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 $\pm 14.5°$ in a single axis, and $\pm 6°$ 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 $\boldsymbol{\theta} = \begin{bmatrix} 0 & 0 \end{bmatrix}^\intercal$, $\approx$ for the original design, as shown in figure **??**. However, this has other effects that are further explained in section II-D that may be undesirable for the application.

In order to increase the angle range significantly, the value of r has to be reduced as shown in figure **??**. This can be done by using smaller motors, or by using the same size or larger motors with offset shafts connected by spur gears. Smaller motors were chosen, Micro Metal Gearmotor (50:1), as they were lighter than the existing motors and the mechanism would be less complex. These motors would have a much lower $\theta_{\max}$ than the existing motors of only $\mathrm{rad\,s^{-1}}$ compared to $\mathrm{rad\,s^{-1}}$, but since the original experiments limited the motor velocity to $\mathrm{rad\,s^{-1}}$ to ensure mechanism stability, this is not a concern.

This design change allowed r to be reduced from 13 mm to 7.25 mm. This reduces the TSA stroke range for a given AUJ angle range accordingly, which also reduces the TSA motor angle accordingly, allowing a greater AUJ angle to be reached before one or more TSA unwind.

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B. Improving AUJ Angle Measurement Accuracy

The original design used a Bosch Sensortec BNO080 9 degree of freedom (DOF) inertial measurement unit (IMU) [2] 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 [3]. 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° [3], so it would be very important to ensure the magnet was initially orientated at a value that would encompass both the

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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 [4]. As a voltage divider at +5 V, the PDB08 would have a resolution of approximately $40\,^{\circ}\,\mathrm{V}^{-1}$. With the 12-bit resolution of the onboard analog to digital converter (ADC) for myRIO analog inputs, this gives a theoretical resolution of ≈0.048°. 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 **??**, 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. However, nylon monofilament, as was used for the TSA string, is still susceptible to torsion fatigue [5], [6] which reduces tensile strength [7]. 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 [8]. Changes to the design of the string clamp allowed for easier installation of string filament, making polyfilament string a practical option.

D. Enabling ATA

Active transmission adjustment (ATA) allows the dynamic properties of the AUJ to change during operation, with a trade off between $f_{\max}$ and $\dot{p}_{\max}$. With ATA a robot could increase joint force when necessary, such as when lifting a heavy payload, and then return to a faster and more responsive configuration when the payload has been released. As r has been reduced from 0.013 to 0.0725 as shown in table **??**, this reduces the TSA stroke range p for a given AUJ angle range. Now the stroke range is smaller, it can be shifted along the curve of the function in equation **??** without exceeding $l_{\min}$. This is done by simply increasing or decreasing $f_{\min}$. As shown in figure **??**, this changes the range of values of $f_{\max}$ and $\dot{p}_{\max}$. Namely, $f_{\max}$ decreases and $\dot{p}_{\max}$ increases as $f_{\min}$ increases, which changes the transmission properties of the system.

III. Experimental Results

A. AUJ Angle Tracking

B. Demonstration of the Effects of ATA

As can be seen in figure **??**, the effect of increasing $f_{\min}$ is to decrease $f_{\max}$ and increase $\dot{p}_{\max}$. This has two measurable effects, an increase in total energy consumption for a given follower mass and AUJ angle trajectory, and an increase in the maximum stroke speed for a given $\theta_{\max}$ for each motor. Therefore to demonstrate the effects of ATA, two experiments are conducted. The first measures the total energy consumption for a given AUJ angle trajectory at increasing values of $f_{\min}$. The total energy consumption can then be calculated using

$$\Sigma_j = \int_{t_0}^{t_n} \sum_{i=1}^{3} v_s a_i\left(t\right) \left|d_i\left(t\right)\right| dt, \tag{1}$$

where v_s is the motor supply voltage, and a_i and d_i are the current consumption and duty cycle $\in [-1, 1]$ (d_i has a negative duty cycle when the motor is running in reverse) of motor i at time t. Figure 2 shows this increase. The second measures the ability of the AUJ to track a trajectory at a constantly increasing velocity given a constrained $\theta_{\max}$. Since increasing $f_{\min}$ increases $\dot{p}_{\max}$, a larger value of $f_{\min}$ should allow the AUJ to track the trajectory for a longer period of time before falling behind. Figure **??** shows this effect.

Test.

An experiment was also conducted to assess the performance of the system when $f_{\min}$ is changed while the AUJ is in motion at a non-zero position. The results of this experiment are shown in figure **??**, and show minimal disturbance to the AUJ trajectory during the transition.

C. The Effect of Follower Mass on AUJ Angle Tracking

Figure **??** shows the setpoint and response trajectory for each experiment for both version 1 and version 2. 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 the "No Mass" configuration, $k_p = 1000$ resulted in a 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.

IV. Discussion

A. Dynamics Gravity Vector

In the experiments, the gravity vector $\boldsymbol{g}$ was assumed to be parallel to the z axis ($\begin{bmatrix}0 & 0 & -9.81\end{bmatrix}$) since the

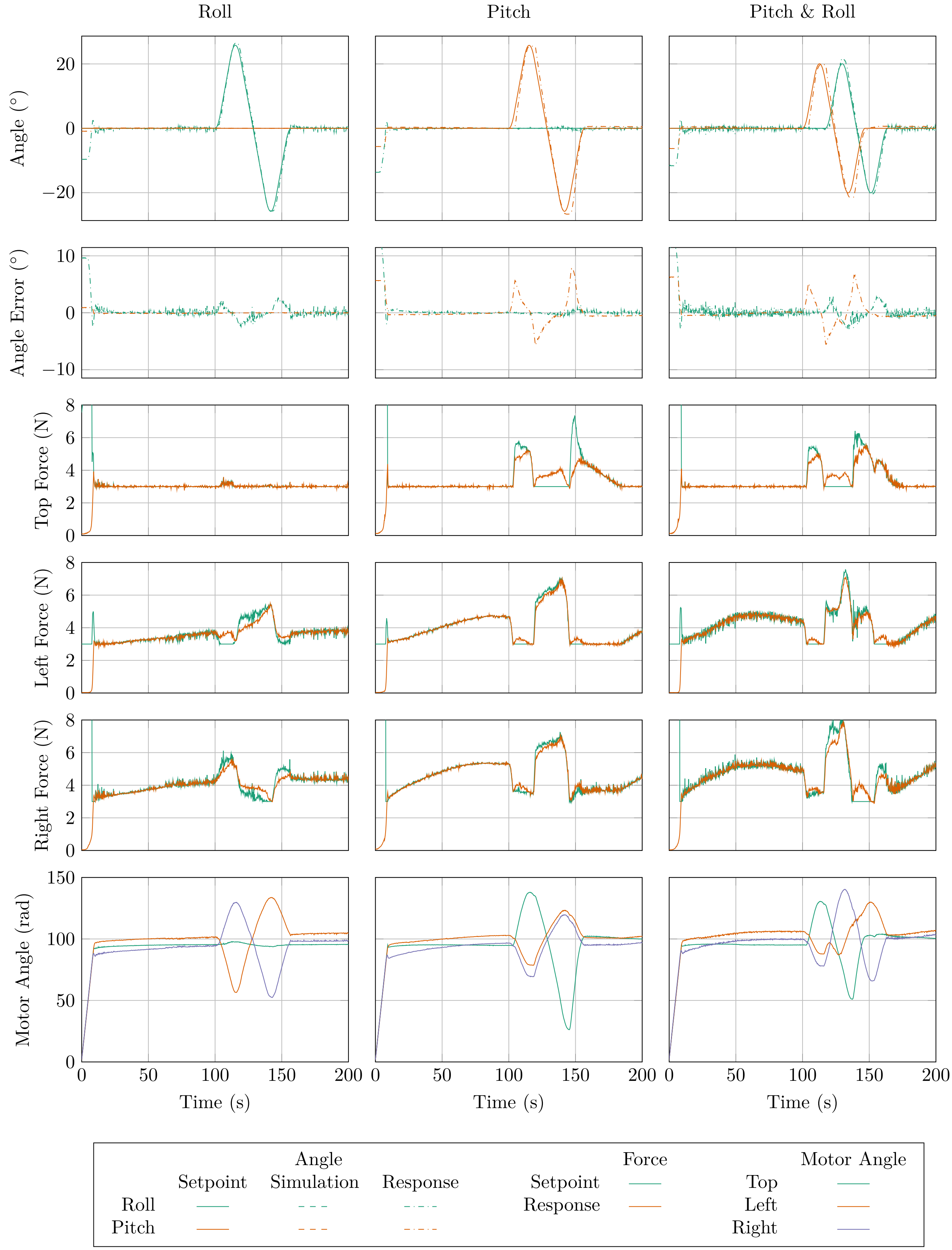

Fig. 1: Plots of the response for three different trajectories, one on only the roll axis θ_1 (column 1), one on only the pitch axis θ_2 (column 2), and one on both axes θ_1 and θ_2 (column 3). Plots include AUJ orientation, forces at the top, left and right TSA, and the motor positions. Note the simulation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

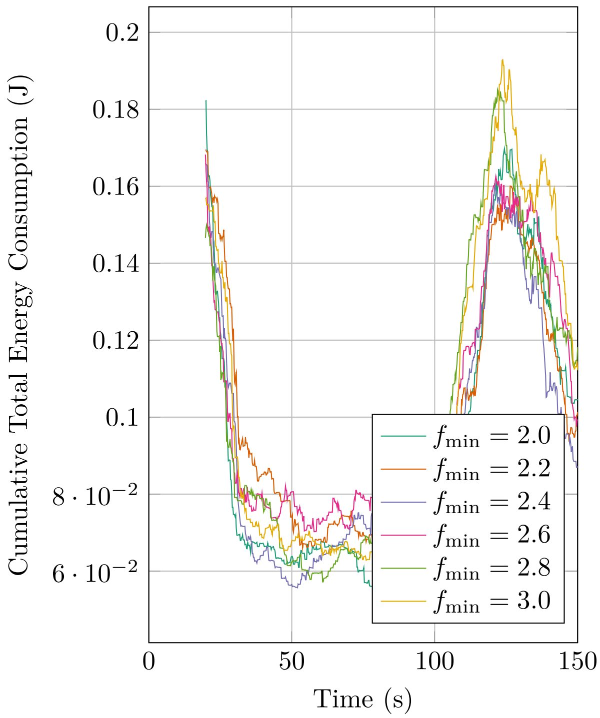

Fig. 2

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).

B. 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.

C. 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.

V. Conclusion

VI. Acknowledgement

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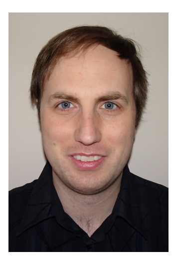

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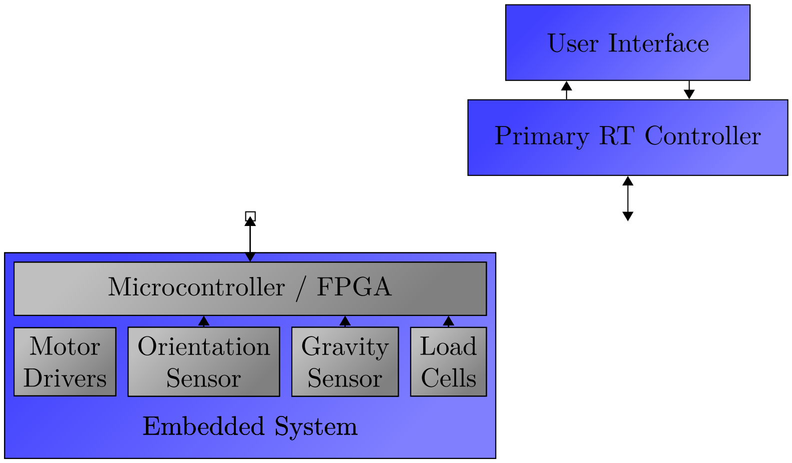

Fig. 3: Proposed system architecture for a future multi-segment system. Each segment has an embedded controller programmed with the cascaded control loop in section **??**. The controller interfaces with the load cells for each TSA, the orientation sensors for the AUJ, an accelerometer to provide the 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.

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