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POSITIONAL SERVO-MECHANISM ACTIVATED BY ARTIFICIAL MUSCLES*†

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Abstract—A positional servo-mechanism was designedt o facilitate multi-layer electronic control of complex orthotic and prosthetic devices. The design aim was to obtain adequate performance of the system using lightweight, flexible and inexpensive components. The mechanism is actuated by an antagonistic pair of McKibben pneumatic muscles. The muscles are controlled by a pair of twin electro-pneumatic valves operating in an on/off regime. System elements are described in the paper and some relevant design factors pointed out.

INTRODUCTION

CONSIDERABLE efforts have been made to develop multi-functional orthoses and prostheses of upper extremities, having several degrees of freedom. The crucial problem—how to obtain smooth co-ordinated movements of such devices when a limited source of information is available on the patient—is still unsolved. One possible approach to that problem is to introduce a multi-layer control system to invervene between the patient and the artificial extremity (GAVRILOVIĆ, MARIĆ and VUKOBRATOVIĆ, 1967). This concept assumes the basic control layer to be made of positional controllers related to particular degrees of freedom.

The role of this control layer may be considered analogous to that of the follow-up systems of skeletal muscles in men. The main task of this control layer is to reduce the interaction of extremity parts and make the system insensitive to parameter and environment changes.

The purpose of the research described in this paper was to design a positional servo-mechanism with artificial muscle actuation suitable for application in multi-layer control systems.

At present pneumatic and electric actuators are most frequently applied in prosthetics and orthotics since the energy for such actuation can be stored efficiently. Pneumatic actuators are lighter, cheaper and more adaptable to bracing. Artificial muscles exhibit no static friction. They do not introduce alignment problems and they are lighter and cheaper than other pneumatic actuators. Therefore, it was considered that the design of a servo-mechanism actuated by means of artificial muscles might be of interest.

SOME STATIC AND DYNAMIC PROPERTIES OF McKIBBEN MUSCLE

McKibben muscles were chosen to actuate servo-mechanism as the only pneumatic muscles commercially available, although better pneumatic muscle types exist. (MORECKI, EKIEL and FIDELUS, 1967). Technological properties of the McKibben muscle are described elsewhere (ENGEN, 1964–67). The muscle characteristics important for its application in servo-mechanisms are treated here to some extent.

This artificial muscle is made of an elastic bladder and a helically woven sheath. Static characteristics of muscle are determined by sheath deformation. If a muscle containing an

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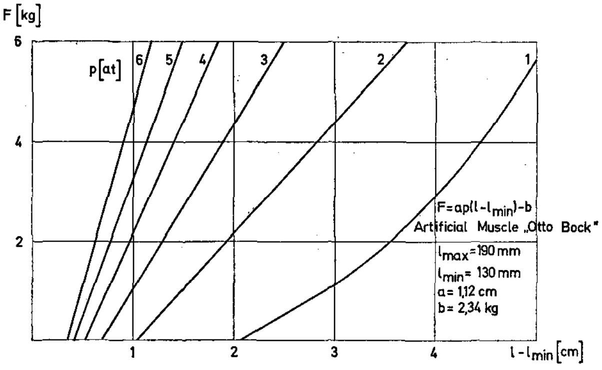


FIG. 1. Static characteristics of McKibben muscle.

amount of gas extends, the gas volume decreases, the pressure increases, so does the reaction force.

The muscle static characteristics are described by the function that relates the force of the muscle to the extension and gas pressure. The characteristics determined experimentally are shown in Fig. 1. The characteristics have a linear and nonlinear region. The nonlinear region corresponds to large extensions. In the linear region the static characteristics can be approximated by a family of straight lines.

$$F = ap(l - l_{\min}) - b$$

where F is muscle force,
p is gas pressure,
l is muscle length,
$l_{\min}$ is minimal muscle length,

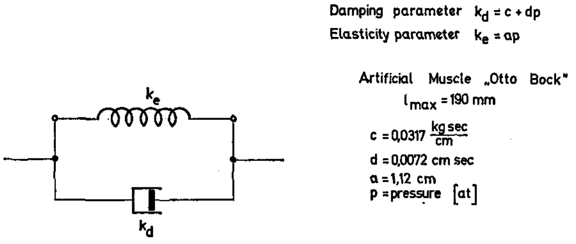
a,b are constants (the value for these constants in the case of a muscle made by Otto Bock are given in Fig. 1).

In the linear region the artificial muscle behaves as a spring with an elasticity parameter proportional to pressure.

The artificial muscle exhibits no static friction, but considerable viscous friction. The muscle containing some amount of gas behaves as a system consisting of a spring and a damper (Fig. 2). Within the working range (2–6 atm) the damping parameter, in practice, does not depend on pressure.

The gas pressure in the muscle can be varied by means of a valve that controls the gas inlet from a constant pressure reservoir and a second valve for the gas outlet to atmosphere.

Since the artificial muscle is a unidirectional actuator, an antagonistic pair of muscles has to be applied. The muscles are fixed to supporting points and tied one to another by means of a steel cord. The cord is laid over a wheel and fixed to it at one point. The wheel itself is fixed to the moving lever of the mechanism. The static characteristics of antagonistic muscle pair are



Damping parameter $k_d = c + dp$
Elasticity parameter $k_e = ap$

Artificial Muscle „Otto Bock"
$l_{max} = 190$ mm
$c = 0{,}0317 \frac{\text{kg sec}}{\text{cm}}$
$d = 0{,}0072$ cm sec
$a = 1{,}12$ cm
p = pressure [at]

FIG. 2. Dynamic model of McKibben muscle.

shown inFig. 3. The fixing point on the wheel can move within an interval $\Delta s = s_{\max} - s_{\min}$. The steady state of the mechanism is described by the face point that can take any position within the $AB_1B_1'B_2'B_2A$ region, (Fig. 3). When both muscles are at maximal pressure, the state of the mechanism is described by the point A at which the relevant characteristics intersect. The mechanism can move in two intervals symmetrical with respect to the point A′. The maximal forces are obtained when the face point moves along the maximum pressure characteristics AB_1 and AB_2.

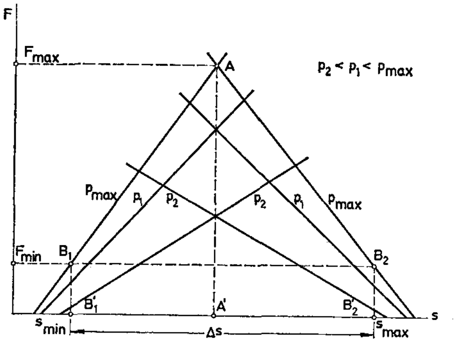


FIG. 3. Static characteristics of antagonistic muscle pair.

For the given force range $\Delta F = F_{\max} - F_{\min}$, the displacement $\Delta s = s_{\max} - s_{\min}$ obtained with the muscle pair is twice as long as that obtained with muscle–spring combination (elasticity parameter of the spring being equal to one of the muscle at maximal gas pressure).

SERVO-MECHANISM CONFIGURATION

In order to control the antagonistic pair of pneumatic muscles by electrical signals, an electro–pneumatic valve system is required. The valve system determines, to a considerable extent, the type of control to be used. On/off valves were chosen since they are considerably simpler and cheaper than valves with continuous positioning. In order to obtain satisfactory following-up capabilities a pulse frequency controller was chosen, although a pulse width system was also considered.

The servo–mechanism configuration is shown in Fig. 4. It comprises a valve system, a pair of pneumatic muscles, a mechanical joint and a potentiometer for angular position measurement.

The controller has two inputs and two outputs. One input is proportional to the desired angular position and the other one is proportional to the angular position of the mechanical joint. The frequency of output pulses is proportional to the difference of input signals. The sign of this difference determines the output at which the pulses will appear.

The valve system consists of two twin electro–pneumatic valves driven by the two controller outputs.

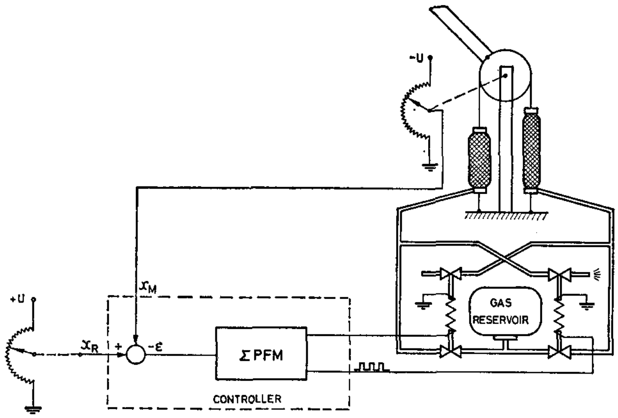
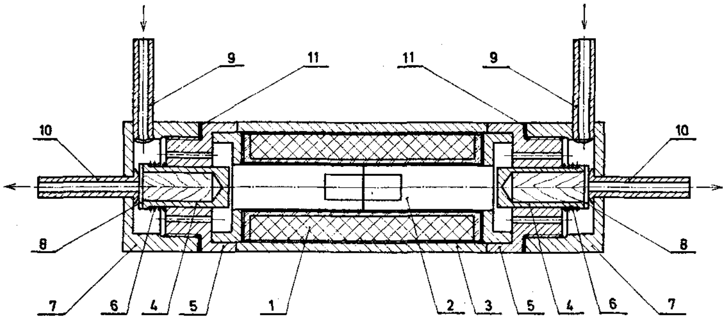


FIG. 4. Positional servo-mechanism activated by artificial muscles. Principle configuration.



Coil resistance : 50 Ohms
Ampereturns : 500
Supply voltage : 12 V
Maximal operating freqvency : 100 Cps

FIG. 5. Electro-pneumatic valve.

ELECTRO-PNEUMATIC VALVE

Two twin electro-pneumatic valves were used instead of four single ones; this simplified the valve system and also the controller.

The construction of the twin valve is shown in Fig. 5.

The valve electromagnet is composed of a coil (1), and of the following soft iron parts: electromagnet core (2), yoke (3), and two anchors (4) with guides (5).

Each of the two valve elements consists of a valve body (7) with an inlet tube (9) and an outlet tube (10). There is a seal between the anchor guides and the body (11).

If the electromagnet is not excited, the helicoidal springs (6) press the anchors against the valve bodies so that the valves are closed against gaskets (8). Overpressures in the valve chambers, (in respect to the pressures in the outlet tubes), contribute to the tight contact.

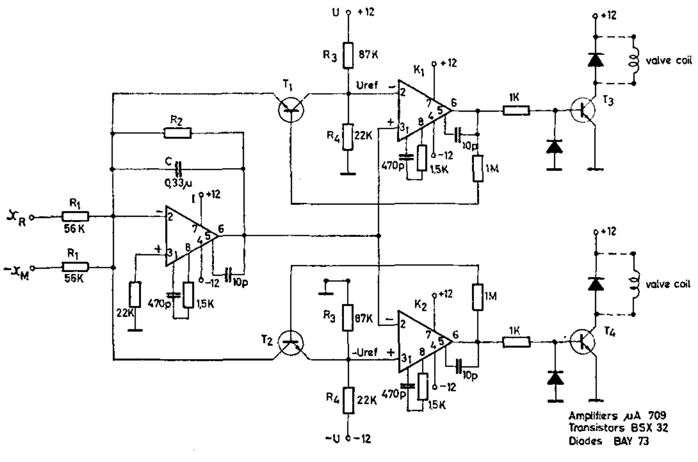
If the electromagnet is excited, the anchors are attracted to the core and the valves open.

Therefore, two states of the twin valve exist: closed and open.

CONTROLLER

The electronic controller performs the discrimination of input signals, the error conversion into the pulse frequency, and drives the valves.

The controller (Fig. 6) consists of an integrator



Amplifiers μA 709
Transistors BSX 32
Diodes BAY 73

FIG. 6. ΣPFM electronic controller.

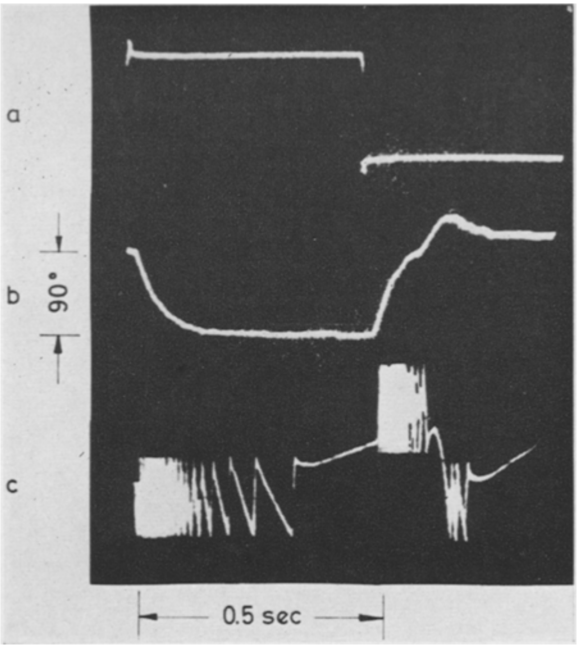


FIG. 7. Servo-mechanism responses to a step input
(a) input angular position.
(b) output angular position.
(c) output waveform of the controller integrator.

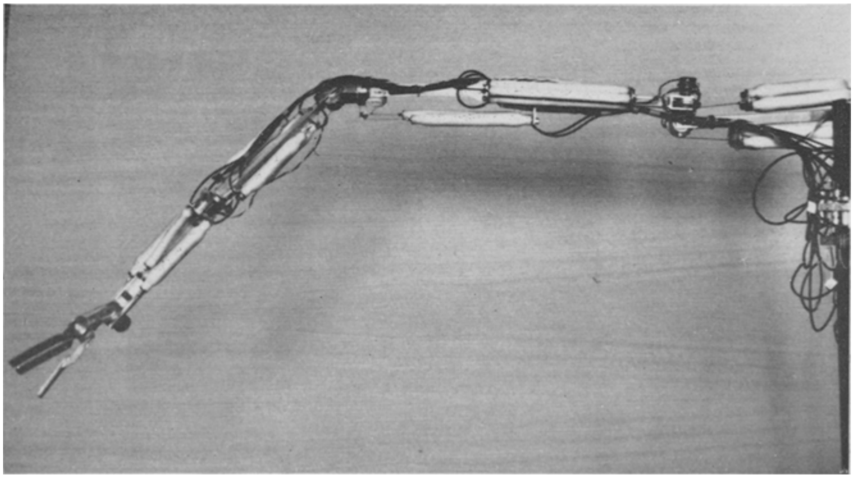


FIG. 8. Artificial arm equipped with seven servo-mechanisms.

(I), comparators (K_1, K_2), integrator switches T_1, T_2) and output switches (T_3, T_4).

The controller is in an excited state if a pulse appears at any of the outputs, otherwise the controller is in an unexcited state. To describe the operation of the controller let us assume that the initial state is the unexcited one, the output voltages of both comparators being negative. The switches T_1, T_2 are open and the voltages U_{ref} and $-U_{ref}$ at the reference inputs of the comparators K_1, K_2 are determined by the resistances R_3, R_4 and the supply voltages U and $-U$. The output voltage of the integrator is proportional to the integral of the error voltage $\epsilon = x_R - x_M$. If the integrator output reaches one of the reference voltages (U_{ref} or $-U_{ref}$), the respective comparator (K_1 or K_2) changes its state, i.e., its output voltage becomes positive. The respective output switch (T_3 or T_4) and the integrator switch (T_1 or T_2) close. The controller is in an excited state. The closure of the integrator switch gives to the comparator reference input a new value close to the ground potential. The condenser C begins to discharge through the resistor R_3 and the integrator switch (T_1 or T_2). The output voltage of the comparator is positive until the condenser C discharges entirely. Then it becomes negative again and the controller returns to the unexcited state. Duration τ of the output pulse is described by the following expression:

$$\tau \cong C \frac{R_3 R_4}{R_3 + R_4}$$

when $\tau \ll 1/f$, f being the pulse frequency.

The pulse frequency is described approximately by the expression:

$$f \cong \frac{1}{CR_1} \cdot \frac{R_4}{U_{ref} R_3} \epsilon$$

when $1/f \gg \tau$.

The resistor R_2 which bypasses the capacitor C determines an insensitivity region

$$\pm \epsilon_0 = \pm U_{ref} \frac{R_2}{R_1}$$

that makes the controller to be one with ΣPF modulation (Pavlides and Jury, 1965).

In Fig. 7 step responses of the servo-mechanism are given. Positive step input was applied first. When a negative step input was applied a time-varying load was introduced so that an overshoot appeared. However, these dynamic performances of the servo-mechanism have local significance as the servo-mechanism is nonlinear.

DESIGN CONSIDERATIONS

The servo-mechanism actuated by means of artificial muscles described in this paper belongs to the class of nonlinear pulse servosystems. The torque delivered by the antagonistic pair of muscles can be described by a nonlinear differential equation of high order, the input variables being the states of valves. The mechanical hardware driven by muscles is a nonlinear element of the servo-mechanism due to gravity.

An axial force to the joint bearings appears due to muscle disposition which causes an additional dry friction. If ball bearings are not used a slip-stick problem may arise.

A straight forward synthesis of such servo-mechanism is not possible. However, some facts may be of value to designers.

The servo-mechanism performances are determined by: maximum inertia of moving parts; static and dynamic characteristics of artificial muscles; geometry of tubing and valves; gas supply pressure; parameters of the controller.

The servo-mechanism always settles so that one muscle is under the pressure which is close to its supply pressure. Therefore, the face point falls close to static characteristics B_1AB_2, (Fig. 3).

The pulse width determines the steady state error of the system. If the pulse width τ is applied to the valve, the angular position of the mechanism will be changed by $\Delta\theta$, which depends on angular position θ and load torque. From the precise positioning point of view narrow pulses are desirable. However, there exists a limiting minimum value of the pulse width for which the valve can still operate reliably.

If a controller without the region of insensitivity were used, the system would oscillate about the preset position. The region of insensitivity, where $\epsilon_0 > \Delta\theta_{max}$, enables the controller to prevent such oscillation.

Having the pulse width determined with respect to the steady state error requirements, controller adjustments can be made in order to attain the best response of the servo-mechanism.

CONCLUSION

The servo-mechanism described in the paper was used for an artificial arm of seven degrees of freedom (Fig. 8). The arm was built to enable the feasibility study of multi-layer control of orthotic and prosthetic devices to be carried out.

The performances of the servo-mechanism have been found satisfactory for the purpose. However, better performances of the servo-mechanism would be obtained if electro–pneumatic valves of improved capabilities were applied. Valves that operate much faster can be designed if the latest achievements of fluidics are applied.

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SERVO-MÉCANISMES DE POSITION POUR MUSCLES ARTIFICIELS

Sommaire—Un servo-mécanisme de position a été conçu pour faciliter la commande électronique à plusieurs niveaux d'appareils de prothèse complexes. L'objet des recherches était d'obtenir des performances adéquates en utilisant des composants legers, souples, et de prix réduit. Le mécanisme est actionné par une paire de muscles pneumatiques antagonistes du type McKibben. Les muscles sont commandés par une paire de valves électro–pneumatiques jumelles fonctionnant en tout ou rien. L'unité de commande est un générateur d'impulsions à modulation de fréquence. L'article décrit les différents éléments du système et met en évidence certains détails de conception significatifs.

LAGESERVOMECHANISMUS, DER VON KÜNSTLICHEN MUSKELN AKTIVIERT WIRD

Zusammenfassung—Ein Lageservomechanismus wurde entwickelt zur Erleichterung mehrstufiger elektronischer Steuerung komplexer orthotischer und prothetischer Geräte. Ziel der Entwicklung war eine adäquate Leistung des Systems unter Verwendung von leichten, flexiblen und preiswerten Bauteilen. Der Mechanismus wird von einem antagonistischen Paar pneumatischer McKibben-Muskeln angetrieben. Die Muskeln werden mit einem Paar elektropneumatischer Doppelventile mit einer Ein/Aus-Steuerung kontrolliert. Eine Kontrollstelle mit Impulsfrequenzmodulation erwies sich als geeignet für die Anwendung. In dieser Mitteilung werden die Systemelemente beschrieben, und einige wesentliche Konstruktionsfaktoren werden erörtert.