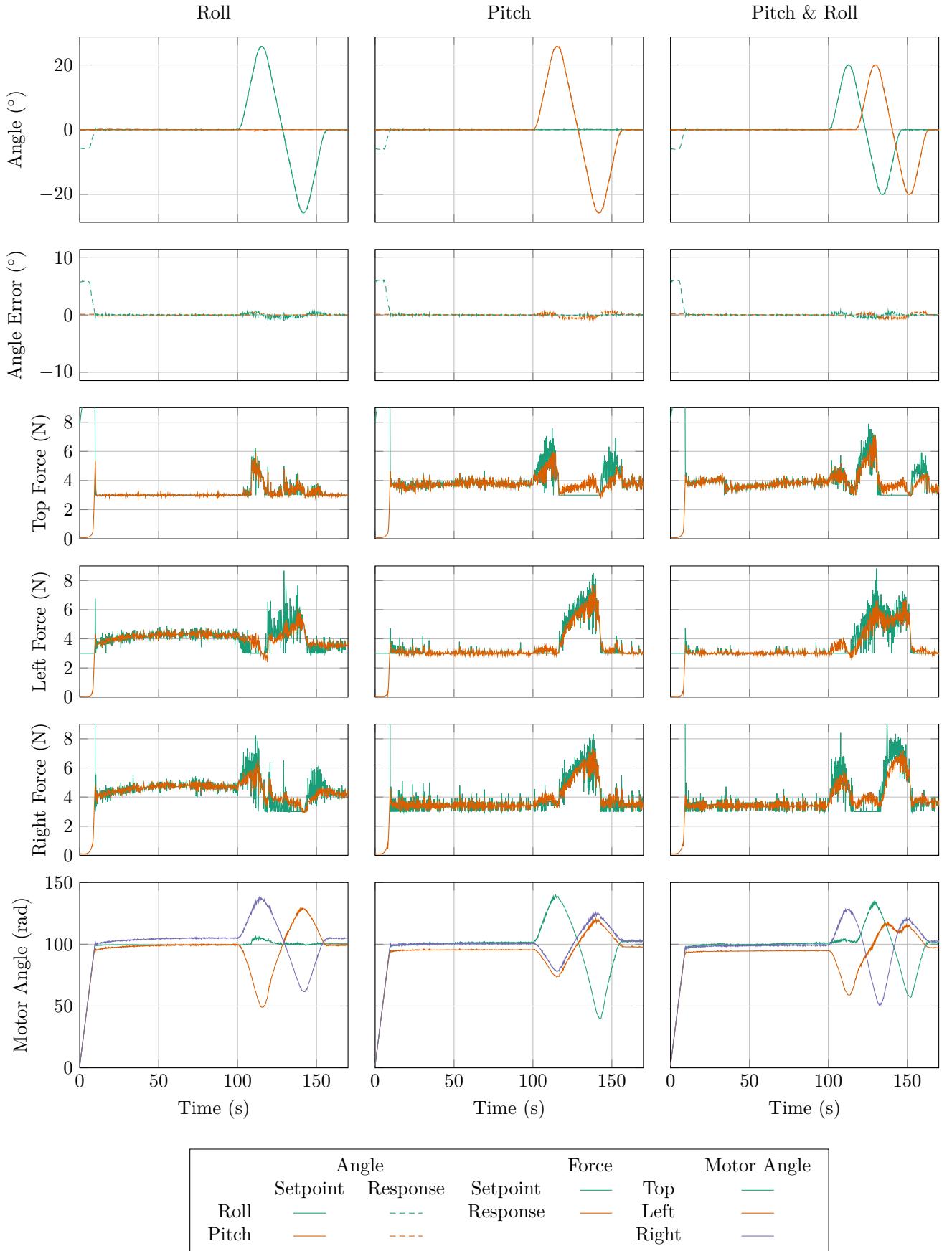
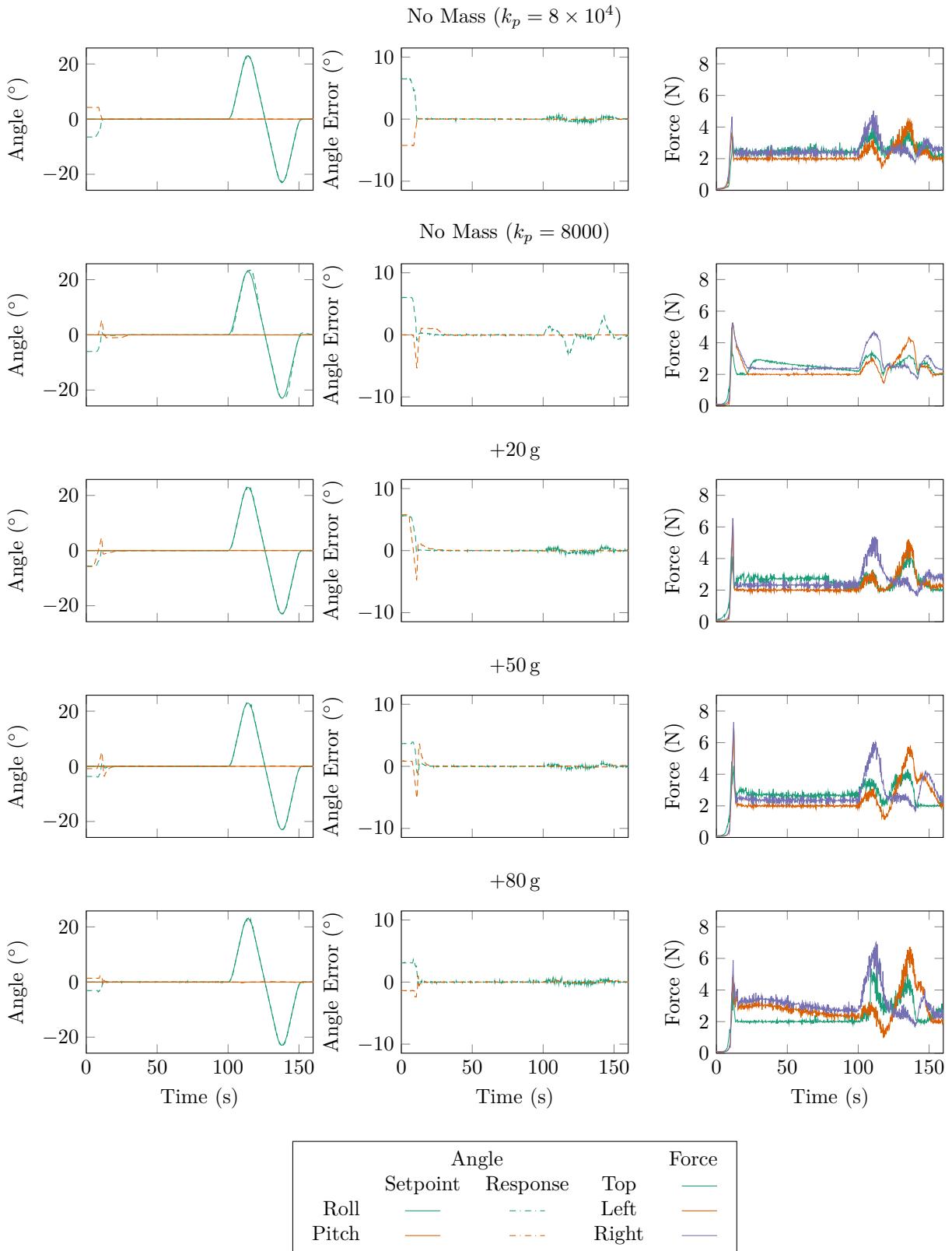


Fig. 7: Plots of the response for three different trajectories, one on only the roll axis θ_1 (column 1), one on only the pitch axis θ_2 (column 2), and one on both axes θ_1 and θ_2 (column 3). Plots include AUJ orientation, forces at the top, left and right TSA, and the motor positions. Note the simulation error is very small, so the plot cannot be seen on the graph.

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

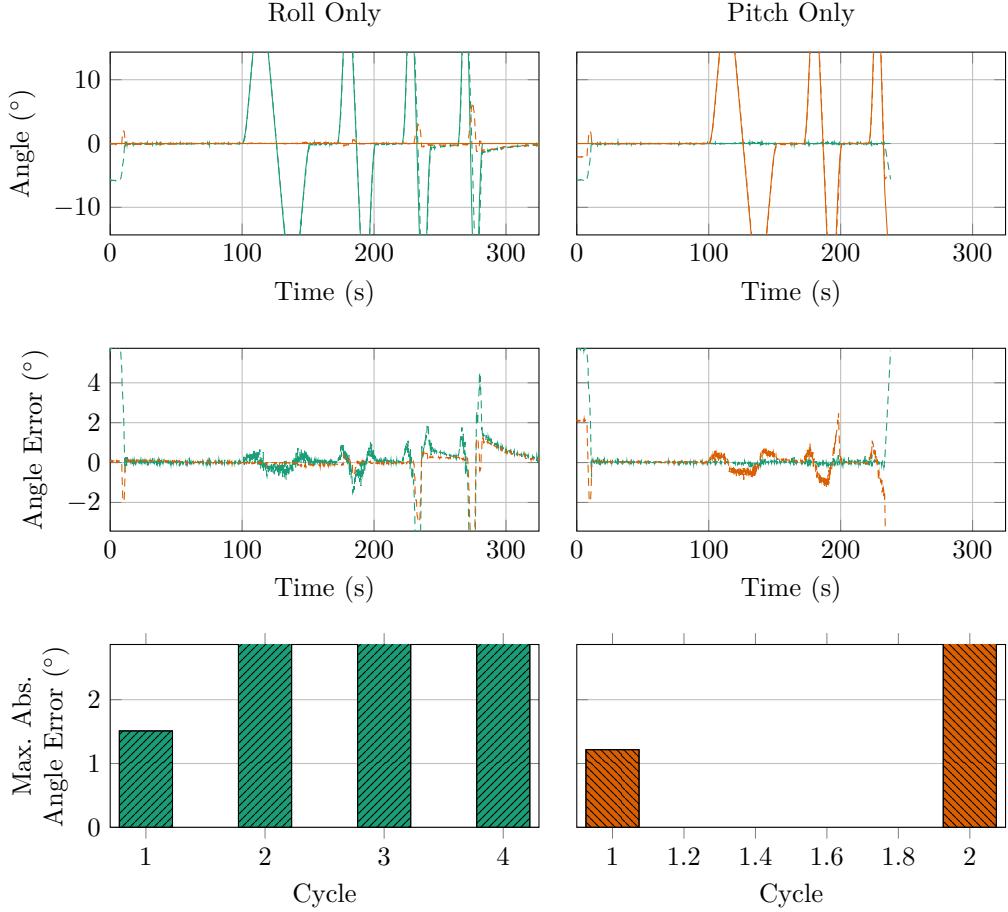


Fig. 9: Results of the trapezoidal velocity trajectory from table II for both AUJ pitch and roll trajectories, including the maximum absolute angle error for each cycle.

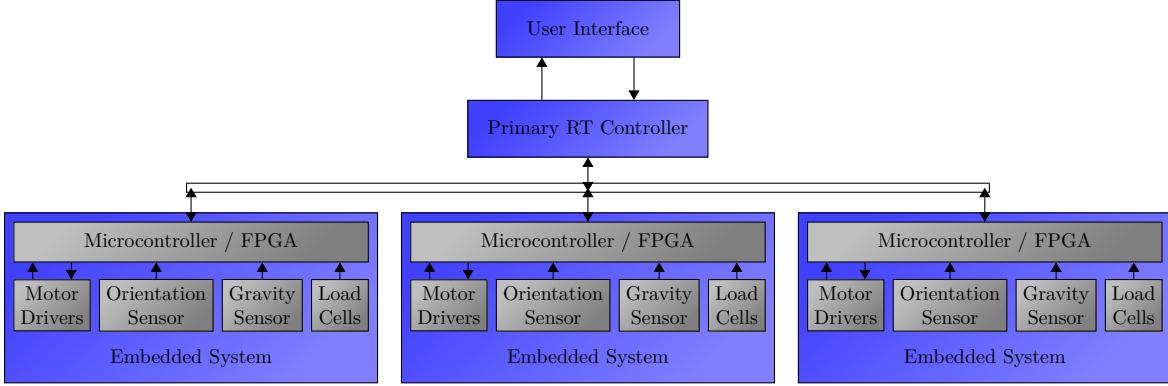


Fig. 10: Proposed system architecture for a future multi-segment system. Each segment has an embedded controller programmed with the cascaded control loop in section ???. The controller interfaces with the load cells for each TSA, the orientation sensors for the AUJ, an accelerometer to provide the local 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.

V. CONCLUSION

VI. ACKNOWLEDGEMENT

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