

# Fuzzy control of an electropneumatic actuator

Lía García-Pérez, José M. Cañas, María C. García-Alegre, Pablo Yáñez, Domingo Guinea  
Instituto de Automática Industrial, CSIC, 28500 Arganda del Rey. Madrid. Spain.  
e-mail: {lia, jmplaza, maria, pyanez, domingo@iai.csic.es}

## Abstract

Present work describes the design and implementation of a fuzzy controller for a pneumatic actuator to control the steering of an unmanned lawnmower. The fuzzy controller expresses in natural language the human expertise on the control of this non-linear system by means of a set of linguistic expressions. Few investigations have been addressed to the control of such system and the existing one offers a theoretical description of the functioning of its different subsystems. Present work is a novel contribution on the fuzzy control of a pneumatic actuator. Some results are displayed to show the fuzzy controller performance in real time, under a wide range of working conditions to get a remote control of outdoor vehicles

**Key words:** Electropneumatic actuators, Fuzzy PD control, outdoor vehicles, autonomy, AMARA architecture.

## 1 INTRODUCTION

The development of an autonomous outdoor vehicle is a great challenge that involves the integration of many research fields. From the mechanical design and control of the actuation system, through the sensors and perception mechanisms to the design of an architecture to deal with intelligent behaviour and environment adaptation and interaction.

The actuation systems used in Robotics are electromagnetic, hydraulic and pneumatic. Pneumatic actuators hold an intermediate position between hydraulic and electromagnetic with respect to the force to mass ratio. Compared with hydraulic actuation systems they are lower cost, cleaner and safer. On the other hand they are more compact and have better response in terms of power and time, than a comparable electric motor [Henri98]. Each actuation system usually represents a non-linear dynamical system, difficult to be modeled. In respect to control models, fuzzy controller has been widely applied

for industrial processes due to their simplicity and effectiveness, as non-analytical model [1], [4], [13], [15]. They have been successfully used for a wide number of applications dealing with complex and non-linear processes, wherein they are proved to be robust and less sensitive to parametric variations and noise than conventional controllers [5], [7], [10], [18]. In addition, research on proportional-derivative (PD) controller shows that they have a high sensitivity and tend to increase the stability of the overall feedback control [14]. Such characteristics are the ones pursued in the control of a pneumatic system. Present work deals with the design of a flexible and robust fuzzy PD controller for an electropneumatic actuator coupled to the steering axle of a lawnmower. The steering fuzzy control has been tested in outdoor scenario aiming for a subsequent autonomous navigation [3], [6], [8], [17].

## 2 THE VEHICLE AND THE ELECTRO \_ PNEUMATIC ACTUATOR

The vehicle is a commercial lawnmower, named ROJO that was acquired to investigate autonomous navigation in outdoor environments, Figure 1.



Figure 1: ROJO Lawnmover

Its initial actuation system has been removed and two specially designed electropneumatic actuators have been coupled to the steering and driving axles for the automation of the elementary motions *turn* and *forward*. Each actuation system is composed of different parts: an electrovalve, a pneumatic cylinder, and an actuator axle coupled to the piston. The piston position is related to the steering angle and to the advance/stop drive and it is detected through potentiometric sensors. The piston is either pushed or pulled by the air pressure entering through the left or right orifice of the cylinder, Figure 2.



Figure 2: Axle, piston, cylinder and electrovalve detail

The air pressure tank is located in the rear part of the vehicle filled with an air pump powered by the vehicle motor, Figure 3.



Figure 3: Air pressure pump

The relevant parameters of the pneumatic cylinders are displayed in Table 1.

Table 1. Pneumatic cylinder physical data

Piston diameter	32 mm
Orifices Diameter	0.9 mm
Supply pressure	7-9 bar
Piston range	200 mm
Cylinder diameter	40 mm
Cylinder length	270 mm

The time response of the piston for a run of 200 mm. is about two hundred milliseconds. This short time response entails a high sensitivity and is a source of instability that has to be considered at the controller design stage.

The admitted tolerance in steering, about 10%, account for all sources of uncertainty inherent to the system as are: imprecision in the current tank pressure, PWD control of the electrovalve, and sensor readings; electrovalves and cylinder orifices readings, free movement in the axle to piston link.

### 3 FUZZY ELECTROPNEUMATIC CONTROL

The difficulty of deriving an analytic model of the actuation system, that is composed of several subsystems, points to the design of a Fuzzy controller, where the model is embodied in the control rules extracted from the expert knowledge. These control rules mimics the relationships between inputs and output as obtained in a classical model based control.

A Proportional-Derivative fuzzy controller is proposed with inputs the current and the former error in the piston position, where a potentiometric sensor measures the position. The derivative component has been introduced to reduce the oscillations smoothing the output as far as the error decreases.

Present approach proposes a fuzzy rule-based system [12] to encapsulate the non-linear dynamic of the whole actuation system to control the steer the front wheels.

The control process is executed on an on-board computer, PC-K6-2/400Mhz., which main characteristics are: low power consumption and high speed floating point operations.

#### 4.1 FUZZY ENVIRONMENT

The knowledge base that defines the qualitative control model has been designed with the aid of a fuzzy library that includes an interpreter of the knowledge base, previously built and recorded as a text file. It is based on former *FuzzyShell* environment [9], and it is an extremely useful to speed up the design and the tuning of the fuzzy controller. It is released as an ANSI-C library and helps to build specific knowledge bases, avoiding the time consuming task of low level programming. Knowledge

base modifications are easy to perform as no disturbance is introduced either in the control program or in the inference engine. This tool keeps the user at a higher level of abstraction at the model definition stage, to focus attention only in the specific interactions between model and application.

The dynamic memory allocation allows the definition of an unbound number of variables, linguistic labels and rules in a text file, with a specific syntax that has to be interpreted by the control program. This text file, namely knowledge base, gathers all the knowledge on the system to be controlled and consequently it is domain dependent.

#### 4.2 FUZZY VARIABLES AND FUZZY RULES

There are two types of variables: input and output. The first one account for the state of the system and the second one correspond to the control actions to be performed on the system. In the text file, input and output variables are indistinguishable and may be entered in any order. The differentiation occurs implicitly, as rules defined as inputs always appear in the rule antecedent and outputs in the consequent. The same variable may be used either as input or as an output [9].

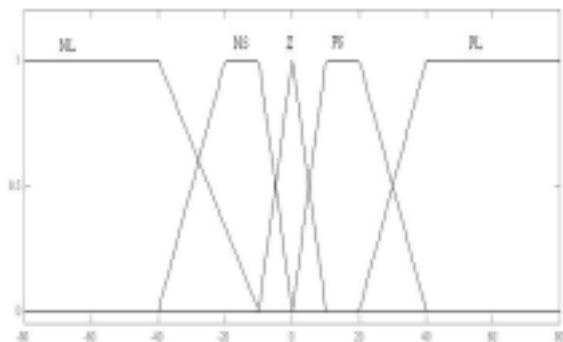


Figure 4 : Linguistic labels for the input variables

The linguistic values of each variable, are represented by a membership function defined by means of four parameters (a, b, c, d), that enable the generation of multiple shapes: (a, b, c, d) trapezium, (a, a, b, b) rectangle, (a, b, b, c), (a, a, a, b), (a, b, b, b) triangle, (a, a, a, a) singleton.

In current application, fuzzy inputs are the current error,  $error(t)$ , Figure4, and the previous one  $error(t-1)$ , Figure 4. Their difference corresponds to the derivative error.

Error is measured subtracting the piston reference signal from the measured signal delivered by the potentiometric

sensor. The output is the width of the voltage pulse,  $pwm$ , to be sent to the electrovalve. This width is related to the opening period of the electrovalve orifice, to control the air volume that enters on the left or right side of the cylinder. Thresholds of the membership functions are fixed in agreement with the expert knowledge and the empirical tests initially performed.

Thus, five linguistic values non uniformly distributed along their universe of discourse have been defined for the variables  $error(t)$ ,  $error(t-1)$  and for the output variable  $pwm$ , Figure 5

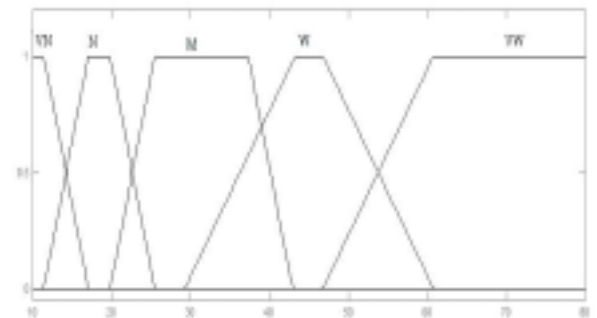


Figure 5: Linguistic labels of the output variable

#### 4.3 THE INFERENCE ALGORITHM

The knowledge base is composed of a set of propositions, in natural language, of the type:

IF {(A is a) AND (B is b)} THEN {(C is c)}

with an unbound number of conjunctive constraints in the antecedent and only one constraint in the consequent. T-norms generalize intersection operation of fuzzy sets. Among the possible T-norm, the product was selected as it displayed a cautious behaviour [2].

A call to the library functions is performed whenever an action on the steering axle is needed. The current input variable provided by the potentiometric sensor is then acquired and the knowledge base is instantiated with current  $error(t)$  and previous  $error(t-1)$ , which are matched against the antecedent of each rule.

Library functions can be called from several controllers, each one defined through a specific knowledge base.

The knowledge base for the fuzzy control of the steering angle is composed of thirteen rules, having two input and one-output variables, Table 2. The syntax of the input file is straightforward and fuzzy rules and variables can be easily modified.

The inference engine is based on a centre of mass (COM) algorithm that weights the output of each rule in the

Table 2. Knowledge base of the fuzzy PD controller

```

#Fuzzy controller data file
steer controller

label error(t) negative_large = -80 -80 -40 -10
label error(t) negative_small = -40 -20 -10 0
label error(t) zero = -10 0 0 10
label error(t) positive_small = 0 10 20 40
label error(t) positive_large = 20 40 80 80

label error(t-1) negative_large = -80 -80 -40 -10
label error(t-1) negative_small = -40 -20 -10 0
label error(t-1) zero = -10 0 0 10
label error(t-1) positive_small = 0 10 20 40
label error(t-1) positive_large = 20 40 80 80

label pwm very_narrow = 10 10 11 17
label pwm narrow = 11 17 19 25
label pwm medium = 19 25 37 42
label pwm wide = 29 43 46 60
label pwm very_wide = 46 60 80 80

IF ( error(t) = zero )
THEN ( pwm = very_narrow )
IF ( error(t) = negative_large) AND ( error(t-1) = negative_large )
THEN ( pwm = very_wide )
IF ( error(t) = negative_large ) AND ( error(t-1) = negative_small )
THEN ( pwm = wide )
IF ( error(t) = negative_large ) AND ( error(t-1) = zero )
THEN ( pwm = wide )
IF ( error(t) = negative_large ) AND ( error(t-1) = positive_small )
THEN ( pwm = wide )
IF ( error(t) = negative_large ) AND ( error(t-1) = positive_large )
THEN ( pwm = wide )
IF ( error(t) = negative_small ) AND ( error(t-1) = negative_large )
THEN ( pwm = medium )
IF ( error(t) = negative_small ) AND ( error(t-1) = negative_small )
THEN ( pwm = narrow )
IF ( error(t) = negative_small ) AND ( error(t-1) = zero )
THEN ( pwm = very_narrow )
IF ( error(t) = negative_small ) AND ( error(t-1) = positive_small )
THEN ( pwm = narrow )
IF ( error(t) = negative_small ) AND ( error(t-1) = positive_large )
THEN ( pwm = medium )
IF ( error(t) = positive_small ) AND ( error(t-1) = negative_large )
THEN ( pwm = medium )
IF ( error(t) = positive_small ) AND ( error(t-1) = negative_small )
THEN ( pwm = narrow )
IF ( error(t) = positive_small ) AND ( error(t-1) = zero )
THEN ( pwm = very_narrow )
IF ( error(t) = positive_small ) AND ( error(t-1) = positive_small )
THEN ( pwm = narrow )
IF ( error(t) = positive_small ) AND ( error(t-1) = positive_large )
THEN ( pwm = medium )
IF ( error(t) = positive_large ) AND ( error(t-1) = negative_large )
THEN ( pwm = wide )
IF ( error(t) = positive_large ) AND ( error(t-1) = negative_small )
THEN ( pwm = wide )
IF ( error(t) = positive_large ) AND ( error(t-1) = zero )
THEN ( pwm = wide )
IF ( error(t) = positive_large ) AND ( error(t-1) = positive_small )
THEN ( pwm = wide )
IF ( error(t) = positive_large ) AND ( error(t-1) = positive_large )
THEN ( pwm = very_wide )

```

knowledge base with the truth degree of its antecedent, to derive a mean crisp value.

## 5. RESULTS

The performance of the controller has been demonstrated under a wide range of working conditions in real time, to comprise the overall steer angle range  $[-40^\circ$  to  $+40^\circ]$ .

The designed control system has achieved the requirements imposed both on speed to reach a reference and on a low oscillation level.

The performance of the fuzzy controller has been evaluated through the analysis of three standard variables: 1) Rising time  $T_r$  2) Stationary error  $E_s$ , and 3) Oscillation amplitude  $O$ . Such values are derived from the empirical control functions that describe the temporal evolution of the steering angle *error* from an initial to a final state. A wide range of piston runs, that corresponds to steering angles, have been accomplished in real time e One of the runs is displayed in Figure 6, wherein the piston position *error* (voltage V) is translated to a steering angle value  $\theta$  *error* through a linear calibration process:

$$\theta(V) = 102.6 \cdot V - 93.3$$

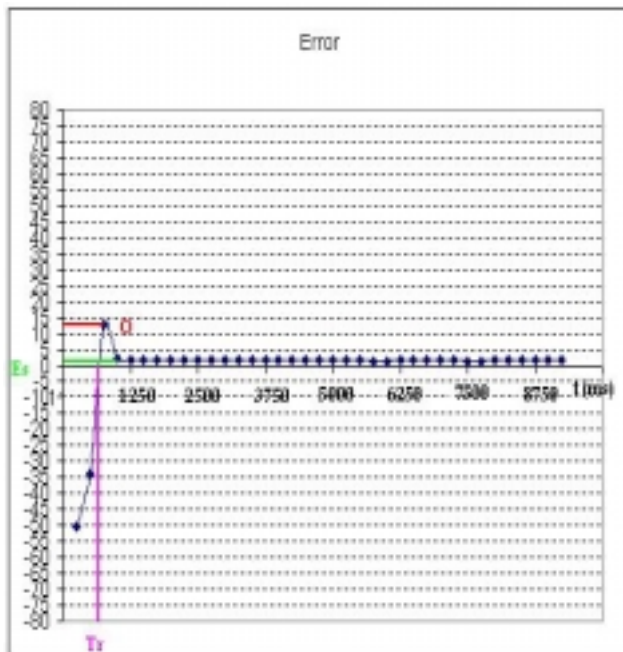


Figure 6: Time response function: steering angle error ( $^\circ$ ) vs. Time (ms.)

Experimental result show that the rise time is well below the time response required for real time performance, having a mean value of 500ms. The oscillation and the stationary error are also within the admitted tolerance, with a mean value equal to five degrees. All data correspond to lawnmover runs on a flat terrain of concrete. The control surface of the Fuzzy PD controller has been represented in Figure 7, with a control cycle of 250ms.

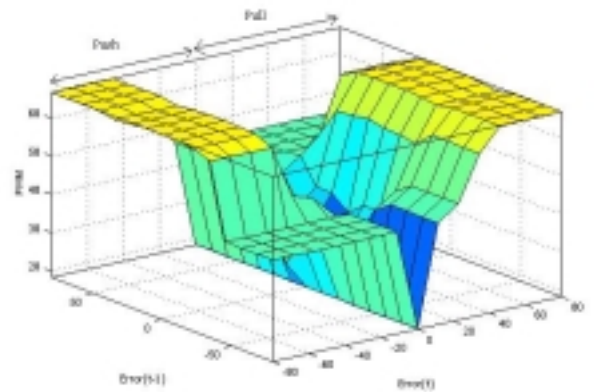


Figure 7: Control surface

## 6 COMMENTS AND CONCLUSIONS

The Fuzzy PD controller here developed is a non-analytic-model, based on an approximate qualitative model that is expressed by means of a set of control rules expressed in natural language.

This Fuzzy PD control system has been implemented and validated for a wide range of initial and final states of the underlying highly complex non linear electropneumatic actuator. It is proved to work within the admitted tolerances in steering angle and time along the whole piston run.

The Fuzzy PD controller developed is able to account, in a single model, for a wide range of operating conditions reaching the desired reference in a short number of control cycles. The vehicle displays a powerful but smooth behaviour when moving in concrete flat terrain. The lawnmover behaviour is as efficient as it could be when driven by a human expert.

The Fuzzy environment allows the design of different controllers by only performing slight changes on the fuzzy control rules and variables (varying the position and width of the linguistic labels), to better adapt the control to the terrain irregularities (rough, rocky, inclined).

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