Accurate Control of a Pneumatic System using an Innovative Fuzzy Gain-Scheduling Pattern

M. G. Papoutsidakis, G. Chamilothoris, F. Dailami, N. Larsen, and A Pipe

Abstract—Due to their high power-to-weight ratio and low cost, pneumatic actuators are attractive for robotics and automation applications; however, achieving fast and accurate control of their position have been known as a complex control problem. A methodology for obtaining high position accuracy with a linear pneumatic actuator is presented. During experimentation with a number of PID classical control approaches over many operations of the pneumatic system, the need for frequent manual re-tuning of the controller could not be eliminated. The reason for this problem is thermal and energy losses inside the cylinder body due to the complex friction forces developed by the piston displacements. Although PD controllers performed very well over short periods, it was necessary in our research project to introduce some form of automatic gain-scheduling to achieve good long-term performance. We chose a fuzzy logic system to do this, which proved to be an easily designed and robust approach. Since the PD approach showed very good behaviour in terms of position accuracy and settling time, it was incorporated into a modified form of the 1st order Tagaki-Sugeno fuzzy method to build an overall controller. This fuzzy gain-scheduler uses an input variable which automatically changes the PD gain values of the controller according to the frequency of repeated system operations. Performance of the new controller was significantly improved and the need for manual re-tuning was eliminated without a decrease in performance. The performance of the controller operating with the above method is going to be tested through a high-speed web network (GRID) for research purposes.

Keywords—Fuzzy logic, gain scheduling, leaky integrator, pneumatic actuator.

I. INTRODUCTION

EXPERIMENTATION with a number of conventional (or "classical") three-term controllers shows that, as repeated

M. G. Papoutsidakis is a Research Associate at the Intelligent Systems Laboratory, Dept of Automation, Technological Institute of Piraeus, Athens, Greece. (TEI Piraeus, dept. Automation, P.Ralli & Thivon 250, Athens 12244, Greece. phone; 0030-210-5381427, fax; 0030-210-5451128, e-mail: mipapou@in.teipir.gr).

Dr. George E. Chamilothoris is a Professor at the Dept of Automation of the Technological Institute of Piraeus and the Head of the Intelligent Systems Laboratory, Dept of Automation, Technological Institute of Piraeus (e-mail: thor@teipir.gr).

F.Dailami, N.Larsen and Dr.A.Pipe are lecturers and researchers in the Intelligent Autonomous Systems Laboratory, University of the West of England, Bristol, Frenchay Campus, Coldharbour Lane, BS16 1QY, UK.

operations accumulate, the characteristics of the pneumatic actuator change requiring frequent re-tuning of the controller parameters (PID gains). Furthermore, three-term controllers are found to perform poorly in recovering the closed-loop system after the application of load or other external disturbances. The key reason for these problems lies in the non-linear exchange of energy inside the cylinder relating, in particular, to the complex friction forces that develop on the piston-wall interface. Therefore, another methodology should be followed in order to improve the performance of such system. There are two well-known fuzzy logic approaches used in control systems. The first is the Mamdani method that has been used to create PI controllers but only a few PID, and mostly in trivial control problems requiring low accuracy and minimal performance [2], [5]. Since there are also no guarantees of stability and robustness, in the case of a complex nonlinear system, such as the pneumatic actuator rig, it is not appropriate to adopt this approach. The second fuzzy logic method, implemented in this project, is the Tagaki-Sugeno approach. It is well known that Takagi-Sugeno fuzzy models can provide an effective representation of complex nonlinear systems in terms of fuzzy sets and fuzzy reasoning and, in the recent past, researchers made this clear in their research projects [9], [7], [8], [2]. Using this approach, we have incorporated a number of PD controllers, one into each of the consequent parts of the fuzzy rules. We then hand-over between controllers, based on rule activations, thus achieving a smooth gain-schedule. Gain scheduling is a popular nonlinear control design approach, which has been widely and successfully applied in fields ranging from aerospace to process control. Whilst much of the classical gain scheduling theory originates from the 1960s, there has recently been a considerable increase in interest in gain scheduling [4], [6], [1]. Although a wide variety of control methods are often described as "gain scheduling" approaches, they normally share a 'divide and conquer' type of design procedure whereby the nonlinear control design task is decomposed into a number of linear sub-problems. This 'divide and conquer' approach is the source of much of the popularity of gain scheduling methods since it enables well established linear design methods to be applied to nonlinear problems. This is the most important advantage of this method and is the reason it was chosen for implementation in this research project. According to earlier researches like [12], [13], [14] the performance of such a control method could be tested over the well-known European high-speed network (GEANT). The experimental rig consists of a pneumatic cylinder with 80mm

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of stroke, 25mm bore and a proportional pneumatic servo valve, model FESTO, MPYE-5-. An LVDT is used as a position sensor and the controller is a Siemens/Infineon 80C164CI, programmed in the C language.

II. THE GAIN-SCHEDULER BASED ON FUZZY LOGIC AND THE CONTROLLER DESIGN

One of the most important parts of the gain-scheduler is the variable input to the fuzzy system and the way this variable is calculated in real time during system operations. By theorising that temperature is, in some way, the main factor in changing the friction forces experienced by the piston and that this is the main factor in determining new PD controller gain values, we managed to build an empirical model of the features and the influence of temperature on the system. This model was based on a "leaky-integrator", which can be used to model thermal effects [3]. An electrical circuit theory interpretation of the leaky-integrator is shown in figure 1. It is actually producing an independent variable, which from now on will be called "alpha" in the rest of this paper. The integrator is charged by a "current pulse" every time a pneumatic control action is undertaken and is discharged by the simulated "resistor". The "alpha generator" is tuned for just one operating regime, for instance every five minutes over a six-hour period, then tested for its generalisation abilities in different regimes, for example every fifteen minutes over another six-hour period, without further tuning. Of course, this structural modelling of what is believed to be the nature of the underlying effect is still based in empirical evidence, rather than mathematical/physical analysis of the cause of the effect. However, a structural model is much more powerful than simply fitting the equation of a curve to the observed effect from conducting experiments for just one operating regime; this model, it is hoped, will generalise across operating regimes adequately. The alpha variable will be used finally as the input that modifies the gain schedule via the fuzzy logic gain-scheduler. The value of alpha, which is the output of the leaky-integrator, is generated automatically every second from an appropriate C code program. This program also includes the fuzzy logic algorithm and will be finally applied to the controller of the pneumatic system.

The Vc voltage across the capacitor represents the value of alpha, the integrator part is the capacitor itself and the leaky part is the resistance. A discrete time version of this circuit, with one-second sampling time, is the alpha generator.

The Tagaki-Sugeno fuzzy logic approach was implemented in the system as stated earlier, thus implementing a fuzzy-gain scheduling method. Earlier research works in this fuzzy gain-scheduling field were accomplished with success in nonlinear systems [10], [11]. In fact, the fuzzy gain scheduling structure implemented here represents a variant from the work referenced above, and the mainstream of Tagaki-Sugeno fuzzy gain scheduling work. A "thought experiment", which stays within the application domain of this investigation, will be employed to illustrate this variance. Let us assume, for the moment, that the plant dynamics are such that different gain schedules are required at different operating positions and piston velocities of the pneumatic actuator although, actually,

this was not found to be the case in work to date. It would be useful, under these hypothetical circumstances, to have fuzzy rules that operated in the inputs domains of the position error and velocity of position error so as to be able to schedule changing Kp and Kd gains at different operational points. This is the form of most other work that uses the Tagaki-Sugeno system for problems similar to ours. Such work is definitely not excluded from further work carrying on from this project, but that is not what is being done here. In this work, the position and velocity of position errors are inputs to the system (as for other work), but the weighted Kp and Kd gains that they are multiplied by are changed as a result of changes in the alpha value, and independent variable. Although this is not a major difference, the authors are unaware of any other work of this nature for control problems of this type. The fuzzy controller that achieved the satisfactory results presented below used just four rules, and was therefore straightforward to tune. Each rule's antecedent identified an equilateral triangular membership function in the alpha value input space and described a sum of products for position error and its derivative; each rule consequent defining a different pair of Kp and Kd gain values.

III. BENEFITS VALIDATION OF THE PATTERN VIA EXPERIMENTAL PROCESS

A very large number of experiments were designed in order to evaluate the benefits of such a technique in the pneumatic actuator position control problem presented here. The idea was to test the behaviour of the system over long time periods on different days. The subject of this investigation was to record how the optimal values for the two gain values (Kp, Kd) change over time so that the system operates with the best position accuracy. A large number of tests with the pneumatic actuator took place initially using the PD controller alone. In each different test the controller was manually retuned in order to record the values of the Kp and Kd gains that provided the best system response. Three different experiments were designed to cover the range of the gain changes. The first experiment includes 52 different tests over six hours of total experimentation. That is, every five minutes one test was done for the first two hours, then one test was done every thirty minutes for the next two hours and finally during the last two-hour interval one test again every five minutes was done. The second experiment of 21 tests had the same overall duration of six hours. It was again split into three continuous intervals of two hours each, like the previous experiment, but the first and the last parts were split into fifteen minute (rather than five minute) time intervals. Finally the third experiment of 243 tests had the same structure, with three major intervals again of two hours each, but this time during the first and the last two-hour intervals, one test every minute took place. These experiments took place on different days to allow the system to 'settle' between tests, and they were designed to provide us with an understanding of how the gain values must change over time after many operations. The results from the first experimentation of five minutes repeated tests were then used to tune the alpha generator. It was also used to create the fuzzy system's input membership functions and rules, including the corresponding gain values for the rule

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consequent parts. All the above process was repeated again with the fuzzy logic controller implemented in the system, because the comparison of the gain values between the two different control methods was necessary. So, another three experiments were performed during different days with 316 tests in total, but keeping the same time intervals as before. This generated another three tables of fuzzy logic gain values. In figure 1, a representative set of values for the proportional Kp gain value for both classical and fuzzy methods is plotted. Kd values varied in a similar way, and are not shown for clarity. The plot shows experimental data from the "fifteen minute" tests, and is illustrative of the general trends. It is noticeable that both curves rise between the first two hours interval, then they settle down between the second two hours interval and rise again in the last two hours of the experimentation. The fact that within the second two-hour interval both profiles reduce to lower values than they were at the end of the first interval is because the experimentation frequency changes. During the second two hour period the gains are recorded every thirty minutes and not every fifteen like in the first period. The system seems to recover partly back to the initial condition when the experimentation frequency decreases. In the third two-hour period, both curves rise again.
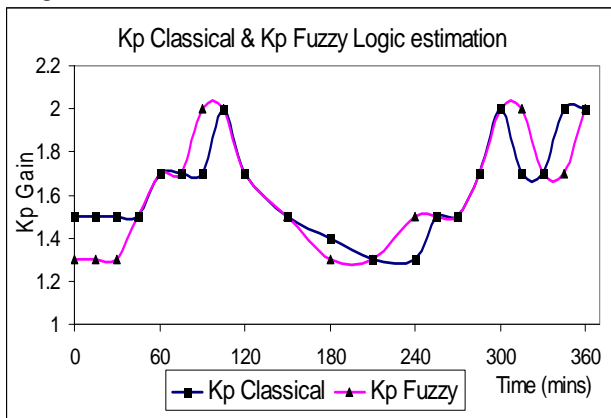

Fig. 1 The combinational plot of classical and fuzzy proportional gain values

IV. THE PERFORMANCE IMPROVEMENT DUE TO 'ALPHA GENERATOR' IMPLEMENTATION

The reason for implementing all the above in the experimental rig is to create a robust controller of improved performance relative to a fixed control gain system. The new controller was applied to the pneumatic rig and tested for different values of air pressure and the piston position accuracy was checked out over the whole piston stroke. We consider that reducing the steady state error of a pneumatic positioning system like this is the most important aim. We also consider that the settling time, which is the time taken by the piston to reach the 95% of its final displacement at any point of the stroke, as the second critical factor in order to evaluate the performance of our experimental rig. In section 3 we described the experimental process that took place to compare the classical control method with the frequent re-tuning with the automatically tuned fuzzy control method. The improvement of the system when the alpha generator

technique and the gain scheduler were applied to the system was obvious. In the following figures we provide all the details of that excellent performance of the system in contrast with the earlier behaviour with only the classical controller applied to it. For simplicity we illustrate two of the three different experiments, those with the 5 and 15 minutes operations respectively, over 6 hours operations in total. In figure 2 the recorded steady state error for both processes of 5 and 15 minutes testing, with the classical and the fuzzy approach, is shown.
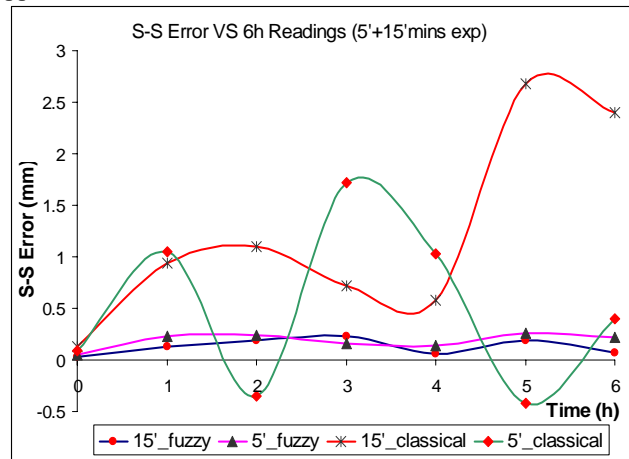

Fig. 2 The combinational plot of the system S-S error with the classical and the fuzzy methods

Although the steady state error is initially the same in all cases since the initial tuning is common, as time passes the system starts to demonstrate an unpredictable performance when it actuates without frequent re-tuning (green and red line). On the contrary when the system actuates with the automatic gain scheduler and the fuzzy controller it shows an excellent performance and the steady state error is never bigger than 0.3mm throughout the six hours of experimentation. In addition to this, we also record the settling time of the system for exactly the same experimentation, and alike with the position error provided before, the combinational plot of the settling time of the system is as shown in Fig. 3.
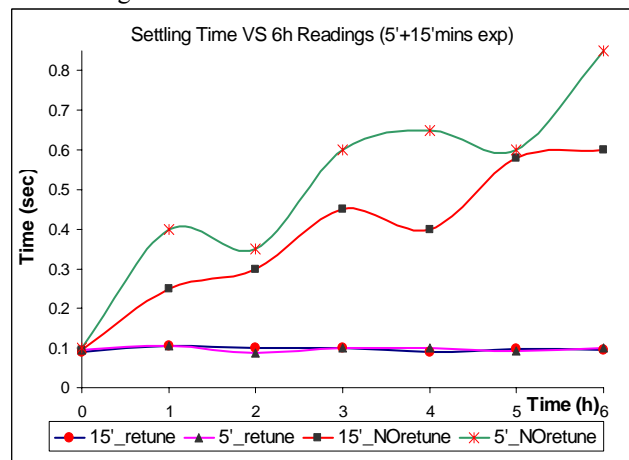

Fig. 3 The combinational plot of the system settling time with the classical and the fuzzy methods

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It is, once again, confirmed that when our pneumatic positioning system actuates with the fuzzy controller the overall performance is improved and the settling time remains close to 0.1 seconds.

V. CONCLUSIONS AND FURTHER RESEARCH STUDY

It is well-known that pneumatic positioning systems are very complex and highly non-linear systems due to the compressibility of air and the multiple physical phenomena that exist within a pneumatic cylinder. In fact, all classical control methods that were implemented faced difficulties in achieving the goal of position control over long term operation and needed frequent retuning in order to operate properly. Although it was possible to retune the controller each time manually, this clearly would not be suitable for an implemented system. The empirically derived fuzzy control approach adopted here was quite straightforward to design; yet yielded acceptable performance over long term operation and benefits from the analytical basis of the manually tuned PD-control approach. With these control methods applied to the system, the basic conclusion is that this form of fuzzy controller is a robust solution that allows effective control of a plant with time-variant dynamics. During this work it has become clear that further research could improve the performance of the system. However, perhaps even more worthy of attention is the control of a pneumatic system with multiple actuators operating together. The development of a combinational actuator circuit, which will control all degrees of freedom of a robot arm, is the final and most challenging further research subject that, it is hoped, will be investigated in the near future. In addition to this, like stated earlier, this project constitutes the first attempt to build a fully controllable remote system. This control system will be shortly tested over a real time high-speed network (GRID), established between two well-known Universities in Budapest-Hungary and Athens-Greece.

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