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# A Pneumatic Manipulator used in Direct Contact with an Operator

Michaël Van Damme, Frank Daerden, Dirk Lefeber
*Vrije Universiteit Brussel, Department of Mechanical Engineering*
*Robotica and Multibody Mechanics Research Group*
*Pleinlaan 2, 1050 Brussel, Belgium*
*michael.vandamme@vub.ac.be*
*http://werk.vub.ac.be/softarm*

*Abstract*— **Repetitive manual handling of heavy loads is common in assembly and is a frequent cause of lower back disorders. This can have a significant impact on the quality of life and has a serious economic cost.**

**This paper presents the concept of a lightweight manipulator that can interact directly with an operator in order to assist him in handling heavy loads. The advantages of the system, ergonomics, low weight, low cost, ease of operation and operator safety are a consequence of the use of Pleated Pneumatic Artificial Muscles as actuators. The design of a small-scale model of such a manipulator using these actuators is presented in detail. A simple position controller for the system is also presented.**

## I. Introduction

Manual material handling tasks such as lifting and carrying heavy loads, or maintaining static postures while supporting loads are a common cause of lower back disorders and other health problems. In fact, manual material handling has been associated with the majority of lower back injuries, which account for 16-19% of all workers compensation claims, while being responsible for 33-41% of all work-related compensations [1]. The problem has an important impact on the quality of life of affected workers, and it presents an important economic cost.

The traditional solution is using a commercially available, manipulator system. Most of these systems use a counterweight, which limits their use to handling loads of a specific mass.

In order to increase safety and productivity of human workers, several other approaches to robot-assisted manipulation have been studied in the robotics community. The devices developed in the course of these studies belong to a class of materials handling equipment called Intelligent Assist Devices (IADs).

One approach is using collaborative robots or "cobots". Cobots use software-defined "virtual surfaces" which constrain and guide motion of the load, but add little or no power [2], [3]. While cobots offer great ergonomic advantages (allowing workers to manipulate loads without assuming uncomfortable body postures), the operator still has to provide most of the power required

Another approach, used in the so-called power extenders, is having the operator wear an exoskeleton type device that amplifies the operator's muscle power [4], [5]. Both hydraulically and electrically actuated versions have been developed. Generally, power extenders are heavy, complex and expensive.

A third approach is to have both the human and the robot holding the load, while they manipulate it collaboratively (see for instance [6], [7]). The design proposed in this paper follows this approach.

Some of this research has resulted in IADs becoming commercially available. Most of these systems are heavy, complex and expensive.

In this paper we present the initial design of a manipulator that will eventually combine ergonomics, operator safety, low cost, low weight and ease of operation. All of this can be achieved through the use of a new actuator, developed at the department of mechanics at the Vrije Universiteit Brussel: the Pleated Pneumatic Artificial Muscle (PPAM) [8], [9]. The PPAM actuators are contractile devices operated by pressurized air. When inflated they bulge, shorten and thereby generate a contraction force. The PPAM actuator has very low mass, high strength and can be attached directly to the structure (without reduction). This allows for a lightweight construction. The goal is to have a direct interaction between manipulator and operator by having them both handle the load simultaneously. This means that no control elements such as joysticks are necessary. The use of PPAM actuators also allows us to avoid using expensive force or torque sensors, as forces and torques can be estimated by measuring the muscle gauge pressures.

We are working towards a system that behaves as follows: when the operator wants to move a load attached to the manipulator, he/she starts moving it as if there were no manipulator. By measuring the muscle gauge pressures, the system continuously estimates the forces applied by the operator and assist him/her in accomplishing the desired load movement. The direct interaction between operator and load (without intermediary control tools) allows for very precise positioning.

The main requirement for any mechanical device that is used in the immediate environment of people is safety. The PPAM actuators greatly contribute to the overall safety of the manipulator system: they allow for a lightweight

Fig. 1. Pleated muscle concept.

construction, there is no danger of electrocution and, most important of all, the muscles are inherently compliant. The controller will also enhance safety, since there is no fundamental difference between forces generated by a collision and forces applied by an operator. The system will always tend to move away from people or objects it collides with.

In this paper, the design of a small-scale proof-of-concept model of such a manipulator, consisting of two PPAM actuated links in inverse elbow configuration, is presented.

## II. Pleated Pneumatic Artificial Muscles

### A. Concept

Pneumatic artificial muscles (PAMs) are contractile devices whose core element is an inflatable membrane. When inflated they bulge, shorten and thereby generate a contraction force. Over the years, different types have been developed, the most well known being the McKibben muscle [10]. It consists of a rubber tube, which expands when inflated, surrounded by a netting that transfers tension. Although easy to make, the McKibben muscle has some important drawbacks, such as substantial hysteresis and a high threshold pressure, under which no contraction occurs. Its total displacement is limited to just 20% to 30% of the initial length. To remedy these problems, a new type of PAM was developed, the PPAM [8], [9]. The PPAM (see figure 1) has a folded membrane, that unfolds as it expands. Because of the unfolding, there is no threshold pressure, hysteresis is strongly reduced, and contractions of up to 50% are possible (depending on the slenderness, see further). If one also takes into account the PPAMs low weight (under 100 g is possible), high power to weight (over 1 kW/kg) and the fact that it can be attached to the structure without reduction, it's clear that this actuator can be useful for some robotic applications.

### B. Characteristics

An accurate mathematical model that describes shape, volume, diameter, exerted force and maximum contraction of PPAMs can be found in [11], [8]. Under the assumption of negligible membrane elasticity the force exerted by the muscle is given by

$$F = p l_0^2 f_{t0}\left(\epsilon, l_0/R\right) \tag{1}$$

In this expression, $p$ is the applied gauge pressure, $l_0$ is the muscle's uncontracted length (or maximum length), $R$ is its radius in uncontracted state (or minimum radius) and

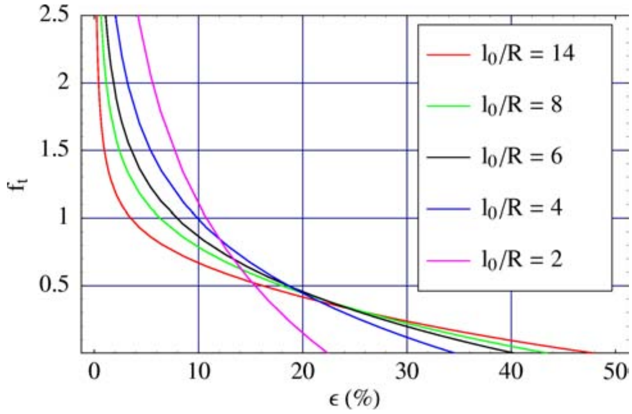


Fig. 2. $f_{t0}$ (dimensionless force function)

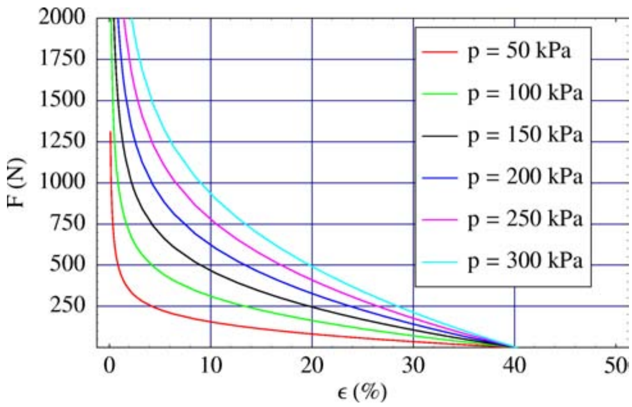


Fig. 3. Force exerted by a PPAM with $l_0/R = 6$ and $l_0 = 6$ cm for different gauge pressures.

$\epsilon$ is the muscle contraction. If we call $l$ the muscle length, we have $\epsilon = 1 - l/l_0$. $f_{t0}$ is a nonlinear, dimensionless function that depends on contraction and on the design-time parameter $l_0/R$ (called the slenderness). $f_{t0}$ is shown in figure 2 for different values of $l_0/R$. As figure 2 and equation (1) show, there is a varying force-displacement relation at constant gauge pressure. This results in muscle-like behaviour, with very high forces being generated at low contractions and very low forces at high contractions, as shown in figure 3 for a muscle with slenderness $l_0/R = 6$ and $l_0 = 6$ cm. To avoid excessive material loading, contraction should be kept above $5\%$.

### C. Creating a revolute joint

Since PAMs are contractile devices, they can only exert force in one direction (they can only pull, not push). In order to have a bidirectionally actuated revolute joint, two PAMs have to be used in what is generally called an antagonistic setup. This is illustrated in figure 4. The torque characteristics of such a joint are determined by the parameters of both muscles (slenderness and maximum length) and by the location of the four attachment points.

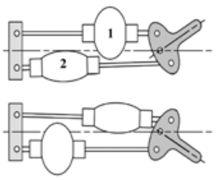


Fig. 4. Antagonistic setup.

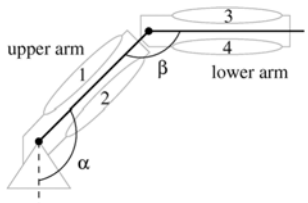


Fig. 5. The inverse elbow configuration.

## III. Manipulator design

### A. Introduction

The goal is to design a machine that will provide assistance in the vertical plane. This means that two actuated degrees of freedom are sufficient. Three possible link configurations were considered: elbow, inverse-elbow and rhombic. Since the design should be as lightweight and simple as possible, the rhombic configuration isn't suitable. As operator and manipulator will be interacting directly, it's important that the manipulator doesn't obstruct the operator's movements. For this reason, the inverse elbow configuration was chosen.

For easier development and testing, and to gain experience with this type of system, we decided to develop a small-scale manipulator first. The length of both links was chosen to be 30 cm.

### B. Design

Figure 5 shows a schematic representation of the two links in inverse elbow configuration. The conventions used in the rest of this document regarding to how both joint angles are defined and how the different pneumatic muscles are numbered are also included in the figure.

The desired operating area was chosen to be

$$\begin{aligned} 110^\circ &\leq \alpha \leq 195^\circ \\ 50^\circ &\leq \beta \leq 150^\circ \end{aligned}$$

Since we have four PPAMs, there are eight attachment points. The location of each of these points can be described by two coordinates. Each muscle has two parameters (slenderness and maximum length). This means there are a total of 24 parameters to be determined. The chosen parameter set has to meet two important conditions:

- producibility: not all imaginable muscles are producible (in general, the higher the slenderness, the more difficult to produce). In addition, attachment point locations cannot be chosen too close to each other, nor too far away from the link axis.
- absence of 'space conflicts': this is the most difficult condition to verify. As PPAMs are inflated, they expand. At maximum contraction, a PPAM's diameter is close to its maximum length. Obviously, the muscle needs space to be able to expand. The transmission rods that transfer the exerted muscle force to the structure can also cause problems. It must be made sure that the rods stay clear of all other structural elements throughout the entire operating area.

| Muscle: | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Max. distance between attachment points (mm) | 345 | 248 | 322 | 311 |

TABLE I

Maximum distance between the attachment points of all muscles for the chosen operating area and attachment point locations.

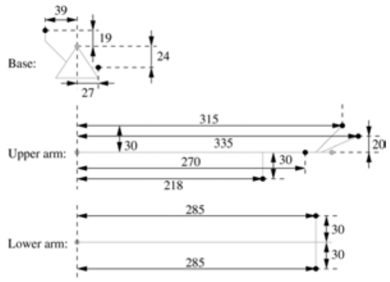


Fig. 6. Attachment point locations (dimensions in mm).

Determining the best design means finding a global optimum in a 24-dimensional parameter space, subject to the above described conditions (some of which have to be verified throughout the entire working area). This has proven to be computationally intractable. Therefore, the different parameters were chosen manually, mainly with ease of production in mind, after extensive computer experiments.

*1) Attachment point locations:* The chosen attachment point locations are shown schematically in figure 6. For this choice of locations and operating area, the maximum distance between the attachment points of a specific muscle is listed in table I for all muscles. Relative to these maximum values, figure 7 shows the contraction curves of the four muscle systems (the muscle and its transmission rods as a whole).

*2) Muscle parameters:* As can be seen from figure 7 and table I, the maximum shortening is around 60 mm for the top muscles (1 and 3) and around 45 mm for the bottom muscles. Since the muscles still need be able to exert force when these maximum shortenings occur, we must be able to provide these shortenings at muscle contraction levels not too close to the maximum (see figure 3). This can only be achieved if we use a very long muscle (same order of magnitude as the link length). Long PPAMs, however, expand to very large diameters

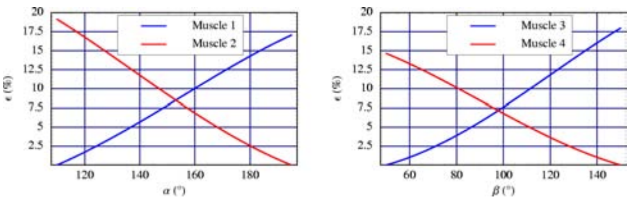


Fig. 7. Contraction curves of the four muscle systems.

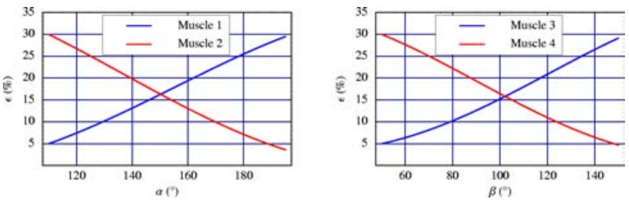


Fig. 8. Individual muscle contraction curves.

when inflated (same order of magnitude as the muscle's maximum length), so they cannot be used. The solution is to use a series arrangement of several identical short PPAMs (all used at the same gauge pressure). A series of $n$ identical PPAMs exerts the same force as a single muscle, but the total shortening is $n$ times larger. This allows for large contractions and relatively small diameters at the same time. The disadvantage of this arrangement is that the maximum force that can be produced is reduced by a factor $n^2$ when compared to a single muscle $n$ times as long. This follows from equation 1. However, since the forces developed by a PPAM can be very high, this needn't be a problem.

In the manipulator design, the top muscles (1 and 3) are realized using a series arrangement of four 6 cm long PPAMs with a slenderness value of 6 (the force exerted by such a muscle is shown in figure 3 for different gauge pressures). Since the bottom muscles (2 and 4) will mainly be used to provide stiffness, they don't have to be able to exert as much force as the other two. Because of this, we can tolerate higher individual muscle contraction for the same amount of total shortening. Therefore, these muscles are realized using three PPAMs (of the same kind as the ones used for 1 and 3) in series.

As previously stated, muscle contractions below $5\%$ should be avoided. Exceeding $30\%$ is also disadvantageous, as the force exerted by the muscle quickly drops to zero. Therefore, we determine the transmission rod lengths in such a way that for $\alpha = 110°$, muscle 1 will have $5\%$ contraction and 2 will have $30\%$ contraction, and for $\beta = 50°$ muscle 3 will have $5\%$ contraction while 4 has $30\%$. Once these lengths are determined, we can calculate the muscle contraction curves (see figure 8).

*3) Torque characteristics:* Since all attachment point locations and PPAM parameters are known, we can determine the torque characteristics of both joints. In view of equation (1), the torque generated by a muscle can be written as

$$\tau = p \cdot m\,(l_0, l_0/R, \gamma) \quad (2)$$

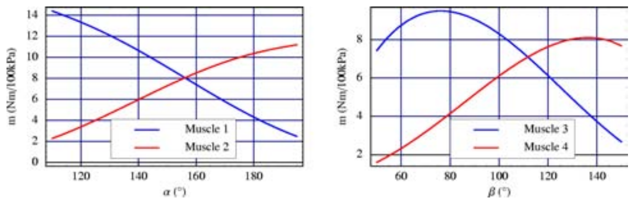


Fig. 9. Torque functions.

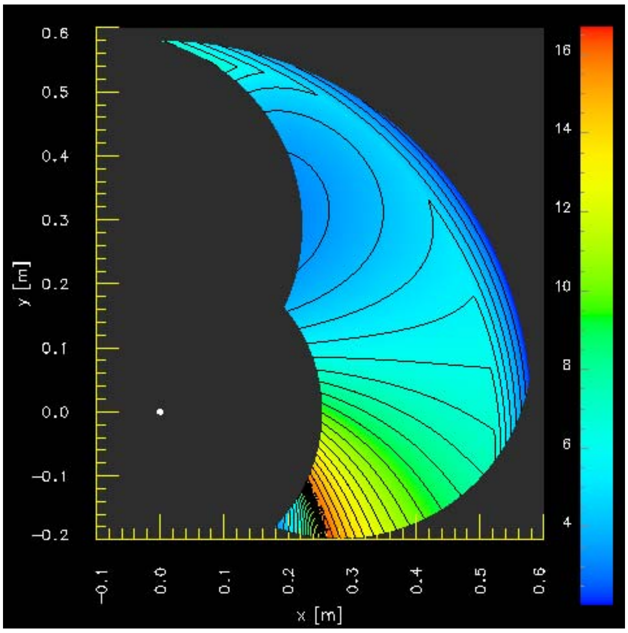


Fig. 10. Maximum mass (in kg) that can be supported in each point of the operating area.

with $\gamma = \alpha$ for muscles 1 and 2 and $\gamma = \beta$ for muscles 3 and 4. Equation (2) provides a clear separation between the two factors that determine torque: gauge pressure and a torque function $m$, that depends on the design parameters and the position. The torque functions are shown in figure 9.

Equation (2) and the torque functions allow us to express static equilibrium in both joints. If we substitute maximum gauge pressure (300 kPa, higher pressures could damage the membrane) for the carrying muscles, and zero pressure for the antagonists, we can calculate the maximum load the manipulator can support in each point of the operating area. For every point, the two joint's equilibrium equations will each yield a certain maximum load. The smallest of both values is the true maximum load in that point. It is presented graphically in figure 10 for the entire operating area. In order to produce this figure, the mass of both links must be known. The values used here were obtained from the actually produced model (upper arm 1.46 kg, lower arm 1.06 kg, both including two muscles of about 100 g).

The smallest maximum load in figure 10 is 2.02 kg. This is the highest mass whose weight can be supported throughout the entire operating area. It should be stressed, however, that the maximum load is much higher in most of the operating range.

As could be expected, the areas with the lowest maximum loads are areas where one or both of the carrying muscle-groups operate at high contractions (around 30%).

*4) Scaling:* Since the presented design is a small-scale model, it's important to know how the characteristics of this model change when the model is scaled up. Let's suppose we scale all dimensions with the same factor $a$. This means the PPAM actuators will become $a$ times longer, while the slenderness remains the same (because $R$ is scaled too). Equation (3) shows that this means the force exerted by the PPAM will scale by a factor of $a^2$. As the torque generated by this force also involves a distance (which is also scaled by $a$), we see that the available torques scale as $a^3$. Of course, since the mass of the manipulator scales as $a^3$, the torque needed to support its own weight scales as $a^4$. Eventually, this will limit the maximum load.

## IV. CONTROL

### A. Introduction

When using pleated pneumatic artificial muscles, controller design is not straightforward. Difficulties encountered when designing a controller include the following:

- Both the manipulator and its actuators are strongly nonlinear systems (see figure 2). Measurements on PPAMs also show a slight hysteresis in the force-pressure characteristic. This makes it hard to estimate actuator force when only pressure measurements are available.
- According to the actual position in the working area there is a varying degree of actuator control redundancy, meaning the manipulator can be in that specific position with a more or less broad range of actuator gauge pressure combinations. This allows for more freedom in control (variable compliance, for instance), but it also makes matters more complex.
- Actuator gauge pressures can take a relatively long time to settle (around 100 ms).

Instead of starting off with a complex control design a straightforward PID position controller (with gravity compensation) was examined. The primary goal was gaining experience with the system rather than achieving high control performance.

### B. $\Delta p$-approach

To reduce the number of actuator outputs that have to be calculated, the $\Delta p$-approach was used [11], [12]. This involves choosing an average pressure $p_m$ for both muscles of an antagonistic pair, and having the controller calculate a pressure difference $\Delta p$ that is added in one muscle ($p+\Delta p$) and subtracted in the other ($p - \Delta p$). The choice of $p_m$ influences compliance while $\Delta p$ determines joint position.

The control of the actuator pressures themselves is handled by off-the-shelf proportional pressure regulating valves with internal PID controllers.

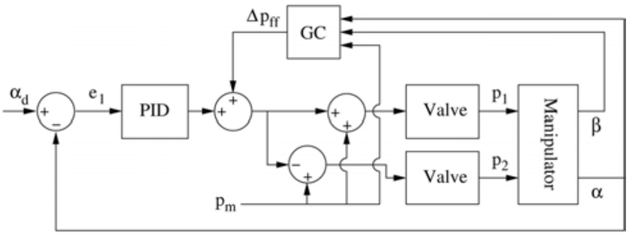


Fig. 11. Control system block diagram (first joint).

### C. Controller

The first part of the controller will provide the actuator outputs needed for static gravity compensation (without load, or with a known load). Combining equation (2) with the $\Delta p$-approach, we have

$$\tau_{act,1} = (m_1 + m_2)\,\Delta p_1 + (m_1 - m_2)\,p_m \quad (3)$$

$$\tau_{act,2} = (m_3 + m_4)\,\Delta p_2 + (m_3 - m_4)\,p_m \quad (4)$$

with $\tau_{act,i}$ the combined actuator torque for joint $i$, $m_i$ the torque function of muscle $i$ (see figure 5) and $\Delta p_i$ the $\Delta p$ value of joint $i$. Using the above equations to express static equilibrium ($\tau_{act,i} = \tau_{gravity,i}$) at an arbitrary manipulator position yields the values of $\Delta p$ that will compensate gravity at that position if the theoretical model would match reality exactly:

$$\Delta p_{gc,1} = \frac{\tau_{gravity,1} - (m_1 - m_2)\,p_m}{(m_1 + m_2)} \quad (5)$$

$$\Delta p_{gc,2} = \frac{\tau_{gravity,2} - (m_3 - m_4)\,p_m}{(m_3 + m_4)} \quad (6)$$

A PID controller is added to correct disturbances and model inaccuracies. This results in the following simple control law:

$$\Delta p_i = K_{p,i} e_i + K_{D,i} \frac{de_i}{dt} + K_{I,i} \int_0^t e_i dt' + \Delta p_{gc,i} \quad (7)$$

with $i = 1 \ldots 2$, $e_i = \gamma_{d,i} - \gamma_i$, $\gamma_1 = \alpha$, $\gamma_2 = \beta$, $\gamma_{d,i}$ the desired angular position of joint $i$ and $K_{P,i}$, $K_{I,i}$ and $K_{D,i}$ the PID controller gains of joint $i$. Figure 11 shows the control block diagram for the first joint.

Initial values for the controller gains were determined in simulation and later fine tuned with experiments on the actual scale model (shown in figure 12).

### D. Results and discussion

Using a PI control law on a 1DOF revolute joint actuated by an antagonistic pair of PPAMs proved to be very satisfactory [11], [12]. However, in the current application the inertia of upper and lower arm did not allow for such a simple controller to be effective. Without the gravity compensation term the system could not be stabilized.

When adding this term in the control law, both simulations and experimental results showed that the controller is stable. The system responded to large steps (across the complete working area) as well as smaller steps without signs of instability. Continuously changing the position set

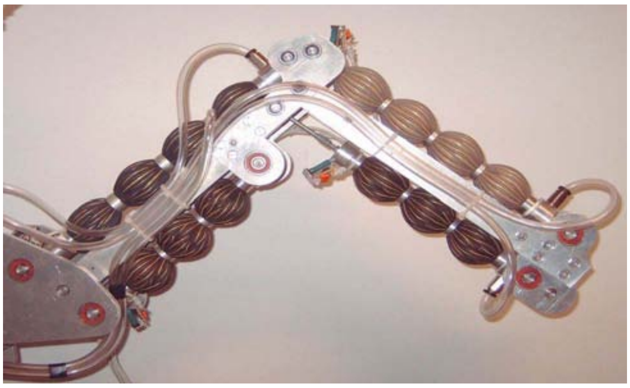

Fig. 12. The manipulator scale model.

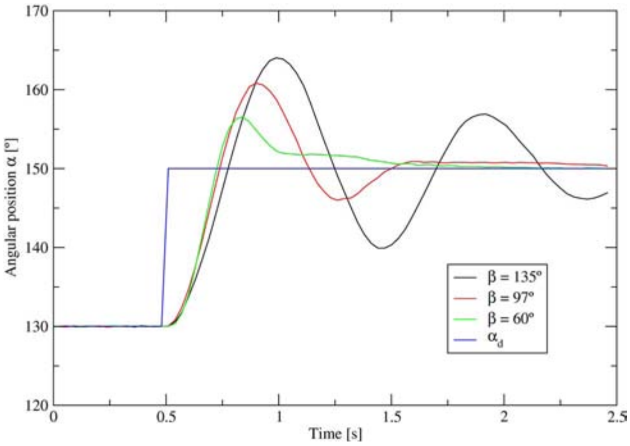


Fig. 13. System response to a change in desired angular position of the upper arm for various lower arm positions.

point along predefined trajectories (e.g. lines, circles, figure eights) didn't cause stability problems either.

As was expected, serious overshoots can occur when the system is subjected to large steps in desired angular position. This problem is especially prominent in the upper arm, since it has to cope with the inertia of the lower arm. This is illustrated in figure 13 for various lower arm positions. Both overshoot and settling time increase significantly with $\beta$, i.e. when the elbow is extended. Better performance should be obtained by adapting joint controller gains to the position of the system.

An important characteristic of this manipulator is its compliance. During system operation human interaction without injury is possible. For instance, pushing the end effector will cause it to yield whereby the reaction forces experienced by the operator are determined by the value of $p_m$ and those of the control gains. Stability is, however, maintained.

Many of the results of this study cannot be illustrated by diagrams, ideally one has to experience the operation of this manipulator. We gladly refer to our website where several short movies give a good impression of this [13].

## V. Conclusion

The design of a small-scale, lightweight manipulator actuated by Pleated Pneumatic Artificial Muscles was presented and its characteristics were determined. The design clearly demonstrates the advantages of these versatile actuators.

A rudimentary PID-based position controller for the system was also presented. The purpose of this controller was to study the system behaviour and examine its controllability. System stability was demonstrated but, as was expected, control performance, e.g. with regard to settling time and overshoot, is rather poor. Besides, using the PID control law will not allow the manipulator to be used as a power extensor or assistant. Other control strategies are therefore currently being studied.

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