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Fuzzy Logic Cross-coupling Control of Wheeled Mobile Robots

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***Abstract*— In order to decrease the orientation error induced by motion control of a differential-drive mobile robot, a fuzzy logic cross-coupling motion controller that integrates the cross-coupling control and fuzzy logic techniques together is presented. Cross-coupling control can directly minimize the orientation error by coordinating the motion of the two drive wheels. Experimental results show that the proposed fuzzy logic cross-coupling controller can be successfully applied to enhancing the motion accuracy of the robot. It's also demonstrated that the performance of the fuzzy logic cross-coupling control scheme is superior to the conventional PID cross-coupling control scheme.**

***Index Terms*— mobile robots, cross-coupling controller, orientation error, motion control**

I. Introduction

With the recent advances in sensors and microelectronics, researchers are beginning to focus on autonomous mobile robots equipped with more intelligent capabilities such as learning from the environment and performing automatically and accurately. Now, mobile robots are mainly used in planet exploration, medicine, Agriculture, nuclear waste cleanup, hazardous materials, defense applications, industry, etc. Motion control is the very heart of any robotic systems and essential to build robust and interesting behavior. Whether the performance is good or not influences directly the application range of robots as well as the reliability of the whole control system.

Wheeled mobile robots can be considered as multi-axis drive servomechanisms. In order to achieve a coordination control, two kinds of basic approaches have been developed. The first approach is the distributed control. In the multi-axis control system, even if each axis is equipped with high performance tracking controller, the error of one axis influences the whole motion of the system. If this phenomenon is not considered and each axis is controlled independently, the motion error is occurred. As a result, it depreciates the whole system performance. The feasible algorithm to achieve a high accuracy of multi-axis motion control is cross-coupling control (CCC) of speed or positioning servomechanisms. In CCC, the whole multi-axis system is considered as a single system. Compensations are calculated by taking into consideration of the mutual influences among axes to increase the degree of matching among axes and consequently reduce the error in the resultant motion control. The first non-symmetrical cross-coupling method was proposed by Sarachik & Ragazzini [1]. The CCC concept with a symmetrical structure was primarily introduced by Koren for the machine tool control [2]. Many structures based on the application of CCC scheme have been proposed and tested in numerous engineering applications. However, CCC are widely applied in machine tool control and scarcely found in the motion control of mobile robots [3], [4], [5].

The robot considered in this research is a differential-drive mobile robot. Conventional motion control method prescribes separate velocities to the left and right wheels. Under normal conditions there are short transient times, during which the motors try to get up to the commanded speeds. However, external disturbances and slippage will interfere with the commanded speeds and result in additional transient times, during which the wheels don't follow the commanded speeds exactly. This situation is exacerbated when driving at very slow speeds, because the internal friction in gears and bearing causes significant disturbances all the time. The CCC method compares the actual encoder pulses from the left and right wheel of a robot and issues corrective commands to the motors to slow down the motor that is faster and speed up the motor that is slower than the other. The overall effect of this method is that the velocities of the left and right wheels of the robot are matched more tightly even in the presence of internal and external disturbances. In this paper, a fuzzy logic cross-coupling controller for wheeled mobile robots is provided. Experimental results show that the proposed CCC method has excellent motion control performance.

II. Kinematic Modeling and Motion Error Analysis

The kinematics of a differential-drive mobile robot can be described by [6]:

$$\dot{x} = \frac{v_l + v_r}{2} \sin\theta \tag{1}$$

$$\dot{y} = \frac{v_l + v_r}{2} \cos\theta \tag{2}$$

$$\dot{\theta} = \frac{v_r - v_l}{b} \tag{3}$$

where (x, y) are the Cartesian coordinates of rear-axle midpoint, θ measures the orientation, v_l, v_r are the linear velocities of the left and right wheels, and b is the distance between the two drive wheels.

Due to the inherent nonholonomic constraints [7], motion of a differential-drive robot can be classified as linear and curved motion. The linear motion is a particular curved case in which radius $R = \infty$. In order to generate a circular path, the reference point of the robot must move along a circle of radius R. The coordination of velocities is provided in Fig.1, where (v, ω) represent respectively the linear and the angular velocities of the robot.

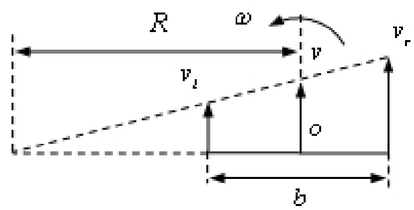

Fig. 1. Coordination of velocities.

The following equations can be concluded from Fig. 1:

$$v_l = \omega(R - b/2) = v(1 - b/2R) \quad (4)$$

$$v_r = \omega(R + b/2) = v(1 + b/2R) \quad (5)$$

Error sources which influence the accuracy of motion control can be classified into two categories: internal errors and external errors. The internal errors are the errors that can be detected by the wheel motion information. The external errors are the errors that only become apparent when the robot wheels interact with the environment. That is, external errors can only detected by absolute robot motion measurements. In this study, motion of robot is detected only by the encoder feedback and consequently internal errors are considered. The main sources resulted in internal errors are: 1. unmatched closed-loop gains and parameters. The inherent nonlinear and time-varying parameters in motors and time-varying loads which depend on control task both account for the different responses of the two loops and motion errors in the resultant path. 2. Different disturbances acting on individual drives. One example is different bearing frictions. The difference in disturbance leads to different transient response and the steady-state response. 3. Inability to track nonlinear trajectories. In tracking a general nonlinear trajectory, the reference inputs to the drive loops are also nonlinear. A conventional control system has lag errors in tracking nonlinear inputs [5].

The motion error of the robot can be decomposed into the components shown in Fig. 2: e_θ, e_l and e_t. The orientation error e_θ is defined as the difference between the real robot orientation and the desired robot orientation. The lateral error e_l is defined as the distance between the actual robot position and the desired robot position in the direction perpendicular to the orientation and the tracking error e_t is the distance between the actual position and the desired position in the direction of travel. The orientation error is the most important to motion control because the decrease in orientation error can make the lateral error approach to zero. This error is certainly due to the different responses of the two control loop. The tracking error can be controlled by adjusting the robot linear velocity as desired. Therefore, e_θ plays the most important role in motion controls and its decrease can improve the motion accuracy maximally.

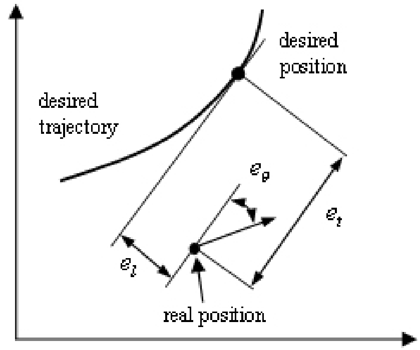

Fig. 2. Motion error decomposition.

III. The Structure of Control System

The whole control system of the robot adopts parallel distributed processing in a multi-DSP architecture, which is mainly composed of mechanical platform, control system for multiple DC motors, sensor system (vision sensor, ultrasonic sensors, infrared sensors, etc.), communication system, etc. The whole system is open and modular. Every subsystem is independent of each other and can be designed with own DSP controller. A high-performance single board computer serves as the main control unit. The control system comprises three levels, as shown in Fig. 3. Based on the sensor information from the environment and the predefined performance index, path planner generates a feasible trajectory which is subjected to the nonholonomic constraints. The task of command interpreter is to generate the reference velocity signals that direct the robot along a specific trajectory. The lowest level of the control hierarchy is the motion controller. The purpose of this controller is to maintain the velocities of each wheel, according to reference velocities prescribed by the command interpreter. The motion controller has an inner velocity feedback loop and an outer CCC loop. The overall effect of the motion controller is the elimination of steady-state orientation error of the robot and the improvement of motion control accuracy.

IV. Cross-coupling Controller

A. Orientation Error Computation

In the case of a differential-drive robot, motion accuracy depends on the coordination between the two velocity control loops and the control of orientation is achieved by adjusting the linear velocities of left and right wheels. When the robot is in straight line motion, at each sampling period, the change in orientation error Δe_θ is determined by

$$\Delta e_\theta = \frac{\Delta q_r - \Delta q_l}{b} \quad (6)$$

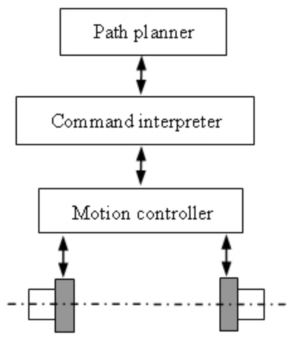

Fig. 3. The structure of control system.

where Δq_l and Δq_r are the left and right wheel displacement during the sampling period. Consequently, the total orientation error e_θ is

$$e_\theta = \sum \Delta e_\theta = \frac{q_r - q_l}{b} \tag{7}$$

where q_l and q_r are the total left and right wheel displacement.

The proposed cross-coupling controller is described in Fig. 4, where c_l and c_r represent the reference velocity inputs to the left and right drive loops. When the robot follows a circular path with radius R, the following can be concluded according to (4) and (5):

$$\frac{v_r}{v_l} = \frac{1 + b/2R}{1 - b/2R} \tag{8}$$

Define the cross-coupling gains for the left and right wheel as g_l and g_r respectively. Therefore, $g_r v_r = g_l v_l$ is expected to be satisfied. The orientation error in (7) becomes

$$e_\theta = \sum \Delta e_\theta = \frac{g_r q_r - g_l q_l}{b} \tag{9}$$

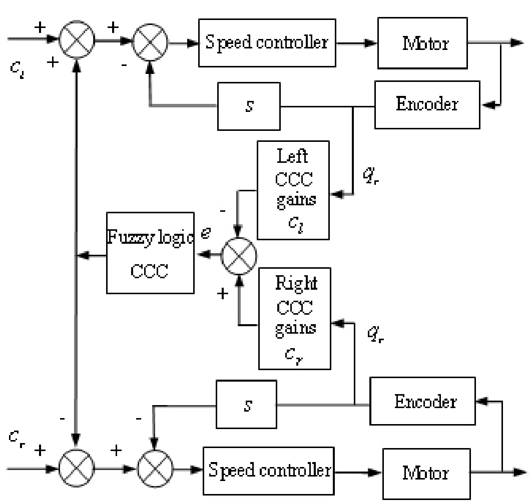

Fig. 4. The cross-coupling control system.

B. Design of Fuzzy Logic Cross-coupling Controller

Originally advocated by Zadeh [8], fuzzy logic has become a mean of collecting human knowledge and experience and dealing with uncertainties in the control process. From its design simplicity, its implementation, and its robustness properties, fuzzy logic control is by far the most useful application to a variety of industrial systems. Fuzzy logic control is also capable of handling the substantial nonlinearities found in robot dynamics. To enhancing the steady-state accuracy, it's often a better solution to configure the controller as an incremental controller. The output of the basic fuzzy controller is an increment to the control signal. A fuzzy incremental controller with an integrator on the output can remove the steady-state error and smooth the control signal, but it has slow dynamic response. The solution is to add a proportional component on the output [9] and the proposed fuzzy logic cross-coupling controller is shown in Fig. 5.

The fuzzy controller inputs are e and ce, and the defuzzification output is Δu. e denotes a control error, i.e., difference between a reference input and an actual process output. ce is the change in error, i.e., the derivative of the error. k_p' and k_i' are the proportional and integral gains of the cross-coupling controller. u is the resultant control signal and defined by

$$u = k_i' \int \Delta u + k_p' \Delta u \tag{10}$$

We have defined seven fuzzy sets for each controller input and for the controller output, respectively. Two kinds of shapes are used for the membership functions: one is a triangle, and the other is a trapezoid which corresponds to both ends of the fuzzy input and output ranges. Fig. 6 shows the defined membership functions, where NL is negative big, NM is negative medium, NS is negative small, ZO is nearly zero, PS is positive small, PM is positive medium, and PB is positive big. There are 49 control rules stored in the rule base which

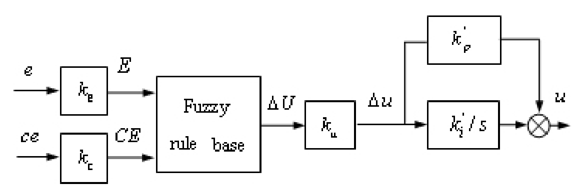

Fig. 5. Fuzzy incremental controller.

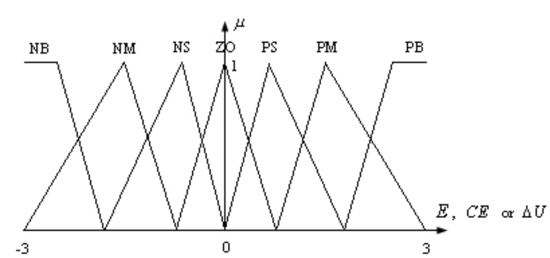

Fig. 6. Membership function for the variables e, ce and Δu.

is developed based on engineering judgments and the control rules can be represented by

$$Rule \quad R_{ij} : IF\ E = A_i\ and\ CE = B_j \\ THEN\ \Delta U = C_{ij},\ i,j = 1,...,7$$

where A_i represents linguistic values of linguistic variable E, B_j represents linguistic values of linguistic variable CE and C_{ij} represents linguistic values of linguistic variable ΔU. In addition, the maximum member of effective control rules at a time is four, because at most two membership functions can be overlapped. Table I shows the fuzzy control rules used in this paper.

Through fuzzy reasoning with the fuzzy control rule base, the fuzzified inputs E and CE can be transformed into an output ΔU. Since the output ΔU also has fuzzy values, a defuzzification procedure is needed to obtain a crisp value output. In order to put the fuzzy controller into operation, the run-time inference is reduced to a table look-up which significantly improves the execution speed.

TABLE I
THE FUZZY CONTROL RULE BASE

Control Action		CE						
		NB	NM	NS	ZO	PS	PM	PB
E	NB	NB	NB	NB	NB	NM	NM	NS
	NM	NB	NB	NM	NM	NS	NS	NS
	NS	NM	NM	NM	NS	NS	NS	ZO
	ZO	ZO	ZO	ZO	ZO	ZO	ZO	ZO
	PS	ZO	PS	PS	PS	PM	PM	PM
	PM	PS	PS	PS	PM	PM	PB	PB
	PB	PS	PM	PM	PB	PB	PB	PB

V. EXPERIMENTAL RESULTS

To test the effectiveness of the proposed control strategy, a series of experiments were conducted on our self-developed mobile robot platform with a maximum speed of 1 m/s. The robot is driven and steered by two independent 24 volt, 12 amp motors and the drive wheels are connected to the dc motors through transmissions. The diameter of the drive wheels is 21cm and the wheel base is 27.5 cm. A 16-b fixed point DSP TMS320LF2407A is implemented as the motion controller and measurement data are recorded for 5 s with a sampling interval of 6 ms. The parameters of the drive loops are deigned individually and the gains of the applied cross-coupling controller are fine-tuned through experiments.

We drive the robot in indoor environment at fixed speed of 220 mm/s along a straight line, while applying three control algorithms: no CCC, conventional PID CCC and the proposed fuzzy logic CCC. So the cross-coupling gains can be selected as $g_l = g_r$. With the kinematics of the mobile robot and the encoder reading, the lateral error and the orientation error are shown in Fig. 7 and Fig. 8 respectively. We can see that the system with no CCC has larger lateral error and orientation error than the CCC system, while the CCC system has a limited lateral error and orientation error which try to approaching zero and do not increase with respect to time. When no CCC is used, the difference in the distance travelled by the two wheels keeps increasing because the two motors have different parameters and unknown external disturbances and, in turn, the orientation error increases and the robot diverges from the desired path.

By contrast, under the CCC, when there is a difference, a correction signal is generated to reduce the error, and the robot travels in the direction of the desired path. In addition, under the same conditions, the proposed fuzzy logic CCC outperforms the PID CCC. From the experimental results in Fig. 7 and Fig. 8, it's obvious that the lateral error and orientation error of fuzzy logic CCC converge faster and have smaller values than those of the PID CCC. The performance index of orientation error for the robot with these control algorithms are shown in Table II. It can be seen that the performance of the fuzzy logic CCC is best.

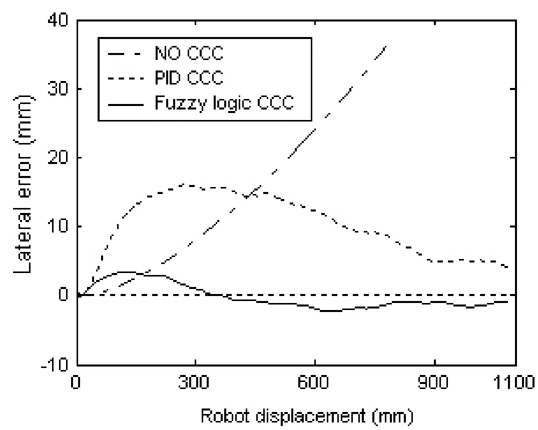

Fig. 7. Lateral error of the robot.

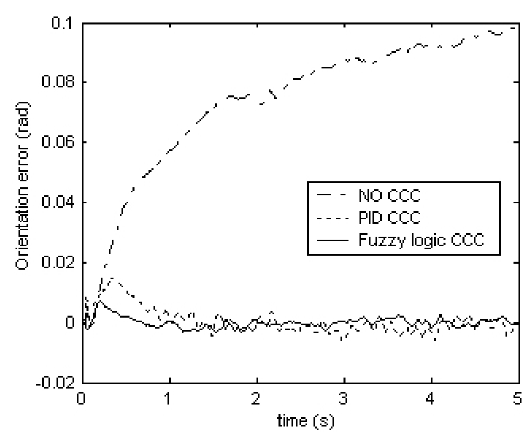

Fig. 8. Orientation error of the robot.

From the analysis of experimental results, we can conclude that the fuzzy logic CCC can significantly reduce the lateral error and orientation error which the system with no CCC can't deal with and have a better performance than the PID CCC.

TABLE II
PERFORMANCE INDEX OF ORIENTATION ERROR

Control System	Magnitude of Orientation Error (rad)			
	Max	Min	IAE	RMS
NO CCC	0.0989	0	58.837	0.0772
PID CCC	0.0148	-0.0065	2.386	0.0043
Fuzzy logic CCC	0.0071	-0.0032	1.0226	0.0017

VI. CONCLUSION

In this research, a fuzzy logic cross-coupling control algorithm that integrates the cross-coupling control (CCC) and fuzzy logic techniques together is proposed. With CCC, the mutual dynamic effects between the two servomechanisms are taken into consideration to generate an error correction signal. It can be seen from the experimental results that the lateral error and orientation error can be significantly reduced. It is also demonstrated that the performance of the fuzzy logic CCC scheme is superior to the conventional PID CCC scheme and very effective in compensating for internal errors, such as difference in motor parameters and external disturbances. Furthermore, it's easy to be implemented in the conventional motion controller with little modification.

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REFERENCES

[1] M. Naumovic, "Cross-coupled motion controller for two cooperating robot arms," *Proceedings of the IEEE International Symposium on Industrial Electronics*, vol. 2, pp. 909-913, 1999.

[2] Y. Koren, "Cross-coupled biaxial computer control for manufacturing systems," *Journal of the Dynamic Systems, Measurement and Control*, vol. 102, pp. 265-272, 1980.

[3] S. S. Yeh and P. L. Hsu, "A new approach to biaxial cross-coupled control," *Proceedings of the IEEE International Conference on Control Applications*, pp. 168-173, 2000.

[4] C. S. Chen and Y. S. Shieh, "Cross-coupled control design of bi-axis feed drive servomechanism based on multitasking real-time kernel," *Proceedings of the IEEE International Conference on Control Applications*, pp. 57-62, 2004.

[5] L. Feng, Y. Koren, andJ. Borenstein, "Cross-coupling motion controller for mobile robots," *IEEE Control Syst. Mag.*, vol. 13, pp. 35-43, 1993.

[6] G. Campion, G. Bastin, and B. D. Novel, "Structural properties and classification of kinematic and dynamic models of wheeled mobile robots," *IEEE Trans. Robot. Automat.*, vol. 12, no. 1, pp. 47-62, 1996.

[7] I. Kolmanovsky and N. H. McClamroch, "Developments in nonholonomic control problem," *IEEE Control Syst. Mag.*, vol. 15, pp. 20-36, 1995.

[8] L. A. Zadeh, "Fuzzy sets," *Journal of Information and Control*, vol. 8, pp. 338-353, 1965.

[9] P. He and H. X. Wang, *Design and Application of Fuzzy Controller*, Beijing: Science Press, 2000.