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Tracking Control Enhancement on Non-Holonomic Leader-Follower Robot

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Abstract—**This paper investigates the leader–follower tracking control problem for non-holonomic mobile robots based on fuzzy controller based approach. The trajectory tracking control for a single mobile robot is extended to the formation control for multiple mobile robots. This paper proposes for enhancement the follower performance, interval fuzzy type-2 controller is used. By taking the simulation and simple real experimental the propose controller is verified. As the result found, the follower has the ability to kept the separation with its leader when it moves in unknown environment and the follower posture the same direction with leader posture. In the future, the research will continue to compare with another controller method and considering the problems like obstacle avoidance, target seeking, and formation keeping in the outdoor environment.**

Keywords—leader-follower robot; tracking control; interval type-2 fuzzy logic

I. INTRODUCTION

Today, robot has find its way to become part of human's everyday life. Especially in leader-follower robot case, the robots are demanded to move automatically, without the needs of human intervention, or so called autonomous. A navigation system is needed to guide mobile robot movement in an unstructured environment, so that it will not be interfered or colliding with another object. In avoiding objects, navigation system has to face uncertainty problems, that is, sensors, actuators, and environments uncertainties. Fuzzy logic has the ability of handling these uncertainties problem [1][2]. The widely used fuzzy technique in a control system is the type-1 Fuzzy Logic (T1FL) techniques [3][4]. Some researchers used such technique in mobile robot control and achieved satisfactory results [5-7].

However, in its implementation it has one restriction. The restriction is that its fuzzy set is certain in the sense that the membership grade for each input is a crisp value [3][8]. It means that it is, in a certain degree, only maps a crisp value into another crisp value ranging from 0 to 1, omitting the uncertainty properties that is initially offered as benefit of fuzzy logic. The loss of uncertainty properties leads to the failure of handling uncertainties in unstructured environment. Recent development has been introduced an improvement of T1FLS called interval type-2 fuzzy logic system (IT2FLS) [9]. The extra degree of freedom where provided by the footprint of uncertainty (FOU) allow an IT2FLS to produce output that cannot be achieved by T1FLS with the same number of MFs [10]. It is known that IT2FLS models higher levels of uncertainty with respect to their traditional counterparts [1]. Experimental evidence has shown that IT2FLS is more robust than T1FLS in several applications [3].

Interval type-2 fuzzy logic controller (IT2FLC) overcomes the navigation control in mobile robot application indicates good result and smooth trajectories [11][12][13]. To the best our knowledge, only a few researchers using this method on multi-robot system. To explore such method in leader-follower robot, this paper aims to investigate the tracking control base on IT2FLC. The rest of the paper is organized as follows: section 2 briefly discusses the fuzzy controller methods while section 3 describes our proposed controller and material. Section 4 present the result and discussion, and finally, the paper is concluded with the conclusion and future work in section 5.

II. LEADER-FOLLOWER TRACKING CONTROL

A. Non-Holonomic Leader-Follower Model

A non-holonomic mobile robot has been considered in this paper. Such robotic system must control the tracking system because the non-holonomic robot operation had two left and right drive wheels mounted on similar axis, while another two free wheels were installed on the back wheels. The robot was driven separately and only moves in a horizontal plane had been taken into account, while any non-holonomic constriction was enforced upon the kinematics. This is because, the kinematic model describes the restrictions equation, which dismisses symbolic integration in determining explicit correlations between the positions of robot at global and local frames of coordinates [14].

The leader-follower robot relation in XY-coordinate can described as Fig. 1. [14]. Where $Q_l = [x_l, y_l, \theta_l]^T$ is the actual posture of the leader robot R_l, $Q_f = [x_f, y_f, \theta_f]^T$ is the actual posture of the follower robot R_f and $Q_n^d = [x_f^d, y_f^d, \theta_f^d]^T$ is desired posture of the follower robot R_f. A_{lf} and ϕ_{lf} are the actual separation and the actual posture between the leader R_l and follower robot R_f, A_{lf}^d and ϕ_{lf}^d are the desired separation and the desired posture between the follower robot R_f and its leader robot R_l.

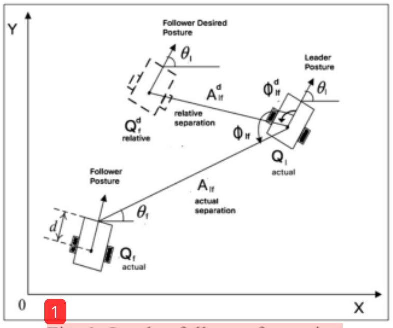


Fig. 1. Leader-follower formation

The model of non-holonomic kinematic equation of leader robot R_l based on the actual position and orientation is described below,

$$\dot{Q}_l = \begin{bmatrix} \dot{x}_l \\ \dot{y}_l \\ \dot{\theta}_l \end{bmatrix} = \begin{bmatrix} \cos\theta_l & -b\sin\theta_l \\ \sin\theta_l & b\cos\theta_l \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v_l \\ \omega_l \end{bmatrix} \quad (1)$$

where v_l is the linear velocity and ω_l and is the angular velocity, respectively and the actual position and orientation of the follower R_f robot is defined,

$$Q_f = \begin{bmatrix} x_l - b\cos\theta_l + a_{lf}\cos(\phi_{lf} + \theta_l) \\ y_l - b\sin\theta_l + a_{lf}\sin(\phi_{lf} + \theta_l) \\ \theta_f \end{bmatrix} \quad (2)$$

The actual distance between the leader and follower is defined,

$$Q_f^d = \begin{bmatrix} x_l - b\cos\theta_l + a_{lf}^d\cos(\phi_{lf}^d + \theta_l) \\ y_l - b\sin\theta_l + a_{lf}^d\sin(\phi_{lf}^d + \theta_l) \\ \theta_l \end{bmatrix} \quad (3)$$

where (x_f, y_f) denote the coordinates of the actual position and (x_f^d, y_f^d) and denote the coordinate of desired position of follower robot R_f. The relative separation and the relative posture between the leader and the follower robot is represented as A_{lf} and the posture of follower robot ϕ_{lf}. The relative distance between leader and follower along X and Y Cartesian coordinate as defined as follow,

$$A_{lf} = \sqrt{{A_{lfx}}^2 + {A_{lfy}}^2} \quad (4)$$

By taking derivative of Eq. (4) and substitution in to Eq. (1), (2) and (3), the model leader-follower formation can be written,

$$\dot{A}_{lf} = -v_l\cos\phi_{lf} + v_f\cos\beta_{lf} + b\omega_f\sin\beta_{lf} \quad (5)$$

$$\dot{\phi}_{lf} = \frac{1}{a_{lf}}\{v_l\sin\phi_{lf} - v_f\sin\beta_{lf} + b\omega_f\cos\beta_{lf}\} - \omega_l \quad (6)$$

where v_l and ω_l denote the linear velocity and angular velocity of the leader robot R_l and v_f and ω_f denote the linear velocity and angular velocity of the follower robot R_f, respectively.

B. *Fuzzy Controller Design*

The IT2FLC is used in leader-follower robots for tracking control is proposed in this paper. Figure 2, show the block diagram of tracking control. The proposes IT2FLC contains five parts, fuzzification, rule-base and inference mechanism, type reduction and defuzzification. In general, IT2FLC process same with T1FLC. However, IT2FLC have type reduction process, due to the fuzzy sets is type-2. Before defuzzification it transforms in to type-1 fuzzy set.

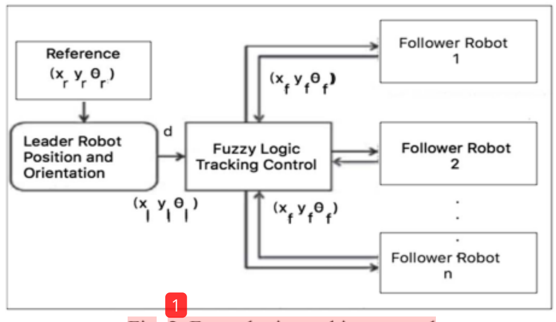


Fig. 2. Fuzzy logic tracking control

The membership functions (MFs) use in this research is Gaussian function with parameters σ and c, for determining the upper bound and lower bound of the Gaussian function μ_i. The foot print of uncertainty (FOU) of the IT2FLC fuzzy sets f_i^l is obtained from deviation standard as follow,

$$f_i^l = \exp\left[-\frac{1}{2}\left(\frac{x_i - c_{i1}^l}{\sigma_i^l}\right)^2\right], \sigma_i^l \in [\sigma_{i1}^l, \sigma_{i2}^l] \quad (7)$$

Therefore, upper membership functions (UMFs) $\bar{f}$ of IT2FLC is defined by using Eq. (8) below,

$$\bar{f} = \begin{cases} (c_{i1}^l, \sigma_i^l; x_i), & x_i < c_{i1}^l \\ 1, & c_{i1}^l \le x_i \le c_{i2}^l \\ (c_{i2}^l, \sigma_i^l; x_i), & x_i > c_{i2}^l \end{cases} \quad (8)$$

Lower membership functions (LMFs) $\underline{f}$ of IT2FLC is defined by using Eq. (9) below

$$\underline{f} = \begin{cases} (c_{i1}^l, \sigma_i^l; x_i), x_i \le \frac{c_{i1}^l + c_{i2}^l}{2} \\ (c_{i2}^l, \sigma_i^l; x_i), x_i > \frac{c_{i1}^l + c_{i2}^l}{2} \end{cases} \quad (9)$$

Based on Eqs. (8) and (9) it can be described in Fig. 3

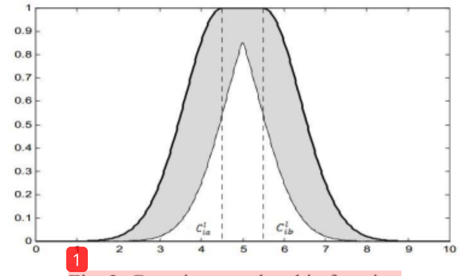


Fig. 3. Gaussian membership function

The variable linguistic of input MFs are produced from distance sensor. In real experiment, the infra-red sensor readings are susceptible to high degrees of radial errors. This work deals with this error to express the uncertainty swarm robot. Detection error of infra-red sensor is observed varies from 10 % to 20 %, this percentage value is utilized for design IT2MFs called bandwidth footprint of uncertainty (FOU). Therefore, near, medium and far are defined as an input MFs. The variable linguistics of output MFs divided into two, such as velocity and steering angle of the leader-follower robot. The robot velocity is defined as slow, medium and fast, and steering angle are defined as straight, left and right.

The IT2FL rule bases have the same structure as the T1FL and it is determined by the number of the fuzzy MFs. The rule bases are used to control the velocity and steering angle of the robot actuator. When the leader robot is very close to an obstacle, because of repulsive force developed between the robot and the obstacle the robot must change its speed and heading angle to avoid the obstacle. The number of rules are generated by processing of inputs MFs and outputs MFs, only 8 rules to control the leader-follower formation tracking. All rules are obtained heuristically using common sense, and the fuzzy rules are listed n in Table 1.

TABLE I. THE FUZZY RULE BASES

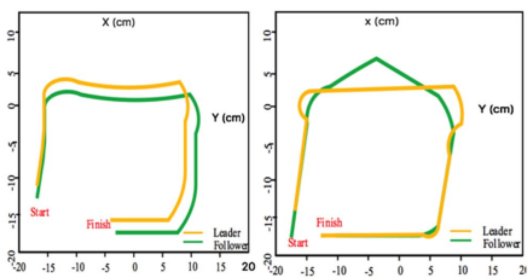
Sensor 1	Sensor 2	Sensor 3	Velocity	Steering Angle
Near	Near	Near	Slow	left
Near	Near	Far	Slow	Right
Near	Far	Near	Slow	Straight
Near	Far	Far	Medium	Right
Far	Near	Near	Slow	Left
Far	Near	Far	Medium	Left
Far	Far	Near	Medium	Medium
Far	Far	Far	Fast	Fast

Before defuzzification stage, the IT2FL sets resulted from the previous step has to be reduced first. In this works, the type reduction is center of sets, where reduced set value comprises of y_{left} and y_{right}, which is the approach of inference result midpoint. The output of defuzzification step of IT2FLC is obtained by summing the value of y_{left} and y_{right} from type reduction step and divide it with two, as shown on equation below,

$$y = \frac{y_{\text{left}} + y_{\text{right}}}{2} \qquad (10)$$

III. Results and Discussion

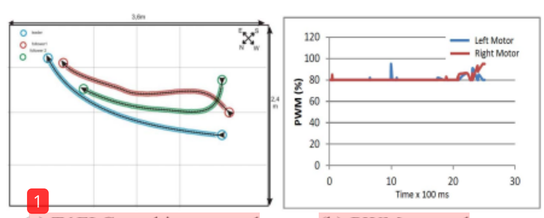
To verify the feasibility and validity of the presented control scheme for the tracking-control problem of leader-follower robot with uncertainties, some numerical simulations are described in this section. The comparison of simulation results between IT2FLC and T1FLC are presented in Figure 4. By using IT2FLC the follower robot tracking produce smoot movement, due to imprecision of the sensor is embed until 20% into the input MFs. Therefore, the controller can compensate the uncertain in sensor value like sensor noise. In the controller design, only 8 rules are used. IT2FLC produce good performance, the leader generates only 291 data and the follower generates only 304 data to force the follower follow its leader. However, the result of T1FLC not smooth like the controller counterpart. Even though the T1FLC generate 1074 data for the leader and 1077 data for the follower when it processes the tracking control. This is because input MFs is crisp, thus the follower make the bad trajectory in some situation, especially when the leader turns right/left and the follower posture must follow the direction.



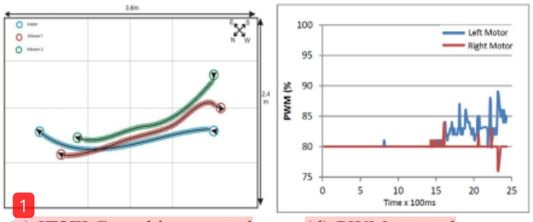
(a) IT2FLC with 8 rules (b) T1FLC with 27 rules

Fig.4. Fuzzy controller performance

After the simulation is done, the proposed method is verified by using a real experiment with three identical mobile robots. Figure. 5 illustrates three identical robots in the leader-follower formation in simple environment without obstacle, they move and keep the safe distance in smooth trajectory. Robot follower have the ability to follow the leader in small distance without collision each other.



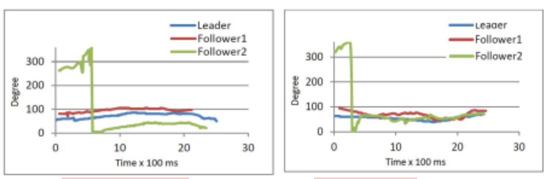
(a) T1FLC tracking control (b) PWM control



(c) IT2FLC tracking control (d) PWM control

Fig.5. Fuzzy controller performance

All robots have initial position with steering angle is opposite direction each other. By using IT2FLC the robots have the ability to make the formation in 0.5 s however T1FLC need 1 s to produce the formation as shown in Figure 5 (a) dan (c). Because IT2FLC has FOU that embed some of uncertainty values in terms of sensor imprecision and inaccuracy actuator. Each follower can control the formation through keeping the limitation of distance and steering angle with the leader. However by using T1FLC the distance between leader and follower is far, but the follower has the ability to keep the safe distance with the leader. By using IT2FLC, the leader robot can control the PWM with a range of changes in the right and left actuators about 12% (refer to Figure. 5(d)). However with T1FLC the leader robot has range the right and left actuators to force the folloer posture about 19% shows in Figure 5 (b).



(a) T1FLC (b) IT2FLC

Fig.6 Steering control with different controller

Figure 6 (a) and (b) shows that formation control with IT2FLC produce past response for follower robot number 2, in this case the follower robot 2 has steering angle with opposite direction with other robots. It able to control and make a formation with other robots in small time about 300 ms. But with T1FLC robot follower number 2 has more time to make the formation about 600 ms. The leader to force the steering when it move, in 150 ms the steering angle of the leader reach 100^o to the target . But the leader based on IT2FLC only 70^o to force the steering reach the target and its produce stable movement.

IV. Conclusion

In this work a study concerning the modeling of tracking control on leader-follower robot is proposed. It was applied the interval type-2 fuzzy logic controller in the tracking control of leader-follower formation strategy. In the controller is considering the sensor uncertainty due to noise and sensor imprecision about 20 % as an FOU of MFs. As found in the results the propose IT2FL controller can enhance the tracking performance in terms of response time, smoothness and stability movement in uncertain environment. The main future works that could be realized is modeling the system with more than three robots, try to compare with another kind of control method and considering problems like obstacle avoidance, target seeking, and formation keeping in the outdoor environment.

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