Mechanical redesign and control with a PLC of an inverted pendulum

Eliana Acurio Méndez
Area of Systems Engineering and Automation
Universidad de Oviedo
Gijon, Spain
eliana.acurio@gmail.com

***Abstract*—The interest in studying the different techniques of control and its real-time responses, has made of the system of inverted pendulum a classic control problem. This system is highly nonlinear, with multiple inputs and a single output and belongs to a special class of mechanical systems called underactuated, in which there are fewer control inputs than degrees of freedom. In order to relate the PLC programming with the control of this kind of systems, classical control algorithms and fuzzy algorithms have been implemented in the PLC Siemens S7-200. The PID control has been developed using the tool that the PLC provides for this controller while the fuzzy control with each of its stages (fuzzification, inference engine and defuzzification) has been configured from a user interface and the mathematical algorithm has been implemented in the PLC.**

Keywords- Pendulum; S7-200; PID; inference; fuzzification; defuzzification; automation.

***Resumen*—El interés por estudiar las diferentes técnicas de control y sus respuestas en tiempo real, ha hecho del sistema de péndulo invertido un problema clásico de control. Este sistema es altamente no lineal, con múltiples entradas y una sola salida y pertenece a una clase especial de sistemas mecánicos llamados subactuados, en los cuales hay menos actuadores que grados de libertad.**

Con el objetivo de relacionar la programación de autómatas con el control de este tipo de sistemas, se ha implementado tanto algoritmos de control clásico como algoritmos difusos en un PLC Siemens S7-200. El control PID se ha realizado utilizando las herramientas que el PLC posee para la configuración de este tipo de controlador, mientras que el control difuso con cada una de sus etapas constitutivas (fusificación, motor de inferencias y defusificación), ha sido configurado desde una interfaz de usuario y el algoritmo matemático desarrollado en el PLC.

Palabras Claves- Péndulo; S7-200; PID; inferencia; fusificación; defusificación; automatización.

I. BACKGROUND AND THEORETICAL BASIS

The inverted pendulum plant is a nonlinear system and it is widely used for testing different control algorithms.

There is a wide variety of applications of this system such as crane stabilization, vehicle development with pendulum system "Segway" and modeling for seismic control of building structures. In the aerospace field, it is used for the active control of a rocket in order to keep it upright at the time of takeoff, the modeling of biped robots, satellite positioning, balance stabilization of ships and aircrafts.

Figure 1. Inverted pendulum system applications

A. *Mathematical model*

Before using different control algorithms, the mathematical model is used in order to analyze the system operation and select an appropriate controller.

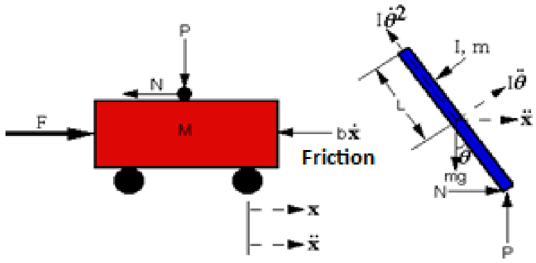

Figure 2. Free body diagram of the system

$$\frac{\emptyset(s)}{U(s)} = \frac{\frac{ml}{q}s}{s^3+\frac{b(I+ml^2)}{q}s^2-\frac{(M+m)mgl}{q}s-\frac{bmgl}{q}}$$

$$q = [(M+m)(I+ml^2)-(ml)^2]$$

Figure 3. Transfer function of the pendulum

TABLE I. TABLE OF PARAMETERS OF THE MECHANISM

Parameters	Values	Units
Pendulum mass (m)	0,233	Kg
Carriage mass (M)	1,9582	Kg
Friction (b)	0,19	N/m/seg
Length to the center of mass (l)	0,3	m
Pendulum inertia (I)	0,000001864	Kgm²

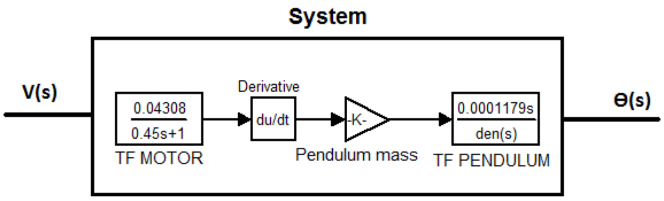

Figure 4. Mathematical model of the system

B. Classic controllers

Inside the classic control algorithms, there are different types of controllers such as, proportional (P), proportional-integral (PI), proportional-derivative (PD) and proportional-integral-derivative (PID) that permit to control this system considering some parameters for tuning. A possibility is using heuristics rules as shown the figure 4.

TABLE II. HEURISTIC RULES FOR SETTING PARAMETERS

PARAMETER	Kp increases	Ti decreases	Td increases
Stability	decreases	decreases	increases
Speed	increases	increases	increases
Steady state error	not removed	removed	not removed
Area error	decreases	decreases slightly	decreases
Disturbance control	increases abruptly	increases gradually	increases abruptly
Frequency loop	not affect	decreases	increases

C. Fuzzy controller

This is another possibility of control for this mechanism because has significant advantages for dynamic systems that can be characterized better in words than by mathematical approximations. Also this controller is considered very robust, appropriate for multiple inputs and outputs and has cheap implementation.

The figure 5 shows the stages of the fuzzy algorithm.

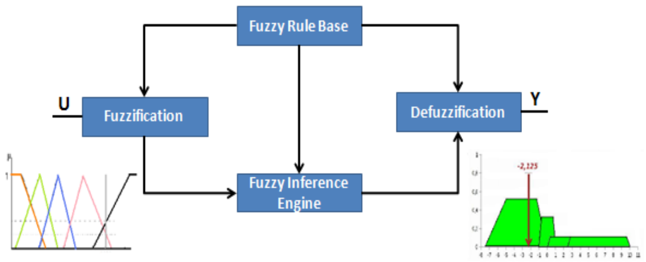

Figure 5. Fuzzy algorithm

II. DESIGN OF ELECTRONIC AND CONTROL SYSTEM

A. Electronic design

The inverted pendulum system consists of a mechanical, electronic and control subsystems that work together to achieve the stabilization of the pendulum.

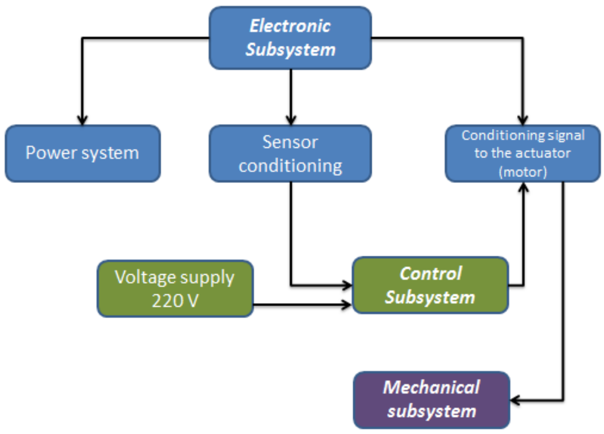

Figure 6. System scheme

Inside the electronic system, a printed circuit board (PCB) was designed in order to adjust the voltage signal of the potentiometer and reduce the frequency of the encoder signal. Furthermore, the servo control signal is amplified in voltage and current in order to adapt this signal to the inputs of the programmable logic controller (PLC).

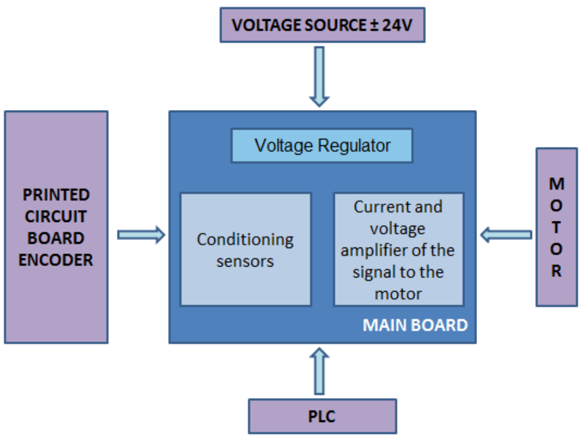

Figure 7. Diagram of main electronic board

B. Control System Design

The control system is developed completely by S7-200 PLC and the user can select between a PID or a fuzzy controller.

1) PID controller: It is implemented with two loops, one for the position control and the other one to stabilize the pendulum. The user can activate one or both loops and configure all the parameters from the PC interface. In the case of using both, there is a gain after each PID to give higher priority to a loop.

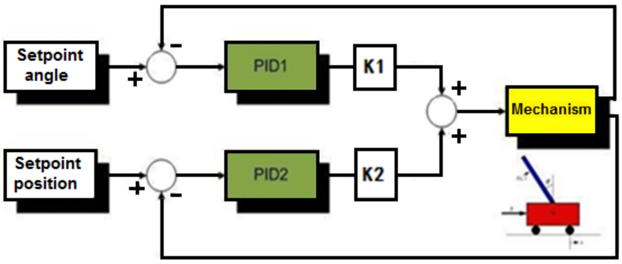

Figure 8. Algorithm with two PID control loops

2) Fuzzy controller: The fuzzy algorithm developed allows one or two inputs (angle error and its derivative) and uses fuzzy sets of triangular geometry that are configured from interface.

TABLE III. NAMES OF FUZZY SETS FOR EACH VARIABLE

Input variables		Output variable
Angle error	**Derivative**	**Motor Speed**
Very left **MI**	High negative speed **VMN**	Fast left **RI**
Left **PI**	Low negative speed **VPN**	Slow left **LI**
Center **C**	Zero speed **VC**	Zero **Z**
Right **PD**	Low positive speed **VPP**	Slow right **LD**
Very right **MD**	High positive speed **VMP**	Fast right **RD**

In the first stage, fuzzification, the inputs are converted to fuzzy variables calculating the degree of membership of each variable in a fuzzy sets.

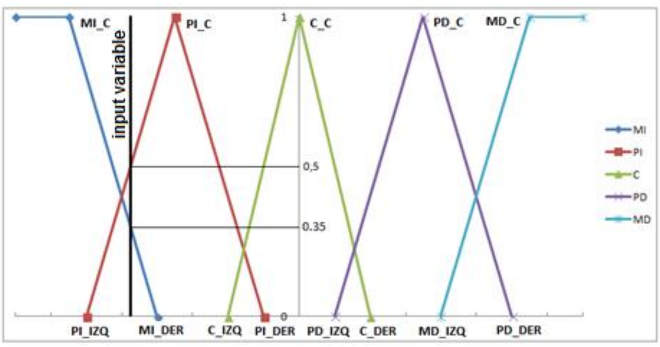

Figure 9. Fuzzification

The next stage is the fuzzy rules base that defines the rules for the control of the mechanism.

The fuzzy rules are of the type:

If X1 is A1 and X2 is A2 and… and Xm is Am

Then Y1 is B1 and Y2 is B2 and… and Yn is Bn

Where A1, A2, ..., Am are the terms that characterize the fuzzy sets for the inputs and B1, B2, ..., Bn are the terms that characterize the fuzzy sets for the outputs. In the case of one fuzzy input there are five rules and for two inputs a total of eleven rules

TABLE IV. FUZZY RULES WITH A INPUT VARIABLE (ANGLE ERROR)

INPUT	OUTPUT
MI	RI
PI	LI
C	Z
PD	LD
MD	RD

TABLE V. FUZZY RULES WITH TWO INPUT VARIABLES (ANGLE ERROR AND DERIVATIVE)

	MI	PI	C	PD	MD
VMN	-	-	RI	-	-
VPN	-	-	LI	Z	-
VC	RI	LI	Z	LD	RD
VPP	-	Z	LD	-	-
VMP	-	-	RD	-	-

After the establishment of the rules, a fuzzy inference engine is used to mathematically interpret the fuzzy rules and get a numeric value in the output sets.

TABLE VI. VARIABLES AFTER FUZZY INFERENCE ENGINE STAGE

Numeric variable	Description
FUS_RI	Numerical value of the fuzzy set "Fast left **RI**"
FUS_LI	Numerical value of the fuzzy set "Slow left **LI**"
FUS_Z	Numerical value of the fuzzy set "Zero **Z**"
FUS_LD	Numerical value of the fuzzy set "Slow right **LD**"
FUS_RD	Numerical value of the fuzzy set "Fast right **RD**"

Finally, the defuzzification stage is implemented in order to convert the output fuzzy subset in a numeric value that can be sent to the motor. The centroid method was used for this conversion.

$$\frac{(RI\_C*FUS\_RI)+(LI\_C*FUS\_LI)+(Z\_C*FUS\_Z)+(LD\_C*FUS\_LD)+(RD\_C*FUS\_RD)}{FUS\_RI+FUS\_LI+FUS\_Z+FUS\_LD+FUS\_RD}$$

Figure 10. Centroid method

III. Mechanical Design

In order to tolerate misalignment during operation, a flexible coupling has been introduced in the prototype.

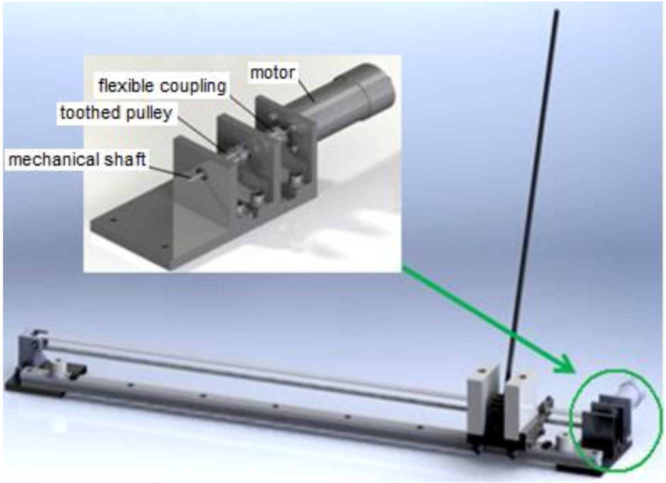

Figure 11. Reconditioning of the prototype

By analyzing the disadvantages of the current system, a new prototype that offers greater facilities to be used as a test platform has been designed . Within of the design conditions, it has been considered:

- Maximum length of 50 cm to the movement path of the carriage.
- Limitations on the rotation side of the pendulum.
- Speed 1.5 m/s.
- Low cost, portable, lightweight, easy to maintain and repair.

Figure 12. Design of a new prototype

IV. Results

The mechanism has been tested with the two types of controllers and the results obtained are shown in the figures below.

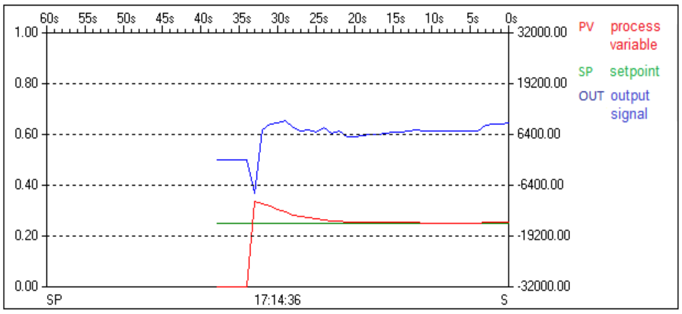

Figure 13. Position control response with PI controller

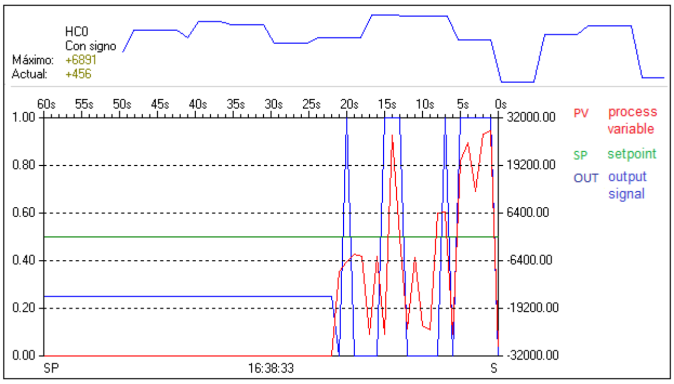

Figure 14. Pendulum control response with PD controller

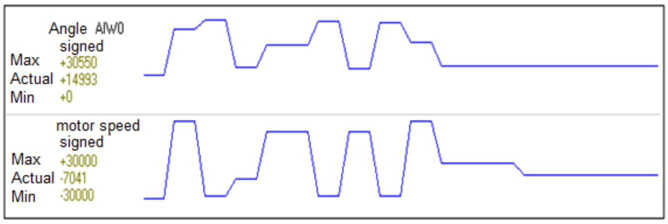

Figure 15. Fuzzy controller response with one input

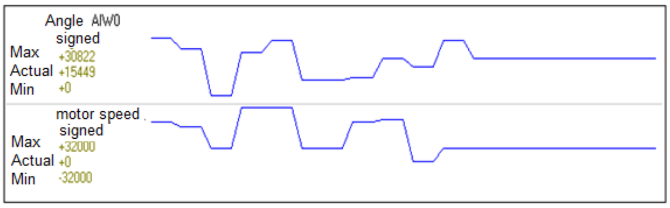

Figure 16. Fuzzy controller response with two inputs

V. CONCLUSIONS

- Classical control methods have great functionality in different types of systems, but have certain limitations in MIMO systems (multiple input and multiple output) and this has been proved when trying to balance the pendulum with PID controller.
- Friction problems in mechanism interfere with the pendulum stabilization because higher voltage to overcome the inertia of the carriage is required.
- For the fuzzy controller, calibration is a process that takes a very long time because it is based on trial and error test, so it is not possible to ensure optimal results immediately. Moreover, the fuzzy control algorithm depends strongly on the ability of the PLC to perform floating point operations. This directly affects the amount of memory needed and the speed in order to process those operations.
- During testing of the fuzzy algorithm, one could realize that the response improves if two input variables are used and with a distribution of the membership functions more concentrated in the center of the range. The more joined the functions are on the near zero values, it has a higher resolution or finer fuzzification at those ranges.

REFERENCES

[1] G. Eason, B. Noble, and I. N. Sneddon, "The Reaction Wheel Pendulum", Morgan & Claypool Publishers, 2007.

[2] M. Antonio, C. Márquez, R. Silva y C. Merlo, "Sistemas dinámicos subactuados: Péndulos invertidos", Instituto Politécnico Nacional, CIDETEC, México.

[3] Siemens, "Manual del sistema de automatización S7-200", 2008.

[4] Siemens, "Ejemplos S7-200. Escalado de valores analógicos", Ejemplo N° 38.

[5] A. Pérez Otero, "Desarrollo de la planta experimental Péndulo Invertido", Universidad de Oviedo, Septiembre 1998.

[6] Huang Chun-E, LI Dong-Hai, SU Yong, "Simulation and Robustness Studies on an Inverted Pendulum", Proceedings of the 30th Chinese Control Conference, July 22-24, 2011, Yantai, China.

[7] M. Pineda, A. Vivas, "Control de un modelo aerodinámico aplicando sistemas difusos", Escuela Politécnica Nacional, Quito, Ecuador, 2008.