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A Fuzzy-Logic Controller for an Electrically Driven Steering System for a Motorcar

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This paper presents an application where a Fuzzy-Logic Controller (FLC) is used at a supervisory level to implement mutual coordination of the steering of the two front wheels of a motorcar. The two front wheels are steered by two independent discrete time state feedback controllers with a view to optimize the steering slip angles. The functions of the two controllers are tied together by way of a FLC. Because of the presence of unmodelled dynamics and disturbances acting on the two sides, it is difficult to achieve the desired performance using conventional control systems. This is the primary reason that FLC is emploged to solve the problem. The results show that the implemented system achieved desired coupling between the two independent systems and thereby reduces the difference between the two steered angles.

Key Words : FLC(Fuzzy-Logic Controller), Feedback Controller, PWM(Pulse Width Modulation), MATLAB System, PID(Proportional Integral Differential)

1. Introduction

Since the introduction of mathematical ways to represent vagueness in everyday life (Zadeh, 1965), there have been further development in fuzzy algorithms (Zadeh, 1968) and linguistic analysis (Zadeh, 1973) which motivated the early laboratory application of fuzzy-logic into control engineering (Mamdani; 1974, Mamdani and Assilian, 1975 ; Tong et al., 1980). Since then, fuzzy logic control theories have been applied to a variety of tasks ranging from water purification (Yagishita et al., 1985), waste water treatment (Ton et al., 1980), stirred tank reaction (King and Mamdani, 1977), cement kiln (Umbers and King, 1980) to more demanding control applications such as automobile speed control (Murakami and Maeda, 1985), aircraft flight control (Larkin, 1985), anti-lock brake systems (Madau et al., 1993) and hydraulic position servos (Zhao and Virvalo, 1993). More recently, a Fuzzy-Logic Controller (FLC) has been used in an innovative manner in an automatic train operation with predictive fuzzy control (Yasunobu and Miyamoto, 1985), in helicopter control (Sugeno, 1990) and robot control (Zhang and Zhu, 1994 ; Katupitiya, et al., 1996).

These widely reported successes in FLC applications motivated the authors to implement such a controller to a steering system which has two front wheels steered independently using electric motors. The present mechanical steering geometry cannot achieve a perfect balance between the two. As a result, it is needed to mechanically couple the two sides. The main

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aim behind the study is to achieve optimum slip angles during steering, thereby to reduce the effects of the oversteer as well as the understeer, the resulting instability and tyre wear.

A schematic diagram of the experimental system is shown in Fig. 1, which represents a front end of a motorcar. The mechanical linkage mechanism from the steering wheel to the two front wheels (such as the steering column, the tie-rods and the usual steering mechanism) was totally removed. Both sides of the wheel was steered by the two electric DC-motors through a non-reversible gear drive. The motors have their own encoders as well as tachos. Each motor is controlled by a motor drive board with Pulse Width Modulation (PWM) amplifiers on them. Each board can receive a command word of its own from a control computer. The control computer receives a common steering signal by way of an encoder mounted on the steering wheel. The on-line computer implements the required geometry for the left wheel as well as for the right wheel and then sends the modified control commands to two discrete-time state feedback controllers. The controllers then generate the commands for the motor drive boards so that the wheels can be steered. The pulse transfer functions for the left hand side as well as the right hand side have been obtained using experimental system identification. The two independent controllers are then designed for the two systems so that both of them will have identical dynamics. This has been achieved by aiming at the same characteristic equation for the two systems. However, when the steering system is implemented in the real world, they will be subjected to random load disturbances and unmodelled dynamics. As a result, it is necessary to couple the control of the two sides together so that the wheels will always be steered in step with each other. This is the reason that a FLC has been employed and implemented. The purpose of the FLC in this paper is to control the turning angles of the two road wheels based on the difference between the measured angles of the two wheels and the rate of the change of the difference between the two measured angles. The output of the FLC is to change the gains of the two controllers on-line in real time so that the difference between the two steered angles is kept to a minimum. Note that because of the presence of unmodelled dynamics and disturbances acting on the two sides, it is difficult to achieve the desired performance using conventional control systems. This is the primary reason that FLC is emploged solve the problem. The results show that the implemented system with FLC achieved desired coupling between the two independent systems and thereby reduces the difference between the two steered angles. Shorter versions of this paper were presented in (Katupitiya et al., 1997; Lee and Katupitiya, 1996).

The remainder of the paper is organized as follows. In Section 2, the experimental system set-up and the procedure of the state feedback controller design are presented. Fuzzy logic controller design procedures are presented in Section 3 and the results are described in Section 4 followed by Conclusions in Section 5.

2. Experimental System Set-Up and State Feedback Controller Design

Figure 1 shows a schematic diagram of the physical system. The non-reversible gear drive at two wheels ensures that the motor will steer the wheel and under any circumstances, the wheel can turn the motor. The front end of the vehicle being used has a McPherson strut configuration so that the steering has to be done about an axis, which coincides with the axis of the suspension strut. Each motor has its own encoder and tacho. The tacho signals are interfaced to the control computer through the analog inputs and the encoder signals are interfaced to the control computer through the quadrature counters on the interface board. The two motors are driven by two PWM amplifiers on two independent motor drive boards. Each motor drive board receives its own command containing the information on the direction and the amount of rotation.

Figure 2 shows the two independent digital controllers for the two side wheels. Both of them receive a common input from the encoder mounted on the steering wheel. This signal is

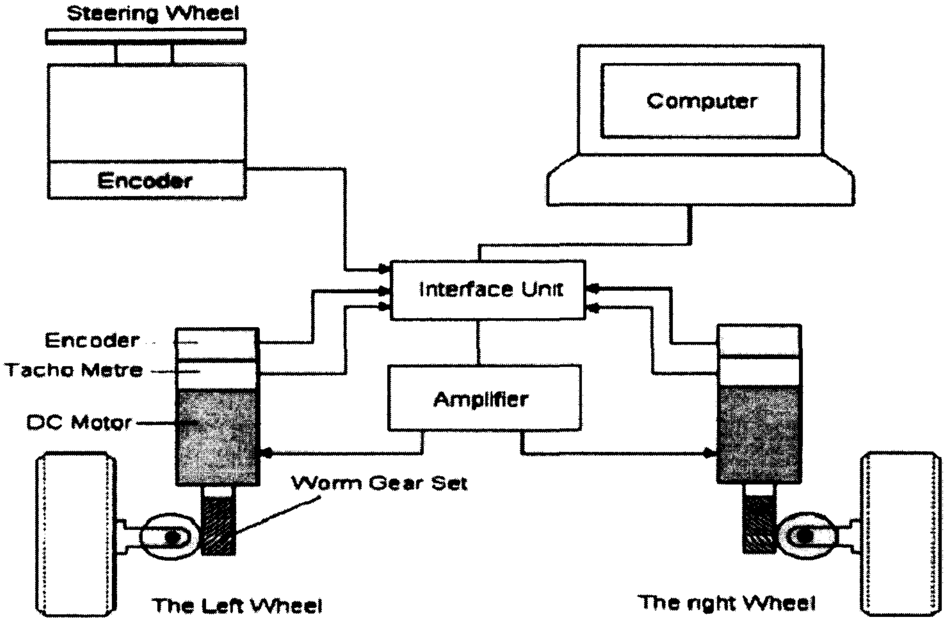


Fig. 1 The schematic diagram of the physical system

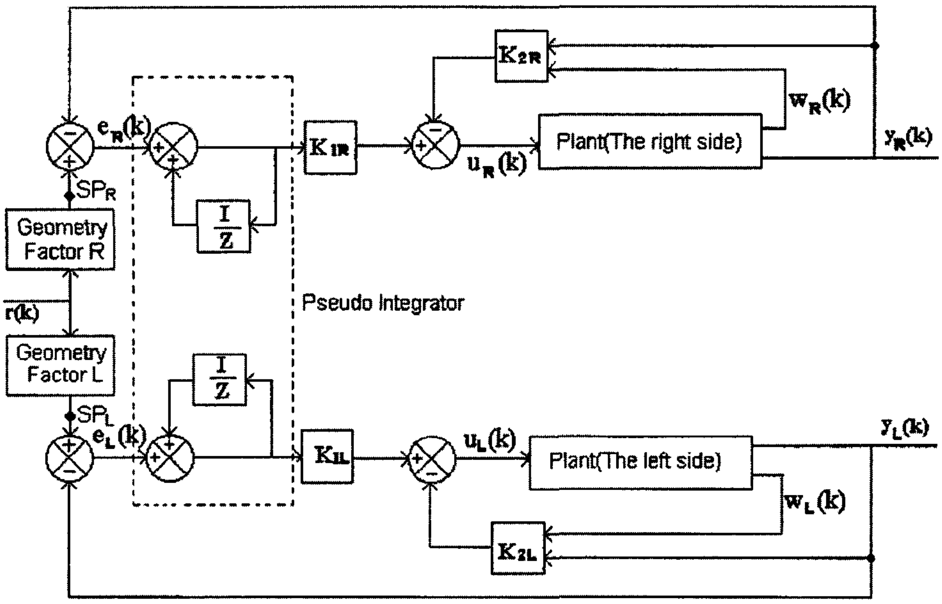


Fig. 2 The system block diagram of the state feedback controllers without fuzzy logic implementation

interfaced to the control computer via the third quadrature counter on the interface board. The control computer itself implements the steering geometry to the incoming steering signal to form two different steering signals, one is called the left steering signal and the other is called the right steering signal, which are meant to drive the two independent controllers.

To design a discrete-time state feedback controller, it is necessary to identify the systems for both the left hand side and right hand side systems. To do that, both systems are randomly excited using a pseudo random binary signal of sufficient strength to cover the full angles of operation of each wheel. The responses at the tachos as well as the encoders were recorded, all with a sampling time of 10ms. The input and output data obtained were related using MATLAB System Identification Toolbox using a least squares method. Parametric models were obtained using mathematical modelling of a permanent magnet DC servomotor driving a mechanical load (Ogata, 1990). The two pulse transfer functions obtained as follows:

Left hand side:

$$G_{PL}(z)=\frac{38.7046(z+0.1035)}{(z-0.9676)(z-0.0389)},$$

Right hand side:

$$G_{PR}(z)=\frac{41.6825(z+0.1986)}{(z-0.9905)(z-0.3009)}.$$

Plots shown in Fig. 3 were obtained to show the validity of the models. The solid line shows the measured response while the dotted lines show the responses from the above two pulse transfer functions for the same input. As can be seen, there are unmodelled non-linearities in the system. This is especially noticeable on the left hand side. The implemented controller is a simple integral controller (Ogata, 1990).

Each controller will have its own integral gain as well as the state feedback matrix. Both controllers were designed to have the same characteristic equation of

$$z^2(z-0.3)=0$$

which gives a first order response with a time constant of 8.3ms with two delays. The integral gains and the state feedback matrices for the two systems are given by

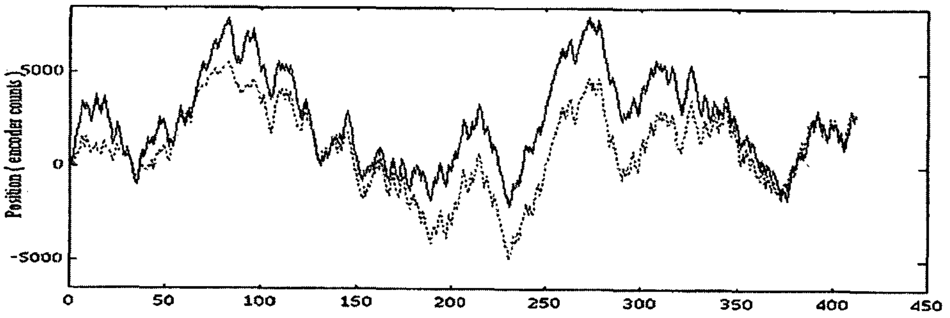
Left hand side:

$$K_{1L}=0.0163 \qquad K_{2L}=[1175.379 \quad 19.637],$$

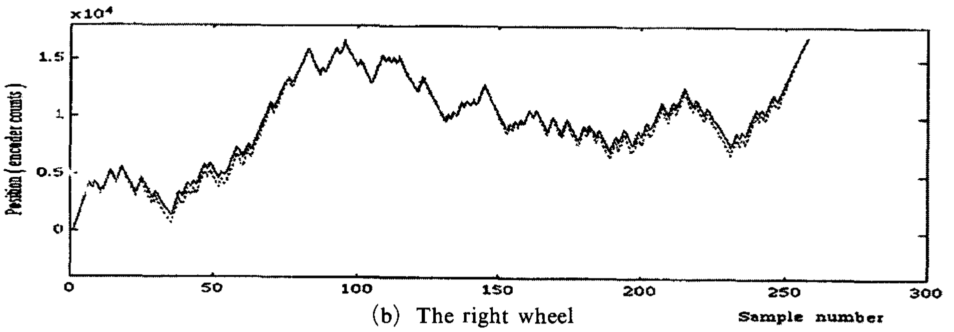
Right hand side:

$$K_{1R}=0.0185 \qquad K_{2R}=[473.0727 \quad 15.6534].$$

To show the difference in the response of the two systems, the step input has been applied into



(a) The left wheel



(b) The right wheel

Fig. 3 Simulated output of the model compared with the measured output (Solid line : measured output, dotted line : model output) them. The responses of individual controllers are shown in Fig. 4. As can be seen, although the two systems were theoretically designed to behave in a similar manner, even without any additional disturbances, they do not behave identically, especially because of unmodelled effects such as non-linearities, static friction, etc. To highlight the problem, Fig. 5(a) shows the differences

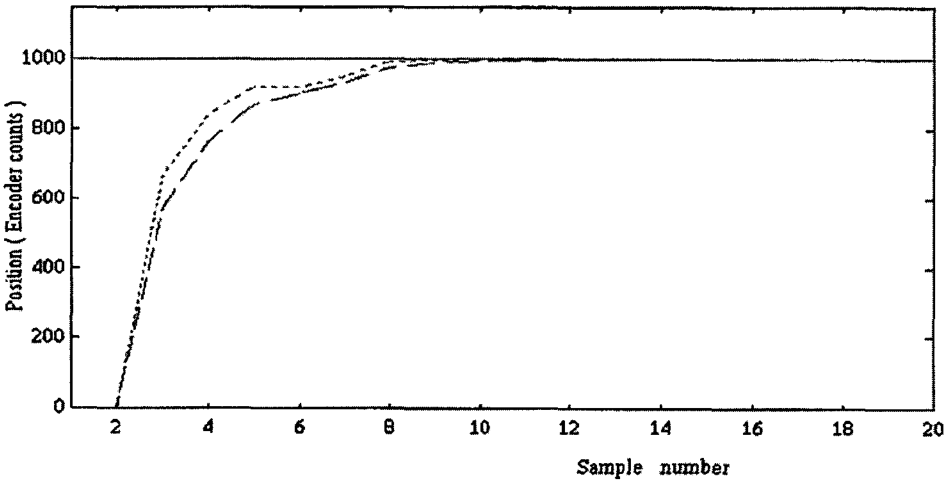
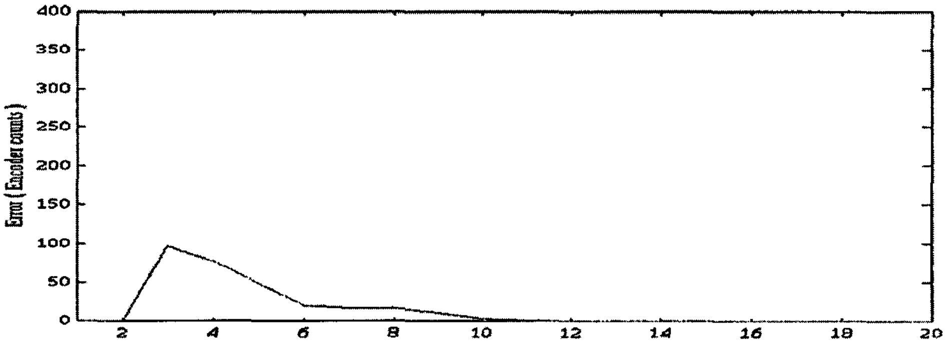
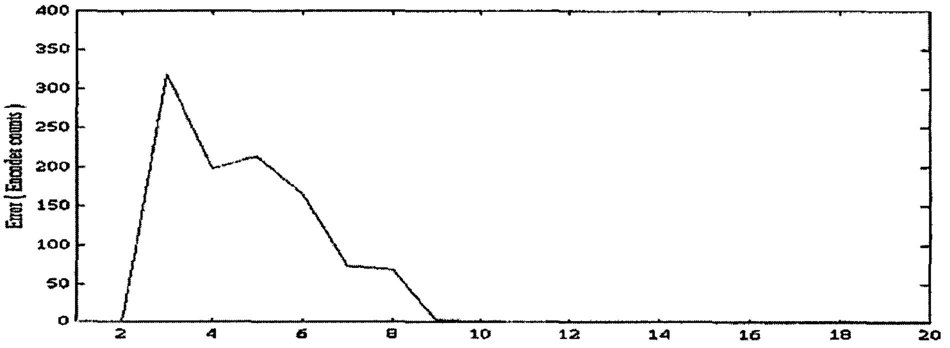


Fig. 4 The step response of individual controller (Solid : step input, dotted line : right hand side, dashed line : left hand side)



(a) Withou load



(b) With load

Fig. 5 The encoder reading differences between the left and the right hand sides in response to a common step input (comparison between with load and without load) between the left hand side encoder and the right hand side encoder during the move. The deviations shown in this curve get much worse, if one of the sides is subjected to a disturbance signal in the form of an additional load on that side (see Fig. 5(b)). Hence there is a need somehow to coordinate the response of the two systems. Conventional PID controller is firstly chosen for an initial trial. However, we found that it could not provide the desired performance. This is mainly because of the presence of unmodelled dynamics and disturbances acting on the systems. This is the reason that a FLC has been emploged and implemented.

3. Fuzzy Logic Controller Design

The FLC is expected to operate at a supervisory level with the aim of minimizing the difference between the encoder values of the two sides during the transient. The final positions of the two sides will be identical at the end, due to the implemented integral controller. In other words, the FLC must minimize the deviations shown in Fig. 5.

3.1 Introduction

In a FLC, the input variables need to be grouped into bands of their values in a process called fuzzification. Rule of thumb for doing this is available in a literature (Cox, 1992). Each band is given by a linguistic variable name, for example, FAST, JUST RIGHT, SLOW, etc. The range of values that can fall within such a band is called a fuzzy set. When the value of an input variable falls within one of these ranges assigned to a linguistic variable, it will have its degree of membership within the range (fuzzy set). Generally, to represent the vagueness or inability to strictly demarcate the border between zones, they are made to overlap. Thus, a certain value of an input variable may have partial membership in one zone as well as in the adjoining another zone. In this paper, we have followed suggestions in (Cox, 1992 ; Berenji, 1991) to fuzzify the two input variables, namely, the position error (encoder values) and the velocity error (tacho values).

The second most important stage is the fuzzy-inference or the rule evaluation stage. Basically, in this paper, we use the expert's experience and knowledge method (Sugeno, 1985) to formulate the fuzzy inference mechanism. The expert's experience and knowledge are expressed in terms of a set of fuzzy rules. The control strategies can be expressed in a limited set of linguistic description rules incorporating the fuzzy conditional statements.

The final stage of a FLC is called the defuzzification. Since the controller needs a crisp value to be used in generating the control action, the linguistic decision that comes out of a decision making logic needs to be converted to a final numerical figure. Among several suggested methods (Berenji, 1991), the means of maximum (MOM) and the centre of area (COA) methods are commonly used. A good illustration of how the defuzzification works can be found in (Berenji, 1991 ; Lee, 1990). In general, the MOM method is used in applications such as risk evaluation and terrain analysis, while the COA method is used in control applications. In this paper the COA method is used.

A non essential, but an important aspect of fuzzy-logic control systems is tuning (Mamdani and Sembi, 1980). The specific area where tuning is necessary is the fuzzy-sets. One way of doing this is by the scaling of the input values, so that the input values will fall into a different fuzzy set. However, this method allows us to carry out only minor improvements (Mamdani and Sembi, 1980). To improve the performance of the controller, what is really necessary is to change the fuzzy sets themselves appropriately so that we will get the desired controller performance.

3.2 Control strategy

As described in Section 2, we have found the controller parameters K_{1L} and K_{2L} for the left hand side, and K_{1R} and K_{2R} for the right hand side. The settling time and percent overshoot, for each side, as a result of varying the controller parameters have been studied. In the results of this study, we have found that a range of effective K_1 values for both sides, which will cause some change in speed of response of the system while avoiding overshoot. However, none of the K_2 values, i.e., either K_{21} s or K_{22} s did not make significant changes in speed of response and K_{22} values were very sensitive in causing overshoot. The conclusion out of this experiment is to use the K_1 values of both sides as the outputs of the FLC. The inputs to the FLC are the difference between the two road wheel encoder values and the rate of change of the difference between the two road wheel encoder values (equivalent to the tacho values). Accordingly, the FLC will continuously monitor the two input signals and deliver the corresponding two output values, one as $K_{1L}$to the left hand side and the othen as K_{1R} to the right hand side. The fuzzy rule set will be chosen so that if one of wheels steers itself faster than the other, the FLC will slow down the faster side and speed up the slower side so that both sides will try to keep the speed of response at a same level, despite the changing and unmodelled dynamics of the two sides.

3.3 The Fuzzy controller design

A schematic diagram of the FLC is shown in the shaded area of Figure 7. The FLC has two inputs, namely the encoder value difference and the rate of change of encoder value difference, which are the same as the tacho value differences. For the encoder differences, five overlapping fuzzy sets were formed. In the ascending order of membership values, the linguistic variables assigned were Negative Large (NL), Negative sMall (NM), Zero (ZO), Positive sMall (PM), and Positive Large (PL). Also for the tacho differences, five overlapping sets were formed; Negative Fast (NF), Negative Slow (NS), Ok (OK), Positive Slow (PS), and Positive Fast (PF). The system has two different outputs K_{1L} and K_{1R}. However, both of them were fuzzified in an identical manner to start with. The fuzzy regions are Very Large (VL), LArge (LA), Medium (ME), SMall (SM), and Very Small (VS).

Initially, symmetrical triangular membership functions were used in all cases. Figure 8 shows the fuzzy sets for the encoder value difference fuzzy membership functions. Similarly, those for tacho value difference and outputs can be obtained. Table 1 shows the boundary values of

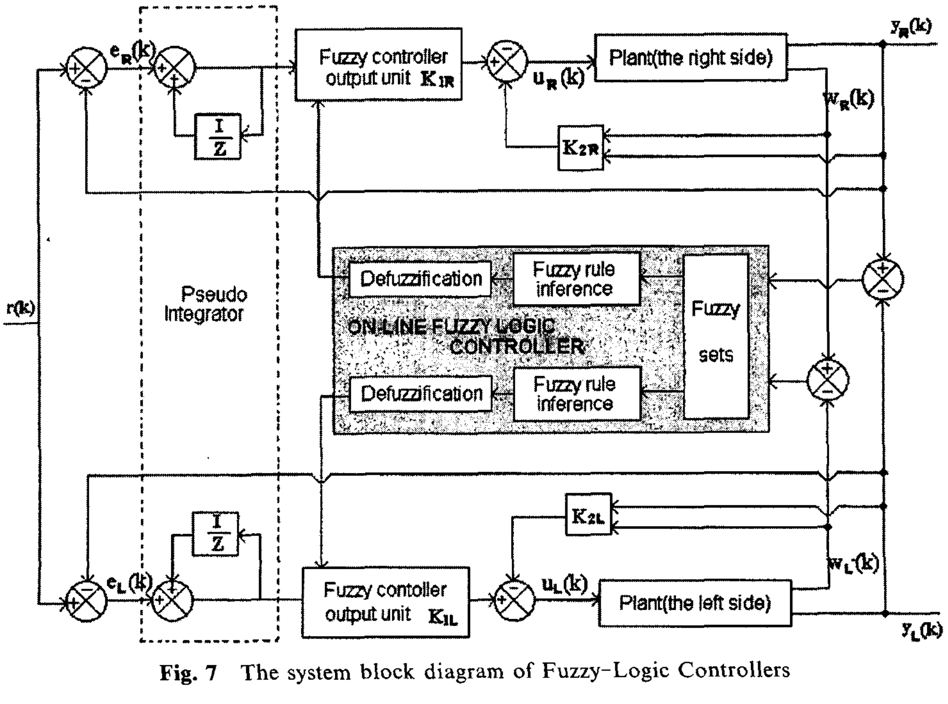


Fig. 7 The system block diagram of Fuzzy-Logic Controllers

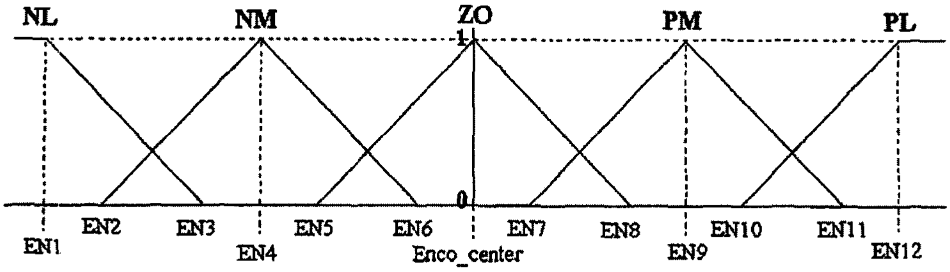


Fig. 8 Encoder value difference fuzzy membership functions

Table 1 Boundary values of fuzzy subsets before tuning (the right-hand side)

Encoder value difference		Tacho value difference		Output value	
				DEF0	0.0115
EN1	−160	TA1	−600	DEF1	0.0125
EN2	−130	TA2	−550	DEF2	0.0135
EN3	−110	TA3	−350	DEF3	0.0145
EN4	−80	TA4	−300	DEF4	0.0155
EN5	−50	TA5	−250	DEF5	0.0165
EN6	−30	TA6	−50	DEF6	0.0175
Enco_cen	0	Tacho_cen	0	DEF7	0.0185
EN7	30	TA7	50	DEF8	0.0195
EN8	50	TA8	250	DEF9	0.0205
EN9	80	TA9	300	DEF10	0.0215
EN10	110	TA10	350	DEF11	0.0225
EN11	130	TA11	550	DEF12	0.0235
EN12	160	TA12	600	DEF13	0.0245
				DEF14	0.0255

Table 2 Boundary values of fuzzy subsets after tuning (the right-hand side)

Encoder value difference		Tacho value difference		Output value	
				DEF0	0.00855
EN1	−140	TA1	−300	DEF1	0.0105
EN2	−135	TA2	−290	DEF2	0.0106
EN3	−75	TA3	−160	DEF3	0.0144
EN4	−70	TA4	−150	DEF4	0.0145
EN5	−65	TA5	−140	DEF5	0.0146
EN6	−5	TA6	−10	DEF6	0.0184
Enco_cen	0	Tacho_cen	0	DEF7	0.0185
EN7	5	TA7	10	DEF8	0.0186
EN8	65	TA8	140	DEF9	0.0224
EN9	70	TA9	150	DEF10	0.0225
EN10	75	TA10	160	DEF11	0.0226
EN11	135	TA11	290	DEF12	0.0264
EN12	140	TA12	300	DEF13	0.0265
				DEF14	0.02845

fuzzy regions for the right-hand side of the wheel. The left-hand side can be represented in a similar way. The only difference in the two sides is in the fuzzy region boundary values for the outputs. This arises from the fact that the identified mathematical models for two sides are different and as a result the desired controllers are slightly different.

The initial experiment which was carried out using these fuzzy sets showed that the current set of fuzzy regions is not capable of controlling the systems as desired. Hence, tuning of the fuzzy regions has then been carried out based on the trial-and-error method. The resulting fuzzy region boundary values are shown in Table 2 for the right-hand side. These values are considerably different in comparison to the values in Table 1. A similar procedure for the left hand side can be carried out.

Having completed the fuzzification for the input, the rule base for fuzzy Inference needs to be formulated. The initial suggested rule base is shown in Table 3(a) and 3(b). The abbreviated linguistic variables were described earlier in this section. Table 3(a) gives the rule base for the right hand side while Table 3(b) gives the rule base for the left hand side. If we carefully analyze how the rule base works, we will easily notice that the fuzzy control actions are complementary. Since the inputs are encoder and tacho error values and we try to achieve a convergence, if we increase the speed of response of one side, the speed of response of the other side must be decreased. This will eventually lead to zero encoder value difference. Although the rule base looks ideal, its performance has been found to be far from it. From the initial experiments with these rules, we found that it caused oscillations, overshoot and large settling times. Therefore, further tuning of the fuzzy rule set is to be carried out to get the desired control system performance. Careful observations for the left hand side as well as the right hand side are necessary to find out fuzzy input conditions under which the system fails to function. For example, some control rules caused overshoot for the right hand side while the rule for the left hand side worked well. The next modification is done for this case.

The old rule for the right hand side IF enco-diff=NL (Negative Large) and tacho-diff=PF (Positive Fast) THEN $\mathbf{K}_{\mathrm{IR}}$=VL (Very Large) was changed to the modified rule IF enco-diff=NL (Negative Large) and tacho-diff=PF (Positive Fast) THEN $\mathbf{K'}_{\mathrm{R}}$=LA (LArge). For this specific pair of input fuzzy conditions, no changes were necessary on the left hand side.

In practice, the higher output command is required in some ranges to overcome substantial friction and reduce the settling time. The next replacement is an example of this case.

One of the rules for the right hand side, the old rule IF enco-diff+NM (Negative Medium) and tacho-diff=PF (Positive Fast) THEN $\mathbf{K}_{\mathrm{IR}}$=ME (Medium) was substituted for the modified rule IF enco-diff=NM (Negative Medium) and tacho-diff=PF (Positive Fast) THEN $\mathbf{K}_{\mathrm{IR}}$=LA (LArge).

This is a further advantage of fuzzy logic control over a conventional control system. Even

Table 3 Protocol of fuzzy control rules for both sides (before tuning)

Encoder difference

Tacho difference

	NL	NM	ZO	PM	PL
NF	VL	VL	ME	ME	VS
NZ	VL	LA	ME	SM	VS
OK	VL	LA	ME	SM	VS
PS	VL	LA	ME	SM	VS
PF	VL	ME	ME	VS	VS

(a) For the right-hand side

Encoder difference

Tacho difference

	NL	NM	ZO	PM	PL
NF	VS	VS	ME	ME	VL
NS	VS	SM	ME	LA	VL
OK	VS	SM	ME	LA	VL
PS	VS	SM	ME	LA	VL
PF	VS	ME	ME	VL	VL

(b) For the left-hand side

Table 4 Fina fuzzy control rules for both wheels (after tuning)

Tacho difference / Encoder difference

	NL	NM	ZO	PM	PL
NF	VL	LA	LA	ME	SM
NZ	VL	LA	ME	SM	VS
OK	VL	LA	ME	SM	VS
PS	VL	LA	ME	SM	VS
PF	LA	LA	ME	SM	VS

(a) For the right-hand side

Tacho difference / Encoder difference

	NL	NM	ZO	PM	PL
NF	VS	SM	SM	ME	LA
NS	VS	SM	ME	LA	VL
OK	VS	SM	ME	LA	VL
PS	VS	SM	ME	LA	VL
PF	VS	SM	ME	LA	VL

(b) For the left-hand side

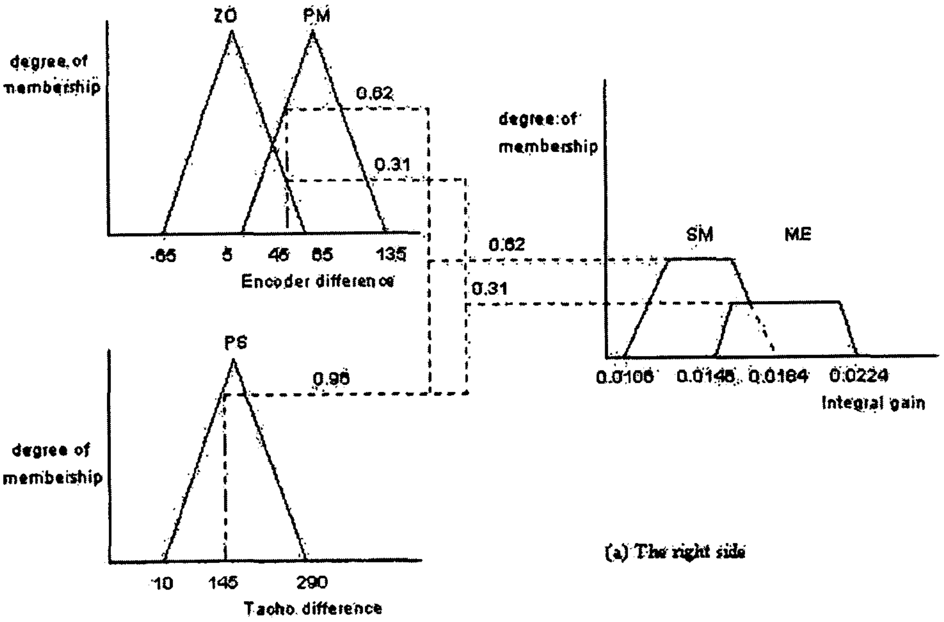


Fig. 9 An example of fuzzy rule evaluation procedure (for the right-hand side)

though tuning process requires tedious trial-and-error processes, it is rather simple process compared with a tuning process of a conventional control design.

The result of the fuzzy rule modification is shown in Table 4(a) and 4(b). Note that these control rule modifications are performed together with the changes of the boundary values of fuzzy regions as shown earlier in this section. The results showed that these modifications gave the desired performance from the two controllers.

3.4 Implementation of Fuzzy logic controller

The two level controllers, i.e., the two discrete-time state feedback controllers, were implemented in a timed interrupt service routine which occurs every 10ms. It reads the tacho and encoder values into global variables, uses the gain values K_{IL} and K_{IR} from the global variables, and generates the command byte for the motor drive boards. Before using the gains, the interrupt routine tests and clears a flag set by the main program to validate the gains. The flag is set by the main program only when the computations of new gain values for both sides are completed by the FLC. The FLC runs at its own pace in the main program and logically uses the sensor readings made by the interrupt service routine.

The max/min compositional rule is used for the FLC to find out the output degree of membership.

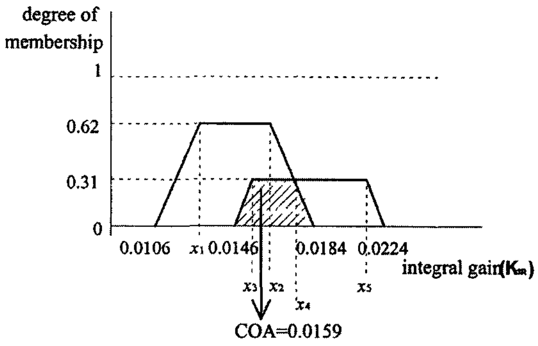


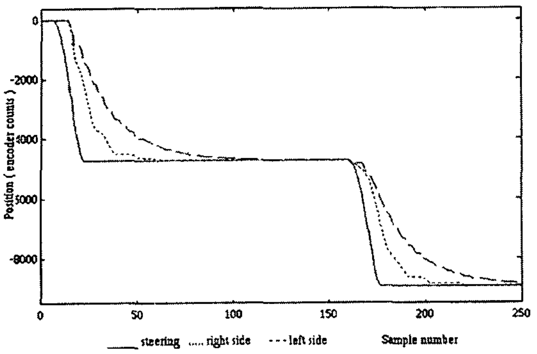
Fig. 10 Deffuzification procedure using the COA method (for the right hand side)

Figure 9 shows how the fuzzification and output degree of membership evaluation takes place for an encoder value difference of +45 and a tacho value difference of +145 for the left hand side. Since this is a control application, we have decided to use the centre of area (COA) method to work out the integral gain values for the left hand side ($\mathbf{K}_{\text{IL}}$) and the right hand side ($\mathbf{K}_{\text{IR}}$). Figure 10 shows the resulting output value ; $\mathbf{K}_{\text{IR}}=0.0159$. Using a similar procedure, one can find the value for the left hand side ; $\mathbf{K}_{\text{IL}}=0.0188$. As expected, this makes the left hand side controller to increase its speed of response and the right hand side to decrease its speed of response. The encoder value differences and the tacho value differences were computed by subtracting the left hand side value from the right hand side value. Thus, a positive difference means that the right hand side is ahead of the left hand side. Therefore, what needs to be done is to slow down the right hand side and speed up the left hand side, which is exactly what the FLC did.

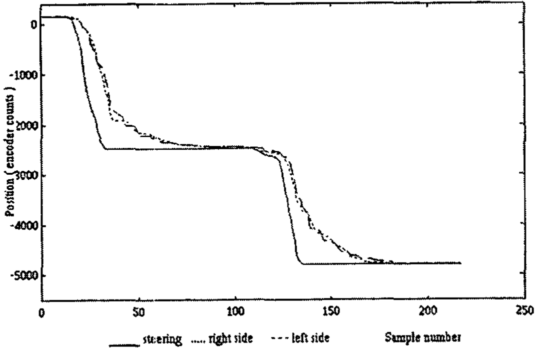
4. Results

Before starting the main experiment, some preparation stages are required. All the electronic components are connected in a proper way and trial tests are performed to confirm whether all the components of the system are working well. Having successfully passed the initial test, it is possible to implement an actual controller to the experimental system. In order to examine the feasibility of the fuzzy approach in tackling a real system, a digital state feedback controller and a fuzzy logic controller are implemented to each wheel so that it is possible to check whether each of the two wheels follows the steering device commands and how both digital and fuzzy controllers perform well. Then the implementation of a FLC with supervisory capacity to coordinate the rotations of the two wheels to maintain steering consistency can be conducted. The state feedback controller of both wheels are combined together and a FLC is applied for coordination. In practice, many attempts are required to get the best performance using trial-and-error methods.

The results are shown in Fig. 11 and 12. Figure 11 is the plots of the encoder values of the steering device, the left wheel and the right wheel. Figure 11(a), which shows the performance of the state feedback controller without FLC, is compared with Figure 11(b), which shows the system behavior with the FLC in place. In both graphs, the solid line shows the command signal in encoder count versus sample number. The dotted line in the same unit represents the right wheel and the dashed line represents the left wheel. When the FLC is not applied there had been encoder differences as large as 1500 counts which amounts to a misalignment of about 6 degrees in our system. When the FLC is put in place the error has been remarkably reduced as can be seen in Fig. 11(b). This is highlighted in Fig. 12(a) and 12(b) which show parts of the encoder error (solid ling) and tacho error (dotted line) in encoder counts versus sample number, without FLC and with FLC, respectively. Fundamentally, encoder value difference represents the position (turning angle) error between the two wheels and tacho values are the rate of change of this error. From the tacho value difference, it is possibly to expect how fast that the error will be increased or decreased. Without the tacho value differences, one might put to much power on the controller, and so the transient time to achieve for the final position of the two sides to be identical. As we can see in Fig. 12, the FLC brought in the required coordination function, especially in terms of instantaneous differences in the encoder

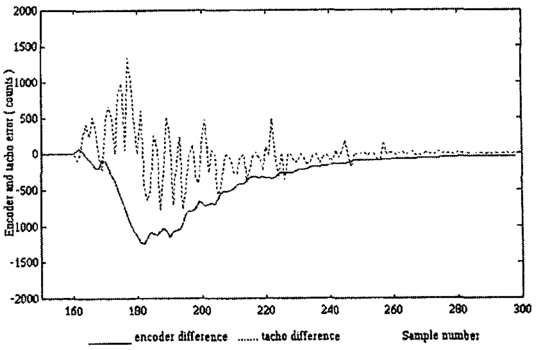


(a) The control system response without a Fuzzy-Logic Controller

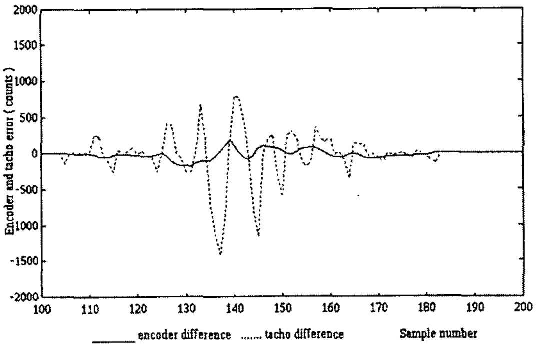


(b) The control system response with a Fuzzy-Logic Controller

Fig. 11 The control system response with and without a fuzzy logic



(a) The tacho and encoder value differences between two sides without a fuzzy logic



(b) The tacho and encoder value differences between two sides with a fuzzy logic

Fig. 12 The tacho and encoder value differences between the two wheels

values of the two wheels. The gap in the turning angle of the two wheels has been noticeably reduced as a result of a fuzzy logic control action.

5. Conclusion

This paper presents convincing results in a complex problem of having to couple two independent systems to deliver desired combined response, despite differing and non-linear dynamics and disturbances that affected the two systems. The improvement has been quite significant and implemented controller configuration is relatively simple and straightforward. While the performance has been promising, the tuning of the FLC was a painful process. It involved so much of intuitive feeling and actions to eventually get acceptable performance out of the system. One of the schemes to overcome this problem is to use an adaptive learning controller which has the capability to create fuzzy control rules and to modify them based on past experiences. Another possible area is the use of neuro fuzzy systems. Furthermore, if mechanical upgrade is allowed, the control of all four wheel steering systems using fuzzy or neuro fuzzy theory could be another potential application.

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