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A Four Step Design Procedure for an Improved Fuzzy Crane Control

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***Abstract*— Fast transportation of the loads without unintentional load sway has become a regular problem with cranes. Any improvement in the time of load transportation leads to higher rate of load accommodation and thus lower costs. In this paper, a four step process is taken to design an optimized fuzzy controller independent and free of any large and expensive computer help. Such a controller can suppress the load sway faster compared to previous reported results of fuzzy crane controls. The proficiency of this controller is confirmed through experimental results.**

Keywords-Gantry Crane; Fuzzy Control; Anti Sway; Microcontroller; Design Process

I. INTRODUCTION

In the world today, heavy loads are being moved by means of man made machines called cranes. Most cranes use a set of cables and pulleys to lift the loads to a definite height and then move the load to a desired place by transporting the trolley, the part from which the load is hung. Quick movement of the trolley leads to quick movement of the load and therefore a shorter time for it to reach the desired place. But the fast movement of the trolley causes the load to sway over its final place, while trolley has reached to its right position, right above the predefined location. This makes it impossible to place the load properly and some extra time should be elapsed so that the sways reduce to zero. To Point out the problem, both the fast movement of the trolley and the minimal sway of the load, though being somewhat contradictory, are crucial.

Several methods have been proposed to solve this problem. Singhose, Singer and Sourencen have worked on several aspects of an open loop control method known as input shaping [1,2,3]. Omar proposed a PD controller [4], Toxqui et al used a PD controller with neural compensation[5] and Wahyoud et al, Szpytko, and Chang used their own fuzzy controllers to solve the problem [6,7,8].

In this paper, a fuzzy controller is designed and optimized for the fine load transportation, without any high computing power source. A four step designing method is proposed to hasten the design procedure. Taking these steps in designing and optimization of the controller leads to a controller with higher efficiency and lower rate of failure in practice within a shorter time period.

The paper developed as follows. First, an introduction to fuzzy control is presented in section two. This section is followed by a four step design procedure. The results of section three and its comparison with previous works are brought in section four. This section also contains some results that confirm the robustness of the proposed controller. Section five consists of conclusions to sum up the results.

II. FUZZY CONTROL

Fuzzy control is an alternative method in many control applications, since it proposes a simple designing method especially in nonlinear controllers. This type of control is based on heuristic information, gathered by experience[10]. To design a fuzzy controller one should understand how to control the process. This information could be used directly in a fuzzy controller. In fact, fuzzy controller emulates the human decision-making process.

A fuzzy inference process consists of five steps [12] as follows:

1. Fuzzification: This step determines the degree to which the inputs belong to each fuzzy set via membership functions.

2. Applying fuzzy operators: When there is more than one input, fuzzy operators should be used to obtain only one truth value for the antecedent. Most commonly used fuzzy operators are AND, OR and Compliment.

3. Implication: According to the truth values obtained in the previous step which are the antecedents of fuzzy rules, the output of each rule is determined in this step. In other words, the certainty of each rule is calculated.

4. Aggregation: By combining all outputs of the rules, one single result is obtained. The decision-making process is based on this result.

5. Defuzzification: In order to have a crisp output, the last result must be defuzzified.

This mechanism, which proceeds from inputs to output, is called a fuzzy inference. There are two kinds of fuzzy inference. Mamdani-type and Sugeno-type. These two types are the same in many cases, except for the shape of the output membership functions and defuzzification process.

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The common fuzzy logic-based controllers are based on Mamdani fuzzy inference method. The output membership functions in this method are fuzzy sets. For defuzzification process, the centroid of a 2-D function should be calculated requiring integration. Such computations require a large amount of memory and a large amount of processing to be performed.

To simplify the defuzzification process, Sugeno-type inference is proposed. In this type, the output membership functions are in the form of single spikes. This type of output is known as a singleton output membership function. In this method, defuzzification process changes from integration to the calculation of a few data points average.

III. DESIGN PROCESS

The main goal of this paper is to propose a design of a stand alone crane controller capable of controlling the position of the trolley as well as the load sway. The plan is likely to fail if it is implemented directly on an individual controller while addressing and correcting the errors may also be hard. Hence, a four step design process is proposed which makes it easy to implement a successful controller for crane control. These four steps include an offline design of the controller, simulation, computer aided control and stand alone control. The controller is designed in the first stage, optimized in the second and third stages, and finally implemented on a microcontroller in the fourth one.

A. Offline Controller Design

As mentioned earlier, the purpose of the crane control is to take the load to its desired location as fast as possible. Precise placing of the load is only feasible when the trolley is exactly placed over the load and the sway of the payload is inclined to zero. This means that the position of the trolley and sway of the payload need to be controlled simultaneously.

There is a variety of different controller structures for this purpose. In this paper, the proposed controller consists of two controllers that control the position of the trolley and the sway of the payload separately. Their output is then mixed to have a single command for the motor. Fig. 1 shows this structure. In this topology, the position controller is dominant while trolley is away from its desired place. As the trolley approaches to its final location, the role of the position controller becomes less significant and anti sway controller takes the lead. This is exactly what is needed for a crane controller, i.e. to be fast at moving the load to its final place and to suppress the load sway when arriving to the place. The design of these two controllers is as follows.

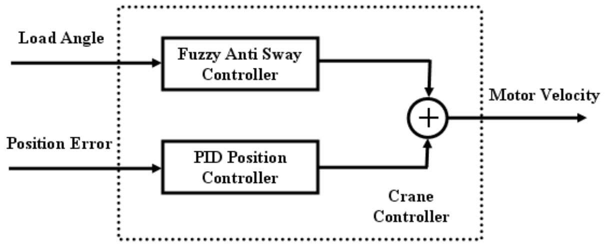

Fig. 1. Crane Controller's Topology

1) Position Control:

Since PID controller is a typical solution for position control in most cases, thus, the position controller selected in this study is a PID controller. Appropriate coefficients of the PID controller are derived by the aid of PIDtune tool of Mathworks' MATLAB® software. These coefficients of the PID controller are determined for a set of desired step response specifications of a desired system. A close model of the system is needed to have a near response in simulation stage. This model is extracted from the experimental response of the motor to a step input. The model is next used by PIDtune block and the coefficients are extracted as below:

$K_p = 1.21$, $K_i = 0.005$, $K_D = 0.43$

2) Sway Control:

A new fuzzy logic-based controller is proposed for the overhead crane system with an emphasis on the reduction of computations to make it implementable on microcontrollers.

For this controller, the two inputs are sway angle and its variation whereas the output is the velocity of the trolley. For input fuzzification seven membership functions are used, since they perfectly match the human perception of linguistic values [11]. Since the shape of membership functions has a little effect on the performance of the controller, triangular and trapezoidal ones are chosen [11]. This choice simplifies the fuzzification process and reduces the amount of computations. NB (negative big), NM (negative medium), NS (negative small), Z (zero), PS (positive small), PM (positive medium) and PB (positive big), represent fuzzy sets.

The density of the functions is higher around "zero" to improve the accuracy. Far apart the zero, where there is no need to be accurate, the density is lowered. The purpose of the controller is to minimize the sway angle by moving the trolley in the correct direction and with the appropriate velocity. Direction and velocity of the trolley are specified by fuzzy rules based on experience. To reduce the sway angle, the trolley should move in the same direction with the load while the velocity depends upon the size of the sway angle is, i.e. the bigger the angle, the higher the velocity. For instance, a positive big angle with a positive big angle rate shows that the sway angle is becoming even greater in the positive direction. To decrease the angle, the trolley should move in the positive direction with its maximum velocity so, the rule becomes "if the angle is PB and the angle rate is PB, then the velocity is PB". Considering another case, when a positive big angle has a negative big rate, no trolley displacement is needed, since the swing angle is decreasing rapidly itself. The rule, then, becomes "if the angle is PB, and the angle rate is NB, then the velocity is Z".

The used fuzzy inference is Sugeno-type, so the output membership functions are chosen to be constant. This choice simplifies the defuzzification process. Each fuzzy set is a single spike with a specific value. The crisp output is achieved from the defuzzification process. The output is the weighted average of all rule outputs and calculated by using (1):

$$Output = \frac{\sum_{i=1}^{N} \omega_i z_i}{\sum_{i=1}^{N} \omega_i} \qquad (1)$$

Where N represents the number of rules, z_i is the value of the output fuzzy set of the i^{th} rule and ω_i is the firing strength of the i^{th} rule. It is simply a function of the inputs. Taking θ and $\Delta\theta$ as inputs, ω_i becomes:

$$\omega_i = \text{AND}\ [\mu_1(\theta),\mu_2(\Delta\theta)] = \mu_1(\theta)\times\mu_2(\Delta\theta) \qquad (2)$$

Where μ_1 and μ_2 are input membership functions and "$\times$" is a multiply operator.

B. Simulation Stage

The controller consists of two independent controllers whose outputs are mixed to form the final output. The mixing operation can cause the performance of each controller to decline. So, it is essential to optimize and match them together as a single controller.

In this step of the design, a mathematical model of the crane is used to evaluate the first hand controller. In order to have a close model of the crane, a model of the experimental crane is needed. The model of the motor and its driver has been extracted in position control subsection of part A, section three. The model of the trolley and the load is derived from (3) describing the dynamics of the crane [9]:

$$\ddot{\theta} L + \beta \dot{\theta} \left|\dot{\theta}\right| + \ddot{x} \cos\theta + g \sin\theta = 0 \qquad (3)$$

Where θ is the sway angle of the payload, x is the position of the trolley, β is the damping factor, L is the cable length and g is the gravity. This equation shows how the load angle can be acquired from the acceleration of the trolley. Based on this evaluation, the Controller is optimized. Since simulation takes much less time to be performed, this can be an ideal way to optimize the controller. Simulation is performed by means of Mathworks' MATLAB SIMULINK software, being a suitable one for this case. Simulation results of the optimized controller are presented in results section.

C. Computer-Aided Control Stage

As the controllers of position and sway have been successfully designed and their performance has been optimized as a single controller in previous stages, the next target is to test this controller and optimize it on an experimental model. This stage is essential in designing a successful controller for a crane, since there are always differences between a model and a real setup. The experimental setup is described afterward and the controller implementation in computer proceeds.

1) Experimental Setup

To test the controller in a real experiment, an experimental model was built. This model was a 2-spare gantry crane used in one direction in experiments. The movement of the trolley in each direction was controlled by a DC servomotor driven from its relevant driver. The angle of the load was read by a high resolution encoder in each direction. The position of the trolley was extracted from the motors' encoders. This model is shown in Fig. 2.

An interface system was made to gain the information of the crane and send the commands to the motors. Six microcontrollers were used as the required interface in a master-slave connection to collect position and angle data and transfer them to a PC. An Advantech PCI-1710 DAQ (Data Acquisition) card was used to transfer the gathered information from the crane to the computer and, on the other hand, to produce a desired analog voltage as a command for the motors. A zero and span circuit was then used to change the analog voltage of this card to some appropriate voltage range.

2) Controller structure

After the simulation phase, a real time control of the crane was performed by using SIMULINK in a real time mode (RTW) with one millisecond time step. The proposed controller was implemented in the computer as before but, the information fed to this controller was read from a DAQ card. The card read one byte at a time and since any data block was considered to be a two-byte value, thus, it was necessary to read eight times from the card to reconstruct the information in the computer. This caused the command, formed by the controller, to be updated every eight milliseconds. This command was sent to motor drivers via the DAQ card and the zero and span circuit.

The experiments show that if the acceleration of the motors is kept below a determined value, a much smoother movement is achieved, at the cost of very little extra time. Since smoother movement of the trolley leads to lower induced load angle, an acceleration limiter block is added to the final command. The smooth movement also avoids unwanted shocks to the system, which is another advantage of using an acceleration limiter block.

Fig. 2. The model crane

After optimization, the PID gains are:

$K_p = 1.2$, $K_i = 0.0035$, $K_D = 0.5$.

The fuzzy controller specifications, after being optimized, are shown in Figs. 3 and 4.

D. Stand Alone Control Stage

The purpose of the final step is to shift the proposed controller from MATLAB environment to an industrial microcontroller.

In order to switch from computer to a microcontroller, one needs to replace the easy-to-use blocks of SIMULINK with codes acting similar to them. The codes can be used later analogously on a microcontroller chip. This is done by employing S-Functions of MATLAB, instead of its predefined blocks. Every S-Function needs a code to perform its predetermined job. This mid-step helps a lot to minimize the rate of the errors while transferring the design into some codes.

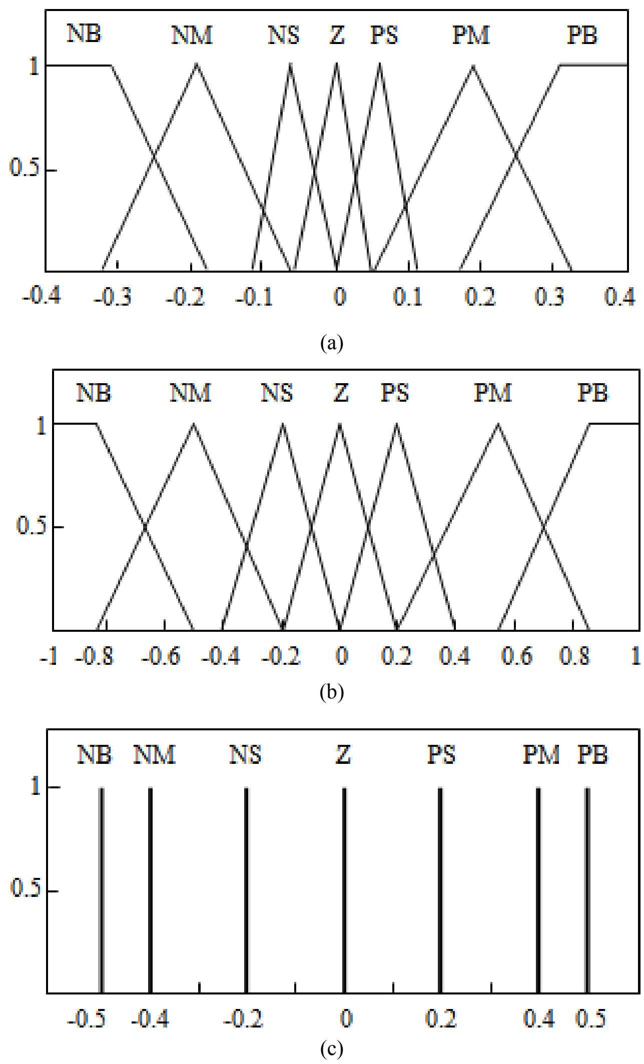

Fig. 3. Fuzzy membership functions: a)Angle input b) Angle rate input c) Output

An ATMEGA16 microcontroller from AVR Family is used to control the crane. This microcontroller takes the reference position, the trolley position, and the load angle as its inputs and leads the crane to the predetermined location with minimal load sway. This chip is selected for this application because of its availability, low price, and high performance. Computer is still in use in this stage but, just for monitoring and no control purpose. Not much difference is seen between the results of the crane control by computer and those of this microcontroller. This success is mainly due to the use of SIMULINK S-Functions. Since there is no significant difference between the results of this controller and those of the computer-based one, the results of this stage are not reported.

IV. RESULTS

The output results of the controller in different stages of designing are shown and compared with other works. Then, based on the experimental results, the robustness of the controller is confirmed.

A. Simulation and Experimental Results

The results of parts A and B of section three demonstrated in Figs. 5 and 6. Since the results of the final stage match with those of part C of section three, it is not shown in the figures.

$\Delta\theta$ / θ	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NM	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB

Fig. 4. Fuzzy rule base

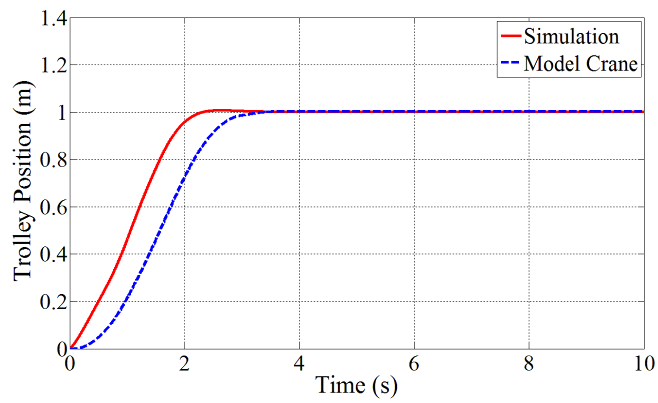

Fig. 5. Position results of simulation and model crane

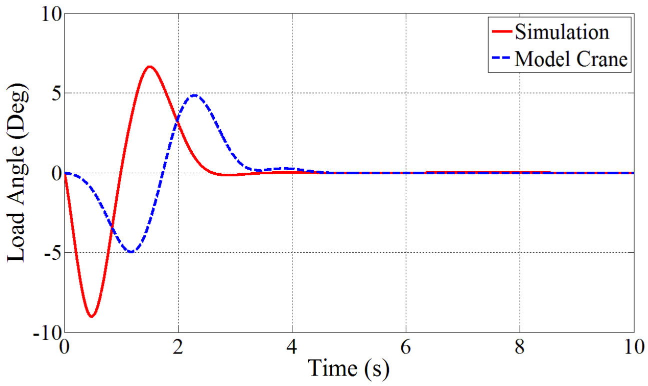

Fig. 6. Load angle results of simulation and model crane

The smoother movement in experimental results is obvious in both figures, as a consequence of using an acceleration limiter. It can be inferred from the results of the experimental model that the controller is capable of suppressing the load angle within 1.45 seconds, after the trolley has reached the predetermined place. The results are far better than previous works. Wahyudi et al. in 2007 proposed a controller that could suppress the load sway in 3.8 to 6.7 seconds, with different positions [6].

In this experiment, the trolley could be moved at a high speed (0.5 m/s), almost three times faster than Wahyudi's model. The cable length of the model used in this experiment is also longer than that of their model [6]. It can be inferred from these facts that the model used in this work was harder to control. Despite the hard conditions, the controller proposed in this work surpassed the results of the previous controllers, designed by Wahyudi et al.

B. *Robustness Evaluation*

The performance of controllers can be investigated from several facets. One of the most important features of a controller is its robustness. The proposed controller is tested with different cable lengths (100±33% of the normal length). This change of cable length leads to a change in sway frequency. The test results are shown in Fig. 7.

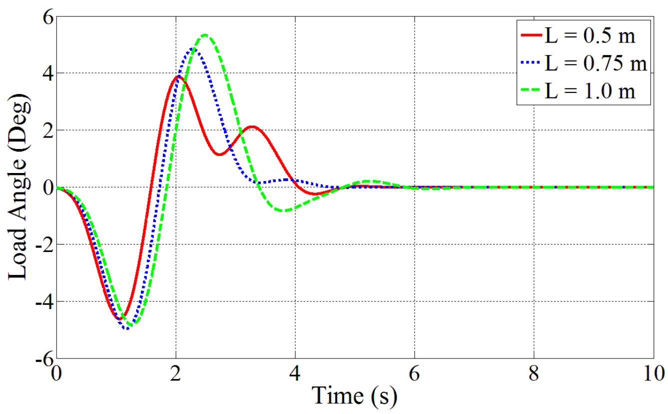

Fig. 7. Load Angle Results with different cable lengths (L)

From the figure, it can be seen that the performance of the controller declines slightly, but it still is good enough to be in use. More deviation from the normal length needs an adaptation in the fuzzy controller output.

V. CONCLUSION

A new anti sway controller for gantry cranes is proposed, using a fuzzy logic controller. A four step designing procedure is taken to fast and successfully come up with this controller. The controller has several benefits over the previous designed controller. It can faster control the load sway by a single microcontroller and work with different cable lengths, while using the proposed steps any change to this controller is feasible.

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