

POSITION CONTROL OF A SERVO-PNEUMATIC SYSTEM

Hybrid Fuzzy P+I Controller of a Servo-Pneumatic Fatigue Simulator

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Abstract: This paper proposes a hybrid fuzzy P+I controller for a servo-pneumatic machine to perform and monitor tests on biomechanical devices, such as orthopaedic prosthesis. The methodology followed is based upon the CompactRIO®, a real-time platform, and the system was fully programmed using LabVIEW language. Separate algorithms of a PI, proportional fuzzy and hybrid fuzzy P+I controllers were developed and compared. The performance of the overall system has already been tested and the experimental results for position control show that the PI controller can reach 2 μm of accuracy but with a very slow rise time. However, the same accuracy can be achieved with Hybrid Fuzzy P+I controller, although with a fast rise time and neglected overshoot. The authors can conclude that this proposal can successfully overcome unknown nonlinear parameters of the pneumatic system and has high position control accuracy.

1 INTRODUCTION

More than 250000 surgeries of total knee replacement and 180000 surgeries of total hip replacement are performed in the US every year. The smart hip joint prosthesis is a new research field, which is integrated in the Biomechanics Research Group (University of Aveiro) strategy. Total Hip Replacement (THR) arthroplasty is currently one of the most performed elective surgical procedures. The most serious complication of THR is loosening of the prosthetic stem and cup. No technique is capable of determining with exactness the levels of loosening, the reasons and the regions of the implant were it occurs with time. It has been referred that more than 80% of the non-successes are due to implant loosening. In this context, the PTDC/EME-PME/70824/2006 project, still running, has been financed, whose main aim is to develop a cemented and instrumented hip prosthesis with sensorial capacities to detect the degree of implant loosening and the regions where it occurs with time, through a non-invasive method that can be used to define clinical correction and prevention

methodologies. Therefore, medical staff could access to “continuous” information about the evolution of the implant behaviour, providing means to avoid the presence of patients frequently in the medical office. The work here presented is mainly related with the project presented above and with an ongoing project where the principal aim is to develop a methodology to produce and study ultra high molecular weight polyethylene reinforced with carbon nanotubes (CNT/UHMWPE composites) and evaluate its suitability for enhancing the wear resistance of acetabular cups and therefore minimizing the above highlighted issues.

This background drew the need to develop a high position control and force accuracy of a 1 degree-of-freedom (DOF) servo-pneumatic machine developed by Biomechanics Research Group of the University of Aveiro (Santos, et al., 2008) to carry out the required fatigue simulation tests or any kind of pneumatic force up to 3 kN . The control system must also be prepared/easily fitted to answer to the accuracy requirements related with new researches on smart implants which may occur in the future. The fatigue simulator is shown in figure 1.

2 MECHANICAL APPARATUS

The main purpose of the fatigue simulator is the simulation of biomechanical actions to the static and dynamic characterization of synthetic femurs and tibias, with and without prostheses. This goal requires the tracking of positional reference trajectories through an upright course, as well as force references. An aluminum frame structure was reinforced to give more stability. The movement of the cylinder's piston and the load cell were protected with two lateral linear guides to compensate asymmetric loads. This press has already been used to perform long time running fatigue tests for more than 2 weeks running non-stop.

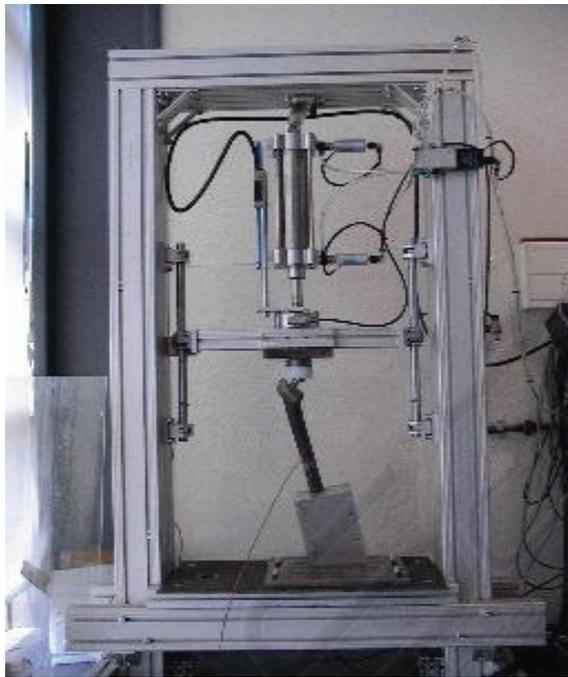


Figure 1: Mechanical Apparatus.

3 INSTRUMENTATION

The servo-pneumatic system consists of:

- A double effect pneumatic cylinder (Festo CRDNGS-80-200-PPV-A) with a 200 mm length and 80 mm diameter to ensure 3016 N at 6 bar;
- A servo-valve (Festo MPYE-5-1/8-HF-010-B) with 750 l/min capacity, to establish the amount of air circulating in each of the two actuator's chambers;
- An optical linear scale (Fagor SV- B220) with resolution of 1 μm is used to measure the machine's actuator moving mass.

- A load cell (AEP TC4), with 10 kN capacity and 0.1% resolution of that value, is used to measure the applied force to the biomechanical device.

4 HARDWARE PLATFORM

The National Instruments PAC CompactRIO® ensures the interface and the connection between the control software and all the instrumentation devices. It is constituted by a Reconfigurable CompactRIO® Intelligent Real-Time Controller/Web Server NI cRIO-9002, a four-slot reconfigurable embedded chassis NI cRIO-9103, a 16 bit Analog Input NI cRIO-9215, a Digital Input NI cRIO-9411 and a 16 bit Analog Output NI cRIO-9263. The real-time controller NI cRIO-9002 has its own 195 MHz industrial processor, 32 MB DRAM memory and a FTP server. With its embedded LabVIEW real-time ETS and a reconfigurable Field Programmable Gate Array (FPGA), this platform makes possible the development of high speed deterministic control applications with high flexibility.

5 SOFTWARE PLATFORM

All the control, monitor and data acquisition software were implemented using LabVIEW 8.0 Professional Development System and LabVIEW Reconfigurable Software Development Kit (includes LabVIEW Real-Time 8.0 and LabVIEW FPGA 8.0 modules), to ensure the controller autonomy, the easy interface with the user operator, the possibility of remote web monitoring and the easy upgrade of controllers. The hardware platform allows a three layer distributed software, as shown in figure 2. Previous work on the design of position and force controllers using this platform were conducted by Santos *et al.* (Santos, *et al.*, 2008).

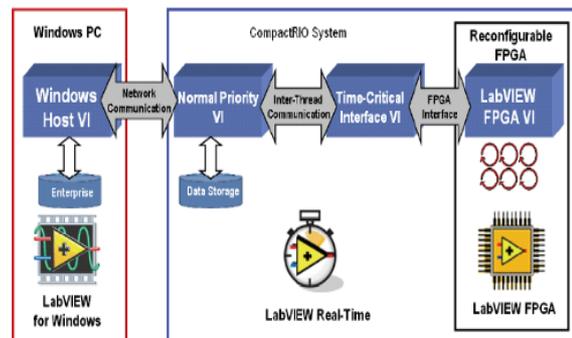


Figure 2: Three layer distributed software.

6 THE PNEUMATIC SYSTEM

The pneumatic servosystem represented in figure 3, is composed by a pneumatic cylinder, which performs movement, and a 5/3 servovalve, that modulates the amount of air entering the cylinder. P_i , T_i and A_i represent pressure, temperature and piston areas of chambers i . M is the actuator moving mass and x is its position. The air supply pressure P_s is set at 6 bar. The servovalve and the pneumatic cylinder are the two system's main blocks. Pneumatic systems usually present a set on nonlinearities that creates problems to close loop controllers. When high accuracy positioning tasks is requested, electrical solutions are normally chosen instead of servopneumatic solutions. The complexity in controlling servopneumatic systems is mainly due to the air compressibility, the piston friction and the non-linear behaviour of the servovalve. In the present case, the servovalve is the highly nonlinear element of the servopneumatic system. The assumption that the orifices area of the servovalve varies linearly with the command input can lead to large modelling errors near the spool central position. Furthermore, there is also the temperature and pressure dynamics of the actuator chambers that should not be neglected (Carneiro, 2006).

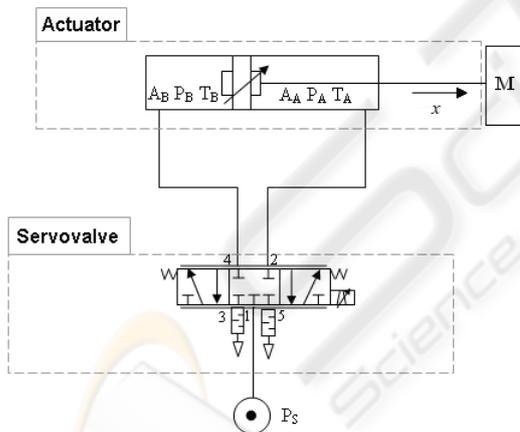


Figure 3: Pneumatic Servosystem.

7 THE CONTROL SYSTEM

The general positioning accuracy in pneumatic control systems only can reach to the range from $\pm 0.1 \text{ mm}$ to $\pm 0.05 \text{ mm}$. Xiang and Wikander (Xiang, 2004) and Carneiro (Carneiro, 2007) have achieved positioning errors below $5 \mu\text{m}$, through the application of nonlinear control methodologies based in the information from mathematical models

of the system, respectively feedback linearization and sliding mode control, to deal with the nonlinearities of the pneumatic system. However, they also have to deal with the inaccuracy of the mathematical model, because it cannot perfectly represent all possible dynamics of the physical process. So, the control system performance depends on the mathematical model accuracy. And cannot be forgotten that the application of some nonlinear control techniques requires lower-order "design models". To deal with these problems, Pai and Shih (Pai, *et al.*, 2003) have developed a fuzzy PD controller and they've got a positioning accuracy of 20 nm (equal to the resolution of the linear digital scale), the best experimental result found in the literature by the authors. They used heuristic information to build a "human-in-the-loop" controller and have written down a set of rules on how to control the process. Then, they incorporated them into a fuzzy controller to emulate their decision-making process. They have defined the error and change of error as inputs, one output and only nine rules; mamdani control rules and the maximum-minimum algorithm; and "center of the gravity" defuzzification method. They don't detail neither about the linear digital scale nor the 3/5-port proportional control valve. The control system was only tested with step and small multi-step inputs.

As opposed to "conventional" control approaches, where the focus is on modelling and the use of the model to build a controller, the fuzzy control is concerned about the intuitive understanding of how to best control the process (Passino, *et al.*, 1998). The performances of a PI and fuzzy logic closed loop control strategies have been studied. Finally, a hybrid fuzzy-P+I controller was implemented to take the advantages of both (Liu, *et al.*, 2007).

7.1 PI Control

The development of a PI controller requires finding the appropriate proportional and integral parameters K_p and K_i , respectively, as shows in Equation 1.

$$u(t) = K_p e(t) + K_i \int_0^t e(t) dt \quad (1)$$

Because of the limited displacement of the pneumatic and the related integral component evolution, an anti-windup technique is used to introduce a dead zone between non-saturated output values (Carneiro, 2007). The optimized parameters found were $K_p=100$ and $K_i=10$.

7.2 Fuzzy Control

The Fuzzy Logic Control (FLC) is based on an input-output function that maps each numerical input to a low-resolution quantization interval and calculates the control signal based on an output quantization interval (Ferreira, *et al.*, 2006). The input values for the position fuzzy feedback control were the position error. Seven membership functions were defined for the error and the same number to the output signal, as shown in the program code below (transcribed from *fis* file) and in figures 4 and 5. Table 1 shows the base-rule. Mamdani control rules and maximum aggregation method are applied. The rule's weight was set equal to 1. The “center of the gravity” method is used to defuzzify and to get the accurate control signal.

```
[Input1] Name='error'
Range= [-1 1]
MF1='-3': [-1 -1 -0.4 -0.1]
MF2='-2': [-0.2 -0.1 0]
MF3='-1': [-0.02 -0.01 0]
MF4='0': [0 0 0]
MF5='1': [0 0.01 0.02]
MF6='2': [0 0.1 0.2]
MF7='3': [0.1 0.4 1 1]

[Output1] Name='signal'
Range= [-1 1];
MF1='-3': [-1 -1 -0.5 -0.25]
MF2='-2': [-0.4 -0.25 -0.05]
MF3='-1': [-0.1 -0.05 0]
MF4='0': [0 0 0]
MF5='1': [0 0.05 0.1]
MF6='2': [0.05 0.25 0.4]
MF7='3': [0.25 0.5 1 1]
```

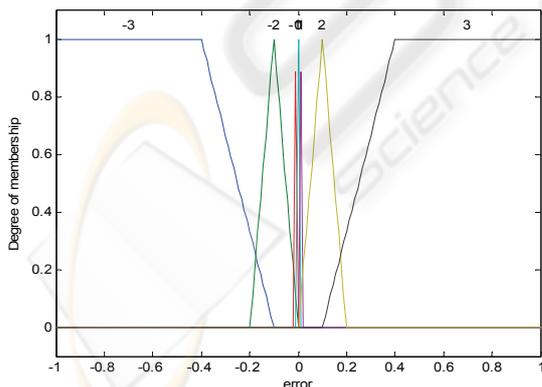


Figure 4: Membership function of the position error.

The saturation limits of the position error were set to -200 and 200 mm. The accuracy of the approximation depends mostly on the membership functions and the rules.

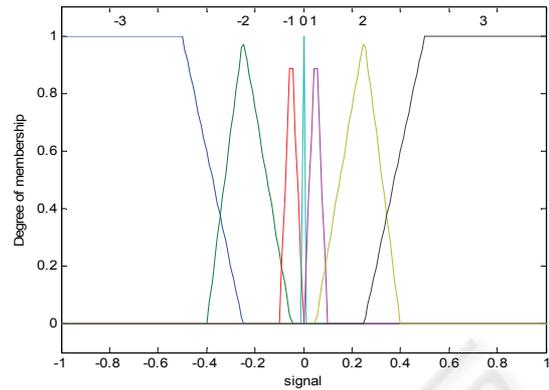


Figure 5: Membership function of the control output.

Table 1: Fuzzy Rule matrix.

	Error						
	-3	-2	-1	0	1	2	3
Signal	-3	-2	-1	0	1	2	3

The optimized control system response can also be seen as a non-linear operation function shown in Figure 6. It models the servovalve opening/closing rate μ_{FUZZY} as a function of the position error. This design has the behaviour of a *fuzzy proportional* (FP). It is the simplest “human-in-the-loop” controller, although must link the requirements of high accuracy, fast rise time and neglected overshoot results with an easy control system parameterization.

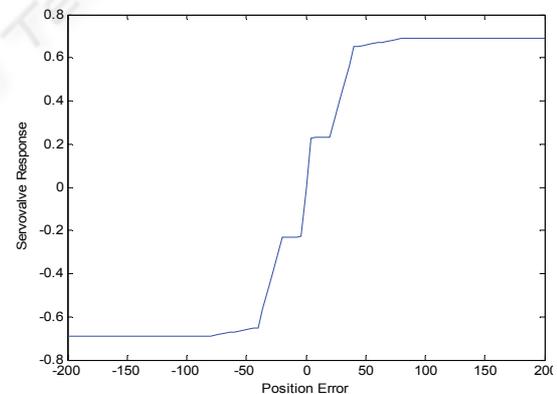


Figure 6: Operation function of the FP controller.

Many researchers have been studying the architecture of fuzzy controllers. On-line processing of the fuzzy inference rules requires high computational processing cost. Several authors proposed a controller in which the values of the membership functions must be fixed before computation of the control process and showed that the fuzzy algorithm can be converted into matrices to represent the parameterized fuzzy model. One of

the advantages of a matrix representation is that its computation is faster than the fuzzy control statements. To carry out a real-time computing system with CompactRIO[®] Controller using the fuzzy logic controller, a 1D *Look-up Table* is generated from the Fuzzy Logic toolbox in Matlab. Once a value for the position error is found, it is cross-referenced in the *Look-Up Table* to find the control output. The selected parameters which create the table were intervals of 0.02 for the position error. For inputs values between these intervals, the output value is established by linear interpolation. So, this algorithm is run *off-line* and the generated table is sent to cRIO-9002 though FTP protocol. The closed loop control was design into the Real-Time Controller. The LabVIEW block diagram is shown in Figure 7. The optimized parameters were $K_e=1$ and $K_s=1$.

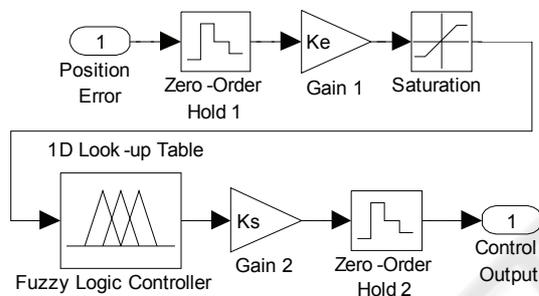


Figure 7: LabVIEW block Diagram of the Fuzzy Logic Controller.

7.3 Hybrid Fuzzy P+I Control

Fuzzy controllers do not need precise information about the nonlinearities of the system to be effective. However, it is useful the use of the integral of the error to deal with steady-state error of the position variable, which is difficult to eliminate only with the developed FLC. Hence, it was developed a hybrid system where it was given a weight of 91,5% to the fuzzy logic controller and a weight of 8,5% to the integrator contribution, in order to achieve its optimized performance. Equation 2 shows the hybrid Fuzzy P+I control law.

$$u(t) = 0.915\mu_{FUZZY} + 0.085K_i \int_0^t e(t)dt \quad (2)$$

The optimized value of K_i is 10. An anti-windup technique is also used.

8 EXPERIMENTAL RESULTS

All the control algorithms presented in section 7 were built-in into cRIO-9002 Controller and compared. Several step signals were applied as the position reference in the control experiments and the cylinder position measurements were recorded. Figures 8 and 9 show the system response when each of the control methods is applied with a step signal reference from 0 to 100 mm.

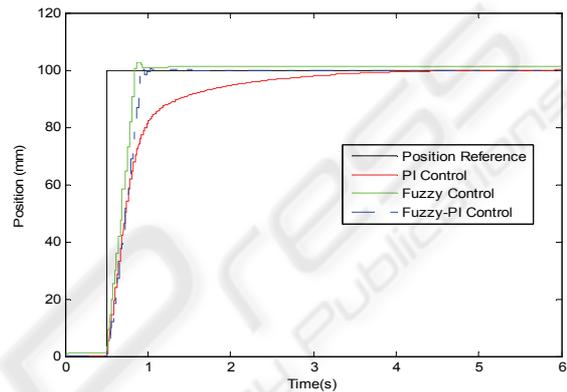


Figure 8: Step signal response curves of PI, Fuzzy and Hybrid Fuzzy-P+I Controllers.

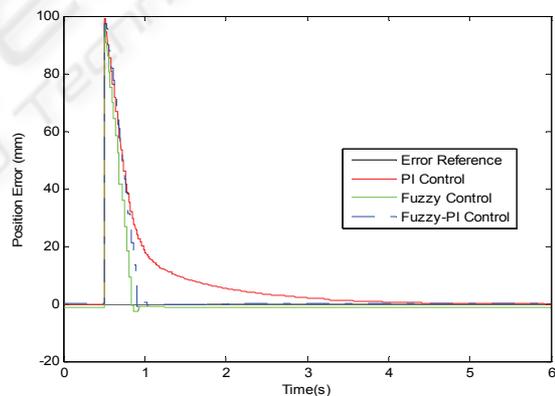


Figure 9: Step signal error curves of PI, Fuzzy and Hybrid Fuzzy-P+I Controllers.

The steady-state position error between actual position and the set point value is 1,104 mm for FP controller and 2 μm for Hybrid Fuzzy-P+I controller. With the PI controller, a position error of 0,014 mm can be achieved only after 60 seconds. With the Hybrid Fuzzy-P+I the position error is less than 0,5 mm after 0,53 seconds response, 0,05 mm after 0,95 seconds, and 2 μm steady-state position error after 1,015 seconds response. The overshoot was 0,358 mm. When the application of the Hybrid Fuzzy-P+I

controller makes the mass M to reach its steady-state position, the position error with the PI controller is about $8,75 \text{ mm}$.

It was also carry out other experiences to study the accuracy and repeatability of the overall control system. Results are shown in Figures 10, which are relative to the steady-state position error of the PI and Hybrid Fuzzy-P+I control, respectively, when were applied step signal references from 0 to REF_signal mm (multiples of 5 mm, i.e., steps: 0 – 5 mm; 0 – 10 mm; ...; 0 – 175 mm; 0 – 180 mm).

The worst steady-state position error of the PI Control is $0,084 \text{ mm}$, but 3 times reaches below $2 \mu\text{m}$ of accuracy and 13 times reaches a accuracy below $10 \mu\text{m}$, although its average is $11 \mu\text{m}$ and needs a long amount of time to reach these accuracies. PI control can accurately control the position of a pneumatic system, however it takes too long. The sticking and restarting phenomena become more evident when applied a step signal reference from 0 to REF_signal mm where $80 \text{ mm} \leq \text{REF_signal} \leq 140 \text{ mm}$.

The worst steady-state position error of the Hybrid Fuzzy-P+I Control is $0,04 \text{ mm}$, but 7 times reaches below $2 \mu\text{m}$ of accuracy and 18 times reaches a accuracy below $5 \mu\text{m}$, although its average is $8,6 \mu\text{m}$. This controller has achieved a diminution in the overshoot and in the steady state error compared with PI and FP controllers, although it suffers some late correcting the position error. The FP controller has the shortest rise time and reaches early the steady-state position. With FLC, with or without the hybrid solution, the sticking and restarting phenomena was not observed.

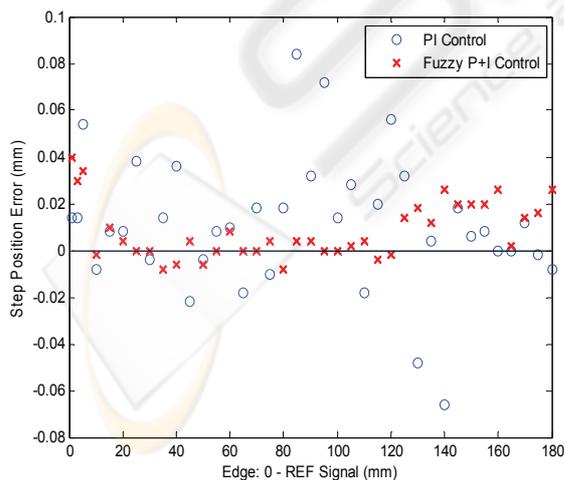


Figure 10: Steady-state position error of PI and Hybrid Fuzzy-P+I Control when step references from 0 to REF_signal mm were applied.

9 CONCLUSIONS

The present paper describes the design and control of a pneumatic press to perform controlled tracking of positional reference trajectories. The control system of the servo pneumatic machine was implemented with LabVIEW using CompactRIO® hardware. Conventional PI, proportional Fuzzy and Hybrid Fuzzy-P+I control strategies were compared in the position control of a moving mass over 200 mm course. The Hybrid Fuzzy-P+I Controller provides the best performance for the performed position control experiments: short rise time, small overshoot and a steady-state position error that can reach the encoder resolution, less than $2 \mu\text{m}$. It has particularly advantageous in terms of simplicity of design and implementation. There is an ongoing work to implement a high performance force controller using FLC and the overall pneumatic system simulation with Matlab/Simulink® platform.

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