A FUZZY CONTROL SCHEME FOR THE GANTRY CRANE POSITION AND LOAD SWING CONTROL

Tonci Popadic[1)], Fetah Kolonic[2)], Alen Poljugan[3)],
Faculty of electrical engineering and computing
University of Zagreb
Unska 3, Zagreb, Croatia
Telefon: 0038516129824 Fax: 0038516129705
[1)]tonci.popadic@apzinst.t-com.hr, [2)]fetah.kolonic@fer.hr, [3)]alen.poljugan@fer.hr

Abstract – Minimization of the load transfer time and load swing angle in the crane applications, is conflicting control demand and requires proper control action. In this paper, fuzzy positioning and anti-swing control scheme for the gantry crane control is proposed. In order to control four system variables, the multivariable fuzzy crane controller is designed by using coefficients of a Linear Quadratic (LQ) crane controller. Fuzzy controller has been tested and compared with the LQ controller in simulation and on a laboratory planar gantry crane model.

I. INTRODUCTION

In modern industrial system, gantry cranes are widely used for the heavy loads transfer. The crane acceleration, required for the motion, causes an undesirable load swing having negative consequences on the system control and safety performances. Beside the load position, for load swinging minimization it is necessary to control load swing angle. To achieve more control efficiency, derivations of the cart position and swing angle should be controlled as well. Neglecting the rope length change, it is necessary to design control system with the four inputs and one output.

For an associated control problem solving, most solutions are based on the linearized mathematical model. Typical control approach is optimal, adaptive or robust, [1]-[4]. Corriga, Giua and Usai [1] have designed gain-scheduling logic with optimal controllers, Wang and Surgenor [2] used LQ controller but Hakamada and Nomura [3] used two controllers; one for the cart position control and second one for the load swing control.

Because of the crane system complexity and the fact that linearized mathematical model mostly doesn't represent real system good enough, some authors used fuzzy controller, [5]-[9]. Controller based on fuzzy logic can solve an undesirable effects caused by the system nonlinearities. From the real world applications point of view, the drawbacks can be in the large calculation time of the controller output caused by the number of controlled variables. Because the fuzzy rules are increasing exponentially with controller inputs, the main control task can be separated on the two controllers; one for the cart positioning and second one for the swing control. In [5]-[7] cart position is realized with classical technique, but in [8] and [9] fuzzy rules are significantly reduced using fuzzy logic for both controllers; cart position and swing angle.

In this paper one fuzzy controller is used to control four system variables. It will be shown how to design a fuzzy controller by using the LQ controller design and how to handle some effects caused by system nonlinearities, such as static friction. Sugeno and Mandani type of fuzzy controllers will be compared as well.

II. FUZZY CONTROLLER DESIGN

From experience it is difficult to design fuzzy controller for more then two system variables based on the system operator knowledge. In multivariable control schemes, Mamdani fuzzy controller based on the LQ controller design can be used [10]. Two components of the LQ controller are the optimal gains *F* and the summation block, Fig. 1.

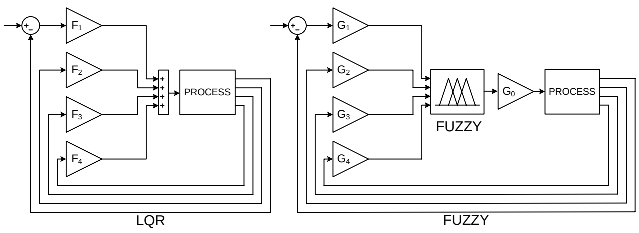

Fig. 1. General form of the control system with the LQR and fuzzy controller

Fuzzy controller has four components: rule-base, interface mechanism, fuzzification interface and defuzzification interface, Fig. 2.

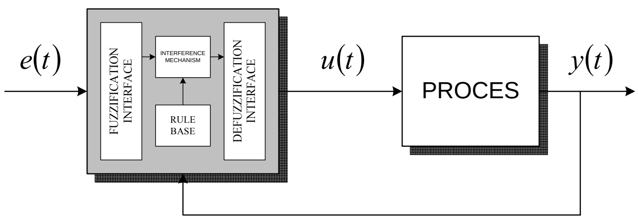

Fig. 2: Control system with fuzzy controller

Input universes of discourse, of a fuzzy controller, are usually designed in [-1, 1] interval. Process variables have to be adapted to the controller input universes of discourse by using the input scaling gains G_1 - G_4 and output variable is adopted by using the output scaling gain G_0. To design fuzzy controller based on the LQ controller design, optimal gains *F* can be replaced with the scaling gains *G*, and summation mechanism can be incorporated into the rule-base of the fuzzy system.

The input membership functions, for all inputs of the fuzzy controller, are used as it is shown on Fig. 3. Linguistic values (big negative, small negative, zero, small positive and big positive) can be labelled with the linguistic-numeric indices which are integers with zero at the middle: -2, -1, 0, 1 and 2.

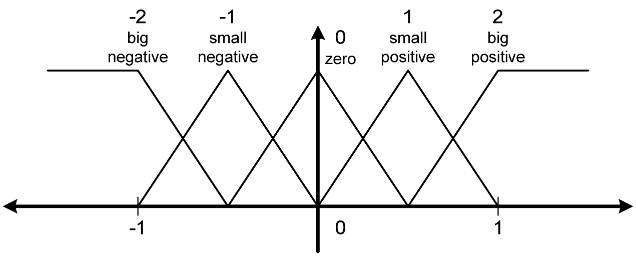

Fig. 3: Input membership functions of the Mamdani fuzzy controller type

Centres of the controller output membership functions can be located at,

$$\left(j+k+l+m\right)\cdot\frac{2}{\left(N-1\right)\cdot n}, \qquad (1)$$

where j, k, l and m are linguistic-numeric indices of the input membership functions (Fig. 3), N is the number of membership functions on each input universe of discourse (it is assumed that there is the same number on each universe of discourse), and n is the number of inputs. Base widths are equal to the distance between neighbour centres of the membership functions, in order to be uniformly distributed on the output universe of discourse. Now, the output universe of discourse looks like as presented on the Fig. 4. Labels of the output membership functions can be determined in the same way as they were determined for the input membership functions.

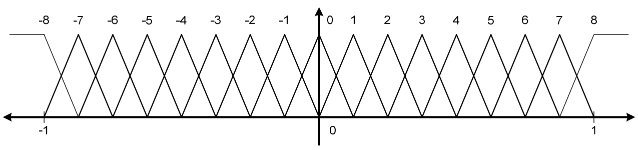

Fig. 4: Output membership functions of Mamdani type fuzzy controller.

To make rule-base implement summation point, rules have to be made based on,

IF x1 **IS** j **AND IF** x2 **IS** k
AND IF x3 **IS** l **AND IF** x4 **IS** m

THEN

OUTPUT z **IS** z=j+k+l+m,

where z is linguistic-numeric index of the output membership function. Scaling gains G_i are determined from the optimal gains F of the LQ controller. The input with the highest influence on the plant behaviour and overall control performance has to be firstly defined. This is the cart position. Since the cart position is in the interval [-0.25, 0.25], G_1 has to be defined in a manner that it is normalized with the fuzzy controller input interval [-1, 1]. It results with scaling gain G_1 is G_1=4. Other scaling gains G_i are determined using the relation,

$$G_i \cdot G_0 = F_i, \qquad (2)$$

where i=2, 3 and 4.

With four fuzzy inputs, calculation time of the controller output could be too long for the real world implementation. According to previous explanation, the number of membership functions has to be reduced or, in the different way, some other fuzzy controller structure should be chosen.

Sugeno type of the fuzzy controller has a simpler defuzzification than Mamdani type, and because of that, shorter calculation time of the controller output In order to achieve smaller number of rules, input membership functions for all Sugeno controller inputs can be chosen as it is presented in the Fig. 5 (two membership functions for each input universe of discourse). In order to design Sugeno fuzzy controller by using the LQ controller gains, scaling gains G should be chosen in the same way as it was done for the Mamdani controller.

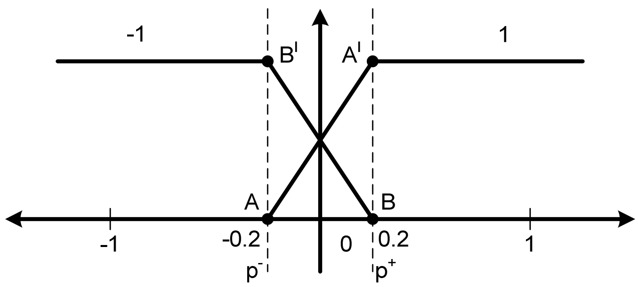

Fig. 5: Input membership functions of Sugeno type fuzzy controller

Since there are four inputs and two membership functions per input, the total number of rules and output membership functions is sixteen. Output membership functions of the Sugeno fuzzy controller are linear functions of the constants. Because controller must have summation function, linear functions for the output membership function will be used and will be defined by equation

$$z = k_0 + k_1x_1 + k_2x_2 + k_3x_3 + k_4x_4 \qquad (3)$$

where x_1, x_2, x_3 and x_4 are values of the controlled variables, and k_0, k_1, k_2, k_3 and k_4 constants defined like k_0=0 and k_1= k_2= k_3= k_4= 1. In this way, Sugeno fuzzy controller has the same function as the summation block of the LQ controller.

Because experimental testing approved that Mamdani type of a fuzzy controller had to long calculation time of output variable for the real time implementation, all investigations further are focused on the LQ and Sugeno type fuzzy controller.

III. MATHEMATICAL EQUATIONS OF THE MOTION

The single pendulum gantry mounted on the linear cart is presented on the Fig. 6. When facing the cart, positive direction of the cart motion is to the right and positive sense of pendulum rotation is defined to be counter clockwise. Also, the zero angle, corresponds to a suspended pendulum vertical rest down position. Single pendulum gantry can be presented as a system with one input u (motor voltage), and two outputs: α (pendulum angle) and x_c (cart position). Mathematical equations of the motion can be defined via Lagrange equations using a total potential and kinetic energy [12]. Nonlinear equations of motion are presented in (4) and (5).

Parameters of equations (4) and (5) are in Table 1. with values taken from [12]. Linear equations of motion, (6) and (7), can be defined after substitution cos(α)= 1 and sin(α)= α in (4) and (5), and the parameters from Table 1.

$$\ddot{x}_c = \frac{-(I_p + M_p l_p^2)B_{eq}\cdot\dot{x}_c + (M_p^2 l_p^3 + l_p M_p I_p)\sin(\alpha)\cdot\dot{\alpha}^2 + M_p l_p \cos(\alpha) B_p\cdot\dot{\alpha}}{(M_c + M_p)I_p + M_c M_p l_p^2 + M_p^2 l_p^2 \sin^2(\alpha(t))} + \frac{M_p^2 l_p^2 g\cos(\alpha)\sin(\alpha) - (I_p + M_p l_p^2)\left(\frac{\eta_g K_g^2 \eta_m K_t K_m\cdot\dot{x}_c}{R_m r_{mp}^2} + (I_p + M_p l_p^2)\frac{\eta_g K_g \eta_m K_t}{R_m r_{mp}} U_m\right)}{(M_c + M_p)I_p + M_c M_p l_p^2 + M_p^2 l_p^2 \sin^2(\alpha)} \quad (4)$$

$$\ddot{\alpha} = \frac{-(M_c + M_p)B_p\cdot\dot{\alpha} - M_p^2 l_p^2 \sin(\alpha)\cos(\alpha)\cdot\dot{\alpha}^2 + M_p l_p \cos(\alpha) B_{eq}\cdot\dot{x}_c}{(M_c + M_p)I_p + M_c M_p l_p^2 + M_p^2 l_p^2\cdot\sin^2(\alpha)} + \frac{-(M_c + M_p)M_p g l_p \sin(\alpha) + M_p l_p \cos(\alpha)\frac{\eta_g K_g^2 \eta_m K_t K_m\cdot\dot{x}_c}{R_m r_{mp}^2} - M_p l_p \cos(\alpha)\frac{\eta_g K_g \eta_m K_t}{R_m r_{mp}} U_m)}{(M_c + M_p)I_p + M_c M_p l_p^2 + M_p^2 l_p^2\cdot\sin^2(\alpha)} \quad (5)$$

$$\begin{bmatrix}\dot{x}_c(t)\\ \dot{\alpha}(t)\\ \ddot{x}_c(t)\\ \ddot{\alpha}(t)\end{bmatrix} = \begin{bmatrix}0 & 0 & 1 & 0\\ 0 & 0 & 0 & 1\\ 0 & 1.5216 & -11.6513 & 0.0049\\ 0 & -26.1093 & 26.8458 & -0.0841\end{bmatrix}\cdot\begin{bmatrix}x_c(t)\\ \alpha(t)\\ \dot{x}_c(t)\\ \dot{\alpha}(t)\end{bmatrix} + \begin{bmatrix}0\\ 0\\ 1.5304\\ -3.5261\end{bmatrix}\cdot U_m(t) \quad (6)$$

$$\begin{bmatrix}x_c(t)\\ \alpha(t)\end{bmatrix} = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\end{bmatrix}\cdot\begin{bmatrix}x_c(t)\\ \alpha(t)\\ \dot{x}_c(t)\\ \dot{\alpha}(t)\end{bmatrix} \quad (7)$$

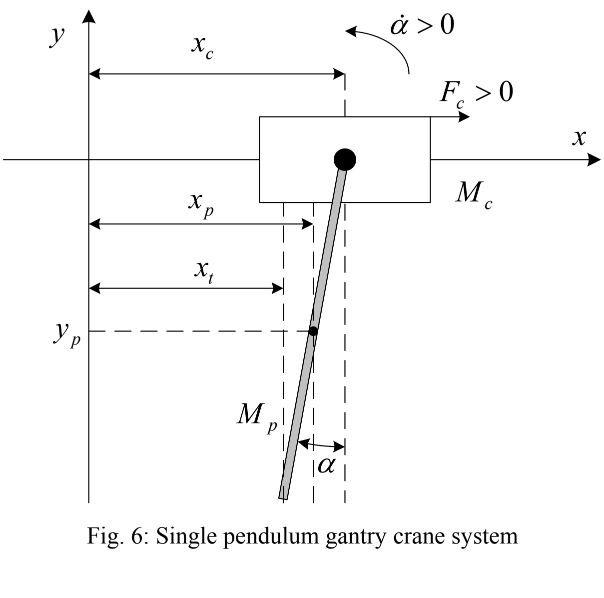

Fig. 6: Single pendulum gantry crane system

TABLE I
SINGLE PENDULUM GANTRY PARAMETERS

Parameters	Description
B_{eq}=5.4 [Nms/rad]	equivalent viscous damping coefficient as seen at the motor pinion
B_p=0.0024 [Nms/rad]	viscous damping coefficient as seen at the pendulum axis
η_g=1	planetary gearbox efficiency
η_m=1	motor efficiency
g=9.81 [m/s^2]	gravitational constant of earth
I_p= 0.0078838 [kgm^2]	pendulum moment of inertia
J_m= 3.9001e-007 [kgm^2]	rotor moment of inertia
K_g= 3.71	planetary gearbox gear ratio
K_m= 0.0076776	back electro-motive force (EMF) constant
K_t= 0.007683	motor torque constant
l_p=0.3302 [m]	pendulum length from pivot to center of gravity
M_c= 1.0731 [kg]	lumped mass of the cart system, including the rotor inertia
M_p= 0.23 [kg]	pendulum mass

R_m= 2.6 [Ω]	motor armature resistance
r_{mp}= 0.00635 [m]	motor pinion radius

IV. SIMULATION RESULTS

System performances with the LQ and Sugeno fuzzy controller are compared in the simulation. Optimal gains of LQ controller are determined as $\underline{F}$ = [26.8585, -104.0562, 21.9539, -5.4359], and according to (2) scaling gains of the fuzzy controller as (G_0=6.7146, G_1=4, G_2=-15.4969, G_3=3.2696 and G_4=-0.8096.). Cart position reference is set as $X_{c,ref}$=0.2m. Simulation results with LQ and Sugeno fuzzy controller are presented on the Fig. 8. and Fig. 9. respectively. Since Sugeno fuzzy controller was designed on the base of the LQ controller gains, simulation results are identical.

VI. EXPERIMENTAL VERIFICATION

Experimental model of a single pendulum gantry has three basic parts: cart with pendulum, AD interface and digital control system implemented on the personal computer [11].

Cart is driven by DC servo motor by the rack and pinion mechanical interface, Fig. 7. Driving motor, two encoders and additional weight are placed on the cart. Encoders are used for the cart position and pendulum angle measurement, and additional weight is used to ensure better cart fitting the pinion on the rack. Cart position resolution is 22.75 µm, swing angle resolution is 0.0015 rad. and available cart distance (the length of the rack) is 1 m.

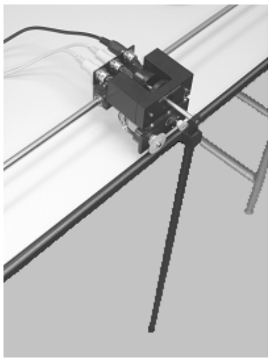

Fig. 7. Single pendulum gantry laboratory model

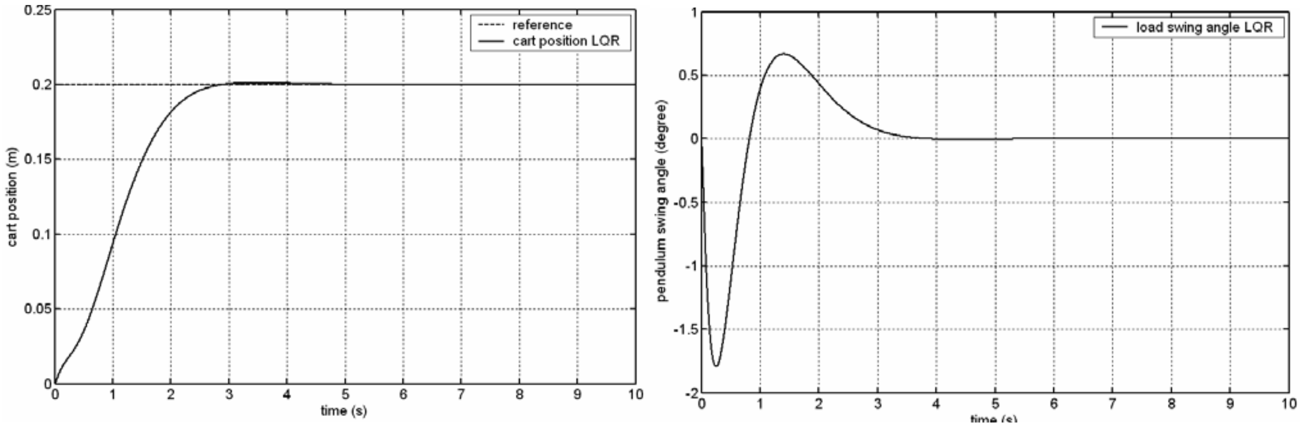

Fig.8. Simulation results for the LQR controller; cart position- left, load angle-right

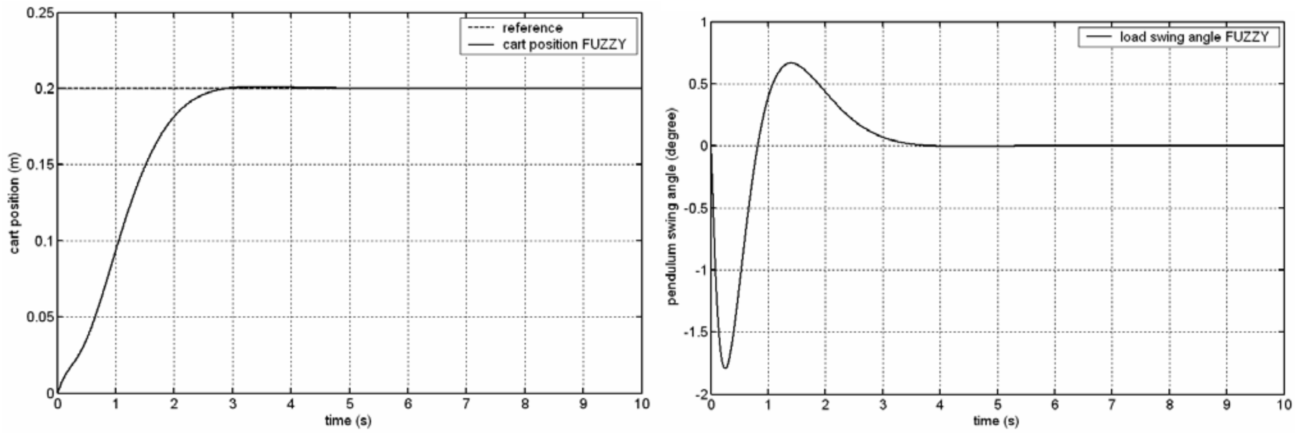

Fig.9. Simulation results for the Sugeno fuzzy controller; cart position- left, load angle-right

Experimental results are presented on the Fig. 11. It can be noticed that steady-state error in final positioning of the real model is presented. It is caused by static friction in mechanical transmission between motor, cart and rack and pinion and isn't included in linear mathematical model of the electromechanical system.

Steady-state error can be minimized with fuzzy controller modification by correcting the membership functions of the position error variable $e_N = K_e\ (x_{ref} - x_c)$. Membership functions can be changed according to the Fig. 10. Points A^I and B^I are being moved closer to the ordinate y, and points A and B are being moved away the ordinate y. New coordinates of these points are: A_x=-0.3, B_x=0.3, $A^I{}_x$=0.05, and $B^I{}_x$=0.05.

After membership functions corrections, experimental test has been repeated. Responses of the cart position and pendulum angle are presented on the Fig. 12. After modification, steady-state error is minimized from 7.5 mm to 1.2 mm. Maximum pendulum angle (α_{max}= -1.67 °) and settling time (t_s= 4 s) was not changed.

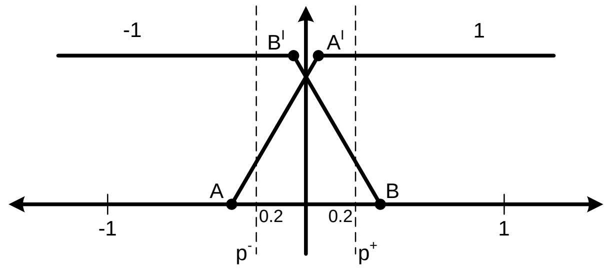

Fig. 10. Sugeno controller membership function after correction.

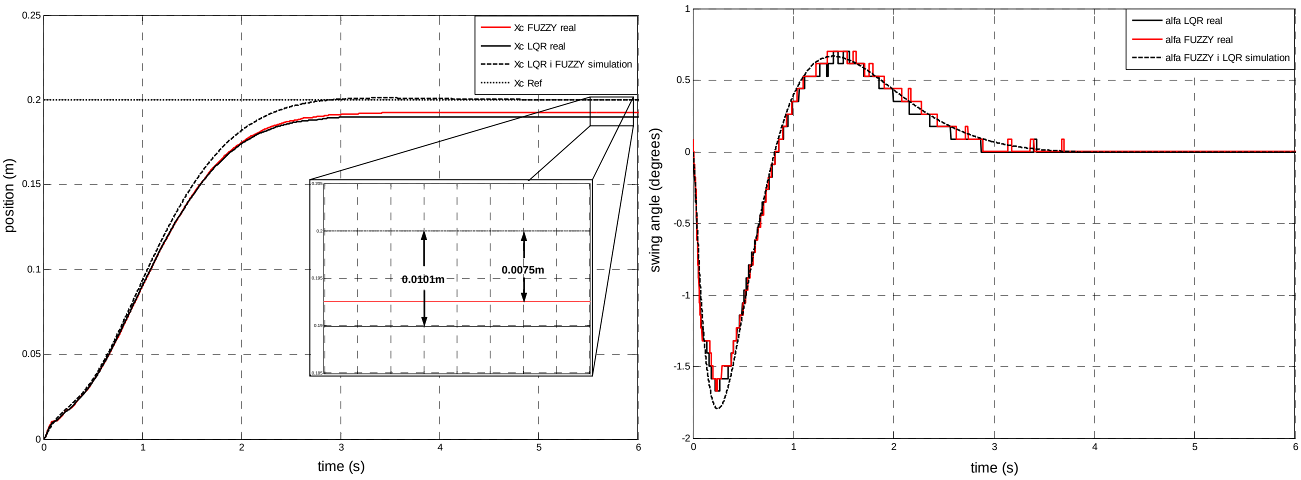

Fig. 11. Experimental verification results; comparison between LQR and fuzzy controller

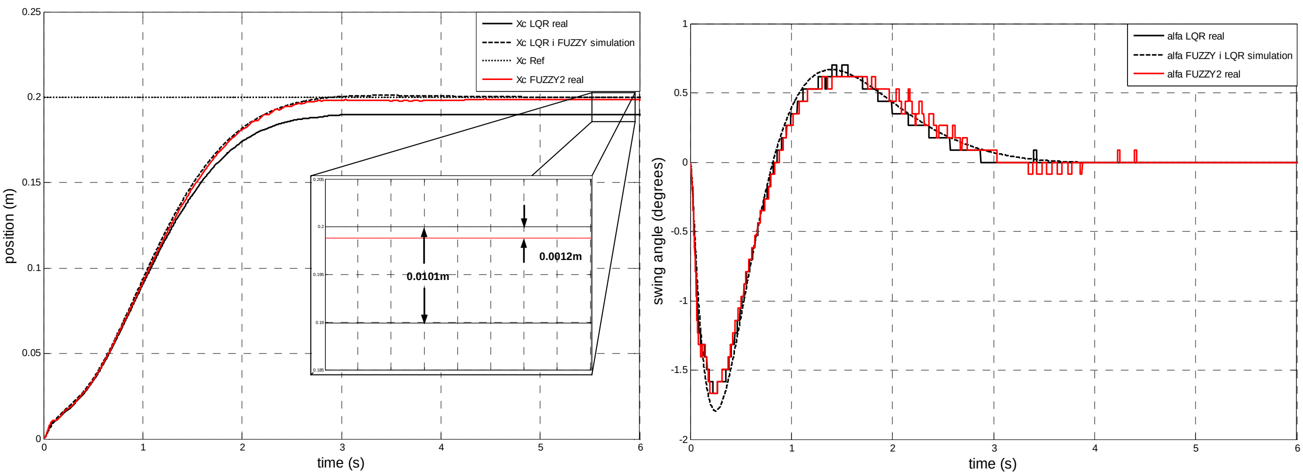

Fig. 12. Experimental verification results after fuzzy controller modification; comparison between LQR and fuzzy controller

VII. CONCLUSION

In this paper fuzzy controller for the single pendulum gantry electromechanical system is designed.

For this real time application, Sugeno type fuzzy controller was used as logic choice since Mamdani type fuzzy controller had too long calculation time of output variable.

Sugeno type fuzzy controller is designed on the base of the LQ controller design and used for control of the four process variables. For this purpose, LQ and fuzzy controllers are tested and compared in the simulation and in the real single pendulum gantry experimental model.

Since the fuzzy controller is designed on the base of the LQ controller, the simulation results are identical for both controller types. In the experimental testing with starting membership function (Fig.5.), cart position steady-state error has been obtained. This error, caused by static friction in mechanical transmission, is minimized by the membership functions modification, Fig.10. After modification steady-state error has been reduced from 7.5 mm to the 1.2mm.

VIII. REFERENCES

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