Development of Robotic Platform for Swarm Robots in Fire Detection Application

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ABSTRACT

In recent years, a team of simple robots, so-called swarm robots, can perform the same level of difficult tasks as a more complicated robot. Due to their abilities, they can be applied to many situations. Fire detection is one application that can be combined with swarm intelligence to increase efficiency and effectiveness. This paper presents a new swarm robotic platform for a fire detection task called FiFiBot that has been developed for low cost and high performance. The average cost per FiFiBot is USD 140. Compared with conventional designs, they are better in terms of computational speed, cost and the number of included sensors. Moreover, two FiFiBots were programmed to perform a leader-follower routine with fire detection, and were successfully tested. Hence, FiFiBots are feasible robotic platforms to be used for research and educational purposes for swarm systems.

Keywords: swarm robotic platform, fire detection, leader-follower, swarm intelligence

INTRODUCTION

Swarm robotics is a new approach that allows a large number of simple robots to perform tasks (Mohan and Ponnambalam, 2009). The concept was inspired by the study of certain types of living creatures, such as schools of fish and colonies of ants where it was noticed that swarm intelligence is a natural feature in the behavior and reactions of these creatures, with three important characteristics: flexibility, scalability and robustness (Bayindir and Sahin, 2007). Swarm intelligence is extremely helpful for solving complex tasks by providing alternative solutions. For example, when a single robot is ordered to work in a bumpy terrain, it may become accidentally stuck or fall into a hole. The imitative behavior of ants can overcome this problem by working as a team. Likewise, robots can be applied to do the same thing (Mondada *et al*., 2005).

In recent years, swarm robots have received considerable attention from many researchers. The e-puck developed by Mondada *et al*. (2009) has very high functionality due to the sensors integrated within it, but it is very expensive and costs USD 1,190 per robot. D'Ademo *et al*. (2011) developed a low-cost, open robotic platform called eBug. The eBug can be used in a number of applications but it costs approximately USD 500. MILyBots were developed by Vega *et al*. (2008) and even though the cost of MILyBots is not mentioned, it appears to be expensive. AutoBot was developed with a reasonable cost of approximately USD 97 per robot (Gupta and Singh, 2010). It is a highly cost effective system but the minimum number of included

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sensors severely limits its usability. These studies illustrate the cost-performance tradeoff inherent in developing a swarm robotics platform.

Rescue robots are one type of application in which swarm intelligence can greatly improve efficiency and effectiveness. There is a high demand for rescue robots in areas which involve danger to humans, such as fighting fires. Following years of research and experimentation, robots have now been developed that can withstand high temperature (Kim *et al*., 2009). Modern technology makes it possible for humans and robots to work together in these situations (Naghsh *et al*., 2008). However, most autonomous robots are mainly developed to operate in specific environments. Autonomous fire-fighting mobile platform (AFFMP) was developed to detect fires by moving along fixed guidelines (Khoon *et al*., 2012). In a similar manner, robots developed to compete in certain contests, as published by Dubel *et al*. (2003) and Miller *et al*. (2003), cannot reach the goal if they are ordered to perform in unfamiliar environments. Due to the limitation of these robots, swarm intelligence can be applied to solve the problem and improve performance; for example, it will allow fire-fighting robots to operate more flexibly and efficiently. However, there are presently no fire-fighting robots that can fully and automatically cooperate with each other.

This paper proposes a feasible platform for swarm robots to perform a fire detection task. FiFiBots have been developed to simulate actual fire-fighting robots working as a swarm for educational and research purposes. The average cost per robot of the proposed platform is USD 140. High-performance microcontrollers are employed that provide sufficient computational power to perform basic image processing. There are two ways for the robots to communicate, using both radio frequency and infrared. In addition, many other useful components are integrated that cannot be found in general low-cost platforms. Beside the design of hardware, two FiFiBots were programmed to perform the leader-follower routine with fire detection, and were tested experimentally. The proposed platform can easily be modified and applied to other applications.

MATERIALS AND METHODS

Hardware development

Research in swarm intelligence has garnered increasing interest in recent years. Most swarm robotic systems are made up of five basic components.

1. Main controller: Each platform has been developed with different speed capabilities and architecture of the controller. This is the main part of the robot; if it has the ability to operate at high speed, it will be able to perform complex, real-time computation, such as image or signal processing.
2. Communication: There are several types of communication systems which have been used in swarm robots, for example, infrared, Xbee and radio frequency. This is a significant feature because each agent should be able to communicate with the swarm so that information can be shared.
3. Obstacle avoidance: A necessary feature is to avoid colliding with other agents or elements. Most swarm robots use infrared proximity sensors to detect an obstacle.
4. Power consumption: This is a critical issue because it determines how long the robot can function in a given environment. Power consumption, and therefore the length of time a robot can operate, depends on the type and size of battery used.
5. Additional functions: There are several optional features available. For instance, some robots have been mounted with a camera for vision, while others have been fitted with heat sensors to measure the temperature of its environment.

These components are crucial for swarm robots. They were considered while developing the FiFiBot for high effectiveness in performing fire detection tasks and imitating the actions of fire-fighters. For this purpose, it has been designed with five key actions.

1. Detecting the fire: It will detect the presence of a fire by image processing and measuring ambient temperature. This information will be shared with other agents to request help in extinguishing the fire.

2. Extinguishing the fire: Having detected the presence of a fire and notifying other agents, it will work alongside them to put out the fire and stop it from spreading.

3. Communicating with other agents: This is an important feature because one robot may not be sufficient to extinguish the fire.

4. Measuring the position and orientation of the robot: This information is useful for robot navigation and localization of the fire. When one FiFiBot finds the fire, it will send the position to other agents.

5. Avoiding obstacles: The robot will move around in the environment to perform fire-fighting tasks. While walking, it needs to have the ability to avoid obstacles which may cause damage and restrict effectiveness to perform tasks.

FiFiBot consists of three layers—a mechanical layer, power layer and logic layer—as seen in Figure 1.

Microcontroller

For the main computation, FiFiBot uses an STM32F4 Discovery Board (supplied by ST Microelectronics; Geneva, Switzerland) which is connected directly to a logic layer. This board is mounted with ARM-Cortex M4, and includes 1 MB Flash and 192 KB RAM which can run at high speed up to 168 MHz. There are several peripheral links that can be used to connect to other modules. Additional benefits include extra sensors, such as an accelerometer, a mini-microphone, an audio jack, four light emitting diodes (LEDs) and a temperature sensor. The main reason for choosing this board is the built-in ST Debugger which helps to simulate other programs and produces consistently good results. Another important advantage is that the cost of this board is relatively cheap at around USD 20. Figure 2 shows the block diagram of the microcontroller.

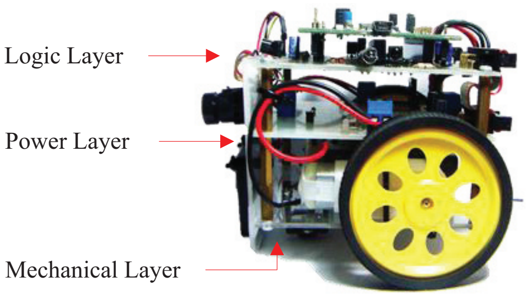

Figure 1 Side view of FiFiBot.

Communication

FiFiBot is equipped with four infrared transmitters and receivers for local communication and has an integrated radio transmitter for long-range communication. An infrared transmitter and receiver pair is mounted on each side of the robot and is used for both communication and obstacle avoidance. This approach is similar to Arvin *et al*. (2009), but applied in a different manner. Phototransistors are used to receive signals from infrared LEDs. They are connected to an analog-to-digital (ADC) port, sensing the light as an

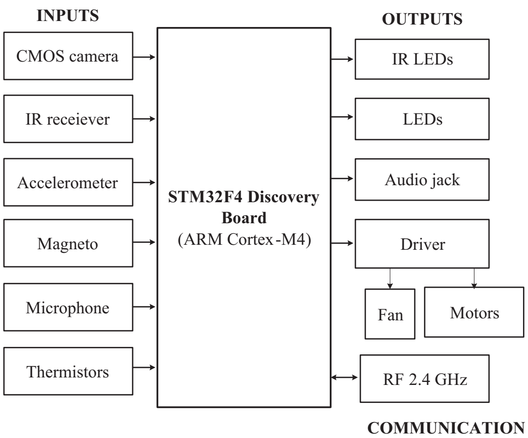

Figure 2 Block diagram of ARM Cortex-M4 connected to peripheral components. (CMOS = Complementary metal-oxide-semiconductor, IR = Infrared, LED = Light emitting diode.)

analog signal. To avoid interference from other light sources, such as fluorescent light bulbs and fire, four infrared (IR) receivers, TSOP4838 (Vishay; Malvern, PA, USA), are used because they are capable of receiving a modulated 38 kHz signal. The NRF24L0 (NORDIC Semiconductor; Trondheim, Norway), a radio frequency module capable of sending data at 2.4 GHz with Gaussian Frequency-Shift Keying modulation, is integrated and efficiently connected to the microcontroller unit (MCU) via a serial peripheral interface (known as SPI).

Sensors and actuators

1. Fire detection: The FiFiBot's primary function is to detect fire and the proposed platform will accomplish this in two parts. The first part involves ‘far-field fire detection’ using an infrared camera and image processing (Hwang *et al*., 2010). The second part is ‘near-field fire detection’, which is very important because it protects FiFiBot from getting too close to the fire and confirms that the detected source is, in fact, a real fire. There are four thermistors used for this purpose. The OV7670 (OmniVision; Santa Clara, CA, USA), complementary metal-oxide-semiconductor (CMOS) camera, was converted to an infrared camera by means of modification using some visible light filters. Three plates of negative film were added to filter out the visible light and receive only the infrared spectrum. This camera was connected directly to the microcontroller via the digital camera interface (DCMI). There are several modes that can be used to capture the image; for this study, a 4-bit gray scale image with dimensions of 80 × 60 pixels was chosen for processing. Four 330-ohm thermistors were wired together with a divider circuit connected by 330-ohm resistors. The range of temperature that they can sense is between -10 and 260 °C. They were connected to the ADC port of the microcontroller.

2. Obstacle avoidance: In addition to communication, the infrared module is also used to detect obstacles. FiFiBot will detect the obstacle from the messages it receives and will formulate possible ways to avoid collision. The range is approximately 15 cm.

3. Status: In order for it to perform many tasks, it must be ensured that the robot is operating properly. Four LEDs mounted on the MCU board are used to show the current status of FiFiBot (that is, the task that it is performing).

4. Position and orientation: The microcontroller is mounted with an accelerometer; thus, it can be used to determine the position of the robot. A 3-axis magneto breakout board was used to measure the orientation and both were connected to the microcontroller via the I2C connection.

5. Extinguishing: FiFiBot has a direct current (DC) fan to perform this action. It is driven by a bipolar transistor which is connected to the MCU port for control.

6. Movement: Two DC gear motors are used for movement. They are driven by an L293D (ST Microelectronics; Geneva, Switzerland) driver integrated circuit (IC) which is connected as a half-bridge drive circuit. Moreover, the speed of the motors can be controlled by the pulse-width modulation port of the MCU.

Power supply

Power is supplied to FiFiBot by a 7.4 V Li-on rechargeable battery with 900 mAh, connected to a power layer. It is wired with 5 V and 3.3 V regulators. The 7.4 V battery is used directly to drive the fan. The 5 V regulator is used to supply power to both motors and IR LEDs. The 3.3 V is connected to the MCU and other devices. When working at full capacity, it can run for approximately 2 to 2½ hr.

Software Development

FiFiBots have been designed to perform simple swarm behavior patterns and have the ability to detect fires. To be certain that they can act like a swarm, two FiFiBots were programmed with the leader-follower routine as an experiment. Accordingly, the main functions of the robot, (communication, movement and fire detection) were programmed to support this operation.

1. Fire detection: FiFiBots were mainly developed to detect fire. The algorithm was first programmed and tested on a computer to ensure proper operation. The CMOS camera and computer were set up for testing by directly connecting through the TTL-to-Serial module. The method used to detect the fire is called 'thresholding'. Since the intensity of fire produces a bright light, it is easy to separate the image of the fire from other images in the vicinity. For instance, the camera will reveal the flame on a candle but not the candle itself. Figure 3 shows the comparison between a captured image and a threshold image.

After thresholding, the position and area of fire are calculated to let the robot know the direction that it should follow and to help decide to stop moving when it is too close. This decision depends on the fire area in the image. When it is far from the fire, the fire area in the image will be small. On the other hand, when it is close to the fire, the fire area in the image will be large (Figures 3d and 3e). The fire area in the image is simply determined by counting the white pixels of the threshold image, and the position of the fire is calculated by center of gravity from Burger and Burge (2009), according to the Equations 1–4. A region R of a binary image can be represented by Equation 1:

$$R = \{x_0, x_1, \ldots, x_{N-1}\} = \{(u_0, v_0), (u_1, v_1), \ldots, (u_{N-1}, v_{N-1})\} \quad (1)$$

where x_i are foreground points, (u,v) are coordinates on the image plane and N is the total number of foreground regions. The area of a binary region can be determined by counting the pixels of foreground points (Equation 2):

$$A(R) = |R| = N \quad (2)$$

The center of gravity of region R is the mean of the coordinates in the x and y directions as shown by Equations 3 and 4:

$$\bar{x} = \frac{1}{|R|} \sum_{(u,v)\in R} u \quad (3)$$

$$\bar{y} = \frac{1}{|R|} \sum_{(u,v)\in R} v \quad (4)$$

Moreover, the thermistor is used to ensure proper fire detection when the robot is near the fire. From experimentation, the thremistor produces a voltage over 1.5 V when it is close to a real fire.

2. Robot movement: The DC gear motors are connected to the L293D (half-bridge driver). The speed of both motors can be varied by reducing the voltage. Due to the fact that there are no encoders to measure the speed, both motors

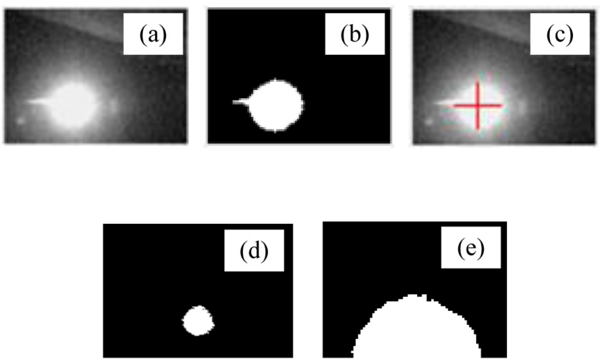

Figure 3 (a) Fire image captured with a complementary metal-oxide-semiconductor camera; (b) Fire image after thresholding; (c) Position of fire calculated using center of gravity; (d) Threshold image captured when fire is far from the camera; and (e) Threshold image captured when fire is close to the camera.

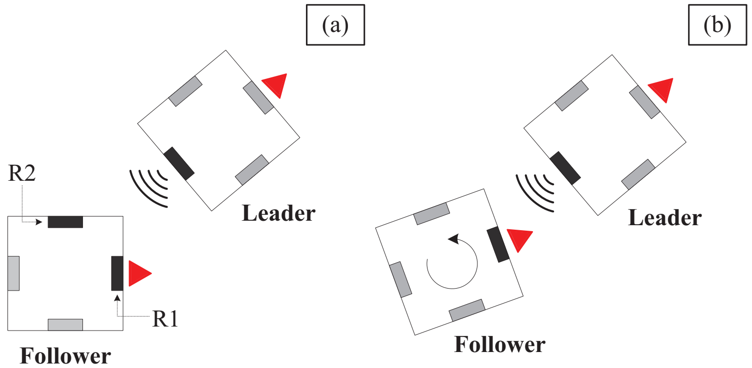

Figure 4 Leader-follower routine using infrared receivers: (a) Infrared receivers, R1 and R2, receive a signal. This means that the leader is situated towards the left of the follower. (b) After sensing the direction that it should follow, the follower will track the leader by turning left.

will be controlled by an open loop controller. Pulse width modulation is used to vary the average amount of voltage.

3. Communication: Due to the leader-follower behavior, local communication is sufficient to allow the sharing of information. In addition, infrared is also used to identify the orientation between the leader and follower. The four infrared receivers will let the FiFiBot know its orientation. Figure 4 shows how the FiFibot knows the direction of the received signal. When sensors R1 and R2 receive the signal from the leader, the follower will know that it should turn left to track the leader.

4. Leader-follower routine: The leader-follower behavior pattern is coordinated by means of local communication between the leader and follower. This behavior is implemented to prove that FiFiBots can properly cooperate to detect a single fire source. The leader will search for the fire; when it finds the fire, it will send a found-fire (f-f) signal to notify the follower and activate movement. Moreover, the leader will move as close as possible to the fire to take appropriate action, and at this point it will cease to move so that it is not damaged by the fire. If the leader does not detect the fire, it will send a not-found-fire (n-f-f) signal to the follower that it should stop moving as there is no need for it to take action. Whenever the follower receives a signal to move, it will follow the direction the signal came from; therefore, if it receives a signal to stop, it will not move forward to follow the leader. This procedure is shown by flow charts in Figures 5 and 6. In an exceptional case where the follower loses communication with the leader, it will wait until a signal is re-established. Moreover, the speeds of both leader and follower robots are set uniformly to maintain a stable communication link.

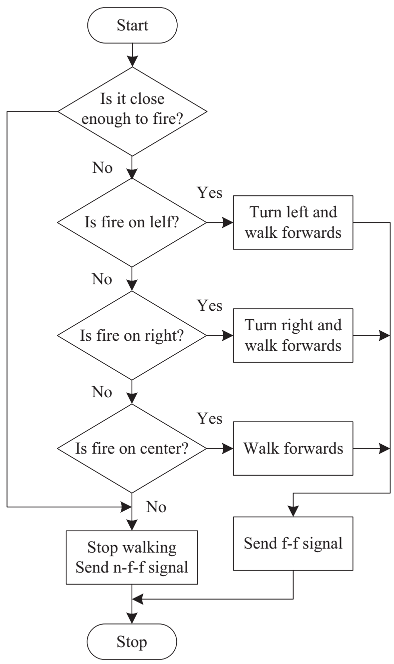

Figure 5 Flow chart of leader FiFiBot performing a leader-follower routine. (f-f = Found fire, n-f-f = Not found fire.)

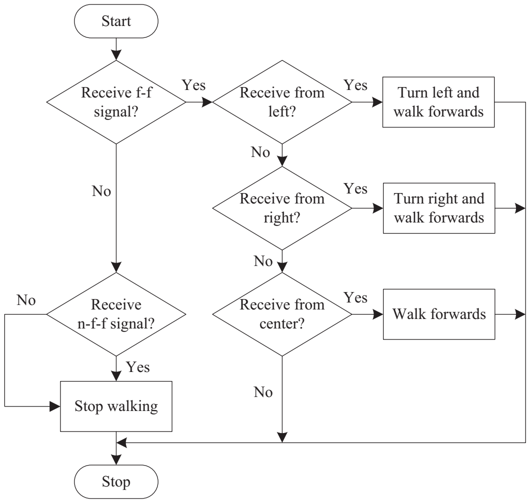

Figure 6 Flow chart of follower FiFiBot performing a leader-follower routine. (f-f = Found fire, n-f-f = Not found fire.)

Experimental Setup

Three experiments were conducted to evaluate the performance of FiFiBot.

1. Communication range. As FiFiBot has two communication devices (infrared and radio frequency), the communication ranges of both devices were measured by varying the distance between two FiFiBots. Infrared communication was tested by changing the distance between the two robots from 1 cm to 20 cm. As the radio frequency can provide a greater range than infrared, the distance between two FiFiBots was varied from 0 to 100 m to test the radio frequency operating range.

2. Fire detection. To detect the fire, FiFibot is designed to use a camera for long range and a thermistor for short range. The fire detection performance was tested by changing the distance between the fire and robot. In the experiment, a candle was used as the fire source. To determine that FiFiBot could detect the actual fire, a fluorescent light bulb was used as another light source to test if the robot could distinguish a fire from a non-fire. The distance between the robot and fire was set at 1.5 m. Moreover, FiFiBot was tested to find the greatest distance of fire detection by increasing the distance between the robot and fire from 1 up to 5 m.

3. Leader-follower routine. Two FiFiBots were used in this experiment and were placed within their communication range (less than 15 cm). A candle was placed randomly in front of the leader to ensure that it could respond to the fire. The candle was moved and placed again for testing to determine if the robot could decide to stop before approaching the fire too closely.

RESULTS AND DISCUSSION

Communication range

The experiment showed that the communication range of the infrared signal was approximately 15 cm. The range was short because infrared is designed for use in both communication and obstacle avoidance. The performance of the infrared signal was limited by the increased resistance to limit the current of the IR LED. The maximum communication range of the radio frequency was 80 m, which would cover most indoor environments.

Fire detection

The FiFibot is programmed to perform fire detection using both a camera and thermistor. It was tested with two sources of heat (a candle and a fluorescent light bulb). The robot was able to detect both sources, but was able to distinguish the real fire using the temperature measured by the thermistor. This was verified by requiring the FiFibot to detect and differentiate between a candle and a fluorescent light bulb in 60 experiments. The result showed that it could detect the candle correctly in 27 of 30 tests (90% accuracy), and in 30 of 30 tests (100% accuracy) for the fluorescent light bulb. This illustrates the FiFiBot does not misidentify a fluorescent light bulb as a real fire. The reason for the 10% error in detecting fire was that the thermistor was not close enough to the heat source in certain cases which was a preprogrammed constraint to prevent accidental damage caused by the fire. The longest range of fire detection was approximately 2.5 m. However, this result depended on the size of the fire. If the fire is large, then FiFiBot still can detect it at greater distances.

Leader-Follower routine

Figure 7 shows the results of this implementation. At $t = 0$ sec, the fire was detected by the leader. After the leader saw the fire, it turned right and moved towards the fire as seen at $t = 2$ sec and the follower began to track the leader. Next, at $t = 4$ sec, the follower turned right to follow the leader. At $t = 6$ sec, the follower was still following the leader. This test showed that FiFiBots can operate properly with a simple leader-follower routine and means that they can be programmed with other swarm behavior in the future.

Robotic platform design

FiFiBots have been developed as low-cost platforms. Compared with previous platforms, they are better in terms of performance as measured by the speed of the controller. They also have cameras which are used to detect fires. There are additional components, such as an accelerometer and a magnetometer, which cannot be found in general low-cost platforms. The average cost is USD 140 per FiFiBot. Table 1 shows the comparison between FiFiBots and other swarm robotic platforms.

CONCLUSION

This paper presented a new platform of swarm robots which were designed to simulate fire detection tasks. FiFiBots were developed for low-cost and high performance. They use an STM32F4-Discovery board as their main controllers and have two communication channels (infrared and radio frequency) between agents. Infrared is used for both communication and obstacle avoidance. A modified CMOS camera and temperature sensors are used to detect the fire. FiFiBots have an accelerometer, magneto sensor and camera which are not generally integrated in low-cost robots. The range of communication for proper use was 15 cm for infrared and 80 m for radio frequency. In the experiment, the FiFiBot was programmed to successfully detect and differentiate between a real fire (90% accuracy) and a fluorescent light source (100% accuracy). Moreover, they were successfully tested with simple swarm behavior using a leader-follower routine with local communication, so that it

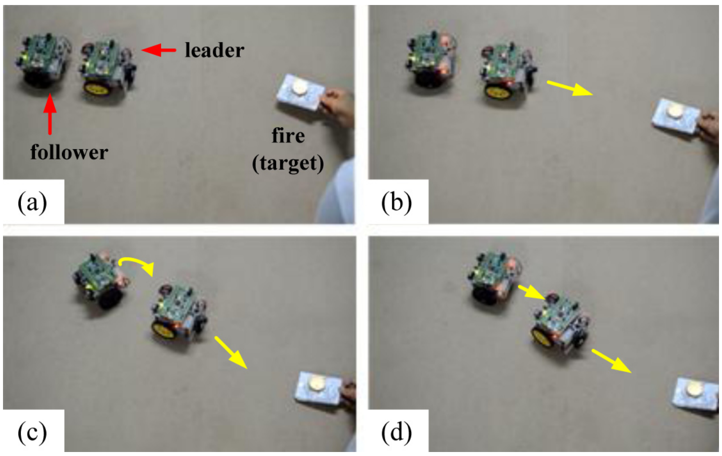

Figure 7 Results of simple leader-follower behavior performed by two FiFiBots: (a) at $t = 0$ sec, (b) at $t = 2$ sec, (c) at $t = 4$ sec and (d) at $t = 6$ sec.

Table 1 Comparison of swarm robotic platforms

Name	Communication	Obstacle avoidance	Movement	Controller and speed	Battery life (hours)	Additional functions	Cost (USD)
e-puck (Mondada *et al*., 2009)	Bluetooth	Infrared	Stepper motors	dsPIC 16Mips 64MHz	1 – 10 (Rubenstein *et al*., 2012)	Camera, accelerometer, microphone, audio, extension board	1119
eBug (D'Ademo *et al*., 2011)	Xbee/Infrared	Infrared	Stepper motors	AVR 8/16 bit 32MHz	N/A	Extension board	500
MILyBots (Vega *et al*., 2008)	XBee	Infrared	Gear motors	8-bit ATMega 19MHz	2½ - 3	-	N/A
AutoBot (Gupta and Singh, 2010)	RF-based	Infrared	DC motors	PSoc 367MHz	N/A	-	97
FiFiBot (current paper)	Infrared/RF-based	Infrared	Gear Motors	ARM Cortec-M4 168MHz	2 – 2(1/2)	Camera, accelerometer, magnetometer, temperature sensors, microphone, audio jack	140

RF = Radio frequency, DC = Direct current

was shown that the two FiFiBots could operate together properly. The leader could detect the fire and approach it. The follower coordinated its movement using only the signals provided by the leader. Hence, it can be concluded that FiFiBots are feasible to use in both research and educational purposes as swarm robots.

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