Proceedings of the ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC/CIE 2013
August 4-7, 2013, Portland, Oregon, USA

DETC2013-13614

CONFIGURABLE COMPLIANCE FOR SERIES ELASTIC ACTUATORS

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ABSTRACT

Variable compliance has been a growing topic of interest in legged robotics due to recent studies showing that animals adjust their leg and joint stiffness to adjust their natural dynamics and to accommodate changes in their environment. However, existing designs add significant weight, size, and complexity. Series Elastic Actuators, on the other hand, are designed with a set stiffness usually tuned for actuator performance. We propose a new concept for implementing a physical spring in series with a linear SEA using a cantilevered spring. A movable pivot is used to adjust the stiffness by changing the effective length of the cantilever. While the proposed design does not allow for variable compliance, it does retain many of the benefits of passive spring elements such as absorbing impacts, storing energy, and enabling force control. The primary advantage of the design is the ability to adjust the stiffness of each joint individually without the increased weight and complexity of variable stiffness designs. This paper introduces the motivation for configurable compliance, describes the proposed design concept, explains the design methods, and presents experimental data from a completed prototype.

INTRODUCTION

The role of compliance in nature continues to be a growing research field as researchers learn more about how animals and humans utilize the natural compliance of muscles and tendons. Compared to state-of-the-art robots, biological systems demonstrate remarkably better efficiency, agility, adaptability, and robustness. Many recent studies suggest that a core principle behind these advantages is compliance.

For example, Alexander proposed that legged animals make use of compliance to absorb foot impacts, to bounce like pogo stick-like springs during walking and running, and to serve as return springs for reversing the direction of swinging limbs [1]. Other studies have found that animals actively adjust the stiffness of their joints and limbs to adjust the natural dynamics of the system in response to disturbances or changes in their environment. For example, Ferris has shown that humans adjust the stiffness of their legs to accommodate changes in surface stiffness during hopping and running [2, 3].

Numerous other studies have investigated compliance in a variety of species and in behaviors even beyond locomotion. Roberts presents a compilation of studies that show how compliance serves diverse roles in metabolic efficiency, muscle power amplification and attenuation, and mechanical feedback for stability [4]. Robots could benefit from many of these advantages, especially in applications where moving naturally, absorbing impact loads, storing energy, and working safely around humans are priorities. Robots with the ability to adjust stiffness could be especially advantageous by being able to adapt to different loading conditions and environments [5].

In this paper we present a design for implementing compliance in robots, especially those using linear series elastic actuators. We start by discussing the variable compliance designs in literature and explain the motivation for a new approach to implementing compliance called configurable compliance. The design is based on a cantilevered spring with a movable pivot capable of changing the effective stiffness of the springs. We describe the benefits and limitations of configurable compliance and then describe the design process for our specific implementation. Finally, experimental data is used to fit a model for how stiffness changes over the adjustment range.

SAFFIR HUMANOID

The configurable compliance design described in this paper is part of a linear series elastic actuator that we have developed for SAFFiR (Shipboard Autonomous Fire Fighting Robot), a full-scale humanoid robot being developed for the Navy to serve in disaster [6]. SAFFiR, pictured in Figure 1, has 33 DOF; two 6 DOF legs and arms, a 1 DOF waist, 2 DOF neck, and 3 DOF hands. When completed, the robot will stand 150 cm tall and weigh 40kg.

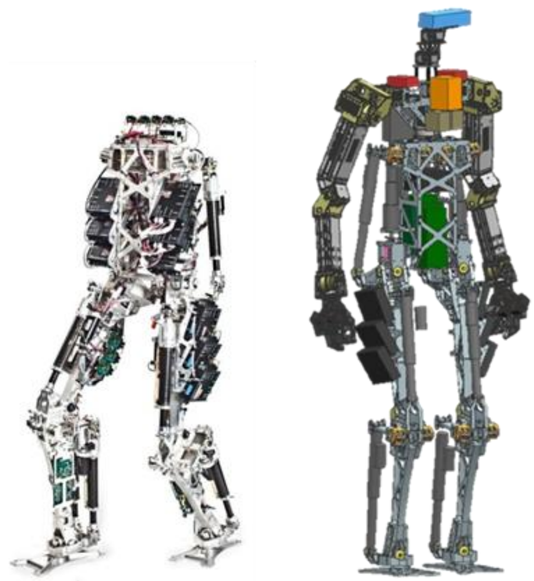


Figure 1: Currently state of completion of SAFFiR on left and proposed final CAD model.

The lower body of SAFFiR employs parallelly actuated joints using custom series elastic actuators. The configurable compliance design presented in this paper is a component of these linear series elastic actuators shown in Figure 2. SAFFiR was designed to investigate and take advantage of more compliant control schemes and to investigate the role of compliance at different joints for locomotion. One of the design challenges, which this paper will address, is determining what the stiffness values at each joint should be and how to physically implement the compliance for linear actuators.

VARIABLE COMPLIANCE

Given the examples and benefits of adjustable compliance found in nature, several groups have been working to develop novel approaches for implementing variable compliance. Each group seems to have a unique approach and will often use different naming conventions. The confusion arises from the complementary nature of the terms compliance and stiffness as well as the interchangeability of the terms adjustable, variable, and controllable.

In this paper we use the term variable compliance, by which we mean a mechanism or method which uses a passive physical spring element, the stiffness of which can be adjusted during operation by some mechanical means. There are many different approaches to variable compliance designs [5, 7]. As is often the case in robotics, the particular implementation of a design depends in large part on the specific needs of the application. Van Ham provides an overview of the main design approaches and provides multiple examples of each [8].

In this paper we are not commenting on the validity or usefulness of any existing designs. Each design has its advantages and is likely well suited for the designer's specific application. However, in the case of full-scale humanoids there are stringent constraints on the weight, complexity, and size of components. Unfortunately, many of the existing variable compliance designs feature one or more of these drawbacks.

The most common drawback of variable compliance designs is the use of two motors. In some cases the motors are arranged antagonistically, using both motors to adjust both the preload and the equilibrium position. In other cases one motor is used to adjust the stiffness while the other motor controls the equilibrium position of the joint. Either way, the addition of a second motor has a significant impact on weight. There are also typically gear trains, mechanisms, or additional moving parts used for adjusting stiffness of the spring element. These additional components not only add to the weight but also increase the actuator's complexity, part count, and volume.

CONFIGURABLE COMPLIANCE

These drawbacks are especially a challenge for humanoids which are high degree of freedom (DOF) systems. Having many DOFs means that any additional weight, complexity, or size gets multiplied by the total number of actuators; leading to large impacts on overall weight.

As an alternative, variable compliance can be mimicked by combining an active software controller with a physical spring of a fixed stiffness [9]. The use of a fixed stiffness loses the ability to adjust the system's natural dynamics, while the active stiffness controller leads to a reduction in efficiency due to its continuous energy use. Nevertheless, the physical spring retains several benefits such as absorbing impacts, storing energy, and enabling force control. An example of fixed stiffness passive springs is Pratt's Series Elastic Actuator (SEA) which essentially uses the spring as a sensor for force control [10]. The fixed stiffness of SEAs is typically designed for actuator performance, tuned for low impedance and high bandwidth control. Because the spring is treated as a component of the actuator, the same spring stiffness is used at every DOF.

In contrast to this "one-stiffness-fits-all" approach, we believe there is a strong case for using different stiffness settings throughout a robot. Each joint has different power requirements, mechanical advantage, velocity profiles, and makes different contributions to the overall locomotion behavior. One example of this principle is the observation that distal joints are more likely to experience impact loads (lower stiffness desired) while proximal joints experience larger inertial loads (higher stiffness desired).

As a way to investigate this principle, we have developed a design for configurable compliance in which a passive physical spring has a fixed stiffness during operation but can be adjusted manually to achieve different stiffness values at any of the DOFs. In contrast to variable compliance, configurable compliance is not controllable and loses the benefit of modifying the natural dynamics. Nevertheless, it does maintain the benefits if having a physical spring and provides a method to tune the compliance in each joint. To use the terminology in [8], our configurable compliance acts as an equilibrium controlled stiffness under operation but has a structure controlled stiffness which can be adjusted manually.

SAFFIR SEA DESIGN

The configurable compliance design in this paper is primarily a method for implementing a physical spring in series with a linear SEA. The overall design of the SAFFiR series elastic actuator is shown in Figure 2. A custom lightweight linear actuator is coupled with a cantilevered titanium beam which serves as the series spring. The actuator is powered by a 100 Watt Maxon EC 4-pole brushless DC motor running at 48 volts which drives a belt reduction and then a ball screw reduction. The actuator is attached to the robot on either end using u-joints. The actuator generates 1000 N, travels at 0.35m/s, has a range of 110mm, and weighs 0.816 kg including the compliant titanium beam.

The cantilevered beam is positioned perpendicular to the actuator such that the beam deflection is in line with the axis of the linear actuator. The u-joints at either end turn the actuator into a two force member and are used to restrict the relative rotation of the ball screw and the ball nut. The upper u-joint has a split-trunnion design, shown in Figure 4a, which serves to house a low-profile load cell for force feedback. A more detailed description of the SAFFiR linear SEA can be found in [11].

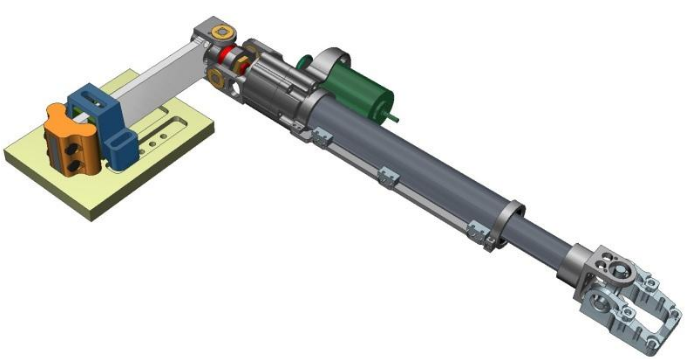


Figure 2: SAFFiR series elastic actuator with configurable compliance.

CONFIGURABLE DESIGN

The configurable compliance design, shown in Figure 3, is composed of a titanium cantilever beam that is fixed to a base plate at one end, has a movable pivot, and is attached to the upper u-joint of an actuator at the other end. One of the benefits of this configuration is that the cantilevered beam serves the dual purposes of providing compliance and serving as an attachment point for the actuator, allowing the beam to serve as a structural component and leading to a reduction in overall weight. The cantilevered beam approach moves the spring element away from the main body of the actuator resulting in a shorter overall length compared to methods which place the spring elements in line with the actuator. Another benefit of the design is modularity; the same components are used at every joint while accommodating a wide range of stiffness settings. The stiffness setting can be adjusted independent of the actuator, making the actuators easily interchangeable and allowing the stiffness of any joint to be adjusted on a fully assembled robot.

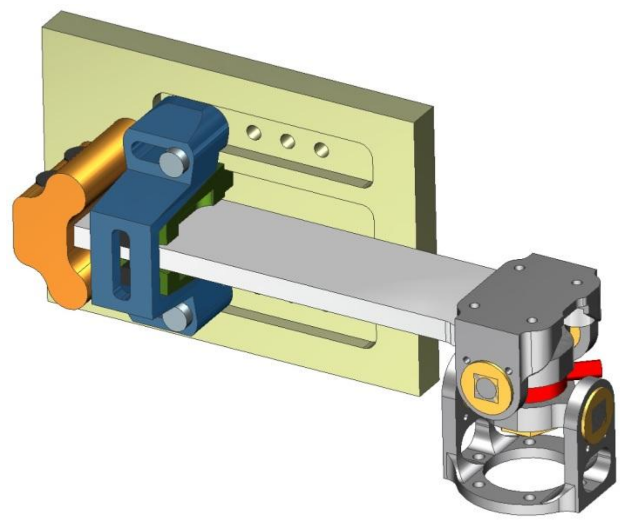
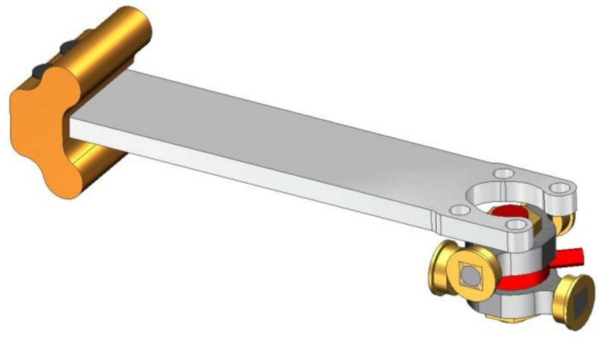


Figure 3: Configurable Compliance design.

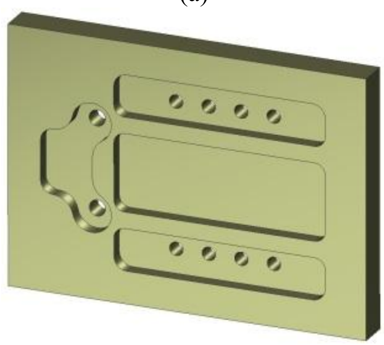
The cantilevered beam central to this design is a well suited method for implementing compliance in linear actuators. Unlike the compression die springs commonly used, a cantilever is bidirectional. A cantilever can be readily designed and fabricated on conventional shop equipment. Selecting the strength and stiffness range of the beam is only a matter of selecting the material and geometry (length, width, thickness). The addition of a movable pivot enables the stiffness to be adjustable from very compliant to infinitely stiff.

The actuator end of the cantilever has a bolt pattern for the u-joint and includes a cutout for the load cell, as shown in Figure 4a. Both the cutout and the split trunnion are features designed to reduce the overall length of the actuator.

The fixed end of the cantilever interfaces with the robot using a fixed clamp, shown in Figure 4a, that fits into a matched recess in a base pattern, shown in Figure 4b. The base pattern can be machined into any rigid support structure or link on the robot and includes other features which interface with the movable pivot. It is important for the pivot to be rigidly fixed to both the robot and the cantilever. We accomplish this by using a tapered outer clamp and two tapered inner pivots, shown in Figure 5a.



(a)



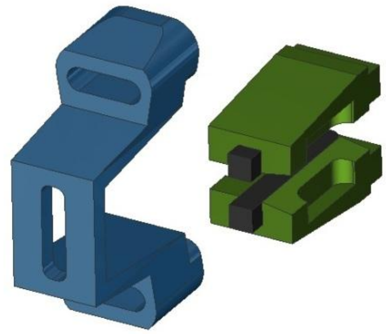
(b)

Figure 4: Cantilever Spring with fixed adapter (a), base pattern which can be machined into any part on the robot (b).

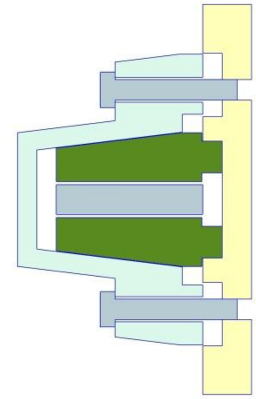
The taper provides a way to tighten the pivots firmly against the cantilever while also clamping the pivots into the base pattern. The cross section view in Figure 5b illustrates the taper and how the clamp interfaces with the base pattern. The clamp is designed with a 7 degree taper and an axial travel of 4mm which translates into a 1mm travel in the direction of the clamping force. The base pattern's two outer slots are used to keep the outer clamp from flexing outward as it is tightened. The inner slot of the base pattern serves a similar purpose, keeping the inner pivots centered and providing a rigid attachment to the base.

Stiffness adjustment is made possible by the threaded holes in the base pattern and the horizontal slots in the outer clamp. The threaded holes are placed 10 mm apart while the slot allows the outer clamp to slide 11 mm horizontally. Since the slot travel overlaps the bolt holes, the movable pivot can be positioned at any length along the cantilever by a combination of sliding the clamp within the slot and changing the threaded holes being used to bolt the pivot together.

The inner pivots are composed of aluminum which would not serve well as a bearing surface. Therefore, two flat steel inserts are used to take the load of the cantilever beam. Note that the forward facing side of the inner pivots has an angled cutout to ensure that the cantilever beam only bends about the steel insert. The inserts are also longer than they need to be such that they extend into the vertical slot in the outer clamp, which serves as a reliable method to align the two inner pivots along the beam.



(a)



(b)

Figure 5: Outer clamp and inner pivots (a), cross section view of the movable pivot clamp (b).

If it becomes necessary to completely lock out the compliance, the titanium cantilever can be easily replaced with an aluminum rigid member shown in Figure 6. The rigid member uses the existing mounting holes and slots in the base pattern to ensure a rigid connection.

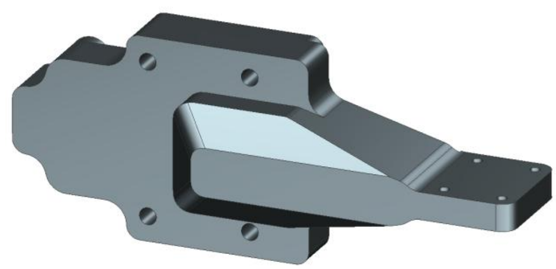


Figure 6: Rigid member.

CANTILEVERED BEAM DESIGN

The most critical variables in the configurable compliance design are the material and the geometry (length, width, thickness) of the cantilevered beam. Considerations for material selection include availability, machinability, creep, thermal properties, electrical conductivity, and many others. However, for compliant mechanisms, an especially important characteristic is the ratio of yield strength to Young's modulus. This ratio provides a measure of how much the material will bend before yielding.

For a beam with a uniform rectangular cross section undergoing bending, the max deflection before failure is given by [12]:

$$\delta_{max} = \frac{2}{3} \frac{S_y}{E} \frac{L^2}{h} \tag{1}$$

Where S_y is the yield strength, E is the Young's modulus, L is the cantilever length, and h is the cantilever thickness. Note that the max deflection is independent of the beam width. The width is still important, however, as it determines the max load, and thus the stiffness.

$$\sigma_{max} = \frac{6FL}{bh^2} \tag{2}$$

Where F is the load and b is the cantilever width.

Equation 1 shows that the maximum deflection is dependent on the geometry and on the ratio of yield strength to Young's modulus. For a given geometry, the material with a higher ratio will result in a larger deflection before failure. Table 1, adapted from [12], lists typical values for materials commonly used in compliant mechanisms. Note that the values, especially the yield strength, for a particular material depend heavily on the specific alloy, heat treatment, or epoxy used.

Table 1: Young's Modulus and Yield Strength of Common Compliance Materials

Material	**E** (GPa)	**S_y** (MPa)	**(S_y/E)** x1000
Steel (1010 hot rolled)	207	179	0.87
Steel (4140 Q&T@400)	207	1641	7.9
Aluminum (7075 Heat Treated)	71.7	503	7.0
Titanium (Ti-13 Heat Treated)	114	1170	10
Polyethylene (HDPE)	1.4	28	20
E-glass (73 vol %)	56	1640	29

While the S_y/E ratio is important, the material's other properties must also be considered. E-glass has a very good ratio and yield strength, but it is susceptible to changes in temperature, which would lead to undesirable changes in stiffness. The actual yield strength and modulus values should also be considered. HDPE has a large S_y/E ratio but both of the individual values are very small. For a given length and thickness, an HDPE spring would have to be very wide to achieve the same stiffness as a material with the same ratio but higher E and S_y values. Aluminum and 1010 Steel can similarly be eliminated from consideration due to their low yield strengths.

Selecting between steel and titanium is a more difficult decision. Titanium has a higher S_y/E ratio but the high grade alloys are more difficult to find and more difficult to machine. A lower S_y would mean that the spring would have to be larger, but titanium is lighter than steel so the spring would end up having a similar weight. For reference, the titanium that we sourced for our design is Ti-6Al-4V ASTM Grade 5, with a Young's modulus of 115 GPa and a yield strength of 828 MPa, leading to a S_y/E ratio of 0.0072. Ultimately, we selected titanium, despite the slightly lower ratio, due to its much better corrosion resistance. With a material in mind, the cantilever geometry can be readily designed using Equations 1 and 2 to achieve both a desired stiffness and a maximum load.

For these calculations, the configurable compliance is modeled as a fixed end cantilever, the length of which varies, defined as the distance from the movable pivot to the centerline of the linear actuator. Space constraints limited the adjustment range of the movable pivot, resulting in a possible cantilever length range of 65mm at the shortest setting to 110mm at the longest setting. The design parameters used were a maximum length of 125mm, a desired stiffness range of 150-350 kN/m, and a maximum force of 1000N.

The final dimensions of our design are a total length of 125mm, a beam thickness of 6mm, and beam width of 30mm. The resulting beam has a deflection safety factor of 1.46, a load safety factor of 1.35, and a theoretical stiffness range of 145-512kN/m. Figure 7 shows the configurable compliance design assembled on the knee joint of SAFFiR.

Figure 7: Configurable compliance in the knee joint of SAFFiR.

EXPERIMENTAL RESULTS

In designing the beam we modeled it as a cantilever with a fixed end and a concentrated load. However the movable pivot of the configurable compliance design may be more accurately modeled either as a pinned-pinned beam with an overhanging load or as a fixed-pinned beam with an overhanging load as shown in Figure 8. The best fit model depends on how well the fixed clamp behaves as a fixed constraint and how well the movable pivot behaves as a pin.

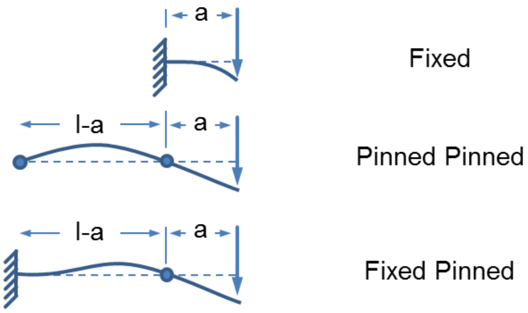


Figure 8: Cantilevered beam loading conditions.

The deflection equations for each loading condition are given below:

$$\delta_{fixed} = -\frac{Fa^3}{3EI} \tag{3}$$

$$\delta_{pinpin} = -\frac{Fla^2}{3EI} \tag{4}$$

$$\delta_{\mathrm{fixedpin}} = -\frac{F}{12EI}\left(a^3 + 3la^2\right) \tag{5}$$

Where **δ** is the deflection at the end of the beam, **F** is the load, **l** is the total length (125mm), and **a** is the distance from the pivot to the centerline of the actuator. Equations 3 and 4 can be found in beam formula tables [13] while Equation 5 can be found by the superposition of a fixed cantilever with a concentrated end load and a fixed cantilever with a concentrated intermediate load.

Of the three models, the fixed end case in Equation 3 is the most conservative model so it was used in the design. However, in predicting the actual compliance as a function of length, it is important to experimentally find a model that best fits the behavior of the beam. Experimental data was collected for a range of stiffness settings and applied loads. The data was used to calculate the stiffness at each setting and then used to formulate a model for the overall configurable compliance behavior.

An actuator with configurable compliance was placed on a test stand with the ability to apply known loads in both tension and compression using a series of calibrated weights, up to 690N (155 lbf). The actual force applied to the cantilever beam was directly measured with the actuator load cell (Futek LCM200) at a resolution of ±2N. A dial indicator with a 0.0127mm (0.0005in) resolution was used to directly measure the deflection of the spring at the centerline of the linear actuator. The movable pivot was adjusted over five different settings (71mm, 80mm, 88mm, 98mm, and 108mm) and at each length a series of loads were applied in both tension and compression (±93N, ±187N, ±280N, ±458N, ±687N). The data from these experiments is shown in Figure 9. Only the tension loading case data is shown for simplicity.

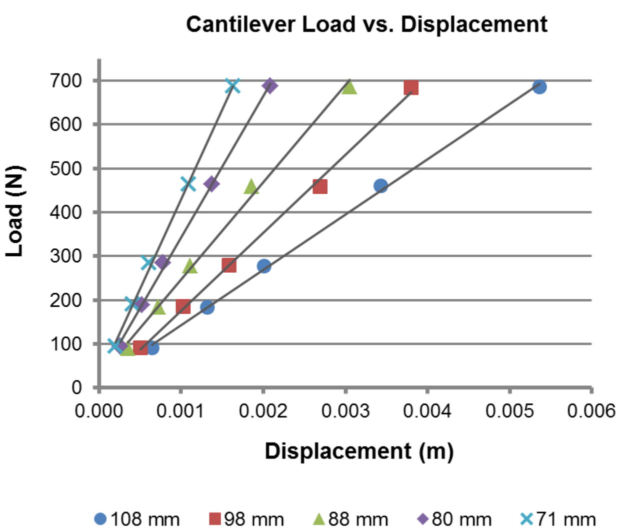


Figure 9: Experimental load vs. deflection.

Each data set was fit with a linear regression to find the spring stiffness as a function of the movable pivot setting. The linear fits and R^2 values are:

$$y_{108} = 126{,}151x + 17 \qquad R^2_{102} = 0.9989 \tag{6}$$

$$y_{98} = 177{,}891x - 2 \qquad R^2_{102} = 0.9979 \tag{7}$$

$$y_{88} = 221{,}842x + 24 \qquad R^2_{102} = 0.9958 \tag{8}$$

$$y_{80} = 321{,}899x + 21 \qquad R^2_{102} = 0.9988 \tag{9}$$

$$y_{71} = 409{,}389x + 21 \qquad R^2_{102} = 0.9985 \tag{10}$$

The results show well matching linear regression fits, indicating that the spring behaves linearly as expected. The small y-intercepts, which we would expect to be nearly zero, also indicate good fits and spring behavior.

To see how the configurable compliance varies with length, the stiffness values at each setting were plotted and fit with a power curve as shown in Figure 10. Also plotted on the curve are the stiffness curves for each of the three theoretical models shown in Figure 8. The equation for the power curve fit of the experimental data is given as:

$$y = 4.12e10\, x^{-2.70} \qquad R^2 = 0.9919 \tag{11}$$

The data and fit show that the configurable compliance design behavior is bounded by the fixed beam and the fixed-pinned beam models. Given that our design has a fixed clamp and a pivot clamp, we would expect the experimental data to be closer to the fixed-pinned case. One of the explanations for this behavior could be that the movable pivot clamp behaves partially like a fixed clamp. Nevertheless, now that we have a model for stiffness, the configurable compliance can be adjusted for any specified setting within the range.

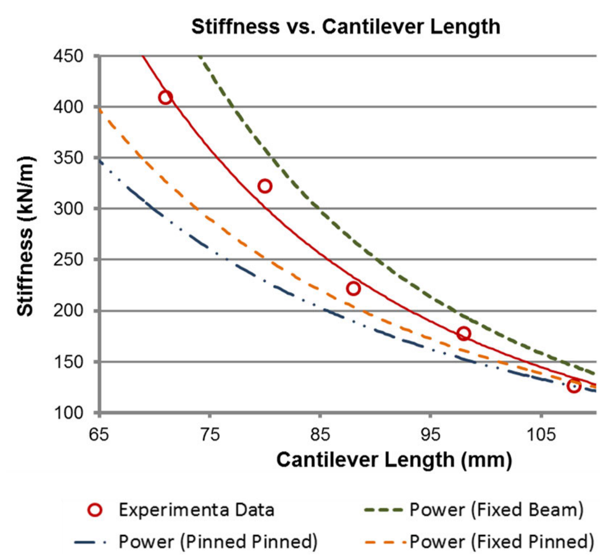


Figure 10: Stiffness vs. movable pivot position.

DISCUSSION

The configurable compliance design described in this paper has several benefits, particularly for linear series elastic actuators. Firstly, it allows for the compliance to be non-uniform across different joints. The compliance is therefore treated as a joint level component instead of simply a force sensor for the actuator. By adjusting the compliance for each joint, the springs can be tuned for different power requirements, mechanical advantage, velocity profiles, and bandwidth requirements.

Secondly, the compliance is decoupled from the actuator which allows the stiffness to be adjusted without changing the actuator length and makes it possible to adjust the stiffness on a fully assembled robot. This also allows the cantilevered spring to serve as a structural member, leading to a shorter, simpler, lighter, and more modular actuator.

Thirdly, we have shown that the cantilevered beam is easy to design for a wide range of stiffness values. Finally, the cantilever has a linear force-deflection curve at all of the stiffness settings and the configurable compliance is modeled well as a simple power relationship. The experimental data shows that the configurable compliance design is able to reliably adjust the stiffness setting over a large range and can do so with very good accuracy.

CONCLUSION

Many researchers believe that incorporating variable compliance will lead to more adaptable, more efficient, and more robust robots. While many examples of variable compliance have been developed and show promise, their size, weight, or complexity limits widespread use. Configurable compliance as presented in this paper is an alternative which provides the benefits of a physical spring (absorbing impacts, storing energy, enabling force control) while avoiding the common pitfalls. The main drawback of configurable compliance is that it is not controllable (manual adjustment) and loses the benefit of actively modifying the system's natural dynamics.

Nevertheless, the design described in this paper provides several benefits: it allows for a robot's compliance to be non-uniform across different joints, it decouples the stiffness adjustment from the actuator setup, allows the spring to serve as a structural member, and can be designed for a wide range of desired stiffness values. A simple model relates the position setting to the effective stiffness value. While the design is especially well suited for linear series elastic actuators, configurable compliance could have wide ranging applications anywhere an adjustable spring is desirable.

FUTURE WORK

One of the drawbacks of the configurable compliance design presented in this paper is the large footprint of the perpendicular arrangement. For future designs we are considering an arrangement in which a similar cantilevered beam is mounted parallel to the actuator as shown in Figure 11. A small lever arm would attach the ends of the actuator and beam such that the beam is being loaded primarily by a moment load.

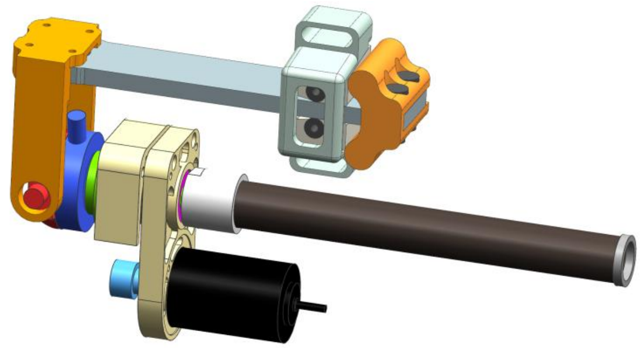


Figure 11: Parallel Beam Configuration.

Other future work includes using the configurable compliance in locomotion. Our approach is to gradually introduce compliance into the lower body in increments. Currently, the lower body of SAFFiR is successfully walking using the rigid members at all of the joints. The next step will be to add configurable compliance at the ankle, then the knee, and then the hip. This approach will allow us to investigate the individual contributions of compliance at each joint.

ACKNOWLEDGMENTS

This work is supported by ONR through grant N00014-11-1-0074 and by DARPA through grant N65236-12-1-1002.

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