Modular Robot Arm Based on Pneumatic Artificial Rubber Muscles (PARM)

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SYNOPSIS

In some industry activities, inspection environments or restoration works, human operators might be exposed to really unsafe environments or atmosphere, such as acid gas, chemical fluids, corrosive gas, temperature, etc. For this kind of situation, the remote control of machinery is required to ensure the workers safety. Nevertheless, such machines should meet drastic requirements and specifications, in order to be resistant enough to environment aggressions. However, on the shelf remote-controlled machinery is limited in type and number. In order to bring a solution to this demand, we developed a set of pneumatic robotic elements with the aim of robustness, easy installation and portability. In this article, we illustrate our concept over the case study of a modular robot arm, using multiple 1-DOF elements based on pneumatic artificial rubber muscles (PARM). After presenting PARM technology and mechanical structure of the proposed elements, we will study both the system architecture and control method required for it. Then, the example of a 3-DOF remote control structure, is used for performing some tracking experiments and evaluating capabilities of this pneumatic control system.

1 INTRODUCTION TO THE PARM TECHNOLOGY

In consideration of portability, the lightweight and powerful pneumatic artificial rubber muscles were adopted as relevant actuators for the chosen application fields (where electrical drives are a problem or might even constitute a danger). Although applications of the PARM to robots have already been performed previously, mainly because of a very interesting high power weight ratio, there are few examples in which robot arm was realised because of the large hysteresis of the muscles. Since a couple of years, techniques in the field of PARM have really improved over reliable commercial products.

1.1 FESTO Fluidic Muscles Technology

The fluidic muscle (refer to Fig. 1) is a membrane contraction system, which contracts in length under pressure. The membrane contraction system is hermetically sealed: incoming compressed air can only escape through the inlet, thereby rendering the pneumatic muscle impervious to dirt, dust, sand, etc. The basic idea is the combination of flexible tubing (impervious to fluids) and a covering of strong fibres in rhomboidal form providing a three-dimensional grid structure [1].

Fig. 1 The FESTO fluidic muscles

When air is admitted, the grid structure change in shape through expansion and a tensile force is created in the axial direction. The grid structure causes the muscle to shorten up to the neutral axis as internal pressure is increased. This correspond to a stroke of approximately 25% of the initial unloaded length. Force developed in relation to contraction ration is given on figure 2.

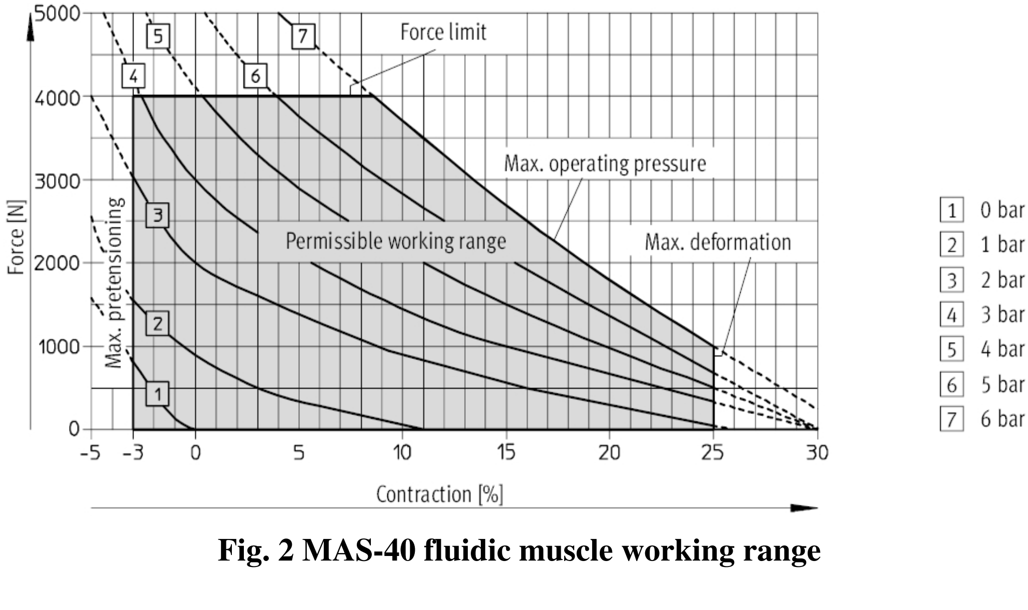

Fig. 2 MAS-40 fluidic muscle working range

Given its weight (0.87 kg at a minimum length of approximately 500 mm) and the maximum lifting force delivered (4000 N), the MAS-40 actuator provides one of the highest power / weight ratio.

1.2 Application of the PARM

In the simplest case, PARM operate as a single-acting actuator against a constant load. Assuming that this is permanently attached to the muscle, it will project from its initial position when in the extended non-pressurised state. When pressurised, the PARM, pretensioned in this way, develops maximum force with optimum dynamic characteristics and minimum air consumption. In the second case, PARM behave as a spring with a changing external force: it follows the direction of the action of the force. The PARM operate as a given spring with constant pressure or constant volume. This means we can easily produce different spring characteristics which allows the spring effect to be matched to a desired application. Those two operating modes are depicted on figure 3.

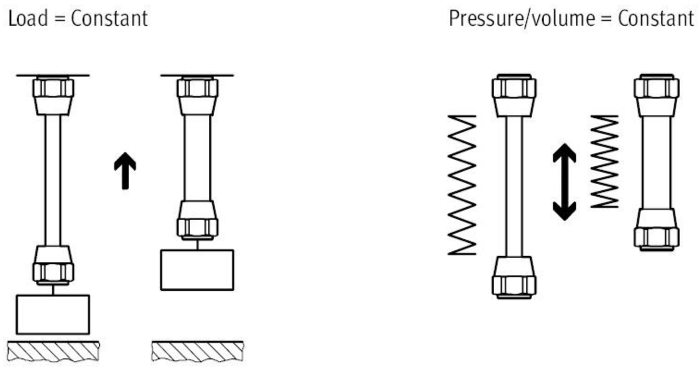

Fig. 3 MAS-40 possible operating modes

2 THE 1-DOF PARM-BASED COMPONENT OVERVIEW

2.1 Mechanical design

The PARM characteristics mentionned above (both spring and lifting effect) were used for designing the 1-DOF component. As shown on figure 4, the rotational motion is provided by a “bi-muscular” driving system. This consists of driving two PARM antagonistically by controlling contraction rate through two independent FESTO servo valves (one for each PARM). Let us not these valves allow to set the air flow sent to the PARM proportionally to an analog voltage command. The resulting differential motion performed by the two PARM is transformed into the desired rotational motion by using a notched belt / wheel mechanical link (refer to figure 5).

In order to measure system both kinematical and pneumatic state, we have at our disposal one analog pressure sensor per PARM valve and an encoder mounted on a sub-belt as shown on figure 5. The first sensor allows to control pressure inside the PARM tubing, when the encoder, returning a value proportional to the main rotating plate, make angular control be possible.

Before dealing with the control structure of the 1-DOF component, we have to observe few recommendations. As an antagonist system and regarding to the pulling power delivered, it is crucial to prevent the two PARM from performing strong pull at the same time: otherwise, a significant force (up to 8000N) would be applied to the rotating plate axle. Realizing a mechanical platform able to support such effort would surely be over sized and drastically in opposition to our “light weight component” goal. This means that pressure control of the

PARM tubing is the most important thing to handle for preserving all mechanical parts. Once the PARM pressure under control, it will be easy to have an higher control loop dedicated to the plate angular position control.

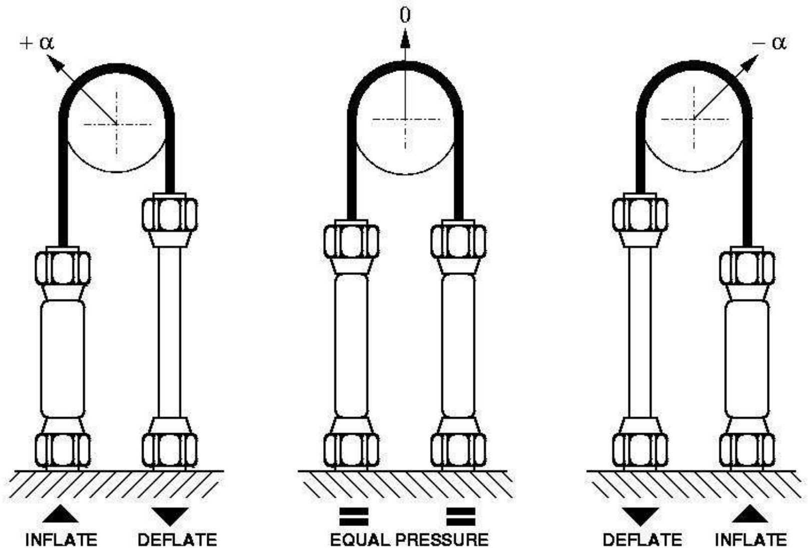

Fig. 4 Basic principle of the 1-DOF pneumatic component

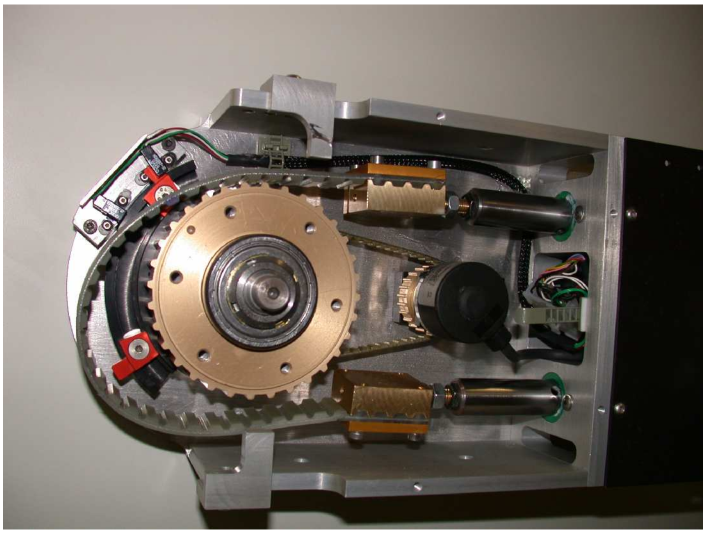

Fig. 5 The 1-DOF element mechanical transmission link

2.2 The 1-DOF element control structure

As previously proved, first theoretically in [3] and later more experimentally in [5], torque of such antagonist PARM based systems is dependent on pressure. Unfortunately, as mentionned in [5], pressure difference, and more generally pressure, is exposed to disturbance resulting from environmental temperature variations. Moreover, even if according to pneumatic servo valves documentation air flow rate is proportional to a voltage input, this assumption should not be considered as physical valves have slightly different characteristics. All these phenomenon, contribute to the high non-linearity of the relation between pressure rate and servo valve opening. As a conclusion, controlling system over the single servo valve opening is definitely not satisfactory. However, as explained in [5], on one hand, hysteresis of the pressure response is much smaller than the positioning one and, on the other hand, pressure response is fast enough to be considered as a minor loop control input. By this way, PARM controllability is significantly enhanced.

Based on these comments, the angular position control of the rotating plate was designed as a cascade of two main control loops: one dedicated to PARM pressure control and a last one relying on pressure control to implement angular position control. Figure 6 describes this control structure. Two PID composed the global control. One 100 Hz PID loop for each PARM handling pressure commands and one 20 Hz PID loop performing angular control. The given frequencies has been chosen according to both servo valve and PARM time constants.

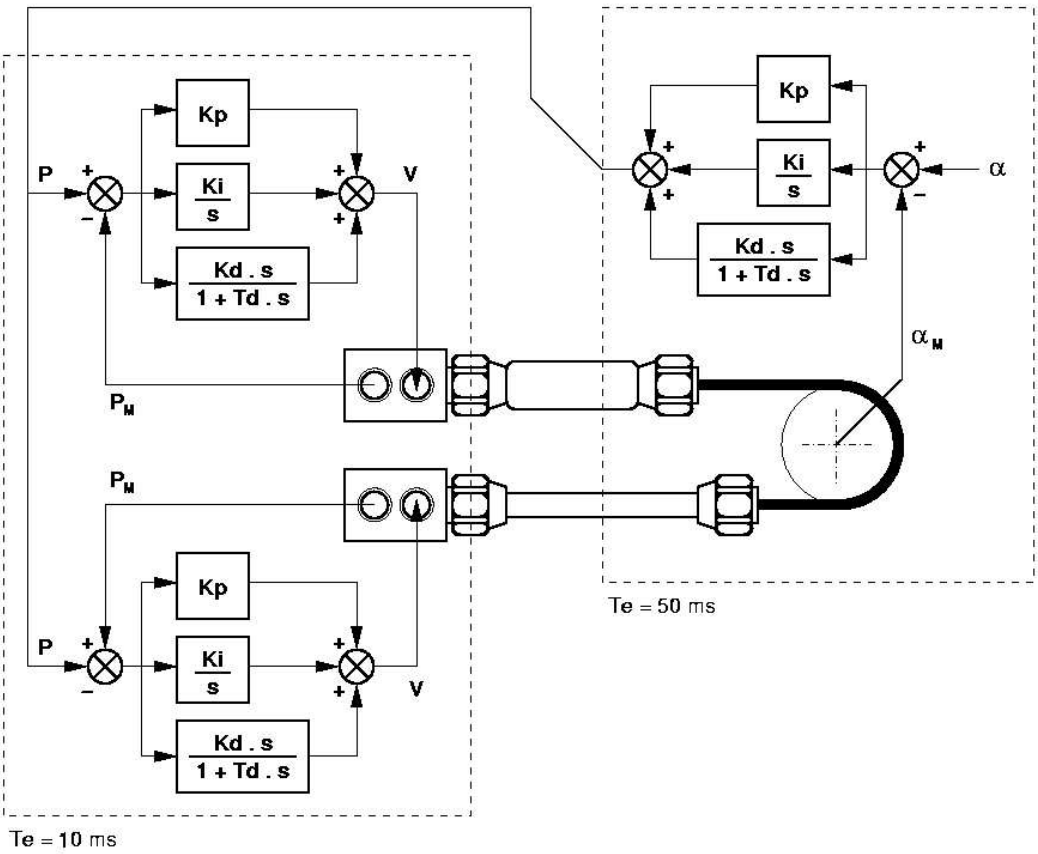

Fig. 6 The 1-DOF PARM based component control structure

2.3 Control system implementation

Embedded control board has been used for driving PARM related hardware. These boards, as parts of our own products, are based on Motorola MPC555 micro-controller relying on a 32-bits PowerPC core. With a 40 MHz frequency, this material can easily handle, at the same time, both pressure and position loops as well as a powerful Linux/RTAI interface [8] able to report, under realtime constraints, any system parameter state through streaming log files. Such realtime reports have been used for getting experimental results and fine tuning control gains. A single of these MPC555-based boards is able to drive two 1-DOF components, that is to say four PARM together. More over, we have to keep in mind our first idea of modularity. Indeed, several of these 1-DOF elements are intended to be arranged together or to take part into the composition of a robotics structure. In order to satisfy this requirements and to enable

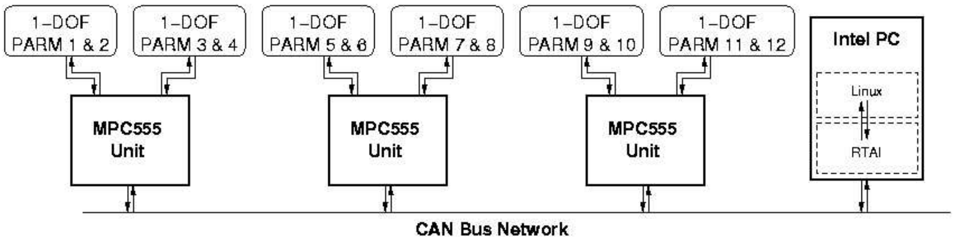

Fig. 7 The heterogeneous distributed control architecture

computing interaction between 1-DOF elements, each MPC555 board is linked to a CAN bus network (refer to figure 7). This functionality appears to be useful in large mechanical systems (containing up to sixteen 1-DOF elements) where global control is much harder than simply controlling 1-DOF elements one by one and implies to consider each 1-DOF element mechanical interactions on its surrounding environment. In order to handle efficiently such a distributed architecture, we used the SynDEx[1] CAD V5 software [9] which Linux/RTAI, MPC555 and CAN kernels were developed in collaboration with INRIA[2].

2.4 Experiment on pressure and position control

Making use of the control architecture proposed above, we manage to identify and fine tune both pressure and position loops, by a classical closed loop Ziegle-Nichols method (analysing system response to a step input). Results we got were fairly satisfactory regarding to both the high non linearity and the important hysteresis of the system.

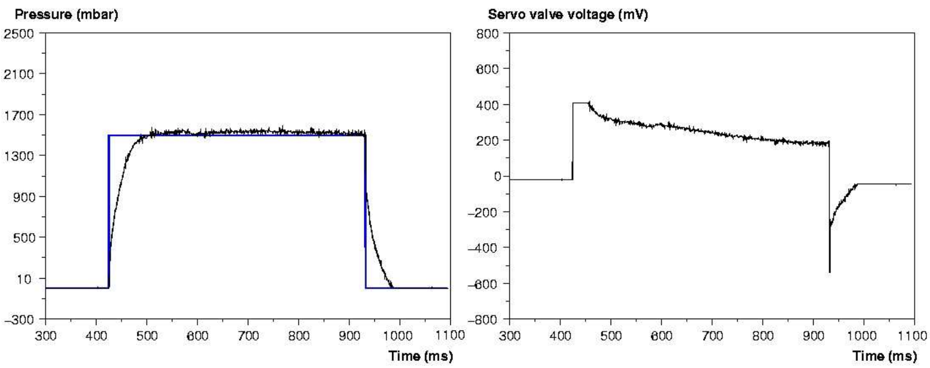

Fig. 8 Response of the 100 Hz PID to a 1.5 bars pressure step command (on the left) and (on the right) voltage commands sent to the servo valve during control.

Figure 8 and 9 give graphical representation of the results observed through the streaming log reports. Figure 8 shows the pressure PID controller response to a 1.5 bars pressure step input. We remark that the system manages to reach pressure stability after less than 100 ms. Static error during pressure tracking is handled by integral time, what explains the very good tracking precision we obtain after the very first oversteps. Servo valve voltage commands generated by the PID during control are displayed on the right part of figure 8. Let us note the voltage is fully saturated during approximately the first 50 ms. This voltage limitation has been intentionally fixed in order to prevent system from getting damaged because of too high pressure inside PARM tubing. Figure 9 shows graphical results related to the higher PID loop

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in charge of angular position control. Data displayed correspond to the complete 1-DOF system (composed of the two PARM) response to a 45 deg angular step command. On the left side, results illustrate the system tracking a ramp shape angular position signal. For this we chose a maximum angular velocity of 50 deg / s (what is surely fast enough for this kind of applications). Regarding results, the tracking error appears to be negligible.

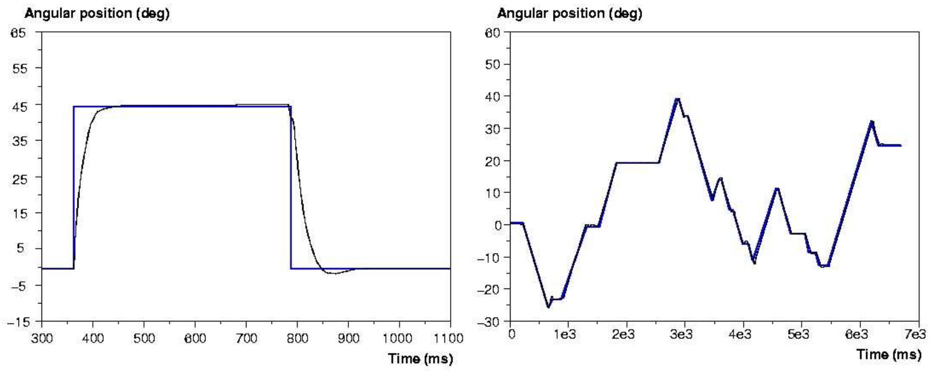

Fig. 9 Response of the 20 Hz PID to a 45 deg angular position step command (on the left) and (on the right) position tracking experiment results recorded over 7 s with a ramp shape position signal as input.

3 APPLICATION TO A 3-DOF ROBOT ARM

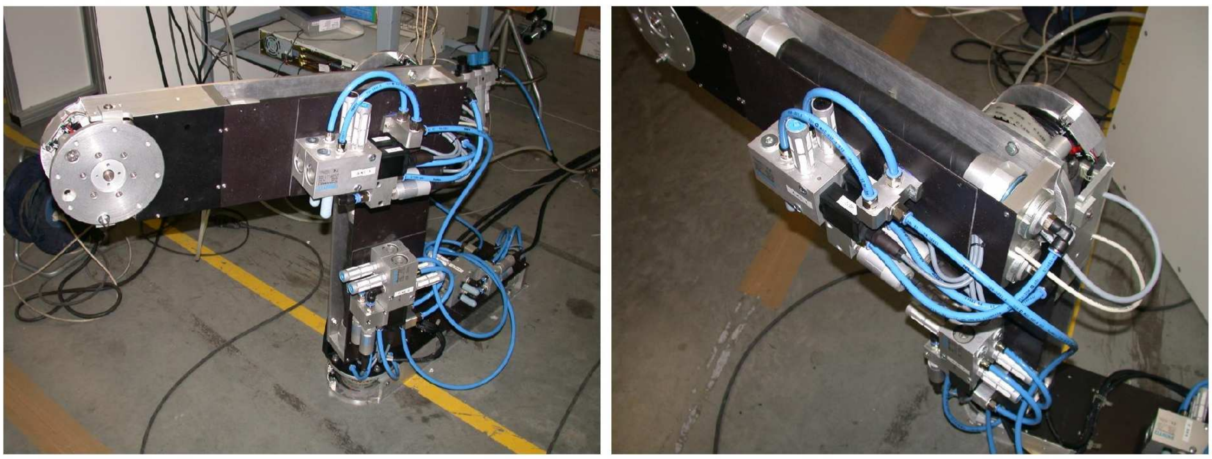

Fig. 10 The 3-DOF pneumatic robot arm composed of three 1-DOF elements

The 1-DOF pneumatic elements, we studied along this article, have been for composing a complete 3-DOF robot arm. This sample application intends to demonstrate the modularity of such approach as well as the ease of mechanically mounting and connecting element each other. Operating the 3-DOF arm joins was done from a remote Linux workstation while control was performed by two MPC 555 boards. During experiment, each join was fairly well controlled making the arm move along a trajectory (previously generated using the arm inverse geometric model) by passing goal point coordinates every 50 ms. Arm precision we reached dynamically (during motion) was about ±1 cm with three 1-DOF elements of 70 cm and a 40 cm metal stick as end effector. Regarding the angular precision we got from previous tests, this results corroborate or expectations. Nevertheless, we have to mention that tuning control gain, for such a global system, is getting much more harder with the increasing number of 1-DOF element, depending on the way they are arranged together. This remark should lead our further investigations toward more complex and adaptative control strategies able to take into account dependent kinematical parameters and linked mechanical constraints.

CONCLUSION

In this research, we developed a modular 1-DOF pneumatic element based on a new generation of artificial muscles: the PARM. In spite of a strong nonlinearity, that makes PARM difficult to drive, these actuators offer several interesting characteristics: light weight, large power and robustness to extreme environment. Control of the bi-muscular 1-DOF system we provide has been significantly improved by implementing a 100 Hz PID minor loop in charge of driving pressure inside PARM tubing. Relying on this first control stage, angular position control of the 1-DOF rotating plate became easier. With such a PID cascade, system precision reached our expectations. This step, allowed us to prove the modularity interest of our approach, by using the studied 1-DOF elements for building a 3-DOF robot arm. The so develop arm was proposed to the research center of Alger as an experimental platform for further developments. Tracking results obtained along computed trajectory was satisfactory enough to consider using such pneumatic structures for various remote operations (e.g. inspection, loading or shifting operations). Nevertheless, the variety of structures that is possible to build from the proposed 1-DOF elements, is actually limited by the complexity of the kinematical structure of the goal structure. Indeed, with the increasing number of 1-DOF elements, both kinematical and mechanical parameters become closely dependent, implying strong interactions between elements control loops. These considerations surely constitute a significant road map for further researches.

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