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Development of IR-Based Short-Range Communication Techniques for Swarm Robot Applications

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***Abstract*—This paper proposes several designs for a reliable infra-red based communication techniques for swarm robotic applications. The communication system was deployed on an autonomous miniature mobile robot (AMiR), a swarm robotic platform developed earlier. In swarm applications, all participating robots must be able to communicate and share data. Hence a suitable communication medium and a reliable technique are required. This work uses infrared radiation for transmission of swarm robots messages. Infrared transmission methods such as amplitude and frequency modulations will be presented along with experimental results. Finally the effects of the modulation techniques and other parameters on collective behavior of swarm robots will be analyzed.**

***Index Terms*—Swarm Robotic, Infrared, AMiR, Modulation Methods**

I. INTRODUCTION

Swarm mobile robot is a new coordination approach for multiple robots to cooperatively achieve a single global task [1]. Each of the mobile robots in the swarm should have autonomous behavior without any central controller. Thus, communication between mobile robots is a significant task which allows multiple robots to accomplish complex behaviors in swarm robots' scenarios. The autonomous mobile robots cannot execute their programmed tasks without suitable data transmission techniques [2], [3].

Infrared (IR) light is an electromagnetic radiation with longer wavelength than visible light. The IR wavelength is between 750nm and 1mm. It is used in many applications such as military, thermal efficiency, remote temperature sensing, and short-range wireless communication. The IR is divided into three bands: i) IR-A is between 700 nm and 1400 nm, ii) IR-B is between 1400 nm and 3000 nm, and iii) IR-C is between 3000 nm and 1 mm. Utilized robot platform uses IR components with 950nm wavelength that are in IR-A band. This wavelength is the popular wavelength in many short-range remote controlling systems that employ IR wireless data communication. Several developed standards are used in IR data transmission [4], [5] and are common approaches in multiple-robots communication environment.

AMiR is an autonomous mobile robot which is designed for swarm applications [6]. This robot uses six IR emitter diodes and IR phototransistors. It is a low-cost platform suitable for education and research in swarm robotics. The AMiR is shown in Fig. 1. It has a small form factor and preliminary tests show the reliability of the communication modules for swarm applications [7].

In this paper, infrared-based communication for swarm application is discussed. Different IR transmission techniques are presented and the performance of each method will be evaluated. Modulation based on amplitude and frequency which are two major approaches in wireless communication are the case of the study. In addition, the reflected IR signal has been utilized to detect surrounding obstacles and estimate obstacle distance.

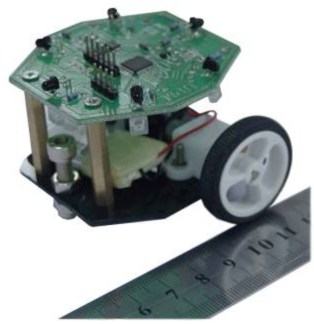

Fig. 1. Autonomous Miniature Robot (AMiR), is a swarm robotic platform

II. SWARM ROBOTIC ENVIRONMENT

In swarm robotic scenarios, in addition to environment perception, each robot could communicate with surrounding robots in the environment [1]. 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 are significant performance parameters for swarm robot.

A powerful yet cost-effective processor is required for the controller unit to provide constant change of reactive individual robot behavior in real-time as well as the group behavior of the robot swarm. Swarm enabled 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.

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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 [8], [9], Bluetooth [10], Ultrasonic [11] and Infrared [12], [13]. Each method has its own advantages and drawbacks 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 [14], [15]. Implementation of vision-based technique is complicated and requires a lot of computing resources. Radio communication has also been used for multiple robots environment [8], [10]. Although radio communication allows long distance communication, several other problems exist [16], [17]. 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 [18]. In this work, infrared is used to implement a reliable local communication as well as sensor system.

III. Infrared-based communication

For swarm robotic application, infrared is a good communication medium choice compared with other wireless communication techniques such as radio frequency. Advantages of using IR in swarm applications include positioning estimation, neighboring robots recognition, direct communication and could be utilized for obstacle avoidance. For implementation of reliable communication between robots, high quality sensors and suitable algorithm using high performance processors are required.

A. IR sensors

Fig. 2 shows the main board of AMiR that uses 60° receivers and transmitters topology. This configuration allows AMiR to scan its surrounding area without turning. The phototransistor chosen is a TEFT-4300 with wide viewing angle feature of approximately 60°. 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 925 nm.

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 a peak wavelength of 950 nm. The maximum radiant power of this emitter diode is approximately 10 mW, and switching time is in microsecond range.

Fig. 3 shows the configuration of IR-emitter and IR-receiver components and also processor's connection to each component. IR-emitter diodes is powered directly by the processor at about 3.5 V while the receiver output signal is pulled-down by an 18 KΩ resistor, so robot detects start of other robots message with first logic '1' which is called start-bit. When the input is zero for long period robot recognizes there is not any message in neighboring and it is called idle-mode IR channel.

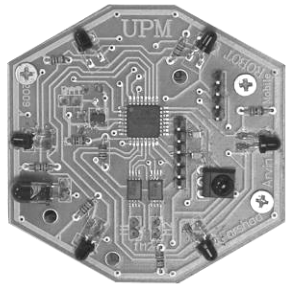

Fig. 2. The main board of platform robot (60° receivers' topology)

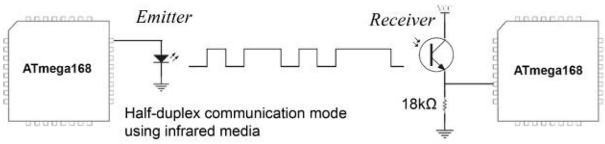

Fig. 3. Configuration of IR transmitter/receiver and processing unit

B. IR reflection

Robot's messages are modulated with unique packet format and broadcasted in the robotic environment. The reflected IR signals are used to detect surrounding obstacles and estimate the obstacle distance [19]. AMiR estimates obstacle distance using reflected IR power by utilizing the analog to digital converter (ADC) unit of the microcontroller. Fig. 4 illustrates emitted signal and reflected signal. The intensity of reflected IR signals is directly relative to the transmission media, obstacle characteristics such as color and texture, and distance of obstacle [20].

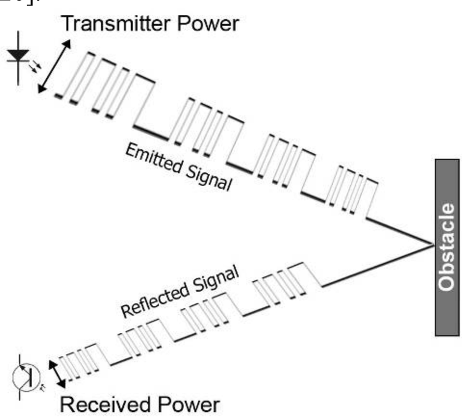

Fig. 4. Emitted and reflected infrared signals

Obstacle detection and distance estimation use fundamental principles of electromagnetic radiation and its reflections. The reflected IR value that is measured by a sensor is mathematically modeled by the following equation [19]:

$$s(x,\theta) = \frac{\alpha \cos \theta}{x^2} + \beta \qquad (1)$$

Where $s(x,\theta)$ is the output value of sensor, x is the distance of obstacle (cm), and θ is the angle of incidence with surface. The model variable α includes several parameters such as reflectivity coefficient, power of emitted IR, and sensitivity of sensor. β is the offset value of amplifier and ambient light effect. White body and black body surfaces reflect and absorb IR radiations with different ratio which is significant issue in selecting obstacle and wall for robotic environment.

C. Message Modulation Techniques

Transmission and broadcast of individual robot message is an important issue in swarm applications. Robot's message must be modulated and transmitted to others. There are several modulation techniques for data transmission which are described in the following section. Basically, digital communication uses two or more signal levels for modulation [21]. Two types of modulation evaluated are i) two signal levels and ii) a mix of frequency and signal levels. The AMiR's hardware is able to support any communication methods allowing evaluation of different modulation techniques with software programming.

1) Two Signal Levels Modulation

In this method the robot's message is represented by binary levels. This technique relies on amplitude modulation known as binary amplitude shift keying (B-ASK). Implementation of this technique is simple however it is susceptible to noise that could corrupt messages. In this technique emitter will be turn-on for data element '1' and turn-off for data element '0'. A time-out parameter is required in each robot for determining between data element and idle-mode. Fig. 5 illustrates modulation of each message using B-ASK modulation.

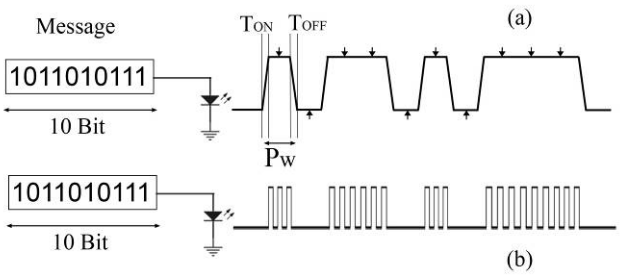

Fig. 5. Binary amplitude shift keying (B-ASK) modulation for robot's message transmission, (a) ON/OFF signals, (b) PULSE/OFF signals

T_{on} and T_{off} in Fig. 5(a) is the rising and falling times of each pulse which directly depends to emitter sensor quality and switching rate. P_W is the selected pulse-width for representing each data bit. The size of P_W is an important parameter for baud-rate calculation. Varying the size of P_W would affect the reliability of communication. Fig. 5(a) illustrates B-ASK modulation with two commands for emitter, on or off. In this case, emitted IR will achieve maximum power after T_{on}. In Fig. 5(b), emitter would stay off for logic '0' and sends pulse for logic '1' [22]. Due to signal transmission configuration, the total output power consumption will be reduced and effect of the environment will be eliminated.

The baud-rate of this method is directly related to switching rate as shown in (2). Thus, the robot's communication bandwidth is determined by several parameters including IR-components switching rate, main processor performance, and experiments environment.

$$B = \frac{1}{P_w}$$
$$P_w = 10\,ms \Rightarrow B = \frac{1}{10\,ms} = 100\,bps \qquad (2)$$

2) Frequency Modulation

The frequency modulation evaluated for the infrared communication is binary frequency shift keying (B-FSK). This modulation technique requires a carrier signal which usually an analog sin wave. This method of modulation is very popular in digital data communication and wireless radio transmission however is not common for robotic applications due to the complexity of implementation. In many wireless applications the performance and reliability of FSK is better than ASK.

Two different frequency carriers are required for implementing B-FSK. The modulated message with B-FSK transmission is shown in Fig. 6. The following relationship between two carriers has been selected for implementing B-FSK:

$$f_2 = 2 \times f_1 \qquad (3)$$

Care must be taken for deciding the carrier frequency to make sure that the switching rate of emitter diodes and phototransistors are in their operating range. A higher frequency, faster than the emitter switching time will cause the IR to lose its emitting power.

The bandwidth available for B-FSK method is calculated using the following formula:

$$B = (1 + d) \times S + 2\Delta f \qquad (4)$$

Where S is the signal rate and d is a constant value between 0 and 1 that depends on the technique of filtering and line characteristic. The Δf is the differences of both carriers' frequencies from the midpoint frequency. Carrier f_1 is used for logic '0' and f_2 is used for logic '1'. Fig. 7 illustrates the flow of demodulating a received message by the robot. It employs the timer counter of processor to partition message's elements. In AMiR, each bit duration is 10 ms.

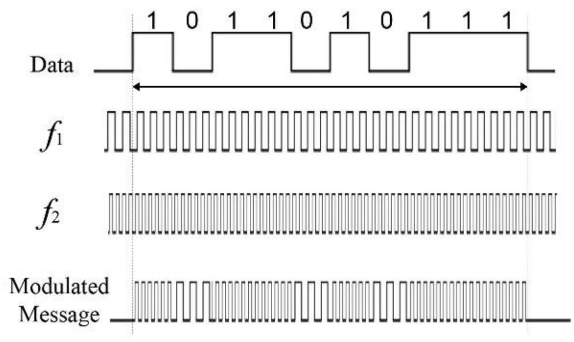

Fig. 6. Modulated robot's message using binary frequency shift keying (B-FSK) method

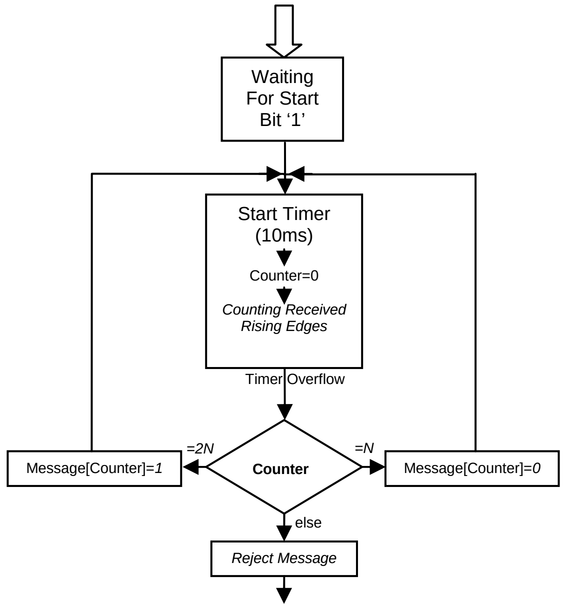

Fig. 7. FSK processing diagram, (using rising edge counter). *N* is the selected frequency for '0' (f_1)

D. Swarm Robot's Message

Several types of messages are employed in AMiR's communication. All messages are modulated with carrier signals using different modulation methods. In this section, each type of messages which AMiR uses for its defined task is discussed. Each message is formatted with 10 bits length as shown in Fig. 8.

Message packet starts with a one bit preamble of logic '1'. The next eight bits are the actual message body which consists of operation code and the operand. This data structure has been defined in the communication software layer. The last bit is reserved for future communication methods between swarm participants robots and other types of robots.

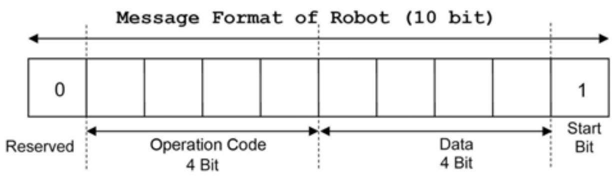

Fig. 8. Message format of mobile robot (10 bit packet)

1) Basic Messages

Swarm robots consist of individual mobile robots which are able to have joint tasks. Basic messages are used when AMiR executes its individual tasks such a collision prevention and movement coordination. Also, some of the cooperating messages which are required to have communication between other nodes such as charger station are classified in basic messages. These types of messages do not need to receive any acknowledgement from other participants. Table I lists basic messages defined for AMiR.

TABLE I
LIST OF DEFINED BASIC MESSAGES FOR SWARM MOBILE ROBOTS

Message	Function
ID	Send ID of Robot. Used for recognizing others
Low-Batt	Send Low-Battery distress signal
Follow-me	Instruct others to follow
Error	Send for any kind of undefined problem

2) Acknowledgement-Based Messages

Multiple robotic scenarios require reliable messages to perform defined swarm task. Usually these messages are acknowledgment-based and implementation of this type of communication is complex since the synchronization of messages packet is important. Table II lists defined acknowledgement-based messages to implement swarm behaviors.

TABLE II
LIST OF DEFINED BASIC MESSAGES FOR SWARM MOBILE ROBOTS

Message	Function
Talk-Req	Send request for communicating with other robot
End-Talk	Send disconnect request
Send-Data	Request for other robot recorded data
Calibration-Req	Request to calibrate IR-sensors
Motor-Speed	Similarity robots' motors speed
Define-Master	Defining a robot as a leader to others
Come-Near	While communicating, when signal-to-noise ratio is low

Fig. 9 illustrates each sent message process flow. After sending each message, AMiR waits for the IR receiver interrupt. If receivers detect any IR radiation, interrupt routine will be called and received packet will be demodulated. The detail of communications mode will be discussed in the following section.

3) Robots Communication Mode

One of the important features of swarm robots is the communication among individual robot. Robots could transmit their recorded data to others to allow accurate decision making in executing each swarm scenario. The sharing of required data between two or more robots according to required behavior is defined as talking. Talking is initiated when a robot receive a new message ID which was sent from a neighboring robots. If receiver robot requires communication, an acknowledge message will be transmitted to the neighboring robot. A complete talking process is shown in Fig. 10.

To ensure reliable communication between robots, some low-level behaviors are defined. One of these behaviors is moving closer to neighbor robot when they are ready to communicate. This ensures that each message packet errors are reduced by increasing the signal-to-noise ratio. Another technique to prevent conflict while communicating between other robots is disabling the other IR units except the one with the strongest signal.

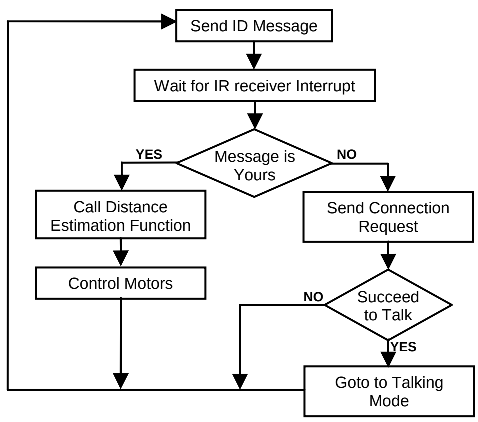

Fig. 9. Communication process to recognize other robot or detect obstacle

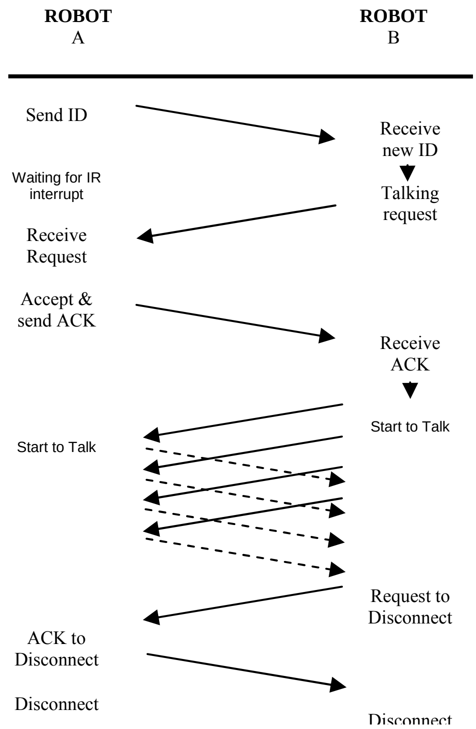

Fig. 10. Talking process between two mobile robots. Robots use basic and acknowledgement based messages

4) *Communication Baud-rate*

Baud-rate is a significant parameter for selecting communication technique which is related to transmission media, emitter's performance, and sensors quality. The designed robot communication system allows IR-emitter's switching time is in microsecond range which allows implementation of high frequency communication.

5) *Experimental Configuration of Swarm Scenario*

Presented techniques and their parameters must be tested in real robotic environment. According to swarm robotic definition [1] which robots should use a limited perception, an audio based exploration behavior is implemented to show the performance of swarm. As shown in Fig. 11, two different roles are defined for robots which are explorer and follower. Explorer robot randomly moves and checks the intensity of ambient sound which is played in one side of robotic arena. Follower robots wait for receiving IR message from explorer and other followers. Hence the reliability of inter-robot communication techniques will be tested and an analysis of collective behavior of robots will be presented.

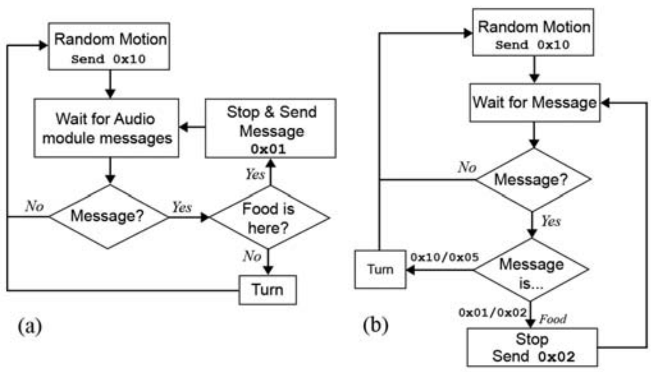

Fig. 11. (a) algorithm of explorer robot, (b) algorithm which is used for follower robots

IV. Results and Discussion

In this section several experimental results from the proposed communication methods are presented. Each method has its own advantages and disadvantages as such, selection of a suitable methods is left to the user. After analysis of independent behavior of robots, an analysis of social behavior of robots using various communication techniques will demonstrate the reliability of the selected techniques in swarm robotic scenario.

A. *IR Sensors*

The sensor system was tested in various lighting environments such as sunlight, dark room, and fluorescent light that is available in experimental environment. The sunlight includes infrared radiation of about 50% [20] and could significantly affect the measured value. The fluorescent light wavelength is less than 700 nm 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. 12 (a) illustrates the converted ADC values of reflected IR radiation from white body obstacle and model (1). White body obstacles reflect more IR radiation than black bodies. The measured samples with black body are shown in Fig. 12(b). The black body is not a good infrared reflector. As such, setup of obstacles in robotic environment requires selection of white body obstacles.

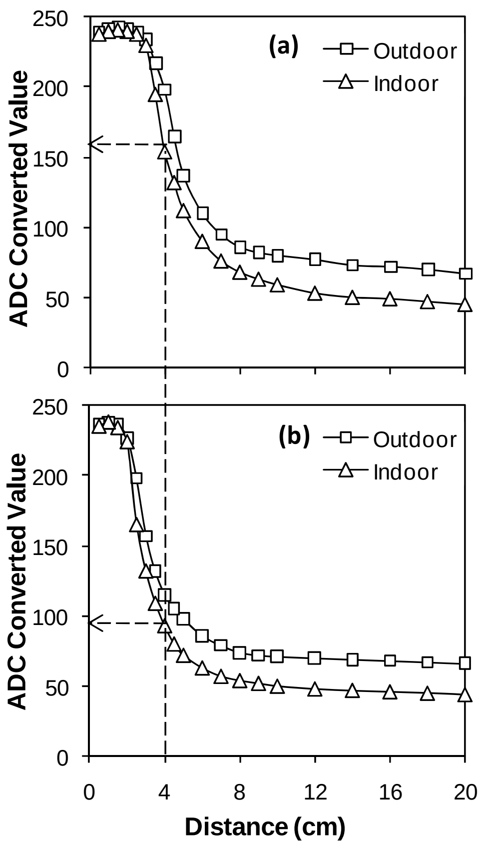

Fig. 12. ADC converted values from IR reflection of (a) white body and (b) black body obstacles

Distance estimation would depend on measured IR samples which are reflected from obstacles. In this design, the maximum distance for obstacle detection is about 12 cm with ±1 cm tolerance. The sensitivity of the sensors also depends on emitter diode intensity which is relative to emitter diode quality and battery level. In this experiment, the battery level is always fully charged to provide an accurate result. The captured IR values from white body and black body obstacles were tested based on proposed model in [19] (1). Fig. 13 depicts captured IR and model values as a function of emitter distance for white and black body obstacles. For white body obstacle, model parameters (α and β) were extracted from ADC converted values and are solved with α = 1719 and β = 41.82. Value of sensor and proposed model meet at 3 cm as shown in Fig. 13(a). For black body obstacle, model parameters were α = 804 and β = 41.87 (Fig. 13b). As described, β is the offset value that depends on emitter characteristics and ambient light hence it was a constant value for both experiments. The model's parameters was fitted with R^2=0.998.

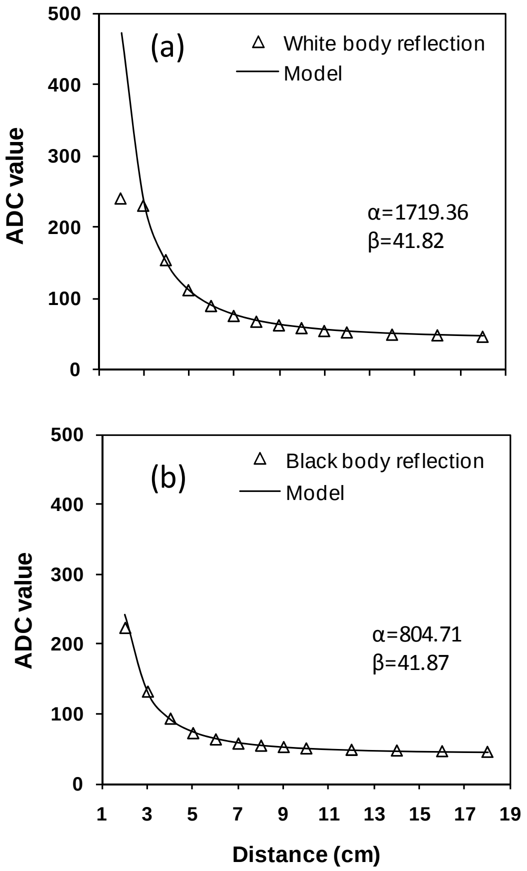

Fig. 13. ADC converted and model values for IR reflection of (a) white body and (b) black body obstacles

B. IR intensity

The IR intensity at different distance with four different viewing angles (0°, 15°, 30°, and 45°) is illustrated in Fig.14. The results are recorded while the infrared is turn-on throughout the experiment to obtain maximum transmission power. Data transmission using digital state for input signal, allows acceptable signal range at 8cm with ±1cm tolerance. The distance covered by the data transmission is reasonable for AMiR considering the robots dimension and the large number of participant robots. To achieve long range communication, analog state of input signal can be utilized.

Measured results from recognized IR radiations which were emitted in pulse mode with four different pulse-widths (30%, 50%, 70%, and 90%) are illustrated in Fig.15. This experiment demonstrates that the received IR power from pulse mode modulation will decreased aggressively with increasing distance. It is also clear that the pulse-widths are an important parameter in pulse-width modulation. Therefore, it is advised to have a large pulse-width parameter for logic '1' to achieve maximum emitting power. Obtained results provide useful parameters for implementing other communication techniques such as Manchester encoding or NRZI.

C. Modulation Experiments

Data modulation is a major concern in communication system. In this section, results of several experiments for evaluating different modulation methods are presented.

1) B-ASK Modulation Method

Results of B-ASK modulation experiments in digital state and analog threshold mode is listed in Table III. Three analog threshold levels for captured ADC values (30, 50, and 70) have been used. In each experiment, 1000 messages were sent and maximum viewing distance and percentage of correct received messages were calculated.

TABLE III
B-ASK MODULATION RESULTS IN DIFFERENT TECHNIQUES

Angle	Digital State		Threshold Level for Analog State: 30		50		70	
	Dist. cm	*Err. Rate %*	*Dist. cm*	*Err. Rate %*	*Dist. Cm*	*Err. Rate %*	*Dist. Cm*	*Err. Rate %*
0º	6.3	0.8	16.5	62	11	51.8	8.7	22.1
15º	5.9	1.6	13.5	64.2	9.2	53.7	7.6	23.1
30º	4.8	2.1	10.8	65.8	7.6	54	6.4	25.4
45º	4	2.3	9.4	68.4	6.2	56.7	5.3	31.2

Highest reliability has been obtained in digital state with less than 2.5% error rate due to the high level of received IR intensity. Maximum distance can be achieved in analog state with lower threshold level however the error rate is about 60% which is not a reliable rate for communication. We have bandwidth limitation in analog techniques because of ADC sampling clock and speed of ADC capturing is about 15 kHz. For software implementation of B-ASK modulation in receiver unit about 3.1% of microcontroller flash memory is required.

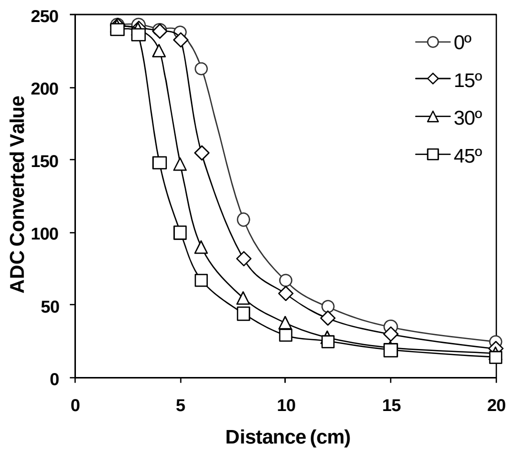

Fig. 14. ADC values as a function of distance with different viewing angles

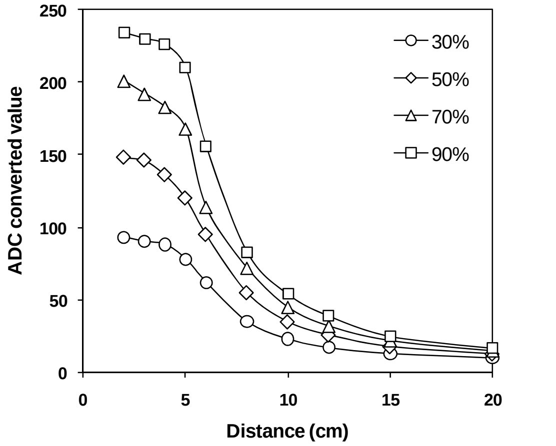

Fig. 15. Measured ADC values for pulse-mode IR transmission with four different pulse widths (30%, 50%, 70%, and 90%)

2) B-FSK Modulation Method

In this method, choosing carrier frequencies is the important parameter. The receiver robot uses digital state of received signals for deciding message elements. Processor extracts data elements using number of rising edges. 1000 messages were sent and different results are shown in Table IV. Detail explanations for error type include whole message errors, first 5 bits errors, second 5 bits errors, unrecognized bits errors and frequency of errors in logic elements '1' and '0'.

TABLE IV
ERROR RATE AND TYPE OF ERROR FOR FSK MODULATION WITH DIFFERENT CARRIER FREQUENCIES IN MAXIMUM DISTANCE

Carrier *N*	Message Error Rate	Un-Recognized bits	1^{st} 5 bit Err.	2^{nd} 5 bit Err.	'1' Err. Rate	'0' Err. Rate
5 (1kHz)	9.7%	0.97%	0 %	9.7%	1.9%	0.4%
10 (2kHz)	41.3%	4.55%	8.5%	35.6%	7.7%	1.4%
20 (4kHz)	100%	0.74%	3.4%	100%	40.2%	28.8%

The lowest error rate can be achieved by B-FSK method with a carrier of 1 kHz (N=5). However, the error rate is still significantly higher than B-ASK method presented earlier. Increasing frequency results in an increase in error rate because IR emitters cannot achieve to maximum power and also limitation of processor cause to lose received data elements in higher frequencies.

D. Analysis of Collective Behavior of Swarm Robots

In this section, exploration behavior (Fig. 11) of swarm robots was analyzed. The effects of communication method and packet size were two important parameters which were examined in social behavior. The goal of swarm was finding and aggregating around a sound source. Fig. 16 shows the effects of selected various values of parameters on aggregation time. Exploration experiments 20 times were repeated for each configuration and the average time was calculated. The ASK technique showed higher reliability than FSK. This result has been reported in individual communication experiments. The packet size also changed the reliability of communication. As shown in the exploration behavior, the small packet size was most reliable than bigger one. Thus, the performance of swarm researched could be improved with simple ASK communication and short messages.

Fig. 17 illustrates captured images of exploration behavior in time intervals of 20 sec. In this experiment, messages were modulated with 5 bit packet and ASK modulation technique.

V. CONCLUSION

This paper compares different infrared communication methods suitable for swarm robot application. Swarm applications require amenable hardware to configure reliable communication. Therefore, various techniques have been implemented in software for a general purpose processor to achieve a flexible robot platform, AMiR. To achieve reliable communication, high quality IR components are utilized. B-ASK and B-FSK modulation experiment results were presented. The feasibility of using digital state ASK modulation for individual robots communication has been demonstrated. The B-FSK method does not perform well for application of multi-robots communication. After testing various methods, the second experiment was the effects of communication techniques on collective behavior of swarm robots. The ASK modulation with small packet size showed higher performance than other techniques.

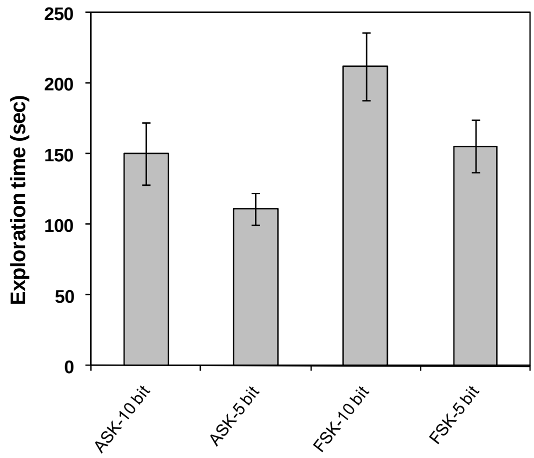

Fig. 16. Exploration time using different methods and packet sizes

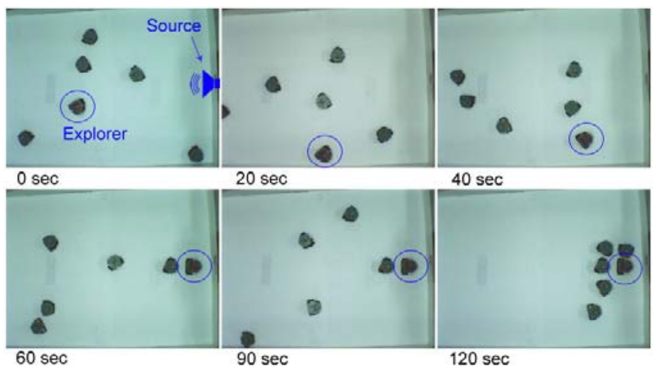

Fig. 17. Exploration behavior of 6 robots.

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