

Design and Validation of a Novel Actuator with Adaptable Compliance for Application in Human-like Robotics

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Abstract. In order to achieve limb actuation similar to that of human muscles, a novel actuator with adaptable compliance is proposed. Three principal design paradigms currently exist in the development of artificial muscles that have been adopted at several research centres, universities and commercial organizations around the world. The first approach consists of using compliant actuator systems such as pneumatic actuators. The second approach undertakes the development of electroactive polymers that deform when a voltage is applied. The third approach involves electromechanical devices typically composed of an electrical actuator and an elastic element in combination. The proposed actuator extends on the upon third approach. It is composed of an electrical DC motor in serial configuration and a novel elastic device exhibiting variable stiffness. The novel elastic device complements the mechanical structure of the device, enabling adaptation to the dynamic effects of external forces. Prototypic experimentation has successfully demonstrated the variable stiffness of the device. Several applications for the actuator with adaptable compliance have been identified in the field of human-like robotics.

Keywords: Compliant Actuators; Artificial muscles; Robotics; Human-like applications; Design.

I. INTRODUCTION

For decades robots have been fantasised as walking, talking, and dexterous humanoids and have materialized in books and on screen. Many challenges impede robots from performing in a manner closer to their human creators. Developments in force sensing, CAD, dynamic simulation, and other fields coming to improve the viability of adopting robots in for example automated assembly and manufacturing applications, and have brought robotics in to mainstream service and personal use markets. Recent applications address close interactions between robotic systems and human beings, including direct human-manipulator contact. In such applications, traditional metrics as bandwidth, maximum force and torque capability, and reachable workspace, do not fully encompass the range of parameters that define the requirements of such systems. Specifically, human-centred robotic systems must consider the requirement of safety in addition to the traditional performance metrics. It is therefore the challenge of human-centred robotics to successfully balance often competing requirements of safety and performance. The primary focus in the design and development of robotic manipulators has been on addressing the limitations of existing mechanical systems and the impact safety and performance. For example, much effort has been made to reduce weight and inertia of the manipulators to improve inherent safety characteristics while maintaining performance levels expected of modern manipulators [1, 2].

Artificial muscles can be defined as actuators that provide human-like design, dynamic complementation and light weight to the robot structure. Recent research in this field has predominantly focused upon three principal approaches:

- compliant actuator systems such as pneumatics;
- electroactive polymers;
- combination of elastic elements such as springs with electrical motors (electromechanical).

Pneumatic artificial muscles are typically contractile devices operated by pressurised air. When inflated, they bulge, shorten and thereby generate a contraction force. The force depends on the applied pressure and on the muscle's length, ranging from an extremely high value at maximum length, i.e. zero contraction, to zero at minimum length or maximum contraction. A paired or antagonistic setup is needed in order to generate a restoring force or movement because of the device one-way force. The simplest use of an air muscle is to move a lever. One muscle will pull the lever in one direction, and a spring can provide a returning force. Alternatively, two muscles allow the lever to be pulled in either direction with considerable force. Because the muscle contracts over a known distance, it can potentially be used to provide safe movement - there is no need to ensure that the lever is not going to be rotated beyond its end-stop, because the muscle will only move the lever to its setup angle.

Several pneumatic systems for compliant actuation have been developed in research centres and industry, for example Shadow [3], Festo [4], and pneumatic artificial muscles of Brussels University [5, 6]. The majority, including Shadow and Festo, are based on the McKibben design [7] and they are also available on the market.

One application of the pneumatic artificial muscle is the Shadow dexterous hand [3]. It is an advanced system that reproduces the movement of the human hand and provides comparable force output and sensitivity. This means that it can for example pick up or handle small to medium sized objects and perform precision tasks. The Shadow Hand has integrated sensing and position control, allowing precise control from off-board computers. It contains an integrated bank of 40 Air muscles which provide actuation. The muscles are compliant, allowing the hand to manipulate soft or fragile objects. The Shadow Hand can be fitted with touch-sensitive fingertips, capable of detecting a single small coin [3]. The sensitivity and compliance of the hand permits manipulating

of delicate objects. Moreover, the hand is considered safe for human interaction, as it does not exert harmful forces.

Other applications of the artificial muscles are the developments of “Soft Arm” [5] and the biped robot Lucy [8]. The Soft Arm and Lucy design paradigm has been to develop proof-of-concept manipulators that will be used in direct contact with an operator, without expensive force or torque sensors and without user interaction through control elements. Lucy design paradigm has been to develop proof-of-concept manipulators that will be used in direct contact with an operator, without expensive force or torque sensors and without user interaction through control elements. The pneumatic artificial actuators contribute to the overall safety of the manipulator systems: they allow for a lightweight construction, there is little danger of electrocution and, most significantly, the muscles are inherently compliant. Controllers for the systems are currently under development [8]. The controllers also aim to enhance safety, since there is no fundamental difference between forces generated by a collision and forces applied by an operator.

The most significant advantages of pneumatic artificial muscles are their low weight, particularly useful for weight-critical applications; they are more economical to manufacture and install than comparable actuators and pneumatic cylinders; they exhibit low-latency responses in a smooth and quasi-natural movement; they can be operated when twisted axially or bent around an object, and need no precise aligning; they produce high forces particularly when fully stretched; they are self-damping when contracting; their flexible material construction makes them inherently cushioning when extending, and they are inherently compliant.

Pneumatic artificial muscles do not only depend on vessel pressure but also dynamically on their state of inflation. This is one of the major disadvantages - the mathematical model that supports air muscle functionality is a non-linear system, making precise control difficult. Other disadvantages include: gas is compressible, so a pneumatic muscle that uses long tubes must have a control system that can compensate for the delay between the movement control signal and the resultant muscle action; a pneumatic artificial actuator system needs electric valves and a compressed air generator impeding compact design.

Electroactive polymers (EAPs) are polymers whose shape is modified when it is applied with a voltage, as reported in [9, 10]. They can be used as actuators or sensors. As actuators, they exhibit the ability to undergo a large amount of deformation. Force and velocity are highly depended on device design such as actuator thickness and length, as reported in [11]. Due to the similarities with biological tissues in terms of achievable stresses and forces, they are often called artificial muscles, and have the potential for application where large linear movements are desired. EAPs are an emerging class of materials with novel properties. One of the main advantages of electroactive polymers is the ability to electrically control and dynamically fine-tune their properties. The contractional volume change can be electrically controlled and used for creating different kinds of moving structures-actuators or micromuscles. In surgical applications, guide wires, leads and catheters are used to reach specific areas inside blood vessels. Adding active control and steerability may make it simpler to reach a desired area.

Artificial Muscle Inc., SRI International and EMPA are examples of industrial companies that produce electroactive polymers used in artificial muscles; other electroactive polymer companies are included in [12]. Micromuscle [11] has developed a bench-top prototype where a common guide wire is modified with an electroactive polymer coating in order to demonstrate active steering in a model of a vessel system. The position of the tip is controlled by applying a small potential to the guide wire. The time to move from one extreme position (end stop) to the opposite was a few seconds.

The principal problem of the artificial muscles made by electroactive polymer is the non-linearity of the control scheme that makes difficult the operation of the devices. The advantages of artificial muscles of electroactive polymer are :

- their movements can be reversed and repeated a large number of times;
- components can be positioned and held at any position;
- material properties, such as volume and stiffness of the polymer, can be changed through electrical control;
- materials have demonstrated biocompatibility and are sterilizable;
- they function in liquid environments such as saline solutions, blood, and urine;
- they can be electrically controlled releasing substances from the polymer.

Series Elastic Actuator (SEA) [13] is one of the well known devices that apply an electromechanical solution in a combination with an elastic element placed between the DC motor/gears and the load. Other examples of these types of devices are the so-called Variable Stiffness Actuator [14], Mechanical Impedance Adjuster [15], selective compliant actuator [16], Series Damper Actuator [17], MACCEPA [18], and the Distributed Macro-Mini actuation approach DM2 [1].

VERONICA (Variable joint Elasticity RObot with a Neuro-Inspired Control Approach) is the first biped equipped with the MACCEPA actuator. In passive walkers, the natural frequency of each limb is defined by the mass distribution in the legs. Therefore, it is fixed during design and cannot be changed during walking. This results in passive walkers that have a single predefined walking speed. Veronica walks using Controlled Passive Walking. Here the control strategy is to change the natural frequencies of the limbs by using actuators with adaptable compliance. This permits variation of the walking speed of a passive based walking robot.

The main advantage of the electromechanical artificial muscles is that they permit compactness in the design with relative low-cost and easy-operation. This approach does not need complex components, as the pneumatic solutions (like pumps, pipes, valves and special connections that increase the cost of the systems). The control scheme is less complex than the used for the control of the previous-mentioned approaches of artificial muscles. A disadvantage of electrically driven actuators is however the relatively big weight of the DC motors. Systems that use the above-mentioned elastic actuators usually suffer from limited performance because the added or natural compliance leads to a slow response to torque inputs and oscillation around the goal position [19].

Human-like robots differ from humans in term of both their mechanics and control mechanism. The majority of human-like manipulators are presently composed of rotary actuators with high bandwidth controllers and path planning

algorithms incorporating trajectory feedback. Humans do not cancel or compensate dynamic forces [1]. This suggests that it is necessary to develop new actuation systems capable of mimic the complexity of human limb structures and behaviours, especially in term of dynamic characteristics. Highly dynamical actuators are a necessary component in the development of biologically inspired human-like actuators.

II. MECHANICAL DESIGN AND SIMULATION OF A NOVEL ACTUATOR WITH ADAPTABLE COMPLIANCE

At least two distinct approaches are available for the implementation of variable joint stiffness. Active systems use measurements of joint movement, and possibly interaction forces, to modulate feedback gains and thus change the effective stiffness of the joint. This approach is very similar to impedance control in robotics [20] which has been shown to have many benefits. In a prosthetic application, the active approach suffers from two major drawbacks. First, most implementations of impedance control using feedback require a significant level of computation. For example, this is a limitation in a prosthetic application where the entire device must match the size and weight of a natural arm. Most important in autonomous robots applications is the fact that the generation of impedance using a feedback approach to the implementation of a conservative joint stiffness requires a constant energy drain as the motor must apply a constant force despite the fact that no work is being performed. This inherent inefficiency results in the requirement for more energy, reducing the time that the arm can operate independently before battery depleting.

The passive approach to implementing variable stiffness uses elastic systems, usually in an antagonistic configuration about the joint. By using physical springs driven by actuators, constant forces can be applied without the constant input of energy as required in the active case.

Figure 1 shows the proposed actuator with adaptable compliance. In particular, figure 1(a) shows a 3D-CAD model of the device and figure 1(b) shows a scheme of the mechanical structure of the test-bed prototype. This elastic device is composed of two flexible bars (3) connected to the frame (2). The rollers (4) that are actuated by a DC motor (6) moves forward and backward changing the flexion of the bars (3), thus the stiffness of the output link (1), as shown in figure 1(b). By changing the distance S of figure 2(a) from S' to S'' , the oscillation angle α is decreased from α' to α'' since the stiffness is increased. The damper (7) adjusts the damping of the elastic element.

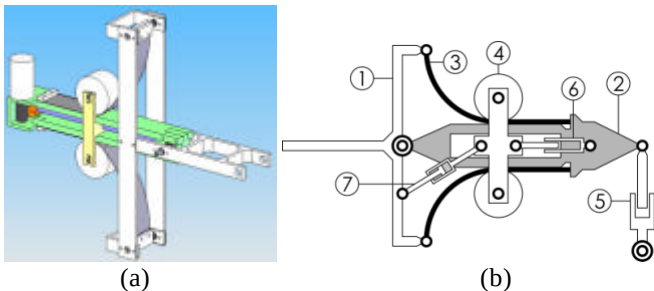


Figure 1. The novel actuator with adaptable compliance: (a) a 3D-CAD model of the elastic device; (c) a scheme of the mechanical structure.

A first DC motor (6) actuates both rollers (4) and damper (7) that change stiffness and damping. The behaviour of the system depends on the relative values of the two fundamental parameters, the natural frequency ω_0 and the damping ratio ζ that have the expressions [21]

$$\omega_0 = (k/m)^{1/2} \quad (1)$$

and

$$\zeta = c / 2 (k m)^{1/2} \quad (2)$$

where k is spring constant; m is mass; and c is damping coefficient.

When $0 < \zeta < 1$, the system is under-damped. In this situation, the system will oscillate at high natural frequency, which is a function of the natural frequency and damping ratio. In fact, when k is increased and c and m are constant, ω_0 is increased in equation (1) and ζ is decreased in Eq. (2). When $\zeta = 1$ the system is said to be critically damped and when $\zeta > 1$ the system is said to be over-damped. The natural frequency in critical damped or over-damped systems is low. For some applications of the proposed compliant actuator, critical damped or over-damped systems with high stiffness are required, as for example in pick and place operations. In this case, the damping coefficient c must be increased in equation (2) for a constant mass of the system. The damper (7) increases the damping in the design of figure 1. In applications of biped robotics, both critical damped or over-damped systems with high stiffness and under-damped system can be required. In this case, another DOF for setting the system damping can be considered to be included. A second DC actuator (5) sets the equilibrium position of whole device around the structure support, as shown in figure 2(b). Therefore, this DOF (5) can represent the joint actuation of a robot structure since the other DOF (6) changes the joint stiffness.

By using the 3D-CAD model of figure 1(a), simulations of the actuator have been examined in ADAMS code in order to validate the feasibility of the assembly and check the operation under dynamic conditions. MSC software ADAMS has been used for dynamic simulations due to its convenient features in simulating the dynamics of multi-body systems. The MSC.ADAMS® can obtain realistic simulations of full-motion behaviour for complex mechanical systems, [22].

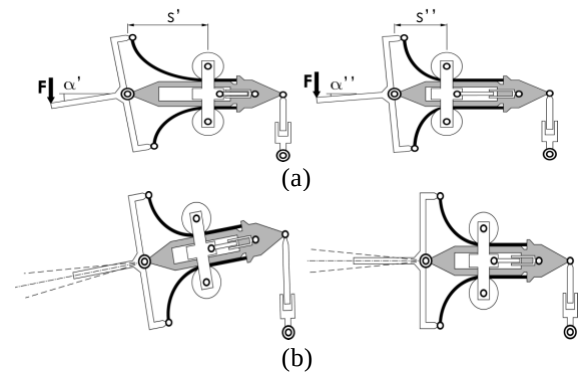


Figure 2. Operation of the elastic device of figure 1: (a) performance of the DOF that provides the variable stiffness; (b) performance of the rotating DOF.

The ADAMS model has been developed by using ADAMS-FLEX toolbox that provides elastic elements for dynamic simulations. The elastic bars (3) of figure 1(b) have been modelled as bars with ten rigid elements connected by flexible joints. The rigid elements have dimensions 40 x 0.5 x 31.4 mm. The used material has a Young's Modulus of Elasticity of 2.07E11 Pa and a Shear Modulus of Elasticity of 8.02E10 Pa. The contact of the elastic bar with the frame and rollers has been modelled with the characteristic of the contact data as:

- stiffness: 1.0E11 Pa;
- damping: 10.0E3 Ns/m;
- force exponent: 2.2 N;
- maximum penetration: 0.1 mm.

The integrator is an algorithm that solves the differential equations of a dynamic problem over an interval of time during a simulation. The used integrator for the simulation has been Gear Stiff integrator (GSTIFF), [22]. The GSTIFF integrator is the default in ADAMS environment since it provides good solutions for simulation of stiff models. The GSTIFF integrator uses a backwards differentiation formula to integrate differential and algebraic equations. In addition, it assumes a fixed time step that results in fixed coefficients for predicting the errors. The time interval 0.1 (10 intervals in 1 sec) has been selected after several attempts for developing the dynamic simulation of the actuator operation in order to obtain suitable numerical results with low-computational efforts. The simulation time has been 20s.

The simulation result of figure 3(a) shows plots of applied torque as function of deflection angle with each curve representing positions of the rollers. Figure 3(b) shows plots of positions of the rollers as function of deflection angle with each curve representing the applied torque. In this case, each curve represents different applied torques. The peaks in figure 3 are due to the rigid segments that compose the ADAMS model. The stiffness changes abruptly when the rollers pass from one rigid segment to the next.

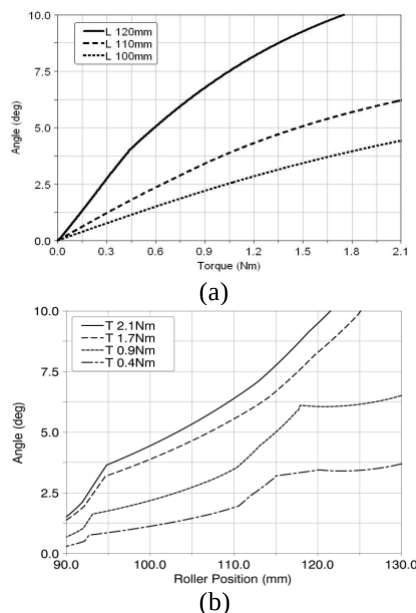


Figure 3. Results obtained during a dynamic simulation with the 3D-CAD model: (a) applied torque vs. deflection angle; (b) positions of the rollers vs. deflection angle.

Anyway figure 3 shows linear tendency of the stiffness and deflection angle when the position of rollers changes. For example, the dotted curve of figure 3(a) presents a linear tendency of torque evolution. The curves of deflection angle of figure 3(a) shows linear tendency even if they present some picks. Nevertheless, for low values of compliance, as in the case of continues and dashed curves of figure 3(a), they present parabolic tendency.

The dynamic effects of applied forces on a robot structure can be suitably compensated for using the above-mentioned solution for a compliant actuator. Variable stiffness of actuated joints by the proposed novel device may be advantageous in application as

- Safe interaction with human being;
- Passive walking;
- High speed operation;
- Humanoid robotics;
- Human prostheses.

A muscle provides both rotational and linear motion as well as variable stiffness for limb joints. Variable stiffness is necessary to obtain a realistic simulation of the movement of the human body. With this approach, the behavior of a human muscle can be mimicked using a variable stiffness spring with a linear actuator simultaneously. Robot inter-actuation with humans requires systems with low stiffness that cannot harm humans or other objects when a collision occurs. The actuator design of figure 1 sets stiffness for the flexible bars in order to address safe operation by imposing the proper compliance. Thus, the control system does not need to change the motor torque to provide suitable stiffness of the joint.

Passive walking is a very efficient schema for mobile legged robots, but nevertheless it even exhibits problems. Passive walkers have a spring of fixed stiffness that elicits limb movement with a pre-established profile of angular velocity. Thus, a passive walker cannot easily change its speed, commence walking or stop. By using a variable stiffness device, the walking pace can be controlled, maintaining efficient passive walking. Moreover, the stand-up position of biped robots can also be controlled using an elastic element with suitable stiffness.

Actuators for humanoid robots must provide a high force in order to manage the mass of the components. Nevertheless, in high speed operation the actuator must work at high velocity, and in some case, high torque. An electric DC motor with high velocity and high torque is typically heavy to be used in humanoid. A variable stiffness spring can be used to drive the movement of the robot structure in a high speed operation. For high speed operation, an under damped system should be set up. The compliance should be set according to the desired response frequency in order to achieve mechanical amplification of the system response [23]. The actuator that changes the equilibrium positions gives the excitation for the movement.

Human prosthesis application is closely related to the humanoid robotic application. It is important to incorporate naturalistic operation, similar to that of the human muscle. An actuator with adaptable compliance and compact design can be installed on human prostheses, for example hands, that can be easily controlled by the patient.

An example of a practical application of the proposed actuator can be incorporating the actuator in the actuation

system of the humanoid robot iCub [24]. The current actuation of iCub is composed by commercial DC motors. The biggest motor is the iCub shoulder actuator RBE01211 from the Kollomorgen which provides a maximum torque of about 0.4 Nm at a maximum speed of 4000 rpm. Coupled with a Harmonic Drive hearhead of 1:100 reduction ratio, it provides 40 Nm at 40 rpm that fulfils the actuating requirement. The weight of the couple motor + Harmonic Drive is about 500 g, [24]. The proposed compliant actuator of figures 1 and 4 is composed by two DC motors. The fist is a RS 248-3671 which it sets compliant for the system with a maximum torque of 100 mNm and weight of 40 g. The second is RS 383-1273 linear actuator which sets the equilibrium position with a maximum force of 100 N and weight of 61gr. The device of figure 1 can be design in order to produce an actuating torque of 40 Nm at a bigger velocity than 40 rpm with the same weight of about 500 g of the iCub shoulder. The dimensions and weight of the components can be optimized in order to achieve the desired weight of the system. High velocities can be achieved oscillating the system at high natural frequency by providing a proper stiffness and damping. Another example of the practicality of the proposed system is a comparison with a commercial DC motor with high torque and high speed. CARTRIDGE DDR CH044A is a commercial motor that provides a maximum torque of 31.6 Nm at 2250 rpm with a weight of 8840 g. The proposed actuator with adaptable compliance can be designed to provide the same toque and speed of the above-mentioned commercial motor with lower weight.

The proposed device has important advantages with respect to the design in [15]. The control of the compliance and equilibrium position are fully independent. These DOFs are driven by different actuators which can be dimensioned according to the power requirements. Another advantage is the symmetry of the design that gives equal deflection and compliance for input torques with inverse orientation.

III. EXPERIMENT WITH A BUILT PROTOTYPE OF THE NOVEL ACTUATOR WITH ADAPTABLE COMPLIANCE

Experimental evaluation has been carried out by using the test-bed prototype of figure 4. This prototype has been design and built at the School of Industrial Engineering of the University of Castilla-La Mancha in Spain. Figure 4 shows an overview of the built prototype. Figure 4(a) shows the general dimensions of the system. In particular, the length of the ball screw A is 93.35 mm with 52 teeth. The length of the ball screw C is 24.54 mm with 9 teeth. The gear C has 30 teeth. Therefore, the velocity of the rollers is 3.7 mm/s. The prototype has been constructed by using rapid steel bars having dimensions 40 x 314 mm, and thickness of 0.5 mm. Two DC actuators have been used for the actuation of the system. The weight of the structure is 2.3 Kg.

The experimental test consisted on checking the variation of system stiffness by changing the applied torque. Commercial dumbbells have been used as payloads, as shown in figure 4. For different payloads, the position of the rollers has been changed and the deflection angles have been measured. Figure 5 shows plots of the experimental test results. In particular, figure 5(a) shows a plot of the applied torque as function of deflection angle. Each curve of figure

5(a) represents a different position of the rollers and consequently different stiffness. Figure 5(b) shows plots of position of the rollers as function of the deflection angle. Similar to figures 3(a) and (b), the curves of figure 5 show, with smooth shapes, linear tendency for the deflection angle curves (figure 5(a)) and parabolic tendency for the torque curves (figure 5(b)).

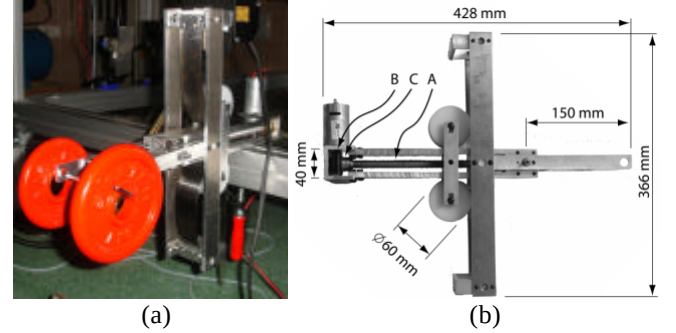


Figure 4. A built test-bed prototype of the novel actuator with adaptable compliance: (a) an overview of the prototype; (b) a top view with the general dimensions.

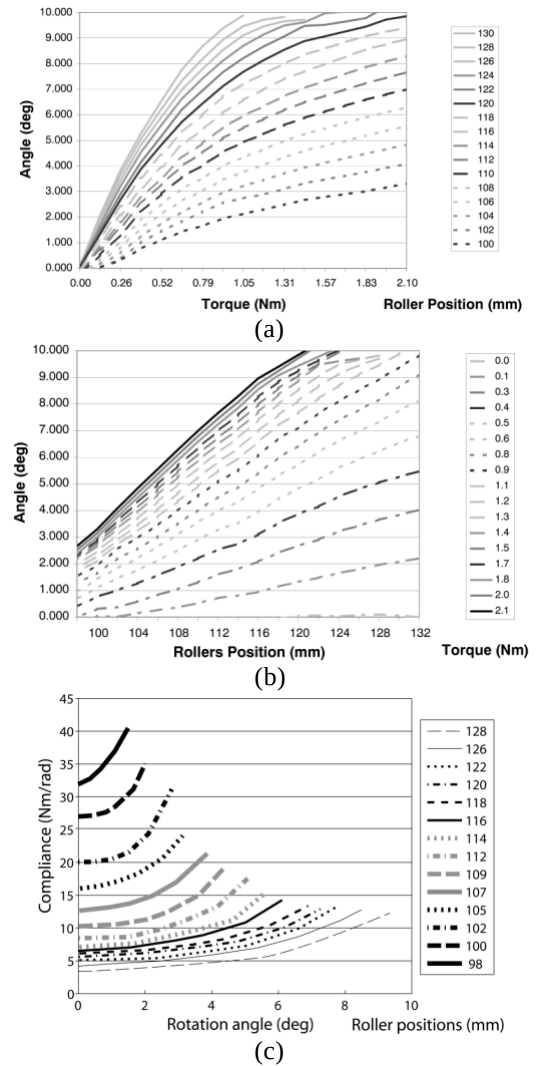


Figure 5. Result plots from an experimental test with the built test-bed prototype of figure 4: (a) applied torque vs. deflection angle; (b) positions of the rollers vs. deflection angle; (c) compliance vs. position of rollers.

Figure 5(c) shows the spring compliance for different position of the rollers. The compliance presents low changes for the beginning of rollers movement (maximum distances from the structure support). Nevertheless, the compliance is increased when the position of the rollers is near the structure support. The results of the experimental test of figure 5 show suitable values of deflection, torque and compliance. The deflection range goes from -12° to 12° . The maximum torque is 2.1 Nm. The compliance range goes from about 3.7 to 40 Nm/rad. These values can be considered proper for practical applications of the proposed actuator in compliant systems.

The comparison of the results of the experimental tests on the built prototype of figure 4 and the dynamic simulation with the 3D-CAD model of figure 1(a) shows satisfactory results. In fact, this comparison validates the operation of the elastic device as an elastic element with variable stiffness for applications of compliant actuation. Similar solution for an elastic element has been adopted by English and Russell in a novel design by using Rolamite [25]. In this solution, two antagonistic non-linear Rolamites are used with a quadratic relation between the deflection distance and applied force. Moreover, this elastic device manifests in a complex design in order to obtain the square applied force response. The proposed novel elastic device of figure 1 and 4 has a relatively non complex design. Significant changes of stiffness can be achieved with relatively small displacements of the rollers since the stiffness of the flexible bars has a non-linear response.

CONCLUSIONS

We propose in this paper a novel actuator with adaptable compliance for robotic applications. The device has two degrees of freedom, one actuates the active joint of the mechanical structure and the second manages the stiffness of the joint at the current position. The proposed device uses non linear elastic bars and two standard DC motor in order to fulfil the variable stiffness operation. The main objective of system development is the design of the elastic element. In order to validate the feasibility of the project, experimental tests have been carried out with a previous elastic device of variable torsion stiffness. This elastic element has been designed and built at the School of Industrial Engineering of the University of Castilla-La Mancha in Spain. The success of the results validates the feasibility of the novel device. The reported results show that the built elastic device can change the stiffness with a quasi-linear behaviour. This linearity of the elastic element operation is useful in compliant actuation for application of human-like design.

The proposed compliant actuation actuator presents a compact design. It does not require heavy systems, as in the case of pneumatic artificial muscles. The structure of the device is composed of easy-manufactured parts and commercial components. It does not require complex mechanisms, as in the case of the Actuator with Mechanically Adjustable Series Compliance (AMASC). The proposed device can provide both high and low compliance depending on the desire application. In the case of the antagonistic setup of two nonlinear springs and the mechanically control stiffness, they can perform mainly low compliance. Finally, the novel actuator with adaptable compliance can be designed

as an actuator with high power, as a pneumatic muscle. Moreover, it can be also designed as an actuator with low power, as a commercial minimotor.

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