Development of a Miniature Robot for Swarm Robotic Application

Farshad Arvin, Khairulmizam Samsudin, and Abdul Rahman Ramli

Abstract— **Biological swarm is a fascinating behavior of nature that has been successfully applied to solve human problem especially for robotics application. The high economical cost and large area required to execute swarm robotics scenarios does not permit experimentation with real robot. Model and simulation of the mass number of these robots are extremely complex and often inaccurate. This paper describes the design decision and presents the development of an autonomous miniature mobile-robot (AMiR) for swarm robotics research and education. The large number of robot in these systems allows designing an individual AMiR unit with simple perception and mobile abilities. Hence a large number of robots can be easily and economically feasible to be replicated. AMiR has been designed as a complete platform with supporting software development tools for robotics education and researches in the Department of Computer and Communication Systems Engineering, UPM. The experimental results demonstrate the feasibility of using this robot to implement swarm robotic applications.**

Index Terms— **Autonomous, AMiR, Swarm intelligent, Low-cost, Platform, Education.**

I. INTRODUCTION

Robots are increasingly being integrated into working tasks to replace humans. They are currently used in many fields of applications including office, military tasks, hospital operations, industrial automation, security systems, dangerous environment and agriculture [1]. Several types of mobile robots with different dimensions are designed [2-9] for various robotic applications. The autonomous swarm mobile robot is a strategy to provide a robust and flexible robotics system by exploiting a large number robot [10, 11]. This strategy allows coordination of simply physical robot to cooperatively execute a single global task. Each individual robot in the swarm should have an autonomous behavior without any human intervention. The economic cost problem are often associated with swarm applications due to the large number of robots required (>100 unit). The design of AMiR has considered this issue and due to its small size, experiment could be conducted cost effectively in a small working area.

Commercial robot manufacturers provide various robotics solutions and accessories for teaching, research and development [12, 13]. However, the associated cost and expandability of the robot architecture is a concern. Nearly all commercial robots does not have suitable development environment to implement swarm scenarios. Although the size of AMiR is small (6cm x 7.3cm x 4.7cm), it has been equipped with required modules such as perception, locomotion and communication. Additional small peripheral can be designed and connected as a stackable extension board with simple communication scheme.

Jasmine [14, 15] is a robot platform designed specifically to implement swarm applications. Although the details of the designs are available, Jasmine is designed as a micro-robot in the size of less then 3cm cube. Hence, it could not be easily reproduced without incurring significant cost. Most of the hardware modules need to be redesigned since the component is not available locally and cheaply. A low-cost and accessible robot platform for students and researchers interested with swarm robotic is required.

One important criteria for a robotic platform especially for educational purpose is the software development tools including basic low-level hardware control, autonomy cycle control and simulation environment. Due to these development tools research experiments could also be conducted quickly. A software stack including low-level and useful functions such as distance estimation and local communication are provided for AMiR. The library of functions allows the user to program the robot for specific single and multi task scenarios without detail knowledge of the mechanical and electronics implementation.

In this paper, we introduce a low-cost Autonomous Miniature Robot (AMiR) to be used in intelligent swarm applications as shown in Fig.1. AMiR employs a reliable short-range communication [16] and smooth motor control based on PWM technique. The robot has been designed with low-power consumption and a small-capacity lithium-polymer battery (3.7v, 400mAh) can provide around two hour of autonomy.

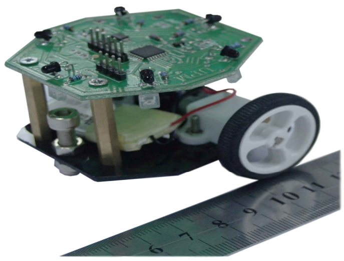

Fig.1 The prototype of Autonomous Miniature Robot (AMiR)

The rest of this paper is organized as follows. Section II provides an overview of swarm robotic and the minimal requirement of each individual robot unit. Section III details the hardware architecture of AMiR including the robot

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sensors, controller unit, local communication, power-supply, stackable extension and locomotion modules. Section IV describes the software stack implemented for AMiR to assist the user in developing swarm application. The characteristics of the modules are evaluated based on experiment presented in section V.

II. Swarm Robotic

In swarm robotic scenarios, in addition to environment perception, each robot could communicate with surrounding robots in the environment. These robots should be able to determine at least one of the information concerning the relative position, orientation, and velocity of other robots. The ability of the robot to communicate depends on the computational resources and also the type and amount of sensors that are employed on the robot. A large number of robots would communicate with each other and cooperate to execute a specific global behavior. This swarm behavior requires frequent updating of sensor-based information between each individual unit. The capability of the controller, sensors and communication system is a significant performance parameter for swarm robot.

A powerful yet cost-effective processor is required for the controller unit to provide constant change of individual behavior in real-time as well as the whole group of robot. Swarm controllers have an additional task compared to the individual mobile robot controllers. The swarm robot controller must be able to perform local communication with nearby robot to decide or share the states of swarm in addition to the basic local behavior such as obstacle avoidance and locomotion.

The inter-robot communication is a significant task which allows multiple robots to accomplish complex behaviors in swarm robot scenarios. The swarm could not achieve the global task without reliable and efficient data transmission techniques. Mobile robots use various communication methods such as wireless network [17], Bluetooth [18], Ultrasonic and Infra-Red (IR) [10, 19]. Each method has its own advantages and drawback for different mobile robot scenarios.

Various communication techniques have been evaluated in multiple robot environments. Several researchers use image processing technique for multiple robotic environment recognition [20, 21]. Implementation of vision-based technique is complicated and requires a lot of computing resources. Radio communication has also been used for multiple robots environment [17, 18]. Although radio communication allows long distance communication, several other problem exist [22]. One of these problems is the limited communication channel especially when a large number of robots are deployed in the environment. Radio-based communication also faced with distance estimation and location approximation problems.

The local communication technique is the most appropriate method for distributed robotic systems [23]. In this work, infrared is used to implement a reliable local communication as well as sensor system. In the following section, the detail requirement of AMiR hardware architecture will be presented.

III. Hardware Architecture

A. *Infra-Red Sensor*

AMiR is equipped with IR emitters and IR phototransistors. The infra-red will be used as environment perception and provide local communication between individual unit. Fig. 2 shows the main board of AMiR that uses 60º receivers and transmitters topology. This configuration allows AMiR to scan all around of its area.

The phototransistor chosen is a TEFT-4300 with wide viewing angle feature of approximately 60º. It is suitable for sensing nearby IR radiation with fast response time of micro-second range. The maximum sensitivity of this receiver occurs in wave-length of 925nm. The maximum working frequency of this receiver is 180 kHz, which provides enough baud-rate to implement the proposed local data transmission technique.

The IR emitting diode is a TSKS-5400 that comes in a side-view plastic package. A small recessed spherical lens provides an improved radiant intensity in a low profile case with peak wavelength 950nm. The maximum radiant power of this emitter component is approximately 10mW, with switching time is in millisecond range.

B. *Controller Unit*

An AVR microcontroller series is deployed as the main processor for managing all AMiR's modules. This microcontroller, an ATMEGA168 clocked at 8.0 MHz using the internal RC oscillator provides the necessary computational power to have a real-time sensory system. The microcontroller has 16 kilobytes of programmable flash memory and one kilobyte of internal SRAM that provides more than enough space to implement basic reactive behavior and different complexity of swarm algorithms. The low-power feature of the microcontroller that only needs approximately 250µA in active mode is important to provide long term autonomy to the robot.

As the infra-red sensors are used for reactive behavior and provide local communication, the microcontroller will serve the input with its interrupt routine. The received analog signals are digitised by the microcontroller's analog to digital converter (ADC), which are used by the distance estimation function.

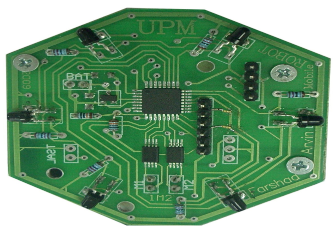

Fig.2 The main board of mobile robot (60º transceivers topology)

The microcontroller would then call a function to decode the received IR packet. As the unique ID of the individual AMiR is included in the broadcast, it will be able to differentiate obstacles and other robots from the received signal as shown in Fig. 3. AMiR detects obstacles when it receives its reflected ID. Further IR packet digestion for communication purposes will be handled by the local communication module. The flowchart for the ID-based processing technique is shown in Fig. 4.

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C. IR-based local communication

AMiR communication messages are crafted using similar packet format as shown in Fig. 5. The broadcast mode communication is used for obstacle detection and trajectory information sharing with neighboring AMiRs. In this mode, all data broadcasted with the IR emitters, will be detected by the phototransistors.

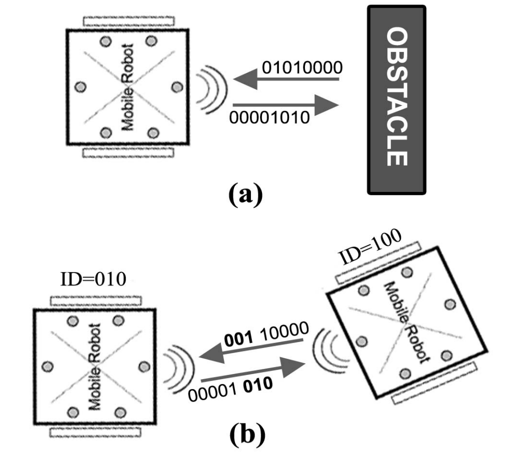


Fig.3 Detection principles: (a) robot detects the obstacle if receives its ID packet that was reflected, (b) recognizes other robot if receives new ID

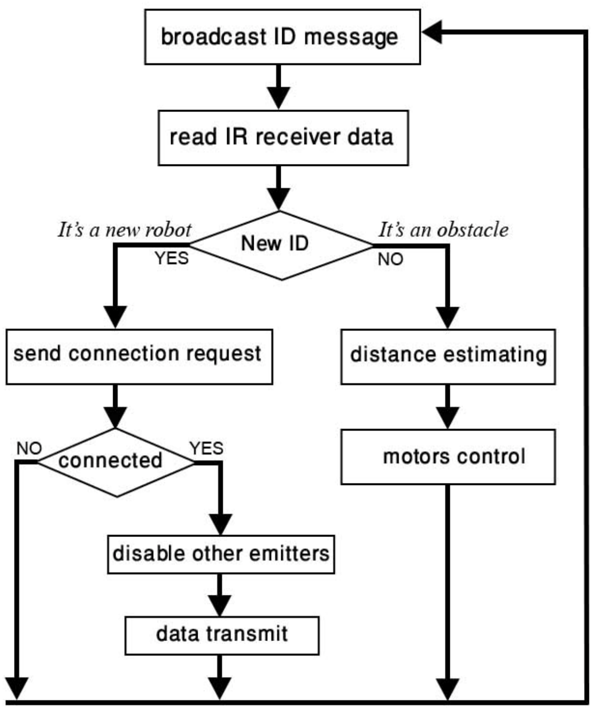


Fig.4 Flowchart of the ID-based processing technique

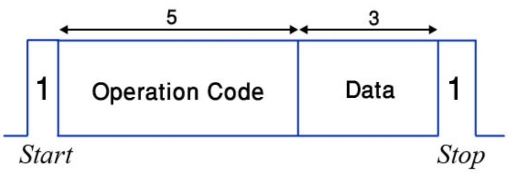


Fig.5 Structure of robot's messages

TABLE I. SELECTED BATTERY SPECIFICATION

Specification	**Value**
Voltage	3.7 v
Capacity	400 mAh , 1.48 Wh
Dimension	40 × 22 × 5 (mm)
Weight	10 g (battery)
Specific energy	$\frac{1.48}{0.01} = 148 \, Wh/kg$
Energy Density	$\frac{1.48}{0.04 \times 0.022 \times 0.005} \approx 337 \, kWh/m^3$

All participating AMiRs in a swarm scenario must be able to communicate among them. They obtain and share recorded data such as recognized obstacles and other robots messages necessary for swam application. This type of communication requires a reliable connection between two AMiRs. A handshake-based communication has been provided for complex cooperation of swarm multiple robots. This message is used to perform high-level behaviors in swarm AMiRs.

The designed communication module modulates its messages with a frequency of 1 kHz. Therefore, AMiR is capable to transmit its messages at 1000 bit per second baud rate. Hence, the required time for transmitting each packet as defined in Fig. 5 will be 10ms including start and stop bits. The demodulation of the messages by the receiver robot use one of the microcontroller timers for sampling. The detail communication related software functions implemented will be provided in the software development section.

D. Power Consumption

Battery or energy is an important issue especially in swarm mobile robots scenarios. Several types of rechargeable batteries are used in mobile robots. The Lithium-Polymer (Li-Po) has several advantages such as higher energy density, thinner size, safety performance as to other rechargeable batteries [24, 25]. It is able to provide high discharge, fast charging period and able to withstand high frequency charge-discharge cycle. In addition, this battery series has capacity retention and low self-discharge rate which is less than 5% discharge rate per month. AMiR is powered by a 3.7v Li-Po battery with 400mAh capacity. A control circuit is required to protect battery-life during charging time [26] as the Li-Po battery is very sensitive in charging period. A microcontroller based recharging station has been developed. The microcontroller provides suitable control to regulate the charging process. The selected battery specification is shown in Table I.

The discharge time is calculated by the flowing formula:

$$t_{discharge} = \frac{C}{I_{avg}} \tag{1}$$

Where C is the capacity of battery and I_{avg} is the average current of AMiR.

The on-line battery level samples are obtained using a simple voltage divider circuit. The controller unit can obtain the battery level of AMiR using the following formula:

$$V_{sample} = \frac{R_1}{R_1 + R_2} V_{Batt} \tag{2}$$

$$R_1 = R_2 \Rightarrow V_{sample} = \frac{1}{2} V_{Batt} \tag{3}$$

Similar 100 kΩ resistors are selected for the voltage divider circuit. The large resistant is selected to ensure that the current consumption of this circuit will be very small (approximately 0.018mA). One channel of the microcontroller ADC is used to measure the battery level during AMiR operation.

E. Modularity

Modularity is an important feature for a robotic platform. The robot must provide an extension interface that allows attachment of GPS, color sensing board, power management board, and Gradient light board [15] to enhance swarm robot researches. AMiR can be extended with additional peripheral and connected as a stackable extension board provide. It uses a versatile serial communication scheme and shares its power supply with the extension board.

F. Motion Control

The locomotion is another significant part of each mobile robot [27, 28]. Differential drive with a caster wheel configuration is used by AMiR and a reliable motion control of differential drive technique is employed [29, 30]. Most mobile robot only provides simple motion control by switching the motor on and off [12]. However, these robots are not able to control their velocity and trajectory precisely. Our designed AMiR is able to select different speeds for its motors. The velocity of AMiR is calculated by the following formula:

$$V = pd_w N \cong 854 \ {}^{cm}\!/_{\min} \qquad (4)$$

Where d_w is the diameter of AMiR wheel is 32mm and N is the speed of the motor which is 85 RPM.

The rotation and motion estimation is required for robot localization. Two different methods are used for AMiR rotation about a point: i) rotation with large diameter as shown in Fig. 6(a) which the axis of rotation is out of AMiR area, and ii) turning in place as shown in Fig. 6 (b) which the axis of rotation is in center of AMiR's wheelbase.

In large diameter rotation, both motors rotational speed is different and calculated by the following formula:

$$N_L = \frac{2R+W}{2R-W} N_R \qquad (5)$$

Where N_L is the speed of left motor and N_R is speed of right motor. W is the wheelbase width and R is the radius of rotation. Also, radius of rotation is calculated by the following formula:

$$R = \frac{W}{2}\left(\frac{N_L + N_R}{N_L - N_R}\right) \qquad (6)$$

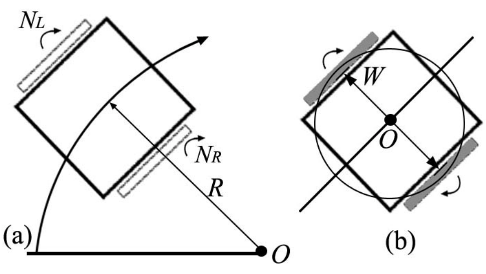


Fig.6 AMiR rotation types , (a) the axis of rotation is out of AMiR area, (b) turning in place

This equation is relative between wheelbase width and wheels' velocities.

For turning in place, both motors run in similar speed with different direction. The speed of wheels is calculated by (4). The time required to n rotate is calculated by:

$$x = npW \qquad (7)$$

$$(4,7) \Rightarrow t = \frac{x}{v} = \frac{n \cdot W}{N \cdot d_w} \qquad (8)$$

The AMiR maximum pushing force is a function of robot's weight. So, the maximum force of designed AMiR is calculated by (9) where μ is the coefficient of friction and W is the weight of AMiR:

$$F_{\max} = m \cdot F_N = m \cdot W_{AMiR} \qquad (9)$$

Pulse-width modulation (PWM) technique is employed to control AMiR DC motors [31]. In this technique, when the logic one pulse-width gets longer, it results in an increase of the motor's speed. The average of output voltage in higher frequency is calculated by the following formula:

$$V_{out} = \frac{t_{ON}}{t_{ON} + t_{OFF}} V_{in} \qquad (10)$$

Where t_{on} is duration of pulses with logic one and t_{off} is duration of pulses with zero logic. The Si9988 integrated H-bridge [32] circuit is used for driving AMiR motors. It is able to provide continuous 650mA current which is used as the motors driver.

IV. Robot Software Development

The robot development software complements the hardware architecture of the robot by providing basic low-level hardware control that include reading the sensors value and controlling the motor speed. It also provides basic functions to implement local communication for different swarm scenarios.

A software library is provided for programming AMiR. The aim of the library is to provide modular programming for defining swarm application with AMiR. The basic functions are implemented using C programming language. However some critical functions such as interrupt routines and timers will be implemented in assembly language.

The library includes basic positioning, sensing and control functions, communication related functions, swarm behavior functions, and data logging.

A. Positioning, sensing and control

These basic functions define important fundamental mobile robot perception and action behavior such as reading sensors, motors control, serial interface communication, interrupt routines, and timer functions. The details of several basic functions are shown in Table II.

B. Communication

In these instructions, after receiving another AMiR message, the individual AMiR will transmit its own message packet to initiate their connection and wait for an acknowledgement message during a defined time as shown in Fig.4. The connection request will be eliminated if the AMiR does not receive any acknowledgement response. Table III is the list of several instructions which AMiR uses to communicate.

C. Swarm Behavior

Several high-level functions are provided to simplify execution of swarm scenarios. These functions will make use of the basic and communication function described earlier. In addition, several implementations of swarm scenarios will be provided.

D. Data Logger

AMiR would store the last 100 converted values of IR receivers to facilitate swarm behavior decision. The allocated memory could be varied depending on requirement of the robot. In addition, the library allows AMiR to record received messages and events which are transmitted by other AMiRs. Successful connection between AMiRs would also be saved with the ID number of communicating robots.

V. Results and Discussion

In this section, the performance of AMiR is evaluated and the experimental results are discussed. Fig. 7 illustrates the experimental environment for evaluating AMiR.

A. Distance estimation

The sensor system was tested in various lighting environments such as sunlight, dark room, and fluorescent light room. The sunlight includes infrared radiation and could significantly affect the measured value. The fluorescent light wavelength is less than 700nm and as a result, the measured values in fluorescent lighted room are almost similar with measurement from dark room. Black body and white body obstacle have been used to evaluate the distance estimation function. Fig. 8 (a) illustrates the converted ADC values of reflected IR radiation from white body obstacle in indoor and outdoor environments. The white body obstacle reflects more IR radiation than black body. The measured samples with black body are shown in Fig. 8 (b).

Distance estimation would depend on measured IR samples which are reflected from obstacles. In this design, the maximum distance for obstacle detection is about 12cm with tolerance ±1cm. The sensitivity of sensors would also depend on emitter diode intensity which is relative to emitter diode quality and battery level.

Results of another experiment for obstacle detecting with narrow obstacle (10mm in width) in different angles are shown in Fig. 9.

B. Message transmission

For multiple-robots cooperation, individual robot must be able to be to communicate with other robots. To perform wireless robot's communication using the Infra-Red system, some communication functions have been provided as shown in Table III. Various messages can be defined for implementing different swarm scenarios.

TABLE II. List of Basic Instruction for AMiR Controlling

Function	Description
Read-Sensors	Read all IR sensors' values
Transmit-Message	Transmit message with IR emitters
Send-Serial-Data	Send data with serial port to PC
Battery-Level	Read battery level
Motors-Enable	Enable DC motors
Motor-Rotate	Rotate motors to left and right
Motor-Direction	Change motors direction, forward and backward
Motors-Speed	Change speed of motors with PWM
Read-Distance	Read the distance of obstacle

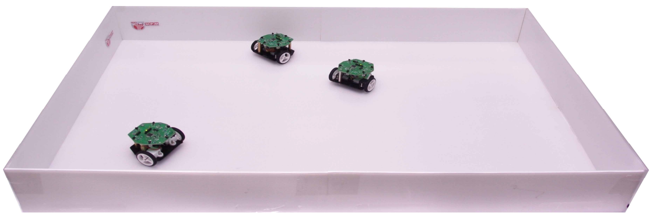
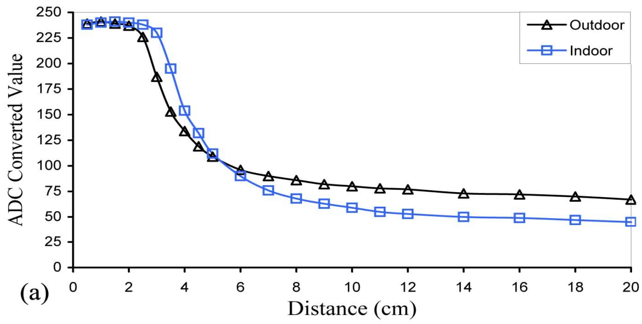


Fig.7 AMiR experimental environment



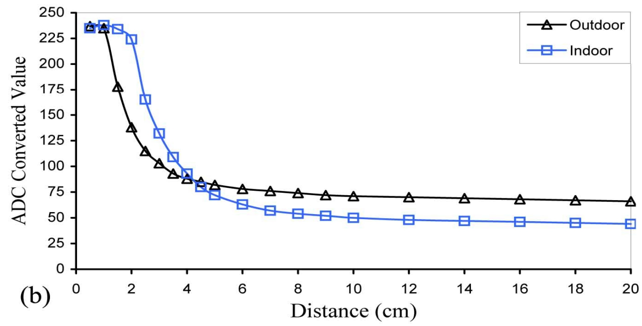


Fig.8 (a) ADC converted values from white body obstacle's reflection, (b) ADC converted values from black body obstacle's reflection

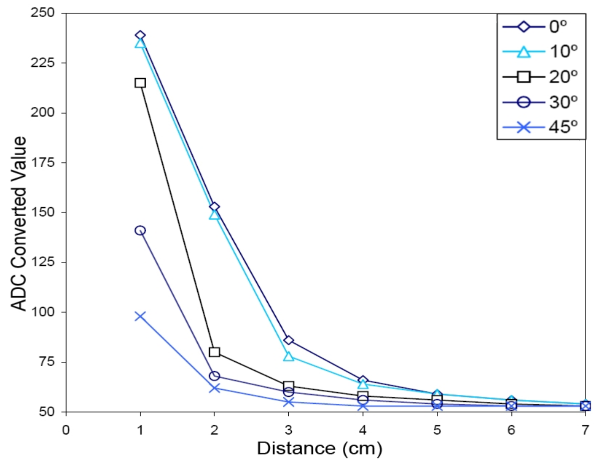


Fig.9 ADC converted value for an obstacle (10mm in width) at different angles and distance

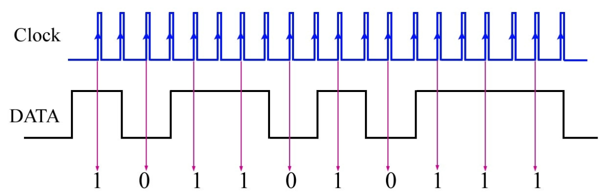


Fig.10 Messages demodulation in receiver AMiR

TABLE III. WIRELESS COMMUNICATION MESSAGES

Function	Description
Receive-Message( )	Read received IR data buffer
Send-Message ( )	Send message with IR emitters
Send-Message-Conf ( )	Send confirm-based message
Send-ACK ( )	Send acknowledge for confirm-based messages

The AMiR is able to modulate its message with defined frequency. It uses asynchronous communication mode to send its serial messages. The sampling process is shown in Fig. 10. The samples are obtained during each odd rising edge of sampling clock.

The communication reliability was tested in four different angles between two robots. One thousand messages were sent in each angles experiment. Fig.11 illustrates correctly received messages percentage in each angle.

C. *Power consumption*

The experimental results of the mobile-robot power consumption were obtained in three different working states. In these states, robot had various power consumption modes. Table IV shows various working tasks of AMiR. The lithium-polymer battery could be used until a minimum working voltage of 3.0v is reached. When battery level reaches this threshold, the robot changes its state to standby mode to protect the battery life time.

Fig. 12 illustrates AMiR power consumption diagram in three tasks that requires more rotational movement, normal tasks, and without rotational movement. Frequent changes of the motors speed and its direction increase the power consumption. However the duration of autonomy is still reasonable to execute swarm application. For long term autonomy, AMiR is able to dock to a recharging unit or a movable charger robot could be included in the swarm as proposed in [33].

D. *Motors' Speed Control*

Fig.13 illustrates the ratio of PWM register value to output voltage. The PWM register value is between 0 and 1023. The values between 0 and 512 are used for forward movement and the values between 512 and 1023 are used for backward movement.

The results of different rotations for turning in place mode are shown in Table V. The second column values are calculated by (8). Third column content are the results of AMiR rotation with *t* millisecond turning and the fourth column values are the ratio of calculated rotation angle to real result which illustrates coefficient of fault in mechanical units. This ratio and also Fig. 14 shows the additional constant gain value equal by about 0.91 which is linear const value. Therefore, to calculate the real turning time for AMiR rotation, we have to multiply 0.91 by result of (8). This number is called coefficient of mechanical fault. Therefore, the new rotation time estimation formula is as follows:

$$t = 0.91 \times \frac{n \cdot W}{N \cdot d_w} = 0.91 \times \left(\frac{n \times 6.5}{45 \times 3.2} \times 60 \right) \sec \qquad (11)$$

TABLE IV. POWER CONSUMPTION OF AMIR IN THREE DIFFERENT TASKS

Working Task	Current	Autonomy
Normal task in robotic environment	210 mA	125 min
Without any fluctuation in velocity	190 mA	135 min
With fluctuation in velocity	260 mA	110 min

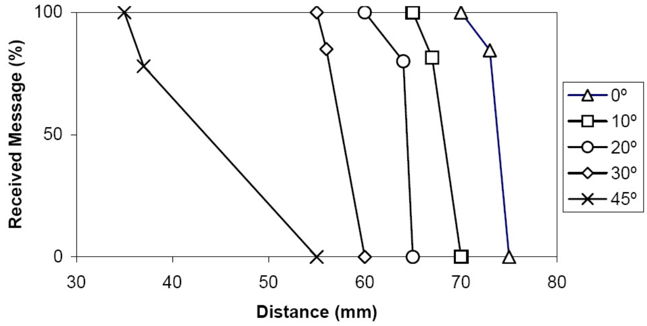


Fig.11 Reliability of local communication in percentage as a function of distance and communication angle

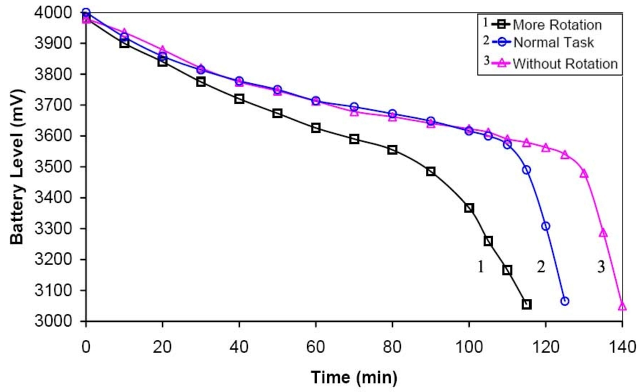


Fig.12 Diagram of AMiR power consumption in three states

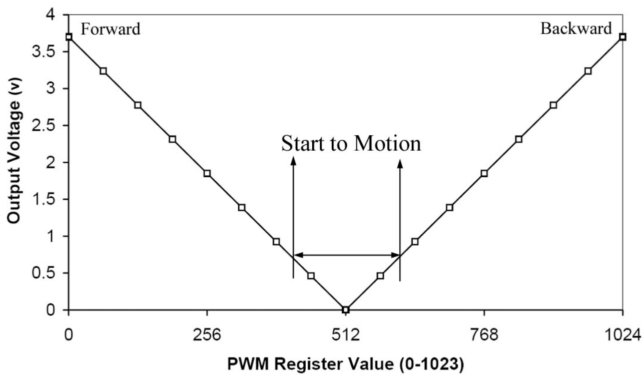


Fig.13 The PWM register value to output voltage (speed) ratio

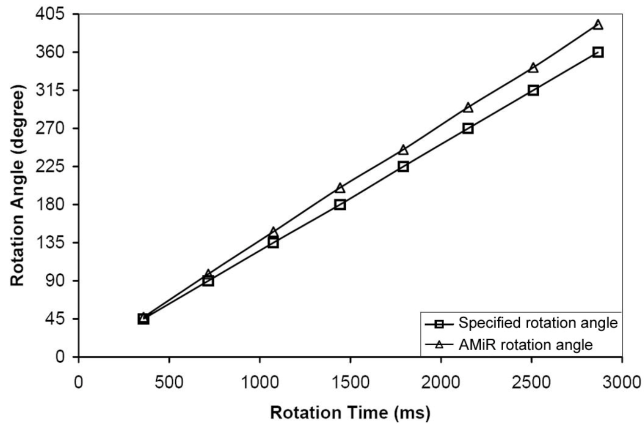


Fig.14 Comparison of AMiR actual and calculated rotation angle as a function of time

TABLE V. RESULT OF AMIR TURNING IN PLACE

Rotation	Calculated *t* by (8)	AMiR Turning	Fault Coefficient
45 º	338 ms	47 º	0.95
90 º	676 ms	98 º	0.91
135 º	1014 ms	148 º	0.91
180 º	1352 ms	200 º	0.90
225 º	1690 ms	245 º	0.91
270 º	2028 ms	295 º	0.91
315 º	2366 ms	342 º	0.92
360 º	2704 ms	393 º	0.91

VI. CONCLUSION

We present a new autonomous miniature robot (AMiR) which has been developed for low-cost swarm applications platform. This robot can estimate distance of obstacles and recognize multiple-robot in an environment. This robot is capable of performing short-range communication using the IR signal. It is able to have around 120 minutes of autonomy period using small capacity lithium-polymer battery. Currently an implementation of AMiR in the PlayerStage simulation environment is actively being developed. Development of AMiR would facilitate and enhance the swarm robotics education and research.

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