Compliant Actuation in New Robotic Applications

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Abstract: **This paper gives an overview of different robotic applications based on two compliant actuator technologies developed within the Robotics & Multibody Mechanics Research Group at Vrije Universiteit Brussel: the Pleated Pneumatic Artificial Muscle (PPAM) and the Mechanically Adaptable Compliance and Controllable Equilibrium Position Actuator (MACCEPA). Both actuators have built-in intrinsic compliance, which makes for two control parameters to be set, namely the equilibrium position of the actuated joint and the equivalent torsion spring stiffness. The increase of control complexity is countered by the added value of adaptable compliance. Compliant actuation, as opposed to conventional, stiff actuators like electrical drives, is currently growing in importance and has applications in a variety of robotic technologies where accurate trajectory tracking is not prevalent: bipedal walking robots, assistive technology, rehabilitation training. The current status of our research projects in compliant actuation and their future perspectives are presented.**

Keywords: **compliant actuator, adaptable compliance, robotics**

I. Introduction

In industrial robotics - accurate - positioning of a manipulator or end effector is by far the most common application. The system is designed to meet the high mechanical stiffness and high feedback gains required, which improves the accuracy, the stability and the bandwidth of the position control. A typical DC-drive with gearbox and conventional feedback control often suits this purpose. New robotic technologies emerge, however, in which accurate positioning or trajectory tracking is not the primary design goal or unable to compensate for the many drawbacks - from this different point of view - that come along with conventional electrical actuators, like high reflective inertia, high stiffness, low force-to-weight ratio. These new robotic applications can strongly benefit from compliant actuator technology. Instead of introducing compliance on the control level through application-specific software, this approach is based on inherent adaptable compliance on a purely mechanical level. In this way intrinsic compliance is assured at all time, enhancing system safety. The equivalent torsion spring stiffness of an actuated joint and the equilibrium position of its end effector, i.e. the joint's configuration in which the actuator torque is zero, leaves us with two adaptable mechanical parameters to be set for each joint, which evidently increases the complexity of control. This is easily countered with the range of potential benefits, adding value to existing applications and also creating new applications in robotics.

In the following section a short description is given of two compliant actuator technologies developed by our research group. Thereafter different robotic applications are outlined in which these compliant actuators are incorporated. The last section briefly touches on some future perspectives.

II. Compliant Actuator Technologies

A. *Pleated Pneumatic Artificial Muscle (PPAM)*

Originally, the pleated pneumatic artificial muscle has been developed for use in bipedal walking robots. It is a lightweight, air-powered, muscle-like actuator consisting of a pleated airtight membrane (fig. 1).

Fig. 1. Pleated pneumatic artificial muscle at different contraction levels

The unfolding of the pressurized membrane causes the artificial muscle to contract and subsequently exert a pulling force along the longitudinal axis. This pulling force is proportional to the muscle's gauge pressure p, to the square of the muscle's maximal length L and to a dimensionless force function f, depending on contraction ε and muscle slenderness L/R, with R being the muscle's minimal radius, as can be seen in equation (1) [1].

$$F = p.L^2.f\left(\varepsilon, \frac{L}{R}\right) \tag{1}$$

Figure 2 shows the force output as a function of contraction at different gauge pressures for one specific muscle geometry.

The pleated design led to a superior muscle compared with for instance McKibben muscles, having a large contraction range, no stick-slip or friction and a very high force-to-weight ratio. As a consequence of the compressibility of air and the dropping force to contraction characteristic the PPAM is a compliant actuator.

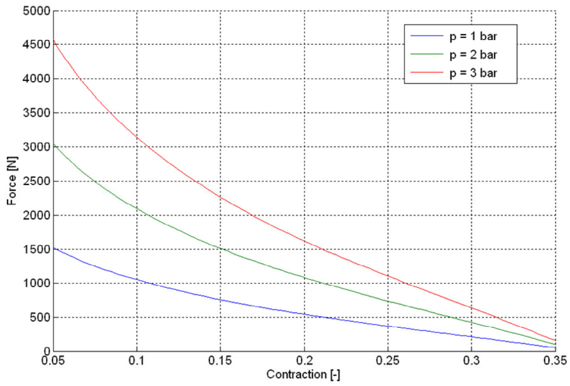

Fig.2. Generated force as a function of contraction at different gauge pressures for a PPAM with L=0.11 m, R=0.016 m

A bidirectional rotational actuator requires an antagonistic configuration of PPAM's (Fig.3), due to the fact that the artificial muscles can only generate a pulling force. The connection between the PPAM's and the joint is realized by fixed lever arms and it is designed to meet torque and compliance requirements. This setup shows a clear resemblance with the human muscle-tendon-bone system. Both the equilibrium position and the joint's compliance can be adapted independently by means of two control parameters, namely the muscle's gauge pressures. The equilibrium position is determined by a weighed difference of these pressures, the inverse of compliance, i.e. the stiffness, by a weighed sum.

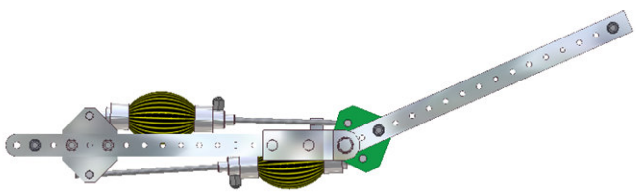

Fig.3. Antagonistic configuration of PPAM's as a bidirectional rotational actuator

B. Mechanically Adaptable Compliance and Controllable Equilibrium Position Actuator (MACCEPA)

Considering the possible drawbacks of a pneumatic system, namely the high cost of pressurized air production and supply requirements for autonomy, our research group has recently developed another compliant actuator type: the Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator (MACCEPA). The primary design goals are a straightforward mechanical concept and a straightforward relation between the mechanical parameters and the control parameters.

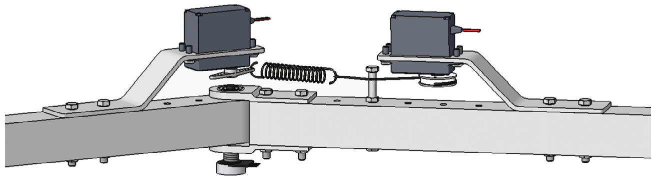

Fig.4. First MACCEPA prototype design view

Fig. 5 shows a schematic drawing of the MACCEPA prototype design depicted in Fig. 4. There are 3 bodies pivoting around a common rotation axis in point a, of which the smallest one is the lever arm ab. A spring is attached between a fixed point b on the lever arm and a cable running around a fixed point c on the right body to a pre-tension mechanism. The angle φ between the lever arm and the left body, is set by an electrical actuator, which in fact sets the equilibrium position. A second actuator, either a rotational or a linear actuator, pulling the cable connected to the spring, sets the pre-tension of the spring. The pre-tension will vary the torque at a certain angle $\boldsymbol{\alpha}$, in this way determining the spring constant of an equivalent torsion spring. As a result both the equilibrium position and the joint's compliance can be adapted independently by means of two control parameters, namely the angle φ and the amount of pre-tension in the linear spring respectively, each being set by means of a separate electrical drive.

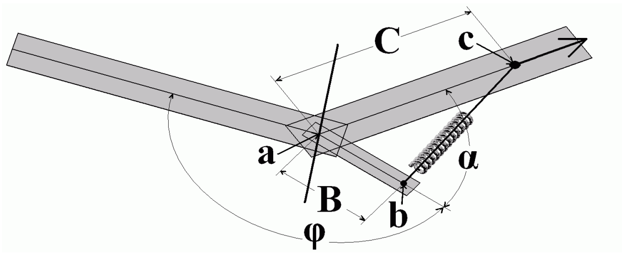

Fig.5. Schematic drawing of the MACCEPA prototype concept

Equation (2) shows that the generated torque is independent of the angle φ and set by lengths B and C, linear spring stiffness k and the pre-tension length P, which is the extension of the spring caused by pre-tensioning. The actuator torque is a result of the combined effect of pre-tension and the length change of bc [2]. For C/B ratio's greater than 5, the torque-angle characteristic of the MACCEPA becomes highly linear for a very large range of $\boldsymbol{\alpha}$ **(-60° < α < 60°)**. Fig. 6 depicts the torque characteristics for different pre-tension length values P and a specific set of B, C and k values.

$$T = k.B.C.\sin\alpha.(1 + \frac{P - |B - C|}{\sqrt{(B^2 + C^2 - 2.B.C.\cos\alpha)}}) \quad (2)$$

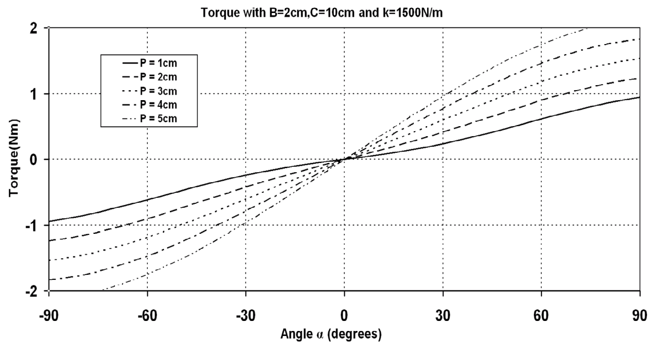

Fig.6. Generated torque as a function of α at different pre-tension length values *P* for a MACCEPA with *B*=0.02m, *C*=0.1m, *k*=1500N/m

Within the quasi-linear working range linearization of equation (2) yields the linearized torque formula (3) equivalent to the angle-torque relation of a linear torsion spring with an adaptable spring constant.

$$T = \alpha.\mu.P \qquad \text{with} \quad \mu = \frac{k.B.C}{|B-C|} \tag{3}$$

In this way the requirement of a straightforward control law is clearly met. Unlike the PPAM powered rotational actuator, the control signals for the equilibrium position and the compliance are independent of the actuator's actual position, which further simplifies the controller. Video material showing the working principle and behavior of the MACCEPA is available on the website [3].

III. Compliant Actuators in Bipeds

In bipedal walking robot design the mechanisms behind human walking evidently serve as the primary source of inspiration. Joint compliance plays a crucial role in human locomotion both to reduce energy consumption and as a means to adapt the gait pattern.

During running tendons and ligaments act as spring-like elements, storing and releasing elastic strain energy and in this way reducing the work required by the muscles [4]. Because the movement of the center of mass during running is similar to a bouncing ball, running is often referred to as *bouncing gait*. This makes it possible for the human body to operate at an efficiency of 40-50%, while the maximum efficiency of a contracting muscle is only about 25%. The global compliance of the legs is a means to adapt gait parameters. Increasing the compliance, for instance, results in higher stride frequencies [5].

During walking different energy saving mechanisms are called upon, of which the most important one is often referred to as the *inverted pendulum mechanism*. About 60% of the mechanical energy required to lift and accelerate the center of mass is being conserved [6]. This observation has led to the development of passive walking mechanisms, the so called *passive walkers* [7]. Joint compliance reduces the impact at heel strike during walking and induces passive motion, in turn reducing motor control and muscle work.

In summary, bipedal walking robots clearly benefit from compliant actuation because of the lowered inertia and the energy storage capability. Not only because it results in energy-efficient and human-like locomotion, but also for a higher level of safety in human-robot interaction.

Our research group has designed and built two bipedal walking robots: *Lucy*, actuated by PPAM's and *Veronica*, powered by MACCEPA's. In the next sections a brief description is given of the two biped projects and the concepts and strategies involved.

A. Biped Lucy Actuated by PPAM's

Lucy (Fig. 7) is a two dimensional walking robot with two articulated legs and an armless body. Each joint module, namely the ankle, the knee and the hip joint, is powered by an antagonistic pair of pleated pneumatic artificial muscles. As the robot's walking motion is restricted to the sagittal plane a guiding mechanism has been incorporated, preventing the robot from falling sideward. A treadmill is used for long distance walking and its speed is controlled according to the biped's walking speed.

The goal of the biped project is to achieve a lightweight bipedal walking robot able to walk in a dynamically stable way while exploiting the adaptable compliance of the pleated pneumatic artificial muscles in order to reduce energy consumption and control efforts [8]. A model-based joint trajectory tracking control strategy is used in combination with real-time planar trajectory generation.

The joint trajectory tracking controller combines a computed torque controller, a Δp-unit and a pressure bang-bang controller. The computed torque controller calculates the required joint torques out of the robot's dynamics. This dynamic model is different for the single and the double support phase. In single support the robot has 6 DOF, in double support the number of DOF is reduced to 3, which makes the system over-actuated. The Δp-unit translates the calculated joint torques into the required pressure levels of the two muscles of each antagonistic set-up. The bang-bang controller determines the control signals to be sent to the valves, setting the required pressures in the muscles. The trajectory generator and both the computed torque and Δp-units are implemented on a central PC, the bang-bang controller is locally implemented on micro-controller units. For more information about this control architecture the reader is referred to [9].

The trajectory generator is based on the inverted pendulum approximation, which models the robot as a single point mass. It keeps the zero moment point in the ankle point during the single support phase, it provides a smooth transition of the ZMP from the rear ankle point to the front ankle point during the double support phase and it allows the step-length, intermediate foot lift and velocity to be chosen differently for each step. The hip is not moving on a straight line as in most of the inverted pendulum based methods, since the strategy uses quasi-stretched knees for more naturally looking walking and reduced knee torques. With this strategy the robot is able to walk with different step-lengths and at different speeds, having a maximum speed of 0.11m/s.

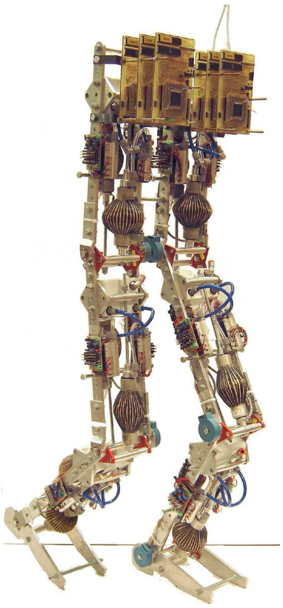

Fig.7. Bipedal walking robot Lucy actuated by PPAM's

Besides a trajectory generator and tracking controller, a compliance controller is to be developed to exploit the benefits of adaptable compliance. For this purpose an online compliance adaptation algorithm has been developed and verified on a single pendulum test setup [10]. The algorithm aims at tuning the stiffness of the PPAM's in such a way that it fits the natural stiffness of the desired trajectory, which is calculated as the derivative of the torque necessary to track the desired trajectory with respect to the joint angle. This approach, in combination with trajectory tracking, will results in semi-passive walking. Experimental results of the single degree-of-freedom joint show the effectiveness of the algorithm, however, additional testing on multi-joint systems is necessary. Moreover the algorithm calculates a local optimum in energy-efficiency, bounded by the underlying concept of the tracking controller and the trajectory generator.

Video material is available on the website of the Lucy project [11].

B. Biped Veronica Actuated by MACCEPA's

Veronica (Variable joint Elasticity RObot with a Neuro-Inspired Control Approach) is a planar biped, like Lucy, with 6 degrees of freedom (Fig. 8) [12]. The hip, knee and ankle joints of the legs are pin joints, actuated each by a *Slimline* MACCEPA [12] (Fig. 9). This MACCEPA-type actuator, consisting of two servo motors incorporated in the link structure, is a more compact variant of the first prototype.

The goal of this project is twofold: the application is meant both to serve as a test-bed for the MACCEPA and to verify a novel control approach, different from the one implemented in Lucy and largely based on the concept of passive walking. In unactuated passive walking the cyclic motion is typically sustained by gravitation on a shallow slope and its frequency is determined by the mechanical properties of the passive walker. Applying this concept to level-ground walking, one needs to take into account friction and impact losses and therefore introduce actuation. Most of the existing walking robots, based on the concept of passive walking, have fixed compliance properties [13] or a small number of different compliance settings [14], resulting in one single stride frequency.

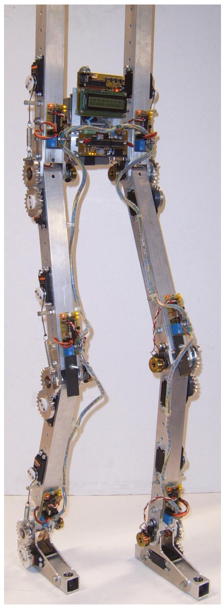

Fig. 8. Bipedal walking robot Veronica actuated by MACCEPA's

The aim of this biped project is to expand the range of natural walking motions by means of adaptable compliance. The natural joint trajectories of the system can be adapted at will by systematically setting the equilibrium positions and compliance values of the different joints, resulting in a variety of semi-passive gait patterns. For this purpose the required gait pattern is split up in distinct phases, each of them corresponding with a natural trajectory and consequently a set of control parameters. At phase transition, the control parameters associated with a particular phase are set and the system performs the required natural motion accordingly.

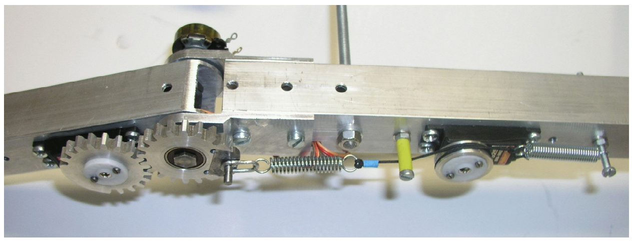

Fig. 9. *Slimline* MACCEPA variant

The approach described above is referred to as *Controlled Passive Walking*. Figure 10 illustrates the concept, applied to a single joint, actuated by a *slimline* MACCEPA, of which the upper link is considered fixed. Three situations *A*, *B* and *C* are depicted, all of them with the same settings of compliance and equilibrium position, but with different lower link positions. *B* shows the state in which no external torque is applied to the joint. By means of an external torque the link position can be changed from the equilibrium position to the position in state *A*. If the link, having zero angular velocity, is released from this state, i.e. by removing the external torque, it will swing, in the absence of friction, to *C*, the mirrored state of *A*. In *C* the link has zero angular velocity and the experiment can be repeated. Without intervention, one obtains an oscillating spring-mass-system. The time elapsed between *A* and *C* depends both on the link's moment of inertia and on the joint's compliance set by the MACCEPA. The end position in state *C* depends on the equilibrium position of the MACCEPA. Given a starting position, one can achieve a desired end position in a desired time within a certain range simply by setting the compliance and the equilibrium position once, at the beginning of the swing phase.

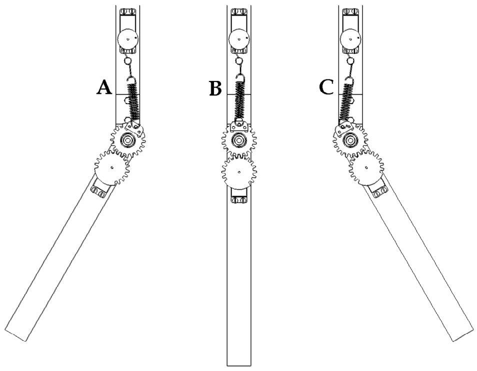

Fig. 10. *Slimline* MACCEPA actuated joint in three different states *A* (-30°), *B* (0°), *C* (30°)

Some preliminary walking experiments on Veronica show promising results. In these experiments control parameters were found by trial-and-error. Through observation of slow motion replays of the walking motion, the different parameters were tuned. The duration of the swing phase for instance was easily adjusted by changing the compliance of the hip joint. Video material of the walking experiments, based on this intuitive control method, is available on the website [3]. Walking with the knees stretched in the stance phase results in a more natural-looking, human-like gait.

IV. Compliant Actuators in Assistive Technology and Rehabilitation

Compliant actuator technology has another broad field of interest: assistive devices for use in industry and in non-industrial sectors, like healthcare.

A. General assistive technology

The use of compliant actuation enables new assistive manipulator designs, combining operator safety, low weight, ease of operation, ergonomics and low cost. The goal of the soft arm research project is to develop a proof-of-concept manipulator actuated with PPAM's that can be used in direct contact with an operator, without expensive force or torque sensors and without user interaction through control elements (such as joysticks). For this purpose a small-scale manipulator model, consisting of two links in inverse elbow configuration and actuated by PPAM's, has been developed (Fig. 11). The proposed concept of robot-assisted manipulation is based on both the manipulator and the operator holding and handling the load at the same time. This direct interaction between operator and manipulator allows the operator to position the load accurately while the weight is being carried by the manipulator. Using the muscles' gauge pressures to estimate the interaction forces of the operator, the system should be able to predict and generate the desired end effector path, in this way carrying most of the payload. Operator safety relies both on hardware properties, such as joint compliance and lightweight design, and on control strategy.

Fig.11. Soft robotic arm small-scale model

The use of PPAM's as compliant actuators and the highly non-linear dynamics of the system make controlling it a complex task. A PID controller with gravity compensation has been implemented for preliminary testing of the manipulator setup. This controller, however, is inadequate for tracking purposes. Instead, a sliding mode controller has been proposed and tested. Control chattering appeared to be a practical issue. It was reduced by adding boundary layers, which affects tracking performance. For a more detailed description of the sliding mode controller the reader is referred to [15]. The gauge pressures, in turn, are set by off-the-shelf proportional pressure regulating valves with internal PID controllers.

Examples of the soft arm's behavior and the underlying effects of compliance are available on the website [16].

B. Medical assistive devices and Rehabilitation

Compliant actuators seem well suited to meet the specific requirements of assistive devices for the disabled, for instance in the fields of prosthetics, orthotics and rehabilitation [17][18][19]. Safety is of primary concern in wearable robotic systems and medical rehabilitation robotics, but ergonomics, design complexity, size, weight and design functionality are equally important and moreover interdependent. In the case of lower limb prostheses, orthoses and step rehabilitation devices the adaptable compliance is an additional advantage in mimicking human gait, as discussed in the section on bipedal walking robots.

The goal of our IPPAM project (Intelligent transtibial prosthesis actuated by Pleated Pneumatic Artificial Muscles) is to develop a transtibial prosthesis for below-knee amputees, able to adapt to the intentions of the wearer and to changing walking surface properties. The current state-of-the-art in prosthetics is limited to passive systems without compliant elements or with fixed compliance properties [20][21]. These restrictions might lead to an unnatural, uncomfortable gait and even result in medical pathologies on a longer term. Introducing compliant actuation enables specific active assistance, for instance at the toe-off phase and during transition of different modes, like starting and stopping, and provides a means to change the ankle joint's compliance according to the stride frequency and the compliance characteristics of the ground surface [22][23]. The PPAM's high force-to-weight ratio is an advantage towards lightweight and compact design. Currently, the project is in the mechanical design phase covering the PPAM type selection, the structural design, stress sizing and dynamics simulation. In the following phase focus will be on the measurement system, providing the basis for the prosthesis' intelligence. Issues of pneumatic power generation and autonomy won't be addressed extensively, as the first prototype will above all be a proof-of-concept for the integration of compliant actuation in prosthetics. After hardware completion and preliminary testing, the prosthesis' performance will be evaluated on a patient group in lab settings both with objective and subjective outcome measures.

V. Future Perspectives

The compliant actuator technologies presented in this paper are not confined to the applications outlined in the previous sections. Adaptable compliance brings added value to other existing applications and creates new functionalities. A recent project in start-off phase focuses on the development of a PPAM actuated step rehabilitation robot [24] (Fig. 12) assisting patients with gait problems, spinal cord injury patients for instance, recovering normal walking abilities. The compliant actuators provide enhanced ergonomics and passively absorb possible spasmodic movements. The adaptable compliance serves as a tool to alter the gait pattern and gradually change the level of assistance during therapy.

Fig. 12. Artistic view of the step rehabilitation robot actuated by PPAM's

On the other hand, the PPAM's high force-to-weight ratio enables the actuated orthosis to provide full bodyweight support. This makes for a small step towards a fully autonomous exoskeleton. Existing exoskeletons however are partially assistive devices of which the control performance relies on the postural stability and motor control of the wearer [25].

In general, compliant actuation creates an interesting approach to many emerging robotic technologies, both in industrial and non-industrial environments, where robots and human beings are in close interaction and accurate positioning or precise trajectory tracking is often secondary.

VI. Conclusion

In this paper two compliant actuator technologies, both developed within the Robotics & Multibody Mechanics Research Group at Vrije Universteit Brussel, were presented: the pleated pneumatic artificial muscle (PPAM) and the mechanically adaptable compliance and controllable equilibrium position actuator (MACCEPA). An overview was given of the different research projects in which these compliant actuator types are incorporated and play a crucial role: bipedal walking robots Lucy and Veronica, a soft robotic manipulator and an intelligent transtibial prosthesis. Also a future research project in the field of step rehabilitation robotics was described in brief.

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