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# Design of an Electric Power Controller for the Control of a Crane-Bridge, Used to Download Containers, with Fuzzy Logic

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**Abstract:** This paper presents the design of an electric power controller for the control of a motor being used to move the head of a crane-bridge. Crane-bridges appear in all commercial ports in order to upload and download containers from/to ships. The movement of the containers is implemented through the movement of the head of the crane-bridge, assisted by a motor. The speed of the crane head is controlled via the control of the electric power of the motor. The classical PID controller was applied but it had reduced performance due to the non-linear dynamic behavior of the motor. That is why this paper suggests the design of an electric power controller that is based on Fuzzy Logic, in order to achieve faster disturbance rejection, like the wind shots that make the movement of the containers more complicated. The Fuzzy Logic Controller offers an improved speed control, proving the advantages of this type of controllers in the control of non-linear systems.

## 1 Description of the natural system

In all commercial ports, and also large storing facilities, big crane-bridges are being used to upload and download containers from/to ships and special trucks. These crane-bridges receive containers through flexible cables that are attached to their “head”. The head of the crane-bridge is a lifting system that consists of whips and whims and moves on steel rails with the assistance of an electric DC motor. A crane-bridge of that type is given in the following representation, fig. 1.

When a container is being uploaded, the crane head starts to move and the container begins to sway. While sway of the container comprises no problem during its transport, a swaying container cannot be released on a truck or a ship. Two trivial ways to solve this problem exist. One is to wait exactly over the target position until the sway dampens and the other to move the container with small velocity. Unfortunately both of them are time-consuming. Another alternative is to adjust additional cables to the crane-bridge in order to keep the position of the container stable. This solution is also avoided due to the high cost of the whole system and is applied in limited crane-bridges.

Instead of these solutions, it is common practice to apply continuous speed control of the motor and its load, meaning the container. An experienced crane operator compensates for the sway of the container, while at the same time he tries to make sure that the container reaches its target in a short time. A conventional three-term PID (Proportional Integral Derivative) controller has been applied in several cases (small number of crane-bridges in the commercial port of Thessaloniki) for the speed control of the container, but it had limited effectiveness.

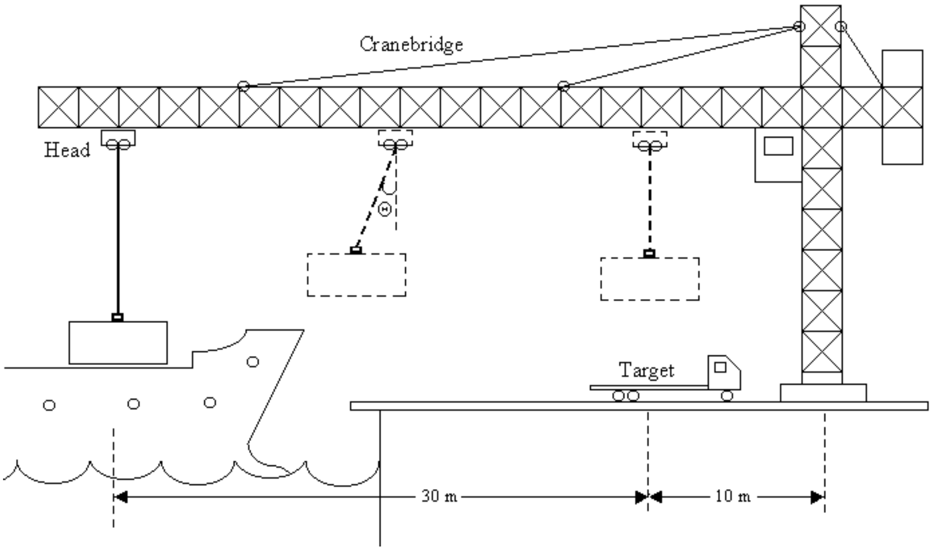


**Fig. 1.** Draft of a typical crane-bridge

The main disability of the PID controller derives from the nature of the control problem. The system is highly non-linear, since only when the container reaches its target position, it is important to minimize its sway. Furthermore, any attempt to create a mathematical model of the natural system is very difficult for various reasons: a) the dynamic behavior of the motor is far less linear than assumed in the model of the natural system b) the crane head only moves with friction c) no disturbance inputs are included in the model such as wind gusts.

On the other hand the operator of the crane-bridge can control the speed of the container, without using any differential equations. When the container is uploaded, then the operator of the crane starts the motor with medium power, to see how the container sways. According to the reaction of the container, he regulates the power of the motor, so that the container gets a little behind the crane head. In this position maximum speed can be reached with minimum sway. While the container reaches its target, the operator reduces the power of the motor, or even applies a sort of braking system (that can also be regarded as negative mechanical power provided by the motor to the load). That action leads to the forward movement of the container, slightly ahead of the crane head, and it continues until the container reaches its desired position. At that point the electric power of the motor increases momentarily, so that the head of the crane-bridge is right above the target without any sway.

So, some of the basic control rules derive form the operators experience. A list of these rules is given below:

1. Start the movement of the crane head with medium power.

2. If the distance from the target is big, adjust the power of the motor, so that the container gets a little behind the crane head.
3. If the distance from the target decreases, then reduce the velocity of the container so that it gets slightly ahead of the crane head.
4. When the container is very close to the target, increase the power of the motor.
5. When the container is right above the target and the sway is zero stop the motor.

Of course these rules can be further analyzed, if this is necessary.

## 2 Selection of the structure of the control system

Using the control systems theory, first, an effort will be made to determine the structure of the speed control system for the electric motor that moves the crane head. When designing a control system there are two basic features that need to be fulfilled: a) the control system must be able to monitor the reference input b) the control system must be able to reject unwanted disturbances. In reality though, these features conflict with one another and is very difficult to satisfy both of them at he same time. So at first, the design of the control system focuses on the disturbance rejection and then continues on to the efficient monitoring of the reference input. In praxis, it proves that is quite easy to accomplish the monitoring of the reference input, by using an appropriate input filter. The rejection of disturbances can be accomplished by using negative feedback.

The next step will be to determine all the variables that need to be measured and controlled. As input of the system R(s), the distance between the relative position of the crane head and the target is chosen, S[m], and as output of the system Y(s), we choose the rounds per minute, ω [rpm] of the motor. In reality though, a natural system has more inputs than originally suspected such as noises and disturbances. Noises are signals of high frequencies that originate from the electronic circuits that are being used by the control system, and disturbances are signals of low frequencies that are created due to the changes of the load of the natural system. For the disturbances, we use the general symbol D(s). For the system in study, D(s) expresses the angle between the cable, which is used to upload the container, and the crane head.

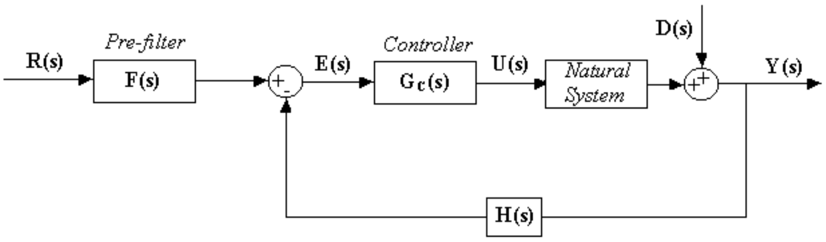


**Fig. 2.** Block diagram of the natural system

Finally the control system results to a general SISO (Single Input Single Output) system with unity negative feedback that has an additive input D(s), the disturbance. The structure of the system is given in the representation above, fig. 2.

The controller of the natural system with the input filter makes up a so-called *2- degree-of-freedom* controller.

## 3 Selection of the controller

The number of inputs of the system has been specified in two, the “Distance” S[m], as input R(s) and the “Angle” Θ[degrees] as disturbance D(s). The controller will have these two inputs and only one output U(s), the electric power of the motor, “Power” [KW]. Furthermore if we make the assumption that the dissipations of the DC motor are nearly close to zero, then the electric power of the motor can be considered nearly equal to the mechanical power that is supplied to the load of the motor:

$$\mathrm{Pe} \cong \mathrm{Pm} = c \cdot \varphi \cdot \omega \cdot i_a \qquad \textbf{(1)}$$

Where c = constant, given by the manufacturer of the motor, φ = magnetic flux of the motor, ω = rounds per minute (rpm), $i_a$ = armature current. Also the motor is considered to operate with nominal power.

There are two possible routes to follow when designing the controller. The first one is to select conventional control design methods. In the beginning, an estimation of the step response of the natural system or process takes place, and then an identification of the system and the finding of a fit prototype. At the end, a three-term PID controller is designed, using the Ziegler-Nichols methods. This design approach has been tested in several field cases but it has been proved that far away from the predefined set point the linear PID controller no longer worked as a human operator.

That is why non-conventional control design methods have been selected, in order to design a fuzzy controller, using MatLAB 5.3.1® by MathWorks Inc and Fuzzy Logic & Simulink Toolboxes®.

## 4 Designing the fuzzy logic controller

The goal is to design a robust controller that is described by simple linguistic rules using human experience in order to achieve optimal control of the system.

Since all inputs and outputs of the controller have been specified, then their fuzzification will take place. Input 1_(Distance)x1 will be defined by five linguistic variables while three linguistic variables will be used to define variable Input_2(Angle)x2.

The linguistic variables for the first input (Distance) are:
*ND* = (Negative Distance)
*VSD* = (Very Small Distance)
*MD* = (Medium Distance)
*LD* = (Large Distance)
*VLD* = (Very Large Distance)
For the second input (Angle) are:
*NA* = (Negative Angle)
*MA* = (Medium Angle)
*PA* = (Positive Angle)

The output U(Power) u is finally defined by the following 5 linguistic variables:
*VNP* = (Very Negative Power)
*NP* = (Negative Power)
*MP* = (Medium Power)
*PP* = (Positive Power)
*VPP* = (Very Positive Power)

The shape and the range of values of the reference hyperset for each input and output variable is selected using the draft of the crane-bridge on fig.1. For Input 1_(Distance)x1 a differential reference hyperset is chosen ranging from –10 to 30, [-10,30]. Minus (-) is used only for quality reasons, to describe the distance between the target and the crane-bridge tower. Input_2(Angle)x2 is assigned a symmetric reference hyperset ranging from –30 to 30, [-30,30]. Also here plus (+) is used to define the movement of the container as positive, when it gets a little behind the crane head and minus (-) when the container gets ahead of the crane head. The values of “Angle Θ [degrees]” range only from –30 degrees to 30 degrees because any value of the angle, that is greater than this limit, will lead to the disaster of the cable, which is used to upload the container. Finally output U(Power) is also assigned a symmetric reference hyperset that ranges from –30 to 30, [-30,30]. The negative values of power are used to signal the reduction of the power of the motor, when applying the breaking-system. On the other hand positive values of the power of the motor suggest that the power is increasing, so as the speed of the moving container.
The next step in the design of the fuzzy controller is to define the linguistic rules of control. For the speed control of the container fifteen rules have been chosen and they are given below:

$R^1$: *If (Distance_s[m] is ND) and (Angle_θ is NA) then (Power_[KW] is PP)*
$R^2$: *If (Distance_s[m] is ND) and (Angle_θ is MA) then (Power_[KW] is MP)*
$R^3$: *If (Distance_s[m] is ND) and (Angle_θ is PA) then (Power_[KW] is VNP)*
$R^4$: *If (Distance_s[m] is VSD) and (Angle_θ is NA) then (Power_[KW] is PP)*
$R^5$: *If (Distance_s[m] is VSD) and (Angle_θ is MA) then (Power_[KW] is MP)*
$R^6$: *If (Distance_s[m] is VSD) and (Angle_θ is PA) then (Power_[KW] is NP)*
$R^7$: *If (Distance_s[m] is MD) and (Angle_θ is NA) then (Power_[KW] is PP)*
$R^8$: *If (Distance_s[m] is MD) and (Angle_θ is MA) then (Power_[KW] is MP)*
$R^9$: *If (Distance_s[m] is MD) and (Angle_θ is PA) then (Power_[KW] is NP)*
$R^{10}$: *If (Distance_s[m] is LD) and (Angle_θ is NA) then (Power_[KW] is PP)*
$R^{11}$: *If (Distance_s[m] is LD) and (Angle_θ is MA) then (Power_[KW] is PP)*
$R^{12}$: *If (Distance_s[m] is LD) and (Angle_θ is PA) then (Power_[KW] is MP)*
$R^{13}$: *If (Distance_s[m] is VLD) and (Angle_θ is NA) then (Power_[KW] is VPP)*
$R^{14}$: *If (Distance_s[m] is VLD) and (Angle_θ is MA) then (Power_[KW] is PP)*
$R^{15}$: *If (Distance_s[m] is VLD) and (Angle_θ is PA) then (Power_[KW] is MP)*

These rules can also be viewed in a more compact form, if they are put in a matrix form, table 1:

**Table 1.** Linguistic rules of the fuzzy controller

| X2 / x1 | ND | VSD | MD | LD | VLD |
|---|---|---|---|---|---|
| NA | PP | PP | PP | PP | VPP |
| MA | MP | MP | MP | PP | PP |
| PA | VNP | NP | NP | MP | MP |

The shape of the fuzzy sets for each variable used as input and output and the degree of participation of each rule ($\sigma_j$) in the final decision of the controller, is selected by using the FIS Editor of Fuzzy Logic Toolbox®. For Input 1_(Distance)x1 a combination of trapezoidal and triangularly sets is chosen and for Input_2(Angle)x2 gaussian sets. The output U(Power) is described also by a combination of trapezoidal and triangularly sets. These selections are available through the dialog box Edit Membership Function and are shown in fig. 3., fig. 4. and fig. 5.

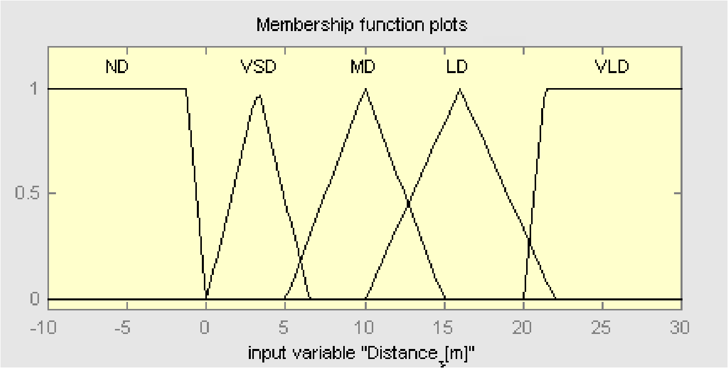


**Fig. 3**. Fuzzy sets of first input

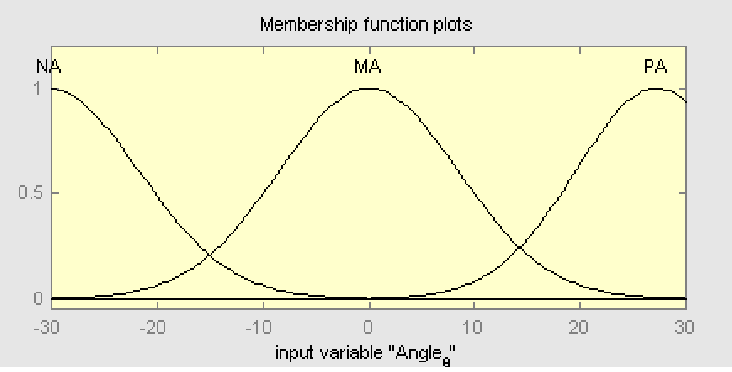


**Fig. 4.** Fuzzy sets of second input

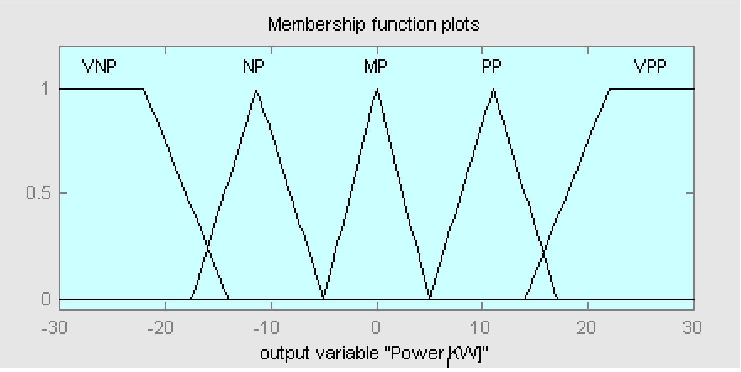


**Fig. 5.** Fuzzy sets of output

The next step is to study the affect of the shape of the sets on the control surface. The control surface is a visualization of the commands of the controller and is the result of the combined selection of fuzzy sets and control rules. Because there is no way to ensure that the selection of fuzzy sets for each variable is the optimal one, without using some method of optimization such as genetic algorithms, one can only experiment with different fuzzy sets. But even then, an optimal set is difficult to define. For this controller design, various sets have been applied but had a minimum affect on the control surface. That leads to the conclusion that the control surface is more affected by the control rules that were selected than of the shape of the fuzzy sets. The control surface is given in fig. 6.

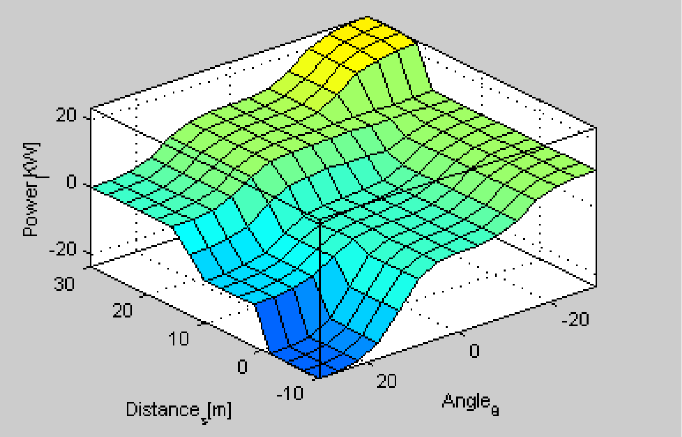
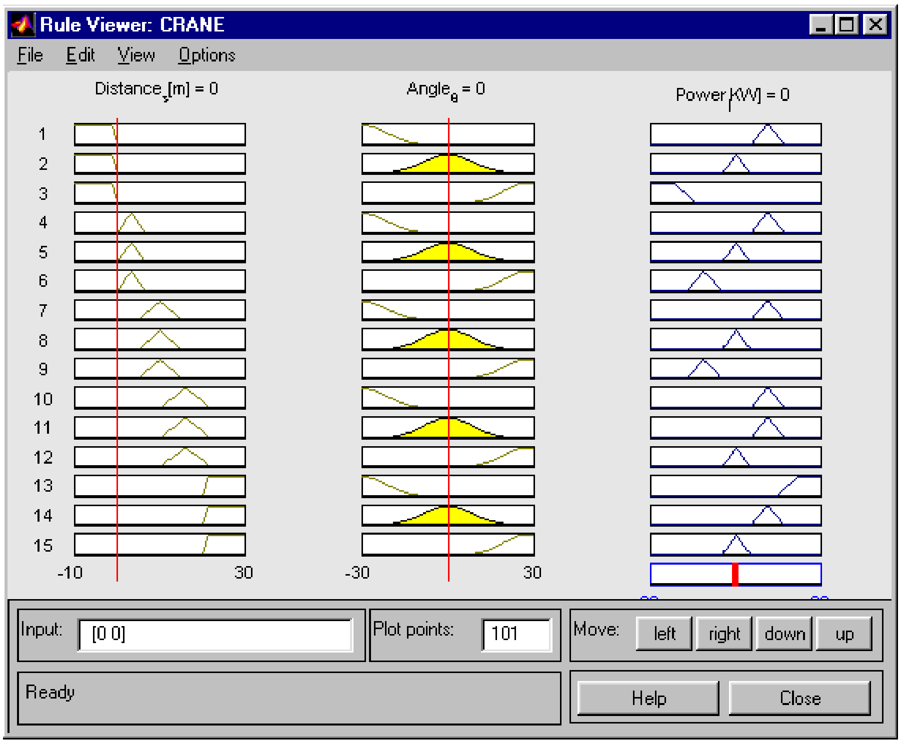


**Fig. 6.** Control surface of the fuzzy controller

The specification of the surface control was done using the Mamdani entailment and the defuzzification of the output was specified using the COG (Center of Gravity) method.

## 5 Checking the operation of the controller using MatLAB/Simulink

The operation of the fuzzy controller can be checked using the Rule Viewer screen.



Distance [m] = 0

Angle$_\theta$ = 0

Power [KW] = 0

Input: [0 0]

Plot points: 101

Ready

**Fig.7.** Rule Viewer

On this screen available on the FIS Editor, it is possible to test the function of the controller giving certain values of "Distance" and "Angle" and obtaining the response of the controller U, through the values of the output "Power". The Rule Viewer screen of the system is given in the above figure, fig. 7. The result of the output for five different sets of inputs is given on table 2.

**Table 2.** Output test results

| Distance [m] | Angle [Θ] | Power [KW] |
|---|---|---|
| 0 | 0 | 0 |
| 30 | 30 | 0.0518 |
| 30 | -30 | 23.9 |
| -10 | 0 | -0.0818 |
| -10 | 30 | -23.8 |

The simulation of the system is done using MatLAB/Simulink. The mathematical model of the system consists of built blocks that represent the DC motor, the tacho-generator, integrators and other subsystems. The block diagram is given in fig. 8.

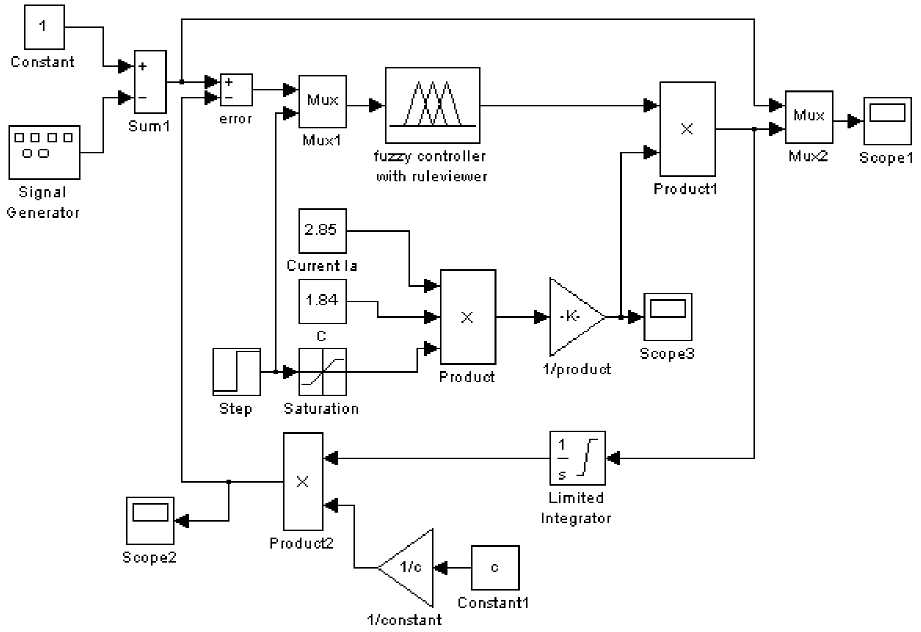


**Fig. 8.** Simulink block diagram

The step response of the system in Simulink has the following shape, fig. 9.

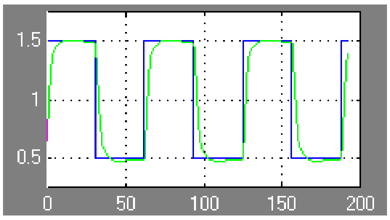


**Fig. 9.** Step response of the system in Simulink

The steady state error is small and the overshot is minimized. So, the simulated system displays an improved dynamic behavior without any unwanted oscillations.

## 6 Implementation of the controller

The fuzzy logic application can be implemented using a variety of target hardware platforms. These range from low-cost-8bit controllers, for simple applications, to programmable logical controllers (PLCs) and distributed control systems (DCSs). PLCs have standard interfaces to sensors and actors and support standard field bus. Furthermore, Siemens, which is one of the biggest manufacturers in industrial automation, offers a series of PLCs such as *SIMATIC S7-300*® and *SIMATIC S7-400*®, that offer high-level language programming in structured programming languages such as C. These PLCs can use a fuzzy logic pre-compiler that generates the system as C code and implement the code on the PLC. For these PLCs exist also, special fuzzy logic function blocks through a powerful programming environment. *Fuzzy Control++* ® is such a configuring tool that can be used to design the fuzzy controller for the crane-bridge. The development of the controller, using the fuzzy logic function block does not require any code generation. The *Fuzzy Control ++*® provides all the necessary tools for the fuzzification of the inputs and output, the setting of the linguistic rules, and the defuzzification of the output.

When the design of the fuzzy controller is completed then the PLC can be linked to the PC, which will monitor the control strategy, and can be downloaded as standard PLC programs (ladder diagram, instruction list, function block diagrams). The following fig.10 displays a PLC based fuzzy controller.

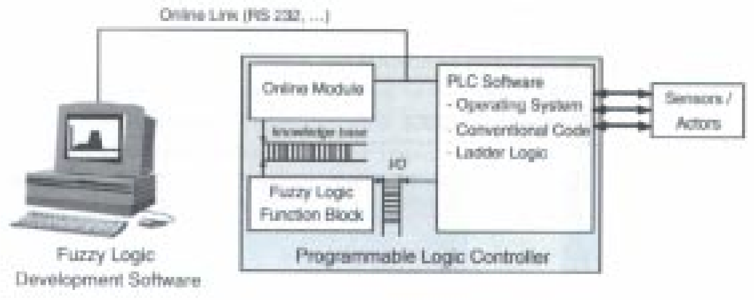
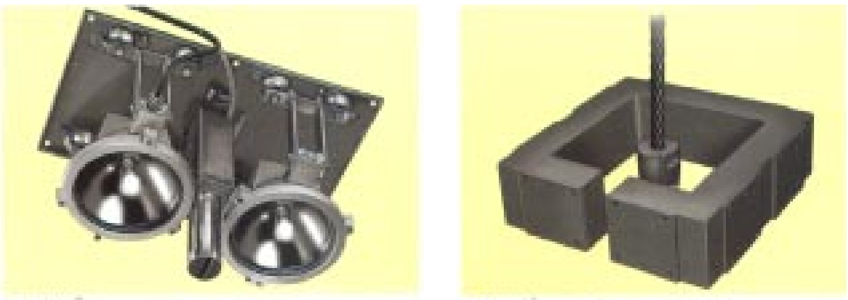


**Fig. 10.** A PLC that can implement the fuzzy controller

The input signals of the fuzzy controller are the outputs of the appropriate sensors. Distance can be measured using any proximity sensor, but the final selection depends on the desired resolution, range of measured values, the desired output of the sensor, analog or digital etc. The angle of the cable can be measured with a swing angle sensor. Siemens has developed such a sensor, especially designed for cranes and crane bridges,, under the name HIPAQ®. This system offers two technical solutions, the OPTOMAT D® line camera and the VEROSWING® measuring frame.

The OPTOMAT D® line camera, comprises a line camera with spotlights and is installed under the trolley. Fitted to the right and left of the camera are two halogen spotlights. These beam download, intensively illuminating the reflector situated on the load lifting equipment. The triple reflector of the load lifting equipment reflects the light directly to the camera. The deflection angle of the load is thus determined via an image evaluation computer integrated in the camera. The swing actual angle value is output as 4 to 20 mA signal. Fig. 11. displays the OPTOMAT D® line camera. The VEROSWING® measuring frame is also fitted under the crane trolley. Then



OPTOMAT D® line camera

VEROSWING® measuring frame

**Fig. 11.** The OPTOMAT D$^{®}$ line camera and the VEROSWING$^{®}$ measuring frame

one of the stationary cables of the crane goes through the frame. A magnet is fixed to this cable at the height of the frame. The frame contains Hall – effect sensors which register the movement of the magnet and, therefore, of the cable within the frame. Fig. 11. also displays the VEROSWING$^{®}$ measuring frame.

Finally appropriate interfaces for the input and output signals of the fuzzy controller may be required, depending on the type of measured and acting signals, analog or digital, amplitude, signal conditioning etc.

## 7 Fuzzy logic controllers in industrial automation

Many industries in the last 15 years have adopted fuzzy logic, integrating conventional methods of control, such as PID controllers and fuzzy logic. Applications cover a wide range of control problems including fuzzy control of motors and hybrid controllers based on PLCs and microcomputers. Reference [19] shows how fuzzy logic control can be employed to optimize the energy efficiency in AC motor variable-speed control, while reference [20] shows a flux and torque control by fuzzy logic direct self-control. NASA has also developed a fuzzy logic system for the control of its Mach 6 wind tunnel. The fuzzy logic solution, that they have implemented, runs on an i486 board controlled by a master PLC and delivered very satisfactory results in tunnel preheating and temperature control in operation (see reference [21]). Unfortunately in Greece only a small number of fuzzy control systems has been developed and installed, mainly because of lack of valid and accurate information on fuzzy logic and its application.

## 8 Conclusions

This paper presents the design methodology of an intelligent controller for the control of natural systems and processes with Fuzzy Logic. The main goal of this controller is to operate as good as a human operator, with the same control rules that derive from the human's knowledge and experience of the process that he supervises. Furthermore this controller must be able to compensate any variations of the process variables and to restore the process to its desired state without the intervention of the operator. One of its main advantages is that although the problem was formed using conventional-control design requirements (for a given process P, design a controller C, that meets the design requirements R) the designed controller was not based on the mathematical model of the process. That allows it to operate regardless from the process model, linear or non-linear. In contrast the 2 or 3 terms PI (Proportional Integral) or PID, industrial controllers satisfy the control requirements only around a predefined point of operation. Another advantage is that disturbances are taken in to account, as the second input of the system. The usage of fuzzy logic in order to solve certain control problems is only the first step. In a bigger application a hybrid neuro-fuzzy controller can be designed to control the speed of the container. In this case the fuzzy controller will operate “on line” or “off line” to provide real numeric data of the control of the operation, that will be stored in a real-time database. After the appropriate training of the neural controller it will co-operate with the fuzzy logic controller in order to achieve further optimization of the dynamic behavior of the process, combining the advantages of both type controllers.

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