Archives of
Transport System
Telematics

Volume 7

Issue 3

September 2014

Implementation of artificial intelligence tools to an industrial controller

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ABSTRACT
This paper considers the issue of vertical position control of a ball placed on a disc. The aim of this work is to create a fuzzy logic controller able to manage the issue of ball and wheel. The second chapter describes the identification system. In the next chapter a Fuzzy controller is described. The last chapter is dedicated to results of implemented fuzzy controller. Most of control tasks in transport are non-linear. This application should help to apply a fuzzy control in such systems.

KEYWORDS: PLC, fuzzy, control

1. Introduction

In industrial technology there are many non-linear systems whose management is implemented with the assistance of conventional controllers. Often the model of non-linear system replaced by a constrained linear one and resulting control deviations are acceptable to the customer. In the case of strongly non-linear systems, it is not possible to apply a single linear controller because it cannot adequately control a complex process and the variation and time consumption for the regulation is becoming difficult.

The system of a ball placed on a wheel in the literature known as "The ball on the wheel system"- BOW is selected for its strong nonlinearity (detailed description in [6] and [7]). The problem of controlling the position of the ball is often a popular topic for various scientific institutions just for strongly nonlinear response of the ball. For this kind of system not only the size ratio of used wheels and balls is crucial but also the transfer between the drive unit and the driven system. Also the place of laying the ball may affect the control.

The solving of the ball and wheel system offers a solution for multiple nonlinear problems encountered in the industry. An overshoot is a critical property, as well as the accuracy of the control output and the time necessary for the regulation. If the used controller is able to adequately regulate the ball on the wheel system, we can assume that its use will also be widely applicable in the industry. In this work some known regulators have been gradually applied. First the PID controller, the other is fuzzy. The results of regulation are described in the final section. The controller has been implemented in B&R PLC. Other methods of controller implementation in PLC are described in [1]. A squirrel-cage induction motor is used as an actuator, which is described in more detail in [2]. This work is a continuation of master thesis [3], which has described the construction of the apparatus and other control methods.

2. System identification

A considerable space in the literature is devoted to the identification of dynamical systems. The first step in identifying is the correct identification of the model representing a realistic model of the system. The system of a ball placed on the top of the wheel is mentioned in the literature under the name "The Ball on Wheel System" (BOW). The system of ball on the wheel is a classic example of a system with single input and single output (SISO) system.

2.1 Ball on wheel system

There are many methods for SISO system description. The most common method used in industry is the method of least squares. The most common model is the ARX linear regression model. This model provides a description of stationary stochastic processes using polynomial functions. This model describes a system using the following equation:

$$A(q)y(t) = B(q)u(t) + e(t) \tag{1}$$

where:
$y(t)$ is an output of the system,
$u(t)$ are control interventions,
$e(t)$ are errors caused by white Gaussian noise, or errors in the system.
Then we can write the relationship:

$$\begin{aligned} y(t) &= -a_1 y(t-1) - a_2 y(t-2) - \cdots - a_N y(t-N) \\ &+ b_1 u(t-1) + b_2 u(t-2) + \cdots + b_N u(t-N) + e(t) \end{aligned} \tag{2}$$

which can be written in the vector form:

$$y(t) = W^T(t)\overline{p}(t) + e(t) \tag{3}$$

where: p is the vector of parameters, which can be written in the form:

$$\overline{p}(t) = [a_1 a_2 \ldots a_N b_1 b_2 \ldots b_N]^T \tag{4}$$

and W^T is a vector of data that can be written as follows:

$$W^T(t) = [-y(t-1) \; -y(t-2) \; \cdots, -y(t-n) \; u(t-1) \; u(t-2) \; \cdots, u(t-m)] \tag{5}$$

2.1 Euler – Lagrange formulation

Solving the problem of control of loosely placed ball on a vertical roll is also historically frequently mentioned theme of various scientific works. In the literature it is possible to find a number of solutions. The first men, who tried to describe such a system in the eighteenth century, were Leonhard Euler – a Swiss mathematician and Joseph Louis Lagrange – an Italian mathematician. These two important mathematicians formulated and derived equations describing the system of balls on the wheel. The definition of Euler - Lagrange formulation dates back to 1750.

The basis of this equation is the Lagrange function, which is given by the difference of kinetic and potential energy $L = T - V$ where T is the kinetic energy and V is the potential energy of the system. Lagrange function L is sometimes called Lagrangian. The system of mutual interaction variables acting on the ball and the wheel is described in the following Fig. 1.

As seen in the figure above, a ball is at the top of the wheel and its motion is close to the edge of fall without intervention. The coordinate system is signed by letters x and y, letter g is the gravitational acceleration, r_b and r_w is the radius of the ball and the wheel, respectively. Similarly, m_b and m_w is the mass of the ball and the wheel and I_b and I_w is the moment of inertia of the ball and the wheel. Symbol θ_1 stands for an angular offset from the center of the system, θ_2 is an angular velocity of the wheel around its center and θ_3 is an angular shift of ball around its center. Letters C_b and C_w designate contact points touching the ball and the wheel. O_w is the center point of the wheel and O_b is the center point of the ball. The following section will describe relationships between variables.

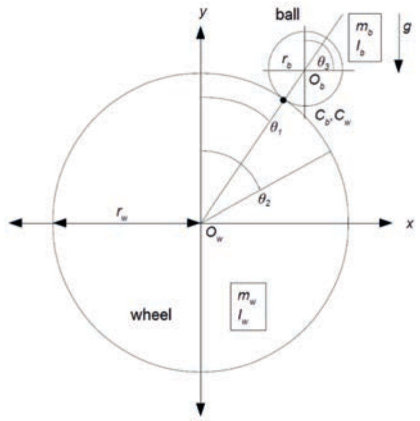

Fig. 1. The system of a ball on the wheel [own study]

The Euler-Lagrange equations formula is given as F:

$$\frac{d}{dt}\left[\frac{\partial L}{\partial q}\right] - \frac{\partial L}{\partial q} = Q \tag{6}$$

When q gives the output state of the system, the following would be valid:

$$q = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} \tag{7}$$

where: θ_1 is an angular displacement of middle of the ball against the center of the system, θ_2 is an angular rotation of the wheel around its center. Forces entering the system are designated as Q and the following is valid:

$$Q = \begin{bmatrix} 0 \\ \tau \end{bmatrix} \tag{8}$$

where τ is the torque applied directly to the wheel. For the calculation of the kinetic energy $T = Tb + Tw$ will be valid. Kinetic energy of the ball Tb will be calculated as:

$$T_b = \frac{1}{2} m_b (r_w + r_b)^2 \left(\frac{d\theta_1}{dt}\right)^2 + \frac{1}{2} I_b \left(\frac{d\theta_3}{dt}\right)^2 \tag{9}$$

The first part of the kinetic energy formula symbolizes the movement of the ball on the wheel and the second part symbolizes the kinetic energy of rotation of the ball around its own axis. The formula for the kinetic energy contains the following expression: $\frac{d\theta_1}{dt}$ which represents in this case the angular velocity of the ball along the surface of the wheel. The moment of inertia of the ball can be calculated according to the following formula:

$$I_b = \frac{2}{5} m_b r_b^2 \tag{10}$$

The kinetic energy of the wheel is calculated as follows:

$$T_W = \frac{1}{2} I_W \left(\frac{d\theta_1}{dt}\right)^2 \tag{11}$$

where: I_w is the moment of inertia of the wheel and for calculation of the moment of inertia of the wheel, the following relation is valid:

$$I_W = \frac{1}{2} m_W r_W^2 \tag{12}$$

Deriving of calculation of the moment of inertia of the wheel is as follows. The moment of inertia of a rotating body is given by the product of the mass of each point and the square of the distance from the center point of rotation. Here, we can derive the total kinetic energy of the system as follows:

$$T = \frac{1}{4} m_w r_w^2 (\theta_2')^2 + \frac{1}{2} m_b (r_w + r_b)^2 (\theta_1')^2 + \frac{1}{5} m_b r_b^2 (\theta_3')^2 \tag{13}$$

The following will be valid to calculate the potential energy:

$$V = m_b g (r_W + r_b) \cos\theta_1 \tag{14}$$

The potential energy of a rotating body is unchanged, but the potential energy of the ball changes, because it changes its position relative to the reference system. The potential energy of the ball depends on the current position of the ball on the wheel, so it is given by the cosine function. Now we can derive Lagrangian $L = T - V$.

$$\frac{\partial L}{\partial \theta_1} = m_b g (r_W + r_b) \sin\theta_1 \tag{15}$$

$$\frac{\partial L}{\partial \frac{d\theta_1}{dt}} = \left(\frac{7}{5} r_W^2 m_b + \frac{14}{5} r_W r_b m_b + \frac{7}{5} r_b^2 m_b\right)\left(\frac{d\theta_1}{dt}\right) - \left(\frac{2}{5} r_W^2 m_b + \frac{2}{5} r_W r_b m_b\right)\left(\frac{d\theta_2}{dt}\right) \tag{16}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \frac{d\theta_1}{dt}}\right) = \left(\frac{7}{5} r_W^2 m_b + \frac{14}{5} r_W r_b m_b + \frac{7}{5} r_b^2 m_b\right)\left(\frac{d^2\theta_1}{dt^2}\right) - \left(\frac{2}{5} r_W^2 m_b + \frac{2}{5} r_W r_b m_b\right)\left(\frac{d^2\theta_2}{dt}\right) \tag{17}$$

$$\frac{\partial L}{\partial \theta_2(t)} = 0 \tag{18}$$

$$\frac{\partial L}{\partial \frac{d\theta_2}{dt}} = \left(\frac{2}{5} r_W^2 m_b + \frac{2}{5} r_W r_b m_b + \frac{7}{5} r_b^2 m_b\right)\left(\frac{d\theta_1}{dt}\right) + \left(I_W + \frac{2}{5} r_W^2 m_b\right)\left(\frac{d\theta_2}{dt}\right) \tag{19}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \frac{d\theta 2}{dt}}\right) = \left(-\frac{2}{5} r_W^2 m_b - \frac{2}{5} r_W r_b m_b\right)\left(\frac{d^2\theta_1}{dt^2}\right) + \left(I_W + \frac{2}{5} r_W^2 m_b\right)\left(\frac{d^2\theta_2}{dt}\right) \tag{20}$$

From these equations it is possible to derive state equations of the system:

$$(7r_b + 7r_W)\theta_1'' - 2r_W\theta_2'' - 5g\sin\theta_1 = 0 \tag{21}$$

$$\left(-\frac{2}{5} r_W^2 m_b - \frac{2}{5} r_W r_b m_b\right)\theta_1'' + \left(I_W + \frac{2}{5} r_W^2 m_b\right)\theta_2'' = \tau \tag{22}$$

These equations are valid only while the forces between the wheel and a ball sufficiently large to maintain a circular movement of the ball on the wheel.

2. Fuzzy regulator

A fuzzy regulator implements all well-known steps necessary for fuzzy control system implementation (more detailed description of a fuzzy controller is available in [4] and other control methods in [5]):

Normalization and fuzzification:

The program implements the normalization and fuzzification in a single step. All fuzzy sets are piecewise constant and linear. Therefore the fuzzification is composed of several IF/THEN conditions and each constant or monotonous part is described by one function. The fuzzification has finally 5 fuzzy sets. The setting is shown in the figure below (Fig. 2.). All breakpoints of all functions are set as constants in the PLC memory. This makes the tuning of fuzzy sets comfortable.

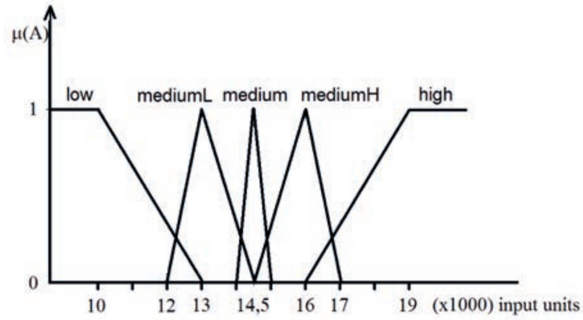

Fig. 2. Input fuzzy set [own study]

Program code implementation (example for two sets)**:**

```
IF Position <= P_low_mid THEN
            Position_low_fuzzy:=1;
            END_IF;
IF Position > P_low_mid AND Position <= P_
low_end THEN
            Position_low_fuzzy:=1-
((Position-
            P_low_end)/(P_low_mid-P_low_
end));
            END_IF;
IF Position > P_low_end THEN
            Position_low_fuzzy:=0;
            END_IF;
IF Position >= P_middleL_beg AND Position <
            P_middleL_mid THEN
            Position_mediumL_
fuzzy:=((Position-
            P_middleL_beg)/(P_middleL_mid-
            P_middleL_beg));
            END_IF;
IF Position >= P_middleL_mid AND Position
            <= P_middleL_end THEN
            Position_mediumL_fuzzy:=1-
((Position-
            P_middleL_mid)/(P_middleL_end-
            P_middleL_mid));
            END_IF;
IF Position < P_middleL_beg OR Position >
P_middleL_end
            THEN
            Position_mediumL_fuzzy:=0;
            END_IF;.
```

Inference:

The inference is the simplest step in the fuzzy control system. The inference consists of simple rules as follows: as constants in PLC memory. This makes the tuning of fuzzy sets comfortable.

Program code implementation:

```
Output_positive_fuzzy:=0.01*Position_
mediumH_fuzzy;
Output_negative_fuzzy:=0.01*Position_
mediumL_fuzzy;
Output_positive_fuzzy:=Position_high_fuzzy;
Output_negative_fuzzy:=Position_low_fuzzy;
Output_neutral_fuzzy:=Position_medium_
fuzzy;
```

Defuzzification and denormalization:

The defuzzification is the most complex part of the program. The center of gravity is used as a defuzzification method. Therefore next steps are necessary:

The first step is to calculate the area of relevant part of fuzzy output set cut-off. Generally all fuzzy sets used in this system are trapezoidal. In fact if a fuzzy set for example of a triangular shape is cut-off at 0.7, the relevant part of the triangle is now trapezoidal. Beside the area, the momentum used in calculation of gravity of a compound shape is the second relevant piece of information.

```
//Area low                        area_
low:=(Output_positive_fuzzy*(Output_low_
end-Output_low_mid)/2)+(Output_low_mid);
gravity_low:=area_low/2;
area_low:=area_low*Output_positive_fuzzy;

//Area medium
gravity_medium1:=(Output_neutral_
fuzzy*(Output_middle_mid-Output_middle_
beg)/2)+Output_middle_beg;
gravity_medium2:=(Output_neutral_
fuzzy*(Output_middle_end-Output_
middle_mid)/2)+Output_middle_mid;
gravity_medium:=(gravity_medium1+gravity_
medium2)/2;
area_medium:=Output_neutral_fuzzy*(gravity_
medium2-gravity_medium1);
```

The next step is to compute the overlay area. These contributions are significant because the calculation of only the area of separate output functions will cause a double counting of overlay areas.

```
//Overlay low and medium
IF Output_positive_fuzzy >= Output_neutral_
fuzzy THEN
gravity_overlay_low_middle1:=(Output_
neutral_fuzzy*(Output_middle_mid-Output_
middle_beg)/2)+Output_middle_beg;
gravity_overlay_low_middle2:=(Output_
neutral_fuzzy*(Output_low_mid-Output_low_
end)/2)+Output_low_mid;
ELSE
gravity_overlay_low_middle1:=(Output_
positive_fuzzy*(Output_middle_mid-Output_
middle_beg)/2)+Output_middle_beg;
gravity_overlay_low_middle2:=(Output_
positive_fuzzy*(Output_low_mid-Output_low_
end)/2)+Output_low_mid;
END_IF;
gravity_overlay_low_middle:=(gravity_
overlay_low_middle1+gravity_overlay_low_
middle2)/2;
IF Output_positive_fuzzy >= Output_neutral_
fuzzy THEN
area_overlay_low_middle:=Output_neutral_
fuzzy*(gravity_overlay_low_middle2-gravity_
overlay_low_middle1);
ELSE
area_overlay_low_middle:=Output_positive_
fuzzy*(gravity_overlay_low_middle2-gravity_
overlay_low_middle1);
END_IF;
```

The last step is to compose the final center of gravity, the separate functions are positive contributions and the overlay areas are the negative contributions.

```
system_output:=(((area_low*gravity_
low)+(area_medium*gravity_medium)+(area_
high*gravity_high)
-(area_overlay_low_middle*gravity_
overlay_low_middle)-(area_overlay_middle_
high*gravity_overlay_middle_high)));
system_output_u:=REAL_TO_DINT(system_
output/(gravity_low+gravity_medium+gravity_
high+gravity_overlay_low_middle+gravity_
overlay_middle_high));
```

3. Conclusion

The fuzzy algorithm was not working optimally due to a very long ultrasonic sensor delay. The response of 40ms is insufficient for this type of application. Because of that the motor wheel was running the ball from one side to another without stabilization at the top of the wheel. Various attempts were made to get a stable output without the desired results. One of the attempts was a two input variables fuzzy regulator (one for the position and another one for the angular velocity). This system was very difficult to set the input variables sets. The next work will be focused on the system improvement. The first step will be the change of an ultrasonic sensor to an optical sensor. The optical sensor has a response time of only 10 ms. This should be sufficient for this kind of application. The program of fuzzy logic controller is running in a 2 ms loop. The duration of the loop does not need to be changed. The output of the regulation is shown in the figure below (Fig. 3.).

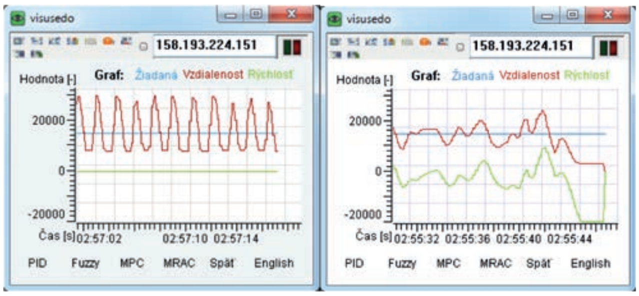

Fig. 3. The position of the ball oscillating around its middle using a fuzzy regulator on the left and using PID on the right side [own study]

Acknowledgments

This work has been supported by the Educational Grant Agency of the Slovak Republic (KEGA) Number: 010ŽU-4/2013: Modernization of didactic equipment and teaching methods with a focus on the area of robotics.

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