Fuzzy Logic Controller Design for Leader-Follower Robot Navigation

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***Abstract*—Mobile robots are applied everywhere in the human's life, starting from industries to domestics. This phenomenon makes it one of the most studied subjects in electronics engineering. Navigation is always an issue for this kind of robot, to ensure it can finish its task safely. Giving it a "brain" is one of the ways to create an autonomous navigating robot. The Fuzzy logic controller is a good choice for the "brain" since it does not need accurate mathematical modeling of the system. Only by utilizing the inputs from sensors are enough to design an effective controller. This paper presents an FLC design for leader-follower robot. This FLC design is the improvement of FLC application in a single two differential-driven mobile robot. The relation between leader and follower robot is modeled linearly as a spring-damper system. Simulation proves the feasibility of the proposed method in several environment setting, and this paper also shows that the method can be easily extended to one leader and more than one follower's formation. The research in this paper has introduced in the classroom as the teaching-learning media to improve students' involvement and interest in robotics and robotics related class. This paper is also part of our campaign and encouragement for teachers and students to use low-cost and open source software since not all the universities in developing country can afford the expensive high-end software.**

***Index Terms*—Fuzzy logic controller, Mobile Robot, Leader-follower formation, Navigation.**

I. Introduction

Mobile robots are applied everywhere, in industries and domestics, ranging from being a transport robot, a vacuum cleaner, or merely for entertainment purpose, such as a dog robot. A navigation strategy needs to be well designed to ensure the robot functions well. Navigation strategy for the autonomous mobile robot is including target reaching, obstacle avoidance, and wall following. A mobile robot is often applied in an ever-changing dynamic environment that creates complexity for the robot. Motion planning becomes a crucial part of the navigation system to ensure the robot can reach a target or final point, the targets to be intercepted by the robot can be static and dynamic (a moving target) [1]. This motion planning can be generated in real-time (online) or pre-mapped (offline). Real-time motion planning requires a specific intelligence installed on the robot. A planted AI (artificial intelligence) can create a smart robot that works better than the ones without AI.

One of the most applied types of AI is fuzzy logic and has been a well-discussed topic in robotics since introduced by Zadeh in 1965 [2]. Fuzzy logic enables a linguistic approach to process the uncertain data using designed rules. This method is best for complex systems that are not easy to be modeled with exact mathematics. Rather than going through exact value, the fuzzy logic linguistic set works using IF-THEN rules fed up to an interference engine. The rules are used to encode the behavior of robot motion against the target (static[3] and dynamic target[4]), obstacles and walls found. In this method, even not so effective rules are sufficient enough. A mobile robot is a complex non-linear system and suffers the non-holonomic constraints; therefore a technique like fuzzy logic is very suitable for navigation planning strategy[5]-[11].

The application of a group of simple mobile robots (swarm robot) is better than deploying one sophisticated robot [12]-[17]. The more robots to control the more complex and uncertain the system is, therefore the application of a fuzzy logic controller (FLC) is appropriate in this situation. The controller for one robot can be extended to a group of robots in a leader-follower formation. The controller for leader-follower formation in some cases can be simplified in static controller design [16][17].

This paper proposes a method for motion planning of robots in leader-follower formation by improving/extending the FLC for a single robot. The navigation system is developed by combining several conditions that might be encountered by the robot, such as target reaching, obstacle avoidance, and wall following. The obstacle avoidances are provided by the proximity sensors attached to the robots. The right sensors for both leader and follower are also utilized for wall follower to keep the robot following the walls in a certain distance. The leader is set to reach a static target, while the follower is set to follow the leader by considering the leader as a moving target to pursue. The proximity sensor attached to the front of the follower robot is assigned to keep a safe distance from the leader. The output of the robots is the velocity of the left and right wheels. The system is updated online until reaching the target.

The novelty of this study is the improvement of FLC design for a single robot following a moving target into FLC for a leader-follower formation robot. The feasibility of the proposed method is presented in the simulation with several environment setting using MobotSim [20]. The

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relationship between input and output of the system is shown by SCILAB[19]. This research is also to teach the students in robotics class how to design robots controller and to encourage them to be pro-active in learning and designing robots[21][22][23].

II. Mobile Robots Modeling

A. Kinematics Modeling of a Single Robot

Mobile robot considered in this paper is a two wheels differential driven mobile robot, presented in fig. 1. The position and orientation of the robot is $q = \begin{bmatrix} x & y & \phi \end{bmatrix}^T$, the translational and rotational velocities are $\dot{q} = \begin{bmatrix} \dot{x} & \dot{y} & \dot{\phi} \end{bmatrix}^T$, where x and y are robot's position, $\dot{x}$ and $\dot{y}$ are translational velocities in x and y-axis, ϕ is the orientation of the robot, and $\omega = \dot{\phi}$ is the rotational velocity.

Robot inverse kinematics is given as

$$\begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} = f\left(\dot{x}, \dot{y}, \dot{\phi}\right), \quad (1)$$

where $\dot{\theta}_R = \frac{1}{2\pi r} \cdot v_R$ and $\dot{\theta}_L = \frac{1}{2\pi r} \cdot v_L$. v_R and v_L are wheel's translational velocities.

Therefore, from eq. 1, robot's velocity is

$$v = r\frac{\dot{\theta}_R - \dot{\theta}_L}{2}, \quad (2)$$

and

$$\omega = \frac{r}{2L}\left(\dot{\theta}_R - \dot{\theta}_L\right). \quad (3)$$

where L is the half width of the robot, r is the wheels' radius, and $\dot{\theta}_R$ and $\dot{\theta}_L$ are right and left wheel's velocities.

Robot presented in fig. 1 suffers the non-holonomic constraint

$$v = \dot{x}\cos\theta + \dot{y}\sin\theta. \quad (4)$$

It means robot only moves in curvature and not in lateral sideward motion, therefore $0 = \dot{x}\cos\theta - \dot{y}\sin\theta$.

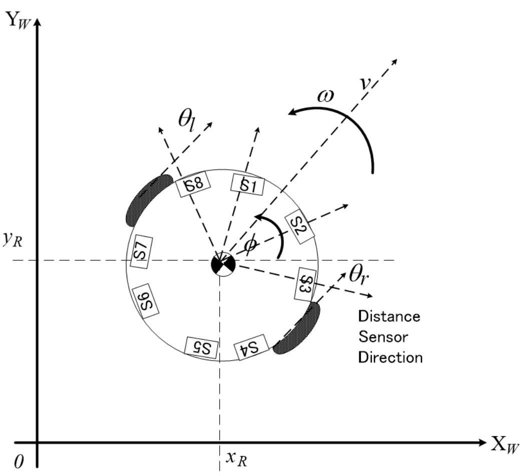


Fig. 1: Single robot in its coordinate frames

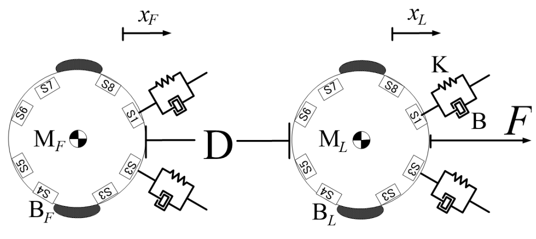


Fig. 2: Leader follower robot spring-damper system modeling

Control input v and ω are defined as

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \quad (5)$$

where in this study v and ω is defined as the control inputs.

B. Leader-Follower Formation Modeling

The dynamics modeling of leader and follower robot relations is considered as a spring-damper system, as shown in fig. 2. This modeling is a representation of proximity sensors attached to the follower [16]. The spring-damper system is also used to model the relation between proximity sensors attached to the leader and the obstacles and walls found. The virtual spring-damper model can be used to describe the flocking robots' behavior where the spring defines the force of attraction to the leader and the damper defines the repelling force.

The dynamics of leader follower robot given in fig. 2 are

1) Leader dynamics

$$F = M_L\ddot{x}_L + B_L\dot{x}_L + B\left(\dot{x}_L - \dot{x}_F -\right) + K\left(x_L - x_F\right), \quad (6)$$

2) Follower dynamics

$$B\left(\dot{x}_L - \dot{x}_F -\right) + K\left(x_L - x_F\right) = M_F\ddot{x}_F + B_F\dot{x}_F, \quad (7)$$

where F is the force applied to robot leader, the force considered here, is the virtual attraction force produced by the target. B is the damping constant, K is the spring constant, B_L and B_F are the Coulomb frictions of leader's and follower's wheels. M_L and M_F are the mass of leader and follower robot. x_L and x_F are the representation of leader and follower displacement along y-axis.

The distance of leader and follower robot is given by

$$D = \sqrt{\left(x_L - x_F\right)^2 - \left(y_L - y_F\right)^2} \quad (8)$$

The target is considered to have a virtual force that attracts the leader robot, and the generated leader's trajectory is considered as the virtual reference trajectory for the follower. The error of trajectory tracking between the leader and follower robot can be written as follow.

$$e_{dist} = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \cos\phi & \sin\phi & 0 \\ -\sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_L - x_F \\ y_L - y_F \\ \phi_L - \phi_F \end{bmatrix} \quad (9)$$

TABLE I: Rules based for FLC design

No	Input					Output	
	S1	S2	S3	S8	Camera	Left Tire	Right Tire
1	N	N	N	N	Detect	Stop	Stop
2	N	N	N	M	Detect	Stop	Slow
3	N	N	M	F	Detect	Slow	Med
4	N	N	M	N	Detect	Slow	Stop
5	N	M	F	M	Detect	Slow	Med
6	N	M	F	F	Detect	Fast	Med
7	N	M	N	N	Detect	Slow	Slow
8	N	M	N	M	Detect	Stop	Slow
9	M	F	M	F	Detect	Fast	Fast
10	M	F	M	N	Detect	Slow	Med
11	M	F	F	M	Detect	Med	Fast
12	M	F	F	F	Detect	Med	Fast
13	M	N	N	N	Detect	Med	Slow
14	M	N	N	M	Detect	Med	Slow
15	M	N	M	F	Detect	Med	Slow
16	M	N	M	N	Detect	Med	Med
17	F	M	F	M	Detect	Med	Med
18	F	M	F	F	Detect	Fast	Med
19	F	M	N	N	Detect	Fast	Med
20	F	M	N	M	Detect	Med	Slow
21	F	F	M	F	Detect	Fast	Med
22	F	F	M	N	Detect	Slow	Fast
23	F	F	F	M	Detect	Med	Fast
24	F	F	F	F	Detect	Fast	Fast

Note: N is near, M is Medium, F is Far, and Med is medium velocity.

III. Fuzzy Logic Controller Design

FLC designed in this paper is based on the FLC design for a single robot, and the rules-based are kept simple. The spring-damper system is adopted between the leader and follower. The virtual trajectory for the leader is set by an attractive force emitted by the target, and this leader trajectory becomes the reference trajectory for the follower robot. Tracking can be defined as an act of approaching an moving object by matching its location and velocity; therefore follower should match its position and velocity to the leader.

Fig. 3 shows the FLC design proposed in this study where the inputs are from proximity sensors and camera. In this current study, the attached camera is considered to be in two states only, detects or no detection. The camera application for the leader is to recognize the target of the leader robot, and for the follower robot to identify the leader. The camera in this paper has no significant role; however, the inclusion of a camera is to prepare the rules for the real system which is an ongoing project at the moment. Eight proximity sensors

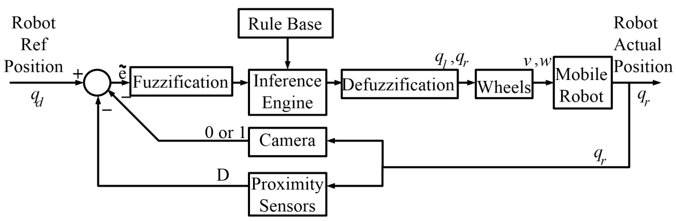


Fig. 3: Diagram block for FLC controller design

are installed on the robot; however, only four are utilized for distance recognition in obstacle avoidance and maintaining the safe distance to leader robot.

FLC is designed by creating a database to define the linguistic variables and fuzzy rules based. Table I shows the rules-based considered in this paper. The linguistic in table I is translated into membership functions of inputs from sensors, given in fig. 4. The fuzzification shown in fig. 3 maps the crisp numbers into a fuzzy set that used to activate the associated fuzzy set. The inference engine handles the way how to combine the rules and represents the knowledge base of the system. The defuzzification converts each of conclusion from inference engines into a single crisp non-fuzzified, and FLC output will be the input to the robots.

Inputs conditions for proximity sensors ($S1, S2, S3$, and $S8$) in table I are N for near, M for medium, and F for Far. Near, medium and far show the distance between the robot to obstacles or the follower robot to leader robot. The output results are the wheels' velocity, which is divided into four conditions, stop, slow, medium, and fast. In this paper, camera condition is only limited to 2 states, detection, and no detection, since robot moves if the camera detects the object (leader or target), then the rules simplified only for camera detection.

IV. Results and Discussion

The feasibility of the proposed FLC designed is tested in MobotSim software by designing leader-follower robots in several environments. The FLC is designed using MobotSim's built-in BASIC editor. Robots are deployed in an environment including several obstacles which considered as walls, and the target is deemed to have an attractive virtual force. Robots move from start to end points by utilizing distance sensors to keep the safe distance to the obstacles and leader robots.

Robots positioned in the starting points are shown in fig. 6a, 7a, 8a, 9a, and 10a, and robots reaching the target shown in fig. 6b, 7b, 8b, 9b, and 10b. Fig. 6 to 10 show that the leader robots avoid obstacles and keep the distance to the wall in the desired distance, and the follower robots keep the safe distance to the leader while avoiding the obstacles and following the wall at the same time. The robot implemented in this paper is based on the real system, therefore the range of distances considered in this research presented in fig. 4 is also based on the real robot. The robots trajectories show that the follower robot follows the leader from start to end point. The simulation of one leader and one follower can easily extend to more that one followers, as shown in fig. 11.

The material presented in this paper was a part of simulations introduced to students at bachelor level in our Polytechnic. The teaching-learning process is enhanced by involving students' active participation. The enhancement was conducted by introducing several simulation software and encouraging the students to design their robots and environments. The software introduced are low-cost software like this MobotSim and open-source software, since not all the polytechnics in developing country can afford the costly

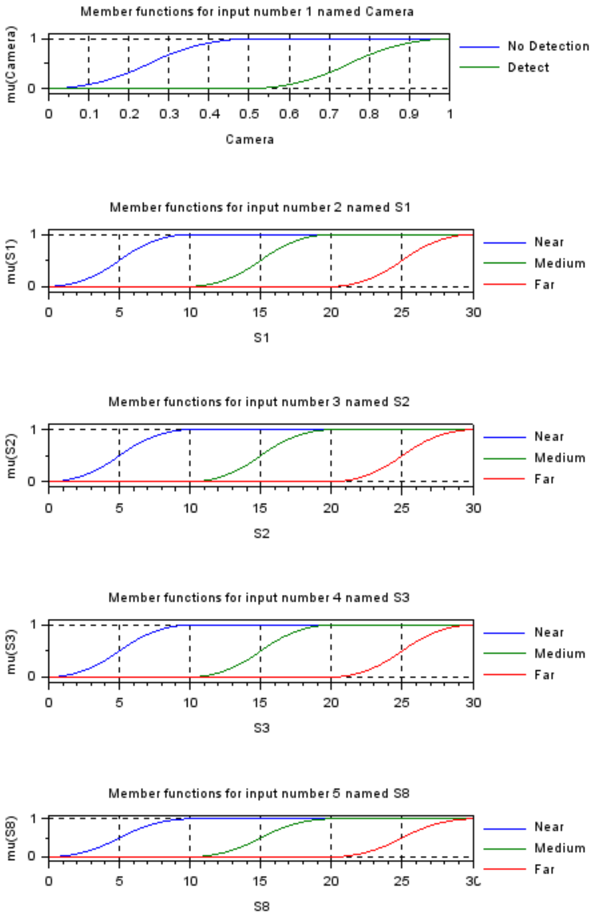


Fig. 4: Membership function of sensors input

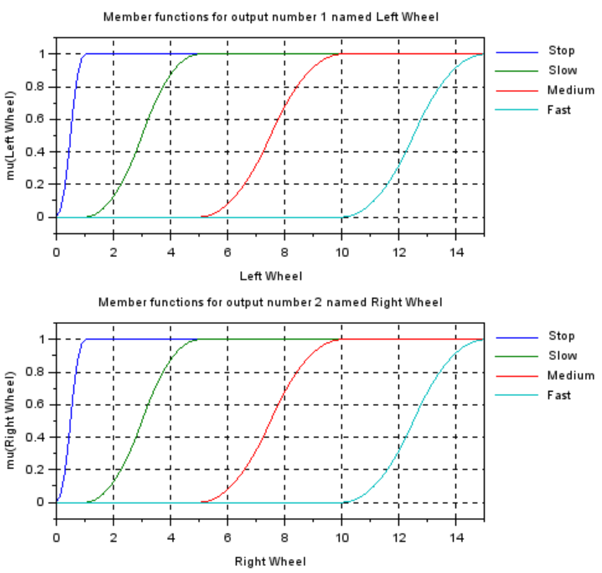
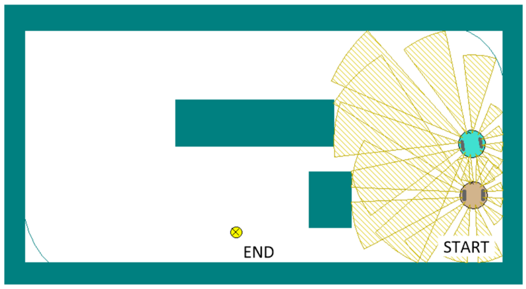
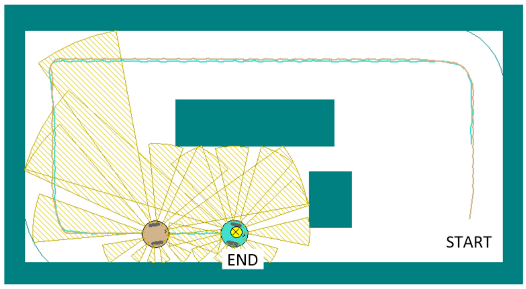


Fig. 5: Output system

high-end software. This paper also parts of our campaign and encouragement to teachers and students working with robotics to use low cost and open source software [23].

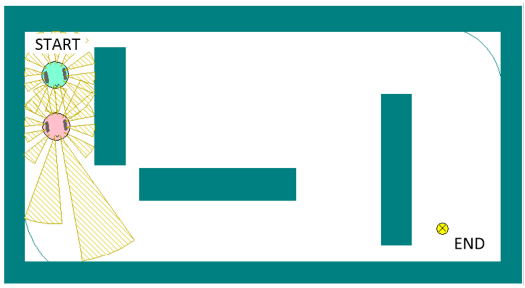


(a) Robots in start position

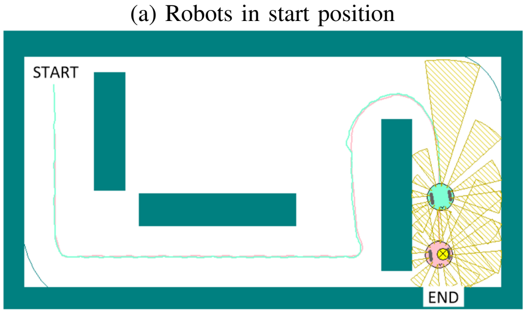


(b) Robots in final position

Fig. 6: Environment 1



(a) Robots in start position

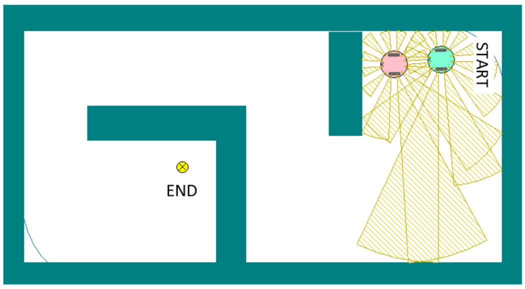


(b) Robots in final position

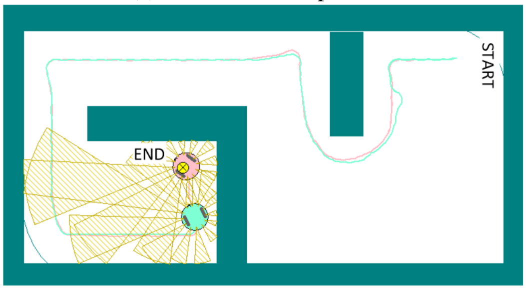
Fig. 7: Environment 2

V. Conclusions

FLC is a good approach to design navigation system for a mobile robot since this type of controller does not require exact mathematical modeling of the system. The mathematical modeling of a two differential-driven mobile robot suffers the non-holonomics constraint and the sensors attached to cannot be solved by simple mathematical integration. By using FLC, one can take data from sensors as the inputs for the controller. This paper presents an improvement/extension from FLC design for one robot to leader-follower formation robots. The relation between leader and follower is modeled as a virtual spring-damper system as presented in our previous work [16]. The feasibility of the proposed method is proven by simulations of leader and follower robot in simulation using SCILAB for input-output representation, and MobotSim for showing the implementation to mobile robots. Simulation results show the effectiveness of the proposed method by

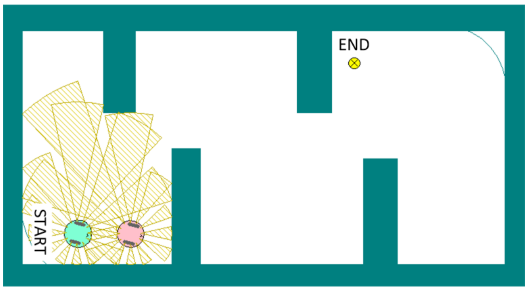


(a) Robots in start position

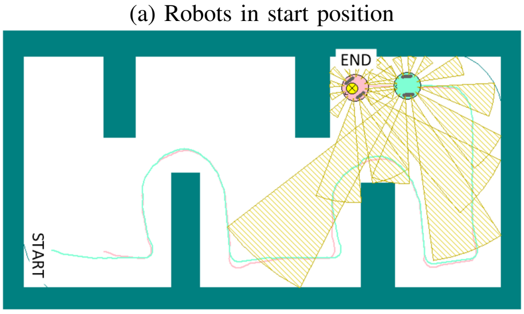


(b) Robots in final position

Fig. 8: Environment 3

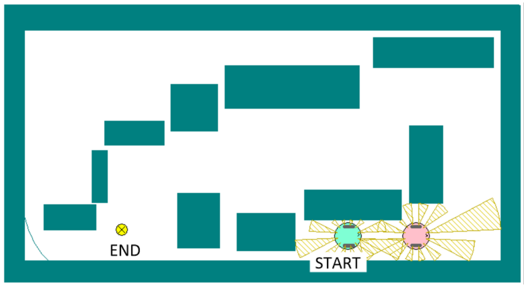


(a) Robots in start position

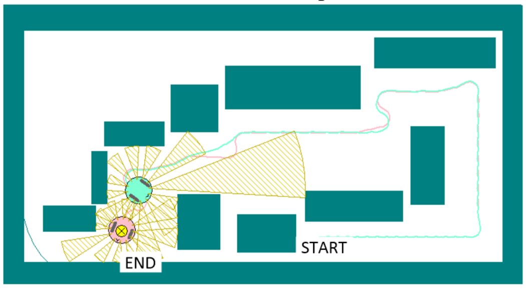


(b) Robots in final position

Fig. 9: Environment 4

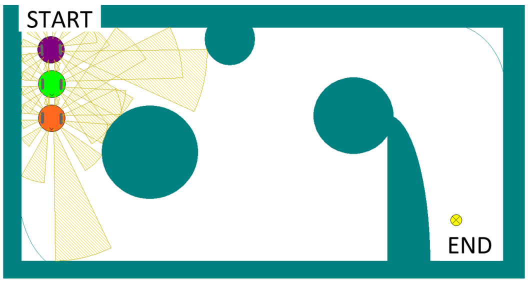


(a) Robots in start position

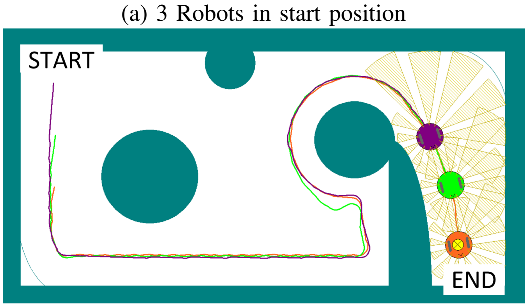


(b) Robots in final position

Fig. 10: Environment 5



(a) 3 Robots in start position



(b) 3 Robots in final position

Fig. 11: 1 leader and 2 followers robot

showing that the follower robot follows the leader in all the environment setting. The proposed method can be easily developed for more than one follower as shown in fig. 11.

The method and software used are also introduced in the author's classroom, as a mean to increase students' involvement in teaching-teaching learning process. By improving the student's involvement, it is also hoped to enhance the creativity and understanding of the students about robotics-related subjects in Politeknik Negeri Sriwijaya. This paper is also part of our encouragement and campaign to encourage teachers and students to use the low-cost, and open source software for teaching-learning process [23], since not all the university and polytechnic in developing countries can afford the costly high-end software.

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