Fuzzy Logic Trajectory Control of Pneumatic Actuators for Rehabilitation Robot System

Nataša Koceska[1], Sašo Koceski[2]

***Abstract* – In this paper the development of efficient fuzzy logic trajectory control of pneumatic system is presented. The pneumatic actuators used in our experiments, are part of a lower limb rehabilitation exoskeleton with 10 DOF (Degrees Of Freedom). The aim of the developed trajectory control system is to guide physiologically the inferior limbs of a rehabilitant according to natural movements. The developed fuzzy controller was implemented and tested on embedded PC104 system.**

The objectives achieved by the proposed controller are mainly high performance, accurate trajectory control and high robustness.

***Keywords* – Fuzzy logic, trajectory control, pneumatic actuators, rehabilitation robot system.**

I. Introduction

Recently there is great demand of pneumatic systems in the field of medical robotics. They are used to meet the need of lower cost, high power-to-weight ratio, long duration, ease of maintenance, cleanliness. However, pneumatic systems exhibit highly non-linear behaviors that are associated with the compressibility of air, the complexity of friction presence and the nonlinearity of valves [1], [2], [3]. Because of all these characteristics, it is very difficult to successfully apply the classical control theory on pneumatic systems. It is relatively easier to use a fuzzy logic control, even though there are difficulties in designing a fuzzy controller and determining its parameters by trial and test.

Applying fuzzy control to a continuous pneumatic positioning system is particularly advantageous in terms of simplicity of design and implementation, and thus significantly reduces the time required to develop the entire system [4], [6]. Also fuzzy control has been demonstrated to provide highly satisfactory results in terms of accuracy, repeatability and insensitivity to changes in operating conditions [5].

A great number of researches have been done in the analysis of fuzzy control systems, in the field of robotics [7], [8].

Despite this prior work, obtaining the accurate control of pneumatic systems is still a very challenging task.

In this paper the development of efficient fuzzy logic controller for simultaneous real-time control of two pneumatic rod cylinders is presented. The pneumatic actuators used in our experiments, are part of a lower limb rehabilitation exoskeleton with 10 DOF (Degrees Of Freedom). The aim of the developed controller is to enable efficient trajectory control which will guide physiologically the inferior limbs of a rehabilitant according to natural movements. The developed fuzzy controller is implemented and tested on embedded PC104 system.

[1]Nataša Koceska is with the Applied Mechanics Laboratory, DIMEG, University of L'Aquila, Via Montorio Al Vomano 6, 67100 L'Aquila (AQ), Italy, E-mail: njankova@yahoo.com

[2]Sašo Koceski is with the Applied Mechanics Laboratory, DIMEG, University of L'Aquila, Via Montorio Al Vomano 6, 67100 L'Aquila (AQ), Italy, E-mail: koceski@yahoo.com

II. Functional Description

On Fig. 1. our robot rehabilitation system composed of two pneumatic cylinders, connected to the femoral and tibia bars on each of the "legs" of the robot, is presented. Through the accurate control of the length of these actuators, it is possible to guide the inferior limbs of a patient.

Fig.1. Design of the lower limbs rehabilitation system with pneumatic servo actuators

III. Fuzzy Controller

Classical control theory can be successfully applied to systems which are well defined and when the parameter variations are not so excessive. The nonlinear processes should often be controlled by heuristic rules of human knowledge. In that situation, it seems that fuzzy control theory can give suitable solutions. The essence of fuzzy logic control is that appropriate linguistic fuzzy rules are chosen, using some decision-making process, from a rule table constructed using human control experience and databases.

Before designing a fuzzy controller, it is necessary to have some supposes for simplification as follows:

- The reference zero position for displacement controlling of the cylinder is defined at the end point of the cylinder's rod when it is completely out.
- The output error e(t) is positive if the reference point r(t) is greater than the real displacement x(t);
- In order to move the piston from bottom to up, the pressure of the bottom chamber controlled by the bottom pressure proportional valve must be greater than the sum of friction, gravity force and the count force produced by the pressure of the upper chamber of the cylinder.

Since the working area of cylinders is overlapping, the same fuzzy controller is used for both of them.

The fuzzy controller is composed of fuzzification, control rules, fuzzy logic inference and defuzzification procedure, as presented on Fig. 2.

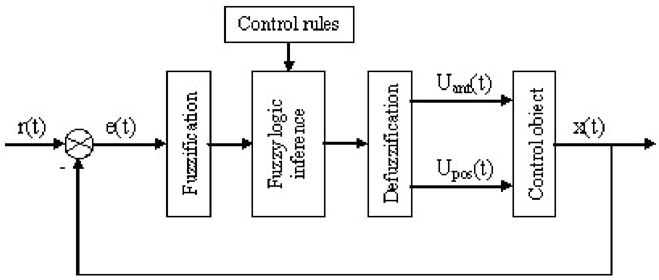

Fig.2. Fuzzy controller structure

The state variables of the pneumatic fuzzy control system are: the displacement error E, which is the input signal and two output control signals U_{ant} and U_{pos} which are control voltages of the bottom and upper valve respectively.

Displacement error in the system is given by:

$$e(kT) = r(kT) - x(kT) \tag{1}$$

where, *r(kT)* is the reference point, *x(kT)* is the actual measured displacement, and T is the sampling time.

Based on this error the output voltage, that controls the pressure in both chambers of the cylinders, is adjusted.

Seven linguistic values non-uniformly distributed along their universe of discourse have been defined for these variables (negative large-NL, negative medium-NM, negative small-NS, zero-Z, positive small-PS, positive medium-PM, positive large-PL). For this study trapezoidal and triangular-shaped fuzzy sets are chosen for input variable and singleton fuzzy sets for output variables.

The membership functions were optimized starting from a first, perfectly symmetrical set. Optimization was performed experimentally by trial and test with different membership function sets. The membership functions that give optimum results are illustrated in Figs. 3a, 3b and 3c.

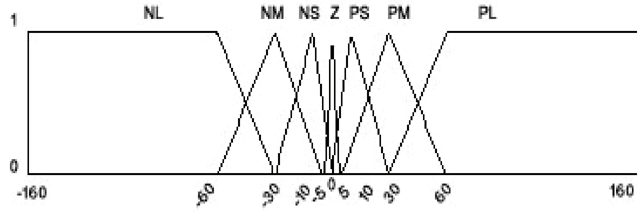

Fig.3a. Membership function of input variable E

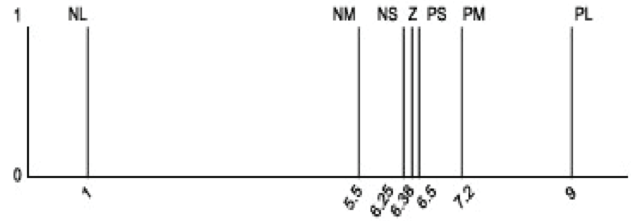

Fig.3b Membership functions of output variables U_{ant}

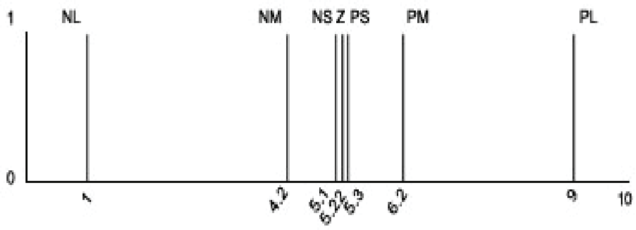

Fig.3c Membership functions of output variables U_{pos}

The rules of the fuzzy algorithm are shown in Table I in a matrix format.

TABLE I
RULE MATRIX OF FUZZY CONTROLLER

Rule n °	E	ANT	POS
1	PL	PL	**NL**
2	PM	PM	**NM**
3	PS	PS	**NS**
4	Z	Z	**Z**
5	NS	NS	**PS**
6	NM	NM	**PM**
7	**NL**	**NL**	**PL**

For convenience the rules of the fuzzy algorithm shown in Table I express the actions to be exerted on the valves connected to the cylinder chambers in order to reduced displacement errors.

For example, Rule 1 is introduced because the rod must be displaced a lot when the actual position is fairly far below the reference value (E = PL). This is translated into control voltages such as to direct a high supply air flow to bottom chamber ANT and to increase the pressure in it (U_{ant} = PL) and also to direct a high flow from upper chamber POS towards discharge and to decrease the pressure in it (U_{pos} = NL). The other rules shown in Table I originate from similar qualitative considerations.

The max-min algorithm is applied and center of gravity (CoG) method is used for deffuzzify and to obtain an accurate control signal.

IV. INVERSE KINEMATICS PROBLEM

Since the aim of the developed controller is to enable efficient trajectory control which will guide a patient according to natural movements, a special experimental procedure for movement analysis of inferior limbs, was performed. The walk of a health person on a treadmill with standard video camera equipped with 3CCD sensor was recorded. Videos were captured with optic axis normal on the plane on the limbs' movement. The videos were post-processed and kinematics movement parameters of limbs' characteristic points (hip, knee and ankle) were extracted.

These data were imported in Working Model 2D which allow to carry out kinematics simulations of complex mechanical systems. By the means of this software the inverse kinematic problem was resolved, and the trajectory which must be performed by the actuators was determined.

V. EXPERIMENTS AND RESULTS

Experimental set up, presented on Fig. 4, is composed of two vertically positioned rod cylinders SMC CM2C32F-160 and SMC CM2C32F-180 (with stroke length l1=160 mm, l2=180 mm, respectively and diameters d=32 mm.). Motion of each cylinder's piston (i.e. supply and discharge of both cylinder chambers) are controlled by two pressure proportional valves (SMC-ITV 1051-312CS3-Q), connected to both cylinder chambers. In order to obtain the information of the piston's position for each cylinder, two linear potentiometers (Celesco DV301-0040-111-1110) are used.

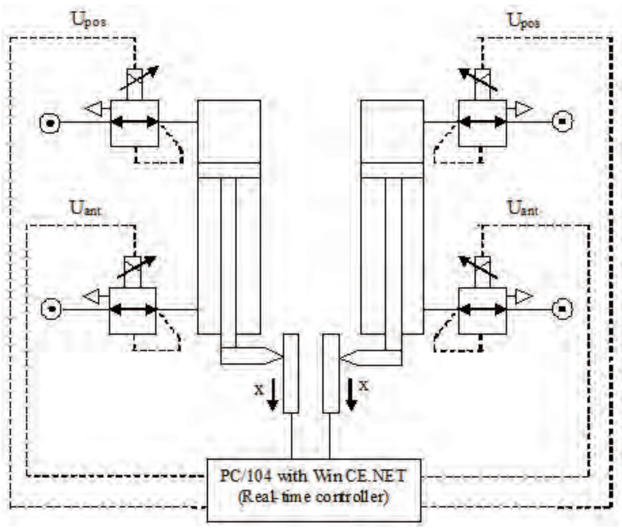

Fig.4. Schema of the experimental setup

The system is managed by an embedded PC104 Athena board from Diamond Systems, with real time Windows CE.Net operating system, which uses the RAM based file system. The Athena board combines the low-power Pentium-III class VIA Eden processor (running at 400MHz) with on-board 128MB RAM memory, 4 USB ports, 4 serial ports, and a 16-bit low-noise data acquisition circuit, into a new compact form factor measuring only 4.2" x 4.5". The data acquisition circuit provides high-accuracy, stable 16-bit A/D performance with 100 KHz sample rate, wide input voltage capability up to +/- 10V, and programmable input ranges. It includes 4 12-bit D/A channels, 24 programmable digital I/O lines, and two programmable counter/timers. A/D operation is enhanced by on-board FIFO with interrupt-based transfers, internal/external A/D triggering, and on-board A/D sample rate clock.

Microsoft embedded C++ programming language is used to program the control algorithm and effectuate the measurements.

The Fuzzy controller, described in section III, is used in trajectory control of pneumatic servo actuators and a lot of experiments have been made. In order to implement the control algorithm on embedded PC104, some necessary operations such as reading and storing data, calculating the output error, normalization, fuzzification, inference and defuzzification, must be performed. All operations must be done in real time with a sampling period of 10ms. In order to meet these constraints the controller is implemented in several optimized program modules. Data acquisition and control modules for both cylinders are loaded and run from RAM memory of the PC104.

The developed controller was first experimentally tested on sinusoidal trajectory control (period-4s, amplitude-40mm). The experimental results are presented on Fig.5.

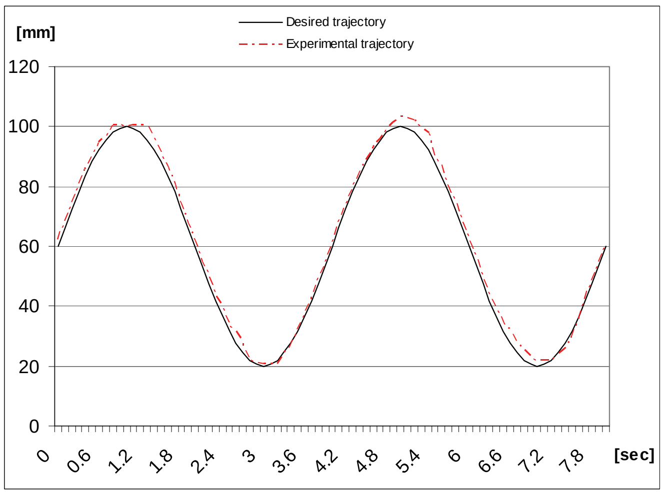

Fig.5 Experimental results with sinusoid trajectory control

After this, the controller was tested on trajectory obtained with inverse kinematics, according the experimental procedure described above.

The results for both cylinders are presented on Figs.6 and 7.

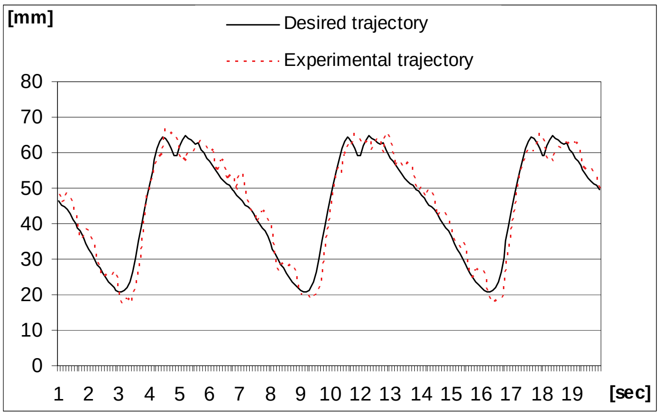

Fig.6 Trajectory control of cylinder connected to femoral bars

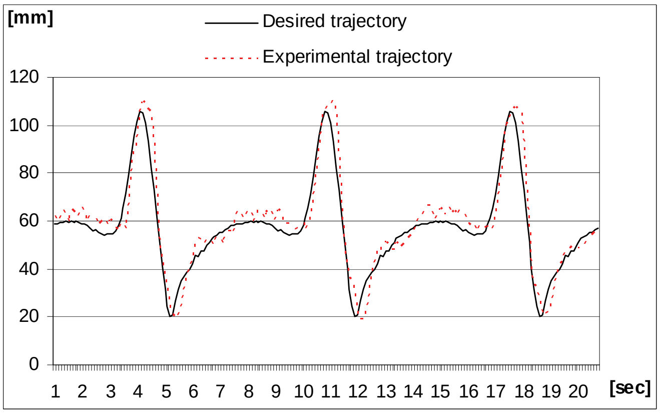

Fig.7 Trajectory control of cylinder connected to tibia bars

VI. Conclusion

It is important to make evident the great potential that fuzzy logic has to offer, in the field of pneumatic systems. However, high system knowledge is necessary to improve the performance of the controlled actuators.

As it is shown in this work, with the developed controller accurate trajectory control and high robustness of the system were achieved. The experiment results show that the trajectories in both cases are mainly followed well and the final output error is less that 5mm. This error is acceptable for our system which will be used for rehabilitation purposes.

VII. Future Work

Future directions of the work include experimental verification of the proposed fuzzy controller on the actuators with the load of 5, 10, 15 and 20 kg., and implementation of the error change rate as a second controlled variable of the fuzzy controller.

References

[1] J. Y. Lai, C. H.. Meng, R. Singh, "Accurate position control of a pneumatic actuator", Transactions of the ASME, Journal of Dynamic Systems, Measurement, and Control, 112, 734-739, 1990.

[2] P. R. Moore, J. Pu, R. Harrison, "Progression of servo pneumatics towards advanced applications", in Fluid Power Circuit, Component and System Design, K. Edge and C. Burrows (pp. 347-365), Research Studies Press, England, 1993.

[3] J. Pu, R. H. Weston, P. R. Moore, "Digital motion control and profile planning for pneumatic servos", Transactions of the ASME, Journal of Dynamic Systems, Measurement, and Control, 114, 634-640, 1992.

[4] C. Ferraresi, M. Velardocchia, "Posizionatore Pneumatico con Controllo Elettrico", *Oleodinamica. Pneumatica*. Italy, 1988.

[5] C. Ferraresi, T. Raparelli, M. Velardocchia, "Studio della Stabilità e della Prontezza di Sistemi di Posizionamento Pneumatici", *X Congresso Nazionale dell'Associazione Italiana de meccatronica*, 1990.

[6] C. Ferraresi, P. Giraudo, G. Quaglia, "Non Conventional Adaptive Control of a Servopneumatic Unit for Vertical Load Positioning", *Proceedings of the 46th National Conference on Fluid Power*, 1994.

[7] M.R. Emami, A.A. Goldenberg, T.R. Burhan, "Systematic design and analysis of fuzzy-logic control and application to robotics", Part I. Modeling, Robotics and Autonomous Systems 33, pp. 65-88, 2000.

[8] B. Novakovic, D. Scap, D. Novakovic, "An analytic approach to fuzzy robot control synthesis", Engineering Applications of Artificial Intelligence 13, pp. 71-83, 2000.