A Novel Triad Twisted String Actuator for Controlling a Two Degrees of Freedom Joint: Design and Experimental Validation

Damian Crosby, Joaquin Carrasco, William Heath, and Andrew Weightman

Actuated universal joints, or equivalent joint systems, are found in a number of robotic applications, in particular mobile snake robots, snake-arm robots and robotic tails. Such joints use a variety of actuation methods, including direct drive motors, linear screw drives, cable based systems, and hydraulics/pneumatics. In this paper the authors present a novel design for a mechanism that utilises the TSA in an antagonistic triad to actuate the universal joint, using orientation sensors and load cells to create a robust cascading closed loop control system. This design realises a light, compact, high-performance actuation system that avoids the extra mass and hardware complexity that alternative actuation methods present, with the additional challenge of nonlinearity. The authors were able to develop a closed loop control system that could track a universal joint orientation setpoint to within  ± 2 ° within a  ± 10 ° range.

settings.render = 4; settings.outformat = "pdf"; import math; import tube; import graph3; import three; unitsize(1cm); currentprojection = orthographic(Y,showtarget=true);

void doublehelix(real radius, real height, int turns)

real x(real t) return radius\*cos(t); real y(real t) return radius\*sin(t); real z(real t) return (height/(2pi\*turns))\*t;

guide3 g = graph(x,y,z,0,2pi\*turns,operator ..);

path3 p = (radius,0,-0.1) — (g) — (radius,0,height+0.1);

draw(tube(p, scale(radius)\*unitcircle), green); draw(tube(rotate(180,Z)\*p, scale(radius)\*unitcircle), green);

???

# Introduction

AUJ mechanisms are found in a wide range of robotic applications, such as confined space inspection using snake-arm robots , highly manoeuvrable mobile snake robots , and biomimetic robot tails for stability . Mobile snake robots must usually incorporate electric actuators inline with their joints. This results in an AUJ having to shift the mass of the follower segments and all the actuators inside the follower segments, which results in high torque requirements. Snake-arm robots and robotic tails can reduce the mass and size of the AUJ by moving their actuators away from the AUJs and use cables to transfer the force to the joints, or use hydraulic or pneumatic actuators which tend to be lighter than equivalent electric motors. This comes at the expense of increased mass and bulk at the base of the arm or tail.

First developed by in , the TSA uses two or more strings between two fixtures as a linear actuator. When one fixture is rotated (typically by an electric motor), the looped string twists into a helix, decreasing the distance between them. TSA actuators have been used for a hand orthosis , elbow joint and foldable robot arm among other functions.

The primary advantage of TSA over similar linear actuators such as a leadscrew is the reduction the TSA provides is not proportional (or even slightly inversely proportional) to the mass of the actuator. By decreasing the string cross-section radius the reduction increases given a constant unwound length and motor angle. While the reduction in a leadscrew can be increased by decreasing the lead on the thread, which also has no increase in mass, this has a limited range and can quickly run up against manufacturing tolerances or material strength requirements. In order to achieve greater or more robust reductions, the screw radius has to be increased, or the driving motor has to have a larger reduction before driving the screw, both of which usually result in more material (typically steel) and therefore more mass and bulk. This would reduce the utility of several applications of AUJ mechanisms, such as each segment being required to support all its follower segments, or being able to operate in confined spaces.

However, TSA does have some disadvantages, the most significant of which is a non-linear reduction equation, which is also dependent on the motor angle (and therefore actuator position). The reduction decreases in a non-linear fashion as the angle increases, with the derivative decreasing as the angle increases. There is also the compliance of the strings to consider, depending on the thickness and material chosen, which becomes a significant factor under high forces. Both of these issues can be addressed with accurate modelling and/or a robust control strategy, as demonstrated in . What is more of an issue is the unidirectional force of the TSA, which can only impart force in tension. This means that for an AUJ, which is a two degree of freedom joint, a minimum of three TSA are required for unless spring return mechanisms are used, which would impart additional force on the TSA and therefore reduce performance. However, the potential high force to mass ratio of the TSA due to the non-proportional reduction may adequately compensate for the additional actuator requirement.

The focus of this research is to investigate if the TSA is a suitable candidate for control of an AUJ considering both the benefits and drawbacks. To this end, the first objective is to perform a simulation and construct a physical experimental prototype to validate the proposed control system. Then, the second objective is to compare the results from both the simulation and experimental prototype with other inline actuation methods for an AUJ to analyse and discuss the potential advantages and disadvantages of TSA actuation against alternatives.

The use of TSA as an actuator for an AUJ is an understudied area of research. have proposed a similar design using a flexible core with continous curvature as opposed to a rigid universal joint, however currently this research has not demonstrated control of both axes of motion with multiple TSA. This reasearch demonstrates robust closed loop control of an AUJ in both axes of motion using three TSA in an ‘‘antagonistic triad’’ confugration. The result is a light, compact AUJ design that has the potential to significantly improve upon exiting inline actuation options.

This publication will first give an outline of the TSA based on the existing literature, and the concept of an antagonistic triad. Then a detailed explanation of the control system is given, followed by results from the simulation and experimental system. Finally, a theoretical anaylsis of the TSA AUJ compared to a similar AUJ using leadscrews is conducted, followed by a discussion and conclusion.

## A TSA

First developed by in 2010, TSA uses two or more strings between two fixtures as a linear actuator. When one fixture is rotated (typically by an electric motor), the strings twist into a helix, decreasing the distance between the fixtures, as shown in figure [[fig:twist]](#fig:twist). Given the unwound length , and the cross-section radius of the string (or + when there are more than two strings) as shown in figure [[fig:stringthickness]](#fig:stringthickness), the actuator length is given by

where is the motor angle, as shown in figure [[fig:tsa]](#fig:tsa).

|  |  |  |  |
| --- | --- | --- | --- |
|  |  |  |  |
|  | path3 p = (0,0,0) – (0,0,7.5);  draw(tube(shift(-0.1,0,0)\*p, scale(0.1)\*unitcircle), green); draw(tube(shift(0.1,0,0)\*p, scale(0.1)\*unitcircle), green);  //draw(shift(0.5,0,0)\*p, arrow=ArcArrows3());  //label("", shift(0.6,0,0)\*p, align=left); | doublehelix(0.1,5,1); | doublehelix(0.1,4,10); |

This equation assumes an infinite string stiffness, so is only reasonably accurate under low tension. Although theoretically the stroke of the TSA can be the entire domain of , in reality the thickness of the string prevents a geometric helix from forming once the helix pitch (or for strings). This limits the lower bound of the stroke as follows,

or approximately 46% of for a two string TSA.

## Antagonistic Triad

As mentioned in the introduction, because the TSA provides only tensile force, a minimum of three actuators are required. These can be arranged in a triangular configuration to create an ‘‘antagonistic triad’’, akin to the antagonistic pairs of muscles found in animals. Where a revolute joint would be found between the connecting ends of the actuator, a universal joint is found instead. The geometric structure of the system can be described with two equilateral triangles of inradius on two planes separated in the axis. The centroids are then connected via a universal joint from each plane normal to an intersecting point, let the vector denote the rotation of the second plane relative to the first, in the and axes around the intersecting point, and let and denote the normal distance from the intersection to the first and second plane centroids respectively. When the triangles are parallel to each other. The distance between the vertex pairs of each triangle is then denoted as for the ‘‘top’’, ‘‘left’’ and ‘‘right’’ vertices of the triangles. When is changed, this will change , and respectively. Figure [[fig:kine]](#fig:kine) illustrates this antagonistic triad.

To calculate the lengths of the strings for a given of the universal joint, we define a vector function as follows.

The output of this is shown in figure [[fig:surf]](#fig:surf) for a domain of .

# Control System

The control system is a four layer cascade design, using feedback of the joint position from the accelerometers and TSA force from the load cells. A second order setpoint trajectory is used as the input, which can either be pre-defined or generated dynamically from user input. Feedback is provided by the AUJ angular position as shown in figure [[fig:kine]](#fig:kine), angular velocity , and TSA tension force as shown in figure [[fig:dyn]](#fig:dyn). Figure [[fig:block]](#fig:block) shows a complete block diagram of the control system.

1. AUJ Position PID Controller
2. Inverse Dynamics
3. TSA Force Optimisation Algorithm
4. TSA Force P Controller

Functions are then combined into a cascade function .

## AUJ Position PID Controller with Acceleration Feedforward

Firstly, a PID controller is used to generate a control signal with the input as the setpoint, and the AUJ angular position and velocity as feedback, plus the addition of a feedforward term for the input acceleration , i.e.

In the discrete implementation used for fixed step simulation and experimental system control, the integral term is replaced by the trapezoidal rule.

## Inverse Dynamics

The control signal from the PID controller is then converted to the desired AUJ torque as follows

Firstly the affine transformation matrix for a coordinate frame between the AUJ pivot and the centre of mass of the follower segment can be defined. The order of and can be reversed, but this requires other terms to be reversed as well.

Then the linear velocity jacobian is simply the jacobian of the translation vector of .

The angular velocity jacobian is calculated using the first joint angle relative to the base frame, and the second in the frame of the first. If is the first rotation in then the first column of the jacobian is (to represent the pitch angle) and the second column is .

Then the mass matrix can be created from the jacobian, the mass for the follower segment and its inertia tensor , and and to express the inertia in the correct frame.

The centrifugal/coriolis matrix is created from the christoffel symbols of , along with the AUJ velocity vector .

Then the gravity term . As the gravity vector direction is the same as the z axis as in figure [[fig:kine]](#fig:kine), the height is equal to , therefore the potential energy is . The jacobian of this then becomes the gravity term.

$$G\left(\boldsymbol{\theta}\right) = \begin{bmatrix} \frac{\partial mg-l\_{2}\cos{\theta\_{1}}\cos{\theta\_{2}}}{\partial \theta\_{1}} \\ \frac{\partial mg-l\_{2}\cos{\theta\_{1}}\cos{\theta\_{2}}}{\partial \theta\_{2}} \end{bmatrix}\\
% &= \begin{bmatrix} mgl\_{2}\cos{\theta\_{2}}\sin{\theta\_{1}} \\ mgl\_{2}\cos{\theta\_{1}}\sin{\theta\_{2}}\end{bmatrix}$$

, and are then combined to form the dynamics equation , along with the AUJ position and velocity vectors. is used as the acceleration term. This results in a setpoint joint torque which can be used in the optimisation algorithm.

## TSA Force Optimisation Algorithm

This uses a modified algorithm from to select an optimal force vector from the desired joint torque. A force matrix is created from the torque input , jacobian from the vector function as defined in equation [[eq:string1]](#eq:string1), and minimum force constant . is equal to , while the other elements in the column are based on a calculation using where is a row removed from the matrix.

The following algorithm then selects one column of to be the output force vector .

## TSA Force Proportional Controller

The selected forces are then used as an input to a Proportional controller using the measured load cell forces as feedback. The output from this can then be used to control the top, left and right TSA motors.

### Simulation Current Control

In the simulation, each TSA was modelled as a state space system from which takes motor current as an input and outputs as the TSA tension force. defines it as such, where is the motor inertia, is the motor coulomb friction (modified from viscous friction as the 1724TSR only has dry friction), is the motor torque constant, and is the load stiffness. As the original definition is for a fixed load distance from the motor a modified model is required which takes into account the varying length between the motor and load defined by . A saturation function is used to prevent incorrect compression forces when the string is slack. All of the motor coefficients were taken from the Faulhaber 1724TSR datasheet as this is the motor used in the experimental system. An estimated value is used for the load stiffness, this was chosen to be a high number as the model is expected to be very stiff.

The state space model was then adapted to include constraints on motor velocity and acceleration set by the motor controller in order to keep the motor within design limits, by replacing with which contains saturation functions for maximum motor velocity and acceleration .

### Experimental Velocity Control with Deadband Compensation

In the experimental system, current control did not result in a stable output, so instead the P controller output would be the motor velocity as (each motor controller has a hardware velocity PI controller). Due to a motor deadband within 10, an adjustable deadband compensator is used,

where is the compensator for the controller . An adjustment value changes the threshold at which the compensator switches on and off, allowing for a small deadband to remain. A graph of this function is shown in figure [[fig:deadband]](#fig:deadband).

The result from the TSA is then a compressive force acting between each of the three TSA and its corresponding endpoint on the Antagonistic Triad, imparting a torque on the axes of the universal joint.

### DCC

This mode takes a preset velocity and uses a hardware PI controller with velocity feedback to generate a control voltage. This voltage is then multiplied by the signum of the result from the cascade function in order to ensure the motor spins in the right direction, and then passed to a current limiter with the current error (the result with the actual current subtracted) as the limit, before being sent to the motor. This ensures the motor stops spinning when the target current is reached.

Where is an unknown hardware limiting function that controls the motor speed depending on the current error.

### Proportional Current Controller

This strategy is a more direct method of current control, using a software P controller to directly set the voltage of the motor, using the MCDC 3002 as simply a passive amplifier. In this case the current error is passed directly to a P controller which has its output limited to prevent damage to the motors.

### Velocity Control

This strategy simply uses the result from the cascade function as a velocity setpoint using the hardware velocity PI controller as in the DCC.

# Simulation & Experimental Results

To design and refine the parameters of the control system, a Simscape Multibodymodel of the antagonistic triad and control system was created in MATLAB/Simulink. This allowed for model design coeffecients and controller gains to be modified in order to have the most stable control within design limits.

Model coefficients.

| Coefficient | Value | Coefficient | Value |
| --- | --- | --- | --- |
|  | 41.8 mm |  | 1 × 10−6 kg m−2 |
|  | 0 mm |  | 1000 N m−1 |
|  | 13 mm |  | 3 N |
|  | 41.8 mm |  | 441.9 rad s−1 |
|  | 200 μm |  | 0.19 A |
|  | 72.61913 g |  | 0.0263 N m A−1 |
|  | 0.1315 N mm |  | 4.5 mN m |
|  | 1 × 105 rad s−2 |  |  |
| Coefficient | Value | | |
|  | kg m−2 | | |

PID gains in the simulation and experiment.

|  |  |  |
| --- | --- | --- |
| Gain | Value | |
|  | Simulation | Experiment |
|  | 800 | 3 × 104 |
|  | 3000 | 350 |
|  | 50 | 50 |
|  | 19 | 100 |

Tracking mode, see section [3.2](#subsec:winduptracking).

## Experimental Setup

For the experimental validation, a physical prototype of the mechanism was constructed with coefficients from table [1](#table:coeff) as design parameters. This was mounted vertically, in order for the IMU to measure the orientation of the universal joint. The TSA mechanisms consist of a compact high torque motor (Faulhaber 1724T024SR) attached to the base segment, with a string clamp attached to the motor shaft. On the follower segment, a load cell is mounted on top of a universal joint to ensure a purely axial load, with a capstan bolt attached to the load cell. The string itself is attached to the clamp at both ends using two grub screws for extra security and easy adjustment, and looped through the hole in the capstan bolt. Figures [1](#fig:cad) and [[fig:photo]](#fig:photo)

The motors were controlled by Fauhaber MCDC3002 motor controllers, which could interface with a National Instruments MyRIO via the USB port, using a USB to serial converter. The load cells were Futek LCM100 minature load cells, selected for their small size. The signals from these were amplified using Flyde FE-359-TA instrumentation amplifiers and decoded using an external AD7606 ADC before being fed into the MyRIO using SPI. The orientation of the AUJ was measured using a Bosch Sensortec BNO080 IMU using the accelerometer data.

Schematic of the experimental system with labelled components.

## Windup & Tracking States

When the mechanism is started with the TSA in a completely unwound state, before it can begin tracking a motion trajectory, the TSA strings must ‘‘wind up’’ to closely match the intial state of . During this phase, the outer PID gains are unsuitable and can result in damage to the mechanism. To mitigate this, two sets of PID gains are chosen, one for the windup state (, ), and another for the tracking state (, ), which the windup state transitions to once suitable stability is achieved. This transition trigger is defined on a per-axis basis, as the first zero crossing of the angle error (as this is effectively ). A graph showing the difference this state change makes to the AUJ orientation is shown in figure [[fig:winduptracking]](#fig:winduptracking).

## Results

### Force Proportional Controller & Motor Characterisation

Before verifying robust control of the AUJ, the control of each individual TSA needed to be tested in order to characterise the performance of the motors and to ensure the inner loop control system was robust. This would involve selecting the control strategy that gave the best performance. A test trajectory consisting of a smooth ramp followed by a sine wave was fed into the inner loop of the cascade function as . Each control strategy was tested, and in the end the velocity control strategy proved most optimal, as is shown in figure [[fig:track]](#fig:track). The results of a sinusoidal force trajectory for the velocity control strategy is shown in figure [[fig:characterisation]](#fig:characterisation). As can be seen in the in the inset, there is a stick-slip friction effect whch causes a sawtooth like effect on the measured force. This means the motor angle has to be contantly adjusted even with a constant force input, in order to mantain the setpoint force.

### AUJ Position PID Controller

Figure [[fig:results]](#fig:results) plots the tracking response of both the simulation and experiment. Three trajectories were created to test the capabilites of the mechanism. Two were only in one axis of the Universal Joint, and the third was in both axes. The deflection angle range was limited due to the low value of , but can easily be extended by increasing this value. A low was chosen as it resulted in easier installation.

# Performance Comparison

To compare the performance of a TSA AUJ against alternatives, we can measure two metrics, the maximum tension force and maximum stroke velocity . This corresponds to the equivalent of maximum torque and maximum velocity in a rotary motor, a larger would be able to actuate a larger follower mass, and a larger would be able to rotate the AUJ more quickly. The alternatives chosen for comparison are leadscrews of various rod diameters and pitches , and a ‘‘direct drive’’ where the motor is rotating the universal joint directly without any reduction or motion transformation.

## TSA

For the TSA metrics, the equations from , in particular and as used for the state space, which can be used to determine and . By extracting coefficient as an input to make and the performance of different string thicknesses can be compared for a given unwound length and over the range of the contraction length .

## Leadscrew

For the leadscrew metrics, the raising torque calculation can be used as the absolute value of , since the TSA only operates in tension, which can be used to determine the same metrics. The performance of different screw diameters and leads can then be compared for a given and coefficient of friction . is then calculated by multiplying with . The performance of different can then be compared for a given .

## Direct Drive

The direct drive metrics are trivially calculated using the lever force and tangential velocity that would be generated at the endpoint of a linear actuator able to impart equivalent angular velocity and torque on the universal joint.

$$f\_{max} = \frac{\tau\_{max}}{\sqrt{l\_{2}^{2} + r^{2}}}\\$$

$$\dot{p}\_{max} = \dot{\theta}\_{max}\sqrt{l\_{2}^{2} + r^{2}}\\$$

## Comparison between TSA and Leadscrew

As the values for and for the TSA depend on , but remain constant for the leadscrew, the performance of the TSA is going to be better or worse than a given leadscrew depending on the value . Figure [[fig:comparison]](#fig:comparison) compares the TSA configuration using the coefficients from table [1](#table:coeff) against a number of common leadscrew configurations that are practical for the dimensions of the AUJ . The TSA outperforms or underperforms different leadscrew configurations depending on .

# Discussion & Conclusion

## Discussion

## Conclusion

This research has demonstrated the robust control of the orientation of a universal joint using TSA in an antagonistic triad configuration. It has also compared the performance of the system to alternative actuation methods. Future developments would include improvements to the orientation sensors, the data from the IMU proved to be unreliable and of poor resolution (2.0 ° static, 3.5 ° dynamic). The magnetomoter was unusable within the indoor experimetal enviroment even after several calibration attempts, so the universal joint angle would not be able to be calculated when the gravity vector is not orthogonal to the unviersal joint DOF. An alternative method for sensing the universal joint orientation should be investigated, such as LVDTs, hall effect sensors or potentiometers. Alternative control algorithms that are less or not dependant on the dynamic properties of the follower segments (mass and inertia) will also be considered, in order to improve the robustness of the control system to external forces. The 1724TSR motors also had poor performance at low speeds, necessitating the deadband compensator. Investigating the use of similar size and torque brushless motors with sinusoidal commutation for stable low speed control could eliminate the need for the compensator, and allow for smoother AUJ motion. Eventually, we wish to develop a system comprised of multiple segments, to demonstrate its suitability for applications such as mobile snake robots or snake-arm robots. This can use a embedded controller for each segment, controlled by a master controller for individual joint control or inverse kinematics, as if figure [[fig.chain]](#fig.chain).

image

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