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Keywords

communication; coordination; fuzzy logic; swarm robot

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ABSTRACT

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1. INTRODUCTION

Coordination among individual robots of swarm is one of interesting topics in robotic science. A better communication among them becomes a significant need [1]. Each of them shoud be able to transmit and distribute the information they have to the other robot [2-3]. These abilities could support the robots to detect the location of the other robots, to send and to receive information among them within the communication range, so that they can perform the task collectively.

For increasing the performance of communcation system in swarm robots, some researchers have proposed a communication netwotk. It is very useful for improving swarm distributed sensing and detecting. It has shown its successful in various applications, such as: formation control [4-5], multi-target tracking [6], search and rescue [7], environmental monitoring [8], and surveillance [9-10]. However, the user should know which communication they can use in their application. This paper presents the analysis on communication among the individu of swarm robots in conducting coordination.

Since communication network development has became one of the main challenges in swarm robots, many significant developments in wireless communication technology among robots has been made, such as: NFC, Wi-Fi, Bluetooth, IrDA, GSM and ZigBee [11–14]. These technology have enabled the development of autonomous air, ground, or underwater robots. NFC (Near Field Communication) and Bluetooth are considered not suitable for swarm robots due to limitations in network size [15]. The Wi-Fi-based approach may be adopted for a small group of robots with high performance, but it is not desirable for swarm robots due to the high system complexity and high cost. In contrary, IrDA and ZigBee are widely accepted in swarm robots because of the low complexity in hardware, relatively easy system implementation, and low power consumption [16-17]. In this research, A Zigbee communication was used.

In performing the communicating task, the robot must be able to coordinate one anther so that they can avoid collision, to keep off the obstacles and to mantain their distance to the other robots (by maintaining an accurate speed to the nearest robots). Maintaining the distances in swarm robots is important in order to obtain good coordination to achieve controlled direction [18]. Fuzzy logic is one of approaches that can be implemented in controlling the direction of swarm robots. it has been successfully and widely used to control the motion of swarm robots [19]. This technique can shorten the time and refine the movement of robots in a very complex system, so that it can avoid obstacles [13-14], [20]. Fuzzy logic is one of the most useful methods of computational intelligence that offers the efficiency and simplicity [21–23]. This systems use linguistic terms that are similar to those that human beings use [24-25].

The objective of this paper is to evaluate the performance of communication among mobile robots in keeping and coordinating their motion. They should be able to move in the same direction and maintain their pre-determined positions. To achieve coordination among individual of swarm robots, in this work, a wireless communication was used. Each individual must maintain a predetermined position and orientation among them when they move in their surrounding. However, the relative position of the robots is not fixed. In their free movement of each robots, it is difficult to know a sufficient robot distance to obstacles and to other robots. Using fuzzy logic as the swarm artificial intelligence in this study, made the motion coordination can be controlled based on input distance to generate correct decision for the output.

For coordination, each robot communicated by using wireless communication, X-Bee module. X-Bee module with The Received Signal Strength Indicator (RSSI) as a parameter to estimate the distance between two X-Bee nodes. In this work, X-Bee has been chosen as a wireless communication module among robots. The purpose of wireless communication was to find the robot position in the experimental environment. The RSSI indicator is in -dBm units that was used to measure signal strength between robots.

2. SWARM ROBOTS COORDINATION

In maintaning the coordination, each robot in the swarm must have the ability to coordinate and share the workload to the other. However, some problems always occur in coordination, such as duties allocation for the group of robots, including: resources usage; time task accomplishment; excessive communication, sensor selections, system reliability, and scalability [26]. Some researchers tried to overcome the problems by making some improvements [27–31]. Kaminka et al. [27] proposed effectiveness index which can reduce times and resources during coordination process. V. Garg [28] described the advantages of using robot-sensor networks. This network is very useful for coordinating multiple robots or swarm robots. It can support the swarm to share sensor data and track its members. To enhance the lifetimes of networks, A. Wichmann established the sensor for robot communication and coordination [29] that can reduce the energy usage. Corkeet.al [30] also analyzed the robot that worked together using a sensor network. M. Schwager in [31] used sensor network of some nodes. These sensors have capability to sense the value of the high sensory function of an area. It will detect the observation in higher density.

3. SWARM ROBOT COMMUNICATION DESIGN AND METHOD

This section explained the results of research gave a comprehensive discussion of swarm robot communication. The Results are presented in figures, graphs, tables, and others to make the reader easily understand the issues in swarm robot communication.

3.1. Design

The communication model in collective behavior is an important element. It relates to the information being distributed to the group [32]. There are a lot communication models of group animals behavior that can be imitated, such as metric [25-26], the topological, and visual models [1], [33]. The metric model is directly based on spatial proximity where two individuals interact if they are within a certain distance of one another [32], [34]. Topological model needs each robot to interact with several limited numbers of nearest group members [35]. The visual model permits an individual to interact with other agents in its visual field based on the sensory capabilities of animals [21].

To determine the performance of different coordination of collective movement algorithms, the set of metrics is used that can be applied only for formations or for flocking, not for both. Due to the different nature, there are some metrics that are used to characterize the flock type. Different subsets have been determined by dividing the set of metrics to group the subset according to its resemblances [33].

The topological and visual models are usually used for performing the metric model in reaching the target [34]. However, there is no clear difference between the visual and topological models. The visual model latency was substantially lower than the topological and metric models; but, the metric model outperformed the topological model in terms of the transfer of information [35].

Selecting a topology that suitable to our swarm robot characteristic needs is an important task. In particular, how to form and maintain an unbroken communication network dynamically so that the information through the swarm can run continuously for the entire swarm becomes an interesting problem [36]. RSSI is one of the solutions in this problem. It is used as a complementary tool to consider the topology of the entire localization system [37]. In general, the swarm robot performance is affected by network topology on noise estimation and robustness. Topology of the network could practically affect the performance of algorithms for large interconnected swarm robots system [38].

Block diagram control of communication among swarm robots is presented in Figure 1. The X-Bee or Zigbee protocol that is connected to the central computer collects experimental data used as a useful communication to control all existing systems on the actual robot platform.

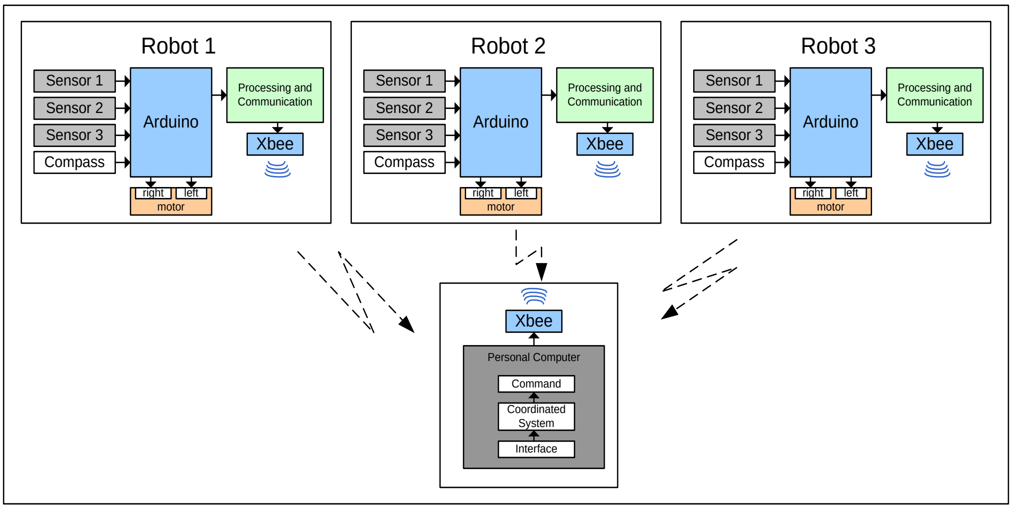


Figure 1. Block diagram control of swarm robot coordination

X-Bee or ZigBee protocol based modems support three different network topologies ie star, mesh, and cluster tree networks, allowing a variety of customized configurations. Coordinator, a set of routers, and end devices are common things that topology mesh pocesses [10]. A router can be linked to one or more routers and end devices. The communication rules of mesh topology are flexible because the routers that are located within the range of each other can communicate directly. An advantage of the mesh network is that there is odds-on another alternative route in case an existing link fails. Thereby, this type of network topology is consistently good in quality or performance.

In paper [39], it was explained the use of RSSI in tracking the swarm robot. The communication used is centered where the robot became a leader and the followers communicate wirelessly through X-Bee. The difference of that research with this research is the robot strategy in coordinating its own movements to avoid the obstacles and collision to other robots. In this research, a fuzzy logic was used.

3.2. Fuzzy Logic for Coordination

In coordinating the swarm robot, each individual robot swarm must have ability to cooperate to perform a specific task, as well as the robot must be able to interact with the environment. The working environment of swarm robot is complex and changeable; in addition each robot consists of many components such as communication devices, system control, sensing etc., making it difficult to determine mathematical models. It is quite impossible to identify. Fuzzy logic algorithm offers the solutions by ignoring the mathematical equations.

Fuzzy Logic Theory is a decision-making technique that translates values expressed in language (linguistics) into specific values, which may be difficult to resolve with traditional mathematics [34]. The fuzzy logic consisting of linguistic control rules that is designed as coordinate motion controller based on the knowledge and experience of the human expert [35-36]. In the movements, coordination controller will turn the robot wheel with a constant range through the fuzzy controller. The conditions used in the controller depend on the movement of the robot.

In this research, 3 swarm robots were used. Each robot should achieve the task of moving to the destination and avoid obstacles. Thus, every robot in the swarm has three tasks: avoiding obstacles, moving to the destination, as well as keeping the swarm by avoiding collisions among robots. The environment used was an environment without obstacles with different arena shapes and sizes. In an environment without obstacles, there was no disturbance effects occured. If the robot was far from that group, then the robot would move towards one another to defend the swarm. If each robot was closed, the robot had to stay away one another to avoid a collision.

In coordination of the swarm robot, the interaction between robots in the swarm depends on the distance between the robots with the obstacles and with other robots detected from each sensor. By using fuzzy logic, the sensor inputs of each robot are the input value for the membership function (MF). In this research, fuzzy control design is shown in Figure 2. The fuzzy control structure based on the procedure consists of the standard procedures, such as: input crips, fuzzification, fuzzy input, rule evaluation, fuzzy output, defuzzification and output crips

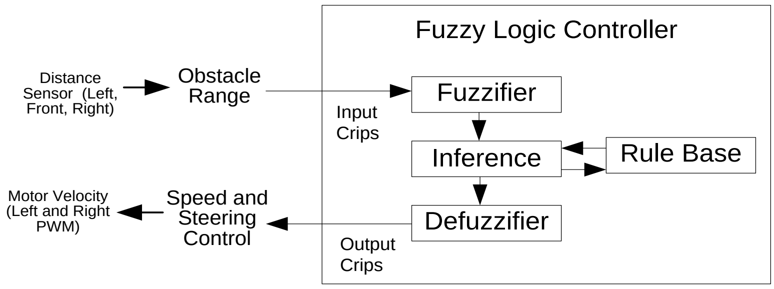
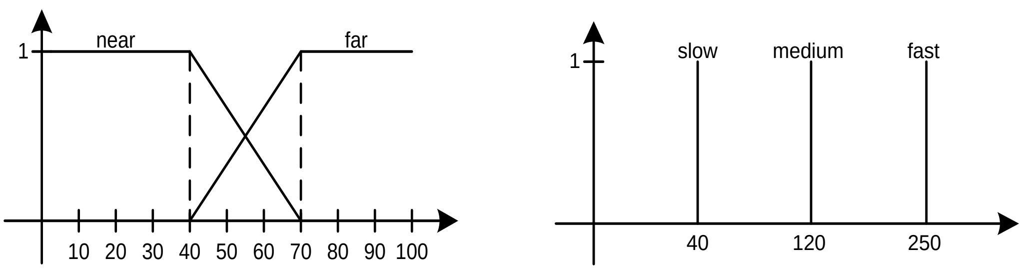


Figure 2. Design fuzzy logic controller

Based on the value of MF, some rules for the response of the motor output of the swarm robot will be made. In this study, the input and output values of MF are shown in Figure 3 (a) and (b). In Figure 3 (a), there are two membership functions (MFs), i.e. far and near. Both of them are in the trapezoidal form of MFs. In Figure 3 (b) the (consequent) output of the system is not a fuzzy set, but rather than a constant or a linear.



(a) Membership function of distance sensor as input

(b) Membership function of motor speed as output

Figure 3. Input MF and output MFvalue

The rule set in the fuzzification process in the form of control decisions, resulting in a combination of input and output. In this study 8 rules were used as shown in Table 1. It presents linguistic variable as the output controller which contains the motor speed for the right and left PWM.

Table 1. Fuzzy Logic Rule Based

Rules	Distance Sensor as Input			Motor Speed as Output	
	Left	Forward	Right	Left PWM	Right PWM
1	Near	Near	Near	Slow	Fast
2	Near	Near	Far	Fast	Slow
3	Near	Far	Near	Medium	Medium
4	Near	Far	Far	Medium	Slow
5	Far	Near	Near	Slow	Fast
6	Far	Near	Far	Slow	Medium
7	Far	Far	Near	Slow	Medium
8	Far	Far	Far	Fast	Fast

4. RESULTS AND ANALYSIS

In this research, three robots were utilized. The real design of the robots are shown in Figure 5. Every robot has three distance sensors, one compass sensor, and one X-Bee. The robots with circular shape have diameter 15 cm and height 17 cm. The robot uses three wheels, two rear wheels of the robot have functioned as a controller, one wheel has functioned as freely mover. Two DC motors are connected to the two driving wheels respectively. The rotation direction of each motor was controlled by the direction of drive current, while the rotation speed was controlled by the duty cycle of Pulse Width Modulation (PWM).

This experiment was done in an indoor environment. The test arena used is 1×6 m, 2×4 m and 3×4 m as shown in Figure 4. The robot moved along the preset path within the scope while maintaining its own positions. They moved along the four sides of a square. Each robot had an equivalent behavior and same localization process.

1×6 m 2×4 m 3×4m

Figure 4. Experimental environment and the localization system

4.1. Experimental Results of Swarm Robot Coordination

In this work we present two kinds of experiments: (i) coordination between robot to perform collective and similar direction movement. Each robot must defend pre-determined positions and orientations among them at the same time; (ii) communication between swarms of robots to exchange the information about the settings of the motion direction.

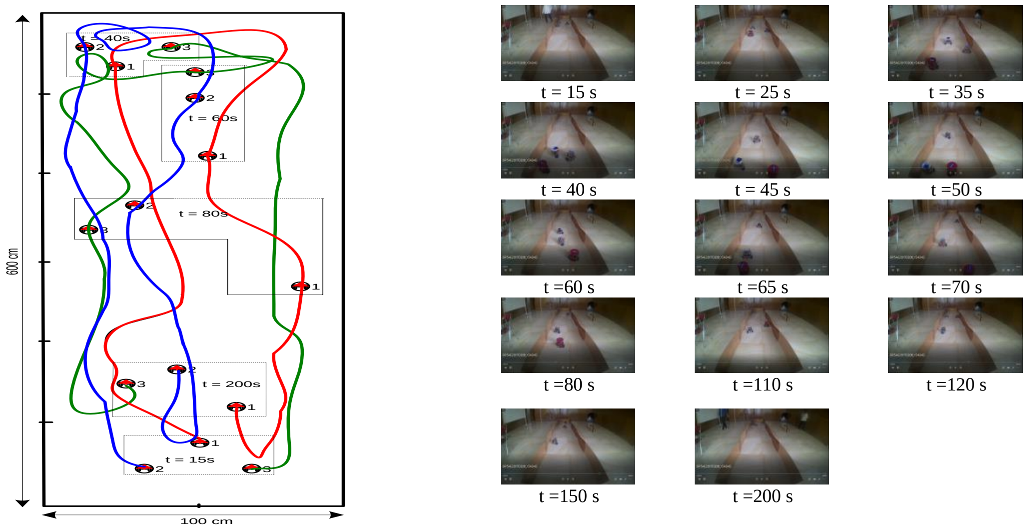
Coordination of robots can be enhanced through communication, for instance, the ability for sensing another robot. The coordination among the robots relies on network communication. In term of its networking capability, every robot communicated to one another only at event times and coordinated the moving of swarm robot trough low-powered radio X-bee. Each robot attempted to follow the trace of other robots by sensing their signal strengths. Once they reached the end of the trace, they will travel further into the unknown environment until they can maintain a minimal connection to the rest of the group.

In this research, the interaction between robots to coordinate depended on the distance among the robots to the obstacles and to other robots detected from each sensors. Using the fuzzy method, the magnitude of the PWM motor speed was calculated using fuzzy controller based on the magnitude of the perceived distances. Fuzzy controllers had three input and two outputs that regulated the right and left PWM speeds.

Three arenas of indoor experiments scenario,1x6 m, 2×4 m and 3x4 m with the obstacle were also conducted in this research. The estimated positions were relatively near to each robot during the process of moving along the first arena of the 2x4 m. However, the robots had different directions and different relative distances to each other when the robots move further.

4.1.1 1×6 m Arena

Figure 5 shows that their destination has reached by all individual robots and mutually avoided collision among the robots along the way. In 0-15 seconds, the swam robot moved in tandem. In the 40 seconds, the robot position were closed to one another, however the robot did not collide, moreover, they could avoid to hit the wall. The movement of robots when avoiding obstacles could be seen in the screenshot of real video image as shown in Figure 4 (b). For first 10 seconds, the robots were dispersed and at next 50 seconds, their positions were closed together and reconnected.



(a) (b)

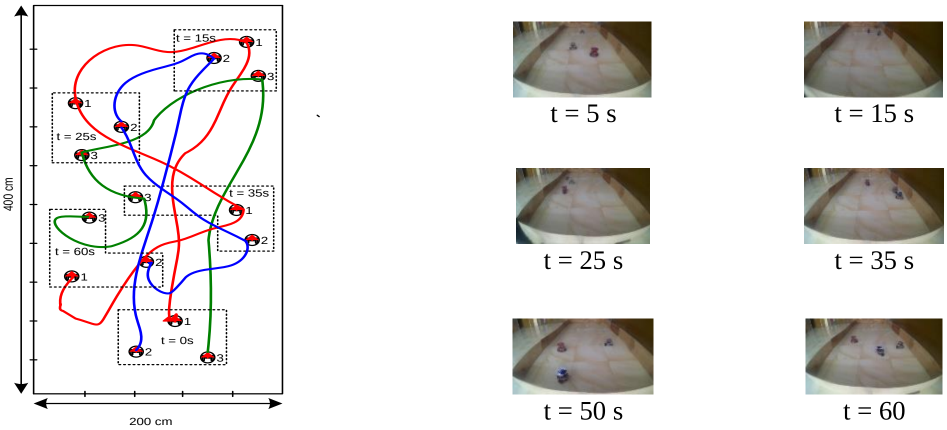
Figure 5. Swarm robot coordination experiments in arena 1x4 m (a) tracking robot (b), experiment photographs

In the 1 × 6 m arena, the motor moved slower than the other arena. This is because of the arena had a width of only 100 cm, while the dimensions of each robot was 17 cm. The robots would search their safe positions to avoid obstacles. In this arena, the movements of swarm robots in maintaining position and direction with a certain distance were difficult to be coordinated due to the narrow space of the arena.

4.1.2 2×4 m Arena

In arena of 2x4 m experiment, the environment was set without obstacles as in arena 1x6 m before. In Figure 6(a), It can be seen the graph of direction angle vs time per second. It can be found that with the increasing of time, the direction angle gradually reached its final position. Figure 6(b) is the experiment photographs of t=5s, t=15s, t=25s, t=35s, t=50s and t=60s, respectively. It can be seen that the robots moved in the same direction and the same distances.

From the experiment, it showed that three robots moved in the coordination one another. Swarm robots movement can be seen in Figure 6. All the robots could avoid obstacles and moved around the arena in smooth movement. The data of direction angle vs time are shown in Figure 6. From the graph, it can be concluded that there were direction angle changes vs time per second in the range of 10-15, 20-25, 45-50 and 75-80. It was due to the robots detected the obstacle and the wall. After reaching a safe position, each robot will lower the speed and waited for another robot to move back in the same direction to reach the specified position. Once individual robots gathered in the specified destination, they would only move around the destination area.



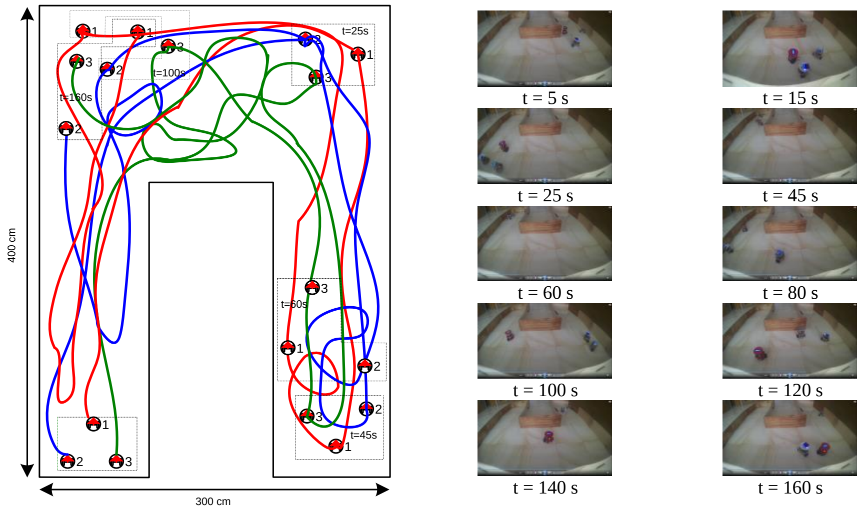
(a) (b)

Figure 6. Swarm robot coordination experiments in arena 2x4 m (a) tracking robot (b) experiment photographs

4.1.3 3×4 m Arena

In a subsequent experiment, to show that the robot can be applied in an unknown environment, some obstacles (walls) were given in the arena. In the 3×4 m arena in Figure 7, it showed that all individual robots had moved positions along with one another and avoided obstacles along the way. At the 25 seconds, each individual robot assembled in an adjacent position, however, they could not move freely. This is because there were obstacles in the form of walls, so they dispersed, and after a safe position, they would return back together (at 45 seconds). In this environment, the movements of the swarm robots were able to coordinate in maintaining the position and direction with a certain distance.

From several experiments that had been conducted in a different arena, it could be concluded that the real robot swarm movement was the individual mobile robot that could achieve its goals effectively. Movement of the swarm robot co-ordination showed the performance of behavior in searching purpose. At the moment of the adjacent position, the robot would reduce the speed and rotate in the other directions until it reached the safe position. Once the safe position got, of the robot would gather to the same location and went hand in hand in the same direction.



(a) (b)

Figure 7. Swarm robot coordination experiments in arena 3x4 m (a) tracking robot(b) experiment photographs

In arena 1x6 m, the motor speed movement was slower than other arenas. This is because of the arena had the width of 100cm, while the dimension of each robot 17cm. The robot would decrease speed to find a secure position in avoiding obstacles. While on the larger arena (2x4 m), the robot moved in the same direction and coexisted almost every time. The movement of swarm robot was more stable. In the arena of 3x4 m with the limiting wall section, the travel time of the robot was slower than in the arena 2x4 m. This is because of the position of the adjacent robot from the beginning and each robots slowed down the speed to achieve a secure position.

4.2. Rssi Measurement

Received Signal Strength Indicator/RSSI is the signal level (in -dBm) of last good packet received. There are two techniques to read RSSI value: 1) RSSI value is encoded into Pulse-Width Modulated signal available at the X-Bee module, and 2) RSSI value is read via an API command. The RSSI value reported by X-Bee Promodule is between -36 to -100 dBm while that of a standard X-bee module is between -23 to -92 dBm. However, the XBee manual says that the reported value is accurate between -40 dBm and the sensitivity of Xbee module's receiver [25].

In this experiment, for RSSI measurement, two XBee Pro modules (for example, one node is a Coordinator and the other is a Router/End device) were connected and then the distance between them was varied to measure the relationship between RSSI values and distances. In the RSSI reading experiments, three mobile robots containing the X-Bee Series modules, one as Coordinator and other as Router/End device.

This experimental setup involved 1 transmitter for each robot and 1 receiver that could communicate continuously. Each robot would attempt to follow the trace of other robots by sensing their signal strengths. The robot could estimate the distance of nearby robots by measuring the Received Signal Strength Indicator (RSSI) of the received radio messages. However, the RSSI measure was very noisy, especially in an indoor environment due to interference and reflections of the radio signals.

As shown in Figure 8, at arena 1x6 m, the time needed by the robot 1 to travel ahead was more than other robots. The distance between robot 2 and Robot 3 was closer, the RSSI value was -72 dBm and -45 dBm. Afterward, all of the robots moved toward the bend, the RSSI value of Robot 1 was increased. This occured because of the arena was narrow and the obstacles were only the walls. If a high RSSI value was observed, this indicated that the robot was near the signal transmitter of other robots. Therefore, the robot would be given a smaller traveling distance. Once they reached the end of the trace, they would travel further into the unknown environment until they could maintain the minimal connection to the rest of the group. Then, a greater travel distance would be given to the robot when the observed RSSI was small. This was done to reduce the execution time and reduce the possibility of errors closed distance.

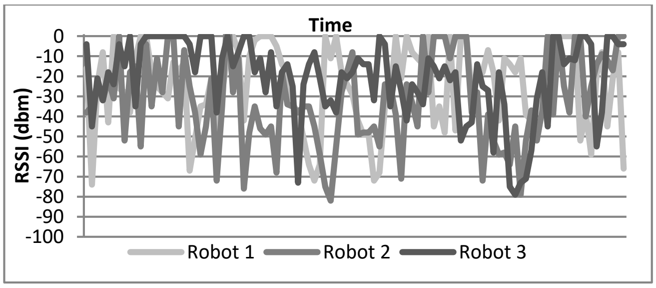
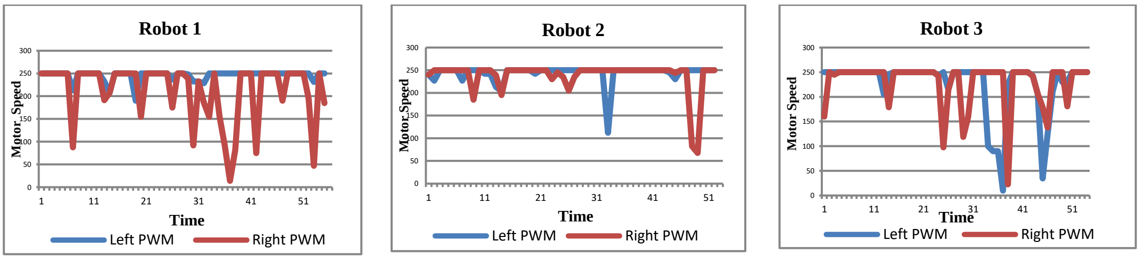


Figure 8. RSSI values from experimental environment

4.3. Experimental Results On Fuzzy Robot For Coordination

The experiment was conducted in a laboratory with an environment conditioned in three arenas 1x6 m, 2 × 4 m and 3x4 m. Swarm robot with three identical robots with different colors moved together in tandem with great coordination among them. At the moment the robot coordinated in a free and broad environment (2x4 m), then the robot moved to turn according to logic. The robot would go together simultaneously if in front ofthem, there was a hitch in the form of a wall, then the robot slowed down the motion and then turned maneuvering (hard velocity). This proved that fuzzy logic was capable to work as a controller on the mobile robot as it could provide a good motion response. In Figure 9, the mobile robot movement response was shown as the change of left and right PWM motor. The robot did not hit the wall or other robots during the move in the free environment.

The data of motor velocity vs time per second are shown Figure 9. It can be seen that if the speed of PWM was fast and the robot went straight, it meant that there was no obstacle; the robot was in a safe position. While in an insecure adjacent position, the robot would reduce the speed and rotate the direction to find a safe position.



(a) (b) (c)

Figure 9. RSSI values from the experimental environment (a) robot 1 (b) robot 2 (c) robot 3

5. CONCLUSION

This paper reported the analysis of a swarm robot coordination using fuzzy logic to control the coordination among individuals in the swarm. The relationship between a direction of motion in the coordination and exchange of information through wireless communication was established. In this experiment, robots coordinated to other members using wireless communication. Each robot would try to follow the other robots by sensing their signal strength. The robot could estimate the distance to the nearest robot by measuring the Accepted Signal Strength Indicator (RSSI) of the received information.

The information received by each robot is based on input from the environment, which is controlled using fuzzy logic. In this experiment, it can be concluded that the size of the environment affected the coordination of the robot movement. In the narrow arena, the robot's movement was slower than the larger arena. This slower speed was due to each robot lowered their speed to find a safe position to avoid obstacles. The swarm robot moved in the same direction in tandem and each robot maintained their position within a certain distance.

Our future work will focus on swarm robots that can coordinate in making and keeping formation. Further research that can be developed is controlling formation with static and dynamic environmental conditions. Thus, better results can be achieved for further research.

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