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Autonomous Safety Mechanism for Building: Fire Fighter Robot with Localized Fire Extinguisher

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Abstract: With advent of robotics technology in the modern days, the use of fire bucket to put up a small fire is seen as outdated. The autonomous approach (by using robots) in safe guarding the human environment building from potential hazard such as fire is deemed necessary. Big fire can be prevented by detecting small fire as quickly as possible. Fire detection device in a building needs to be reliable and effective. Autonomous system can be leveraged to accomplish the hazard detection without human supervision. Moreover, if the hazard eradication follows the detection in an autonomous mode, the solution has a profound impact to the safety of a building. A conceptual Fire Fighter Robot prototype is proposed in this paper. The dynamic model of the conceptual robot is derived. The control system based on nonlinear feedback control is designed to control the movement of the robot when dispersing the sand to put out the fire source. The designed autonomous system detects small flame in a confined area and put it out before it turns to big fire and spreads. A microcontroller, forming the brain of the robot, is coded with a supervisory control algorithm integrated with flame sensor modules are used for the detection of flame. The robot scans the room from front to back and vice versa. When flame is detected, the robot is deployed to directly above the flame source. Sand is used to extinguish the flame by targeting precise location of flame source. At the same time, the alarm will ring and send the message to the owner via Wi-Fi. The robot is capable of extinguishing fire from chemical substances and petrol. Sensitivity of flame sensors at different environment with different brightness is tested through analog reading of the serial monitor.

Keywords: Fire-fighting robot, mobile robot, smart building, nonlinear control

1. Introduction

Fire break-outs usually starts from small fire, thus it is imperative that initial ignition of fire is targeted as soon as possible. Confined areas are high risk areas as they spread fire easily, in particular, places like laboratory and kitchen that have higher chances of fire break-out will spread fire through furniture or chemicals quickly [1]. Most of the conventional fire detection system triggers only when the existence of fire flame is too apparent and large. The cause of such delay is largely due to the way the smoke detectors are installed at the ceiling such that, the fire needs to be large enough to reach the sensors and thereby, triggering the fire alarm. In general, the fire detection device is fixed on the wall or ceiling [2]. The method proves to be inflexible. On the other hand, installing numerous fire detection modules in a building may not be a convenience option. It is inevitable that sometimes these places are left unnoticed, which then disaster takes place.

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Therefore, small flames must be detected and put out as soon as possible before it turns to fire, especially in confined areas. Thus, it can significantly reduce property damage, personal injuries and loss of life.

Traditional method uses fixed smoke sensors that have limited range of detection and do not always succeed in detecting fire in less-discoverable areas like corners of the room. Besides that, smoke sensors require certain concentration of smoke to be triggered. By the time it is triggered, it also means that fire might have already turned uncontrollable. In addition, sprinkler used is not accurate as it splashes water in all directions without first identifying the precise location of fire.

Building safety system against occurrence of hazard such as fire is very important. This also includes the safety standard to which every contractor needs to adhere to. Orbeck [3] discusses about the fire standard concluding that common ignition of sources of fire originates from electrical wiring while Ball & Fisher [4] discusses on the safety issue of a rooftop and the safety of a fire fighter which motivates us to resolve the fire-fighting issues through automating the detection and elimination of fire source.

Previous work from researchers in the service robot addressed in developing target-tracking system [5], [6]. The work in Kobayashi & Yanagida [7] proposed a method to detect human being by an autonomous mobile guard robot. A portable fire evacuation guide robot system is proposed in Kim et al. [8] and demonstrated that the proposed robot system can be thrown into a fire to gather information, to locate displaced people and to perform an effective evacuation procedure safely. They designed the robot with aluminum compound metal for thermal resistance with waterproofing and an impact distribution frame for impact resistance. A vehicle mounted fire-fighting system is proposed by White [9] and included a series of flame and heat retardant coverings placed on all exposed parts of the system to prevent damage from exposure to extreme heat.

An Autonomous Fire Fighting Robot with Multisensor Fire Detection Using PID Controller is designed by Rakib & Sarkar [10]. The robot utilizes temperature sensor and flame sensors to locate fire. Centrifugal pump is then used to pump water to extinguish fire. Similar robot is developed by Yunchun et al. [11] using sensors, such as GSM module, thermistor, UV sensors and flame sensors and controlled by microcontroller.

In this paper, a conceptual prototype design of a fire detection and suppression system, namely fire fighter robot is proposed. A longitudinal dynamic model is firstly presented to allow the lateral motion of the robot to be simulated. A simple nonlinear feedback control is designed to control the robot (with nonlinear model) to follow a trajectory which represents the displacement motion which guarantee soft movement of the robot during the sand dispensing task. Important features such as faster detection time and localized extinguisher are emphasized. A microcontroller is incorporated inside our proposed system to control the mechanism to displace a localized proportion of sand on the fire source. A sensor to locate the fire source will send its signal to alarm the system. The salient feature exhibited by our conceptual design is that the locomotion of the robot is rather suspended on a track above the room instead roaming on the floor. Cartesian motion is employed to allow maximal scanning (by virtue of flame sensors) across the room for possible fire flame and thereby, allowing the fire to be extinguished.

2. Fire source Detection and Extinguishing Paradigm

The proposed fire-fighting robot motion mechanism can be divided into 3 main parts; lateral motion platform, longitudinal motion platform and dispensing action mechanism. The lateral motion platform actually actuates the whole platform along the room from one end to another end whilst scanning through for any source of fire flame. The scanning and detection are accomplished by an array of flame detector installed on the longitudinal platform. Once a small fire source is detected, the robot suspended on the longitudinal platform will move across perpendicular to the lateral motion (earlier actuated) to the location of suspected fire flame. The mobile robot will stop the longitudinal motion and begin to command the dispenser to release the sand by virtue of a servo motor connected to the valve opening of the dispenser.

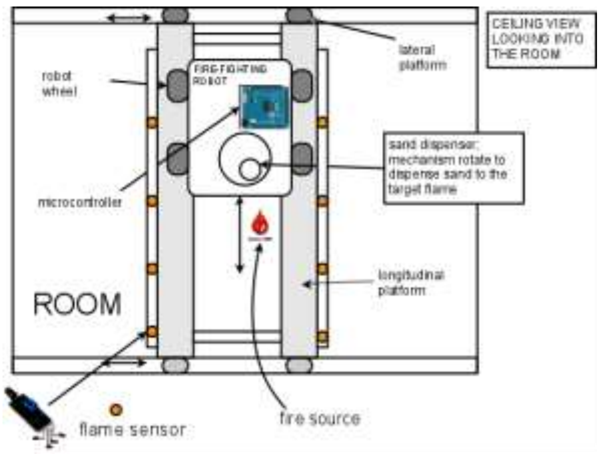

Fig. 1 - Fire detection and extinguishing method illustration

The working principle is rather simple. At the beginning of operation, the 360º servo-motor-driven mobile track will move along the static tracks. As it moves, flame sensors underneath mobile track scans the area for flame. It takes 16 seconds to complete a round trip scanning of 70cmx25cm demo box. When flame sensors sense flame, the mobile track will stop and 360º servo-motor-driven robot will be deployed to the exact location of flame source. A flame sensor under the gate of the sand-pouring mechanism is used to detect the precise location of flame source. If it detects flame, the 180º servo-motor-driven gate will be opened and sand will be poured down to until flame is extinguished. At the same time, buzzer will ring and an alert message will be sent to user's twitter account via WIFI module ESP 8266. After flame is extinguished, the process runs all over again where mobile track starts scanning the whole room for presence of flame.

3. Dynamic Modeling and Control of a Fire Fighter Robot

To be able to control the motion of the fire fighter robot for the fire extinguishing task, a suitable model is required to simulate the robot's motion to the destination of the detected fire place. A dynamic controller will be designed based on this assumed model under the following assumption:

- The slippage between the robot's wheel and the surface of the lateral platform is negligible, thereby, an almost perfect traction is assumed.
- The driving wheel is assumed non-differential, i.e. the right and left wheel traverse at the same speed.
- The swaying of the robot due to the weight of the sand it carries is sufficiently small as to minimize the dynamic hindering motion.

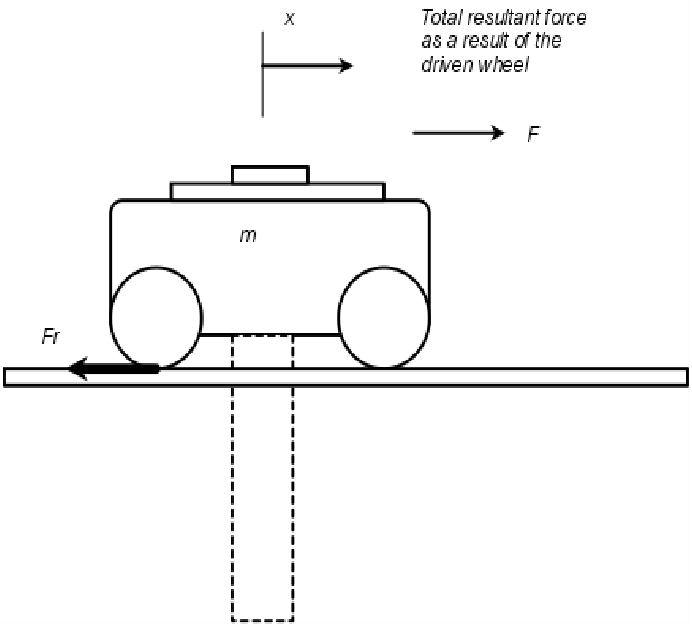

Fig. 3 - Free body diagram representing fire fighter robot

3.1 Longitudinal Dynamic Model

A fire fighter robot can be represented by the following Newtonian model,

$$m\ddot{x} + F_r + \gamma_{sand} = \eta \qquad (1)$$

where *m* is the net mass of the fire fighter robot which includes the microcontroller, power unit, gear, mechanism, actuators and also the sand reservoir, $\dot{x}$ is the acceleration of the robot, $\gamma_{sand} = k_{sand}x^3$ is the nonlinear springiness due to the sand disposing mechanism. F_r is the friction force exist between the tyre and the surface of the platform which can be expressed as:

$$F_r = k_r\dot{x} \qquad (2)$$

where k_r is the friction coefficient which is assumed constant, x is the velocity.

3.2 Nonlinear Feedback Control Design

A nonlinear feedback control input in (1) is to be designed in the following structure:

$$\eta = u + \vartheta \tag{3}$$

where u constitutes the servo mechanism whilst ϑ representing the nonlinear feedback linearization to compensate for the friction and nonlinear terms. Let the servo control input u be defined as:

$$u = m\ddot{x}_d + k_p sign(\varepsilon) \tag{4}$$

where $\varepsilon = e + \lambda\dot{e}$ is the sliding plane into which error $e = x_d - x$ and error rate $\dot{e} - \dot{x}_d - \dot{x}$ converge to zero. x_d is the desired acceleration. k_p,k_v is the proportional and derivative component to be suitably chosen based on the desired preference of the fire fighter robot dynamic.

$$\vartheta = k_r \dot{x} + k_{sand} x^3 \tag{5}$$

where ϑ is the term to feedback linearization term for the system dynamics in Rehman et al. [1].

3.3 Longitudinal Dynamic Control Simulation

Fig. 4 shows a simulation result whereby the robot is able to follow a trajectory which is assumed to provide a soft movement for the robot.

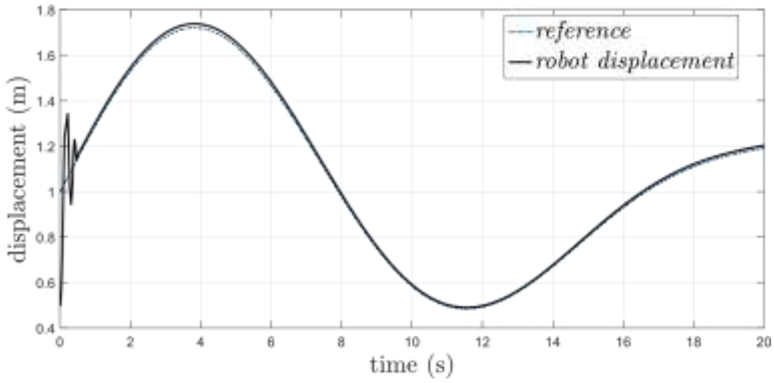

Fig. 4 - Displacement of the fire fighter robot following a desired trajectory emulating the soft movement of the robot to avoid sand spillage

Fig. 5 shows the control signal actuating the robot movement. The aggressive nature of the control signal is largely attributed by the existence of a sliding mode control element in Parker and Emmons [6] rejecting the occurrence of nonlinear effect of the load being carried.

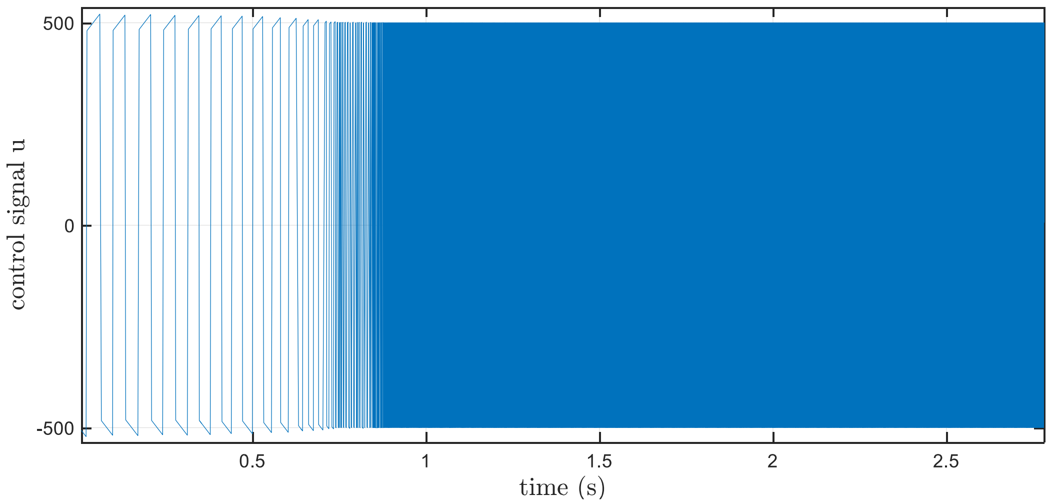

Fig. 5 - Control signal actuate

4. Fabrication of Mechanical Components

The purpose of the design is to prove that fire fighter robot can detect the presence of flame, localize and extinguish it. All the mechanical parts were fabricated for proof of concept and the materials used in the fabrication of fire fighter robot were found locally.

4.1 Demo Box

In order to illustrate the working principle of fire fighter robot in a confined space, a demo box is constructed. The demo box as shown is made from cardboard boxes. The dimension of the demo box is 70 cm × 45 cm × 42 cm. To prevent the demo box from catching fire during demonstration, the demo box is covered with aluminum foil.

4.2 Track

The track is made from PVC pipe so it is light and strong enough to support fire fighter robot running on it. An "H" shaped track is designed so that the motion of fire fighter robot is in two directions. A pair of longer tracks is slicked to the demo box as a static track and another pair of shorter tracks is placed perpendicularly on it as a mobile track. The mobile track (as shown in Fig. 6) carries the fire fighter robot and move together with it along the longer static track. The movement of the track is controlled by a 360º servo motor attached to wheel which responds to the signal from Arduino Mega. The servo motor has high torque and speed.

4.3 Fire Fighter Robot

The body of the fire fighter robot (shown in Fig. 7) is made from light material such as plastic container. The dimension of the plastic container is 11cm×10cm×6cm. The locomotion configuration of the fire fighter robot is based on four wheels with one of it connected to 360º servo motor.

4.4 Sand-Pouring Mechanism

The sand container is made from hard cardboard by rolling it into cylinder shape. It has the capacity to contain 100gram of sand which is enough to put out flame during demonstration. The capacity of the sand container can be increased for the fire fighter robot in real situation. A hole is punched in the plastic container of fire fighter robot and the cylindrical sand container is placed vertically passing through the hole. A gate is used to cover the opening of sand container so the sand inside the container will flow out due to gravity once the gate is opening. The gate is controlled by a 180º servo motor. Fig. 8 shows the sand pouring mechanism.

Fig. 6 - Design of tracks

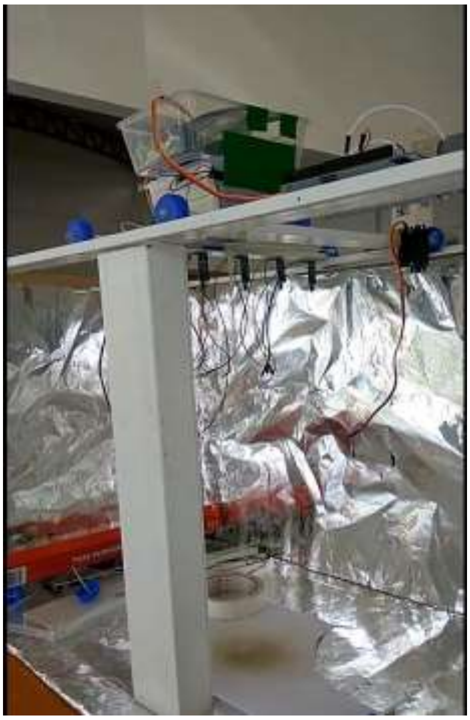

Fig. 7 - A scaled robot prototype

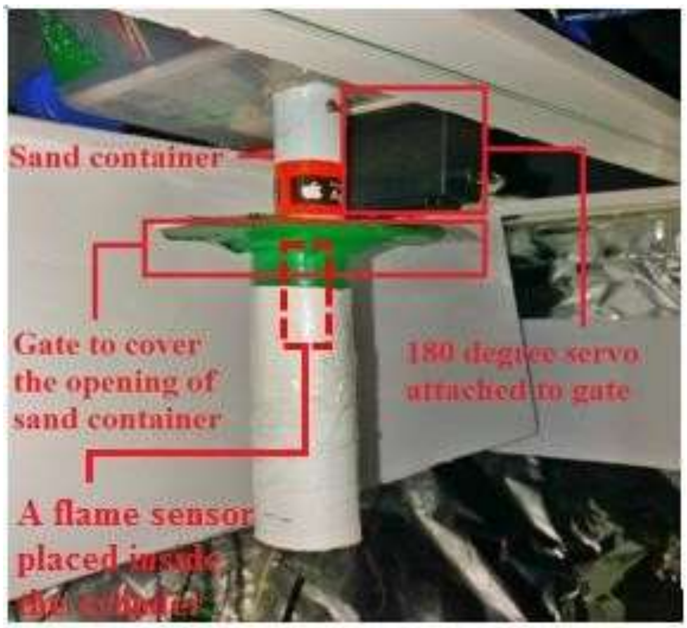

Fig. 8 - Sand-Pouring Mechanism

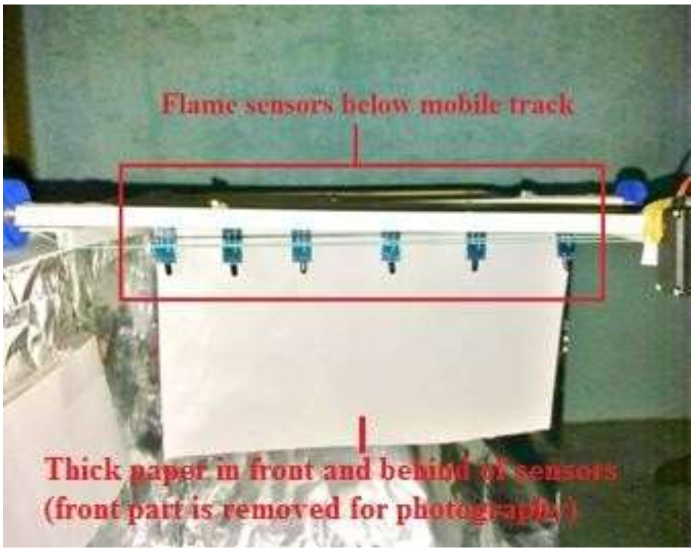

Fig. 9 - an array of flame sensor mechanism

4.5 Flame Sensors Mechanism

Flame sensors are used to detect flames. Six flame sensors are placed beneath mobile track of the moving platform unit to provide maximum scanning coverage detecting for possible fire occurrence in a building. The placement of flame sensor beneath the gate of sand-pouring mechanism is to allow precise fire extinguishing (shown in Fig. 10). As flame sensor has 60º of field detection, a slight modification was performed by using 2 thick papers and cylindrical roll to cover the flames sensor sideways to ensure only vertical direction (0º) of flame detection is achieved. Such modification is to allow the flame sensors detect the flame that is directly below it rather from afar and falsely trigger the fire extinguishing system.

5. Control, Sensors and Communication Units

The robot needs to sense, communicate and actuate in order to perform the fire detection and extinguishing action. The control unit is accomplished using Arduino Mega, the sensor unit is by flame sensors whilst the communication unit established by a WIFI module ESP 8266.

5.1 Control Units

The logic control unit of the robot is solely an Arduino Mega (Fig. 8). Arduino Mega provides an Integrated Development Environment (IDE) which has a base of programming for the C and C++ languages. The Arduino Mega is a microcontroller board based on the ATmega1280. It has 54 digital input/output pins (of which 14 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. The input/output pins are connected in different ways with the servo motor, sensors and WIFI module through jumper wires and breadboard.

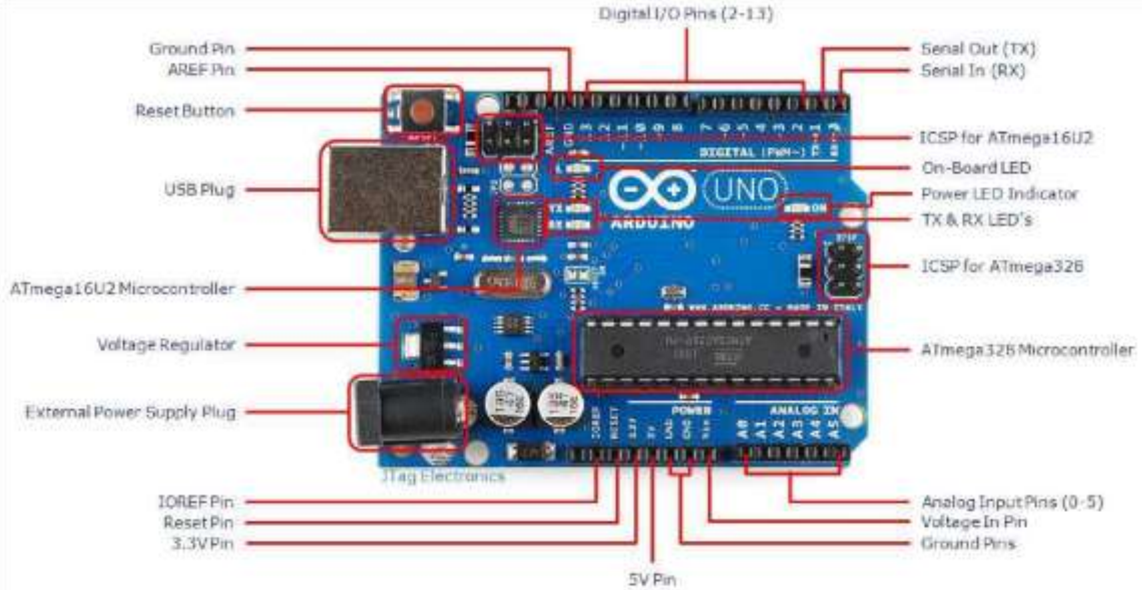

Fig. 10 - Arduino Mega as the microcontroller used in the robot

In this way, it establishes control over each component of the robot and the robot does the job as per the program coded in the Arduino Mega. The power supply to control unit is a Lithium Polymer battery with a power rating of 5000 mAH. A 5V battery is connected to the USB port of Arduino Mega. Although the current supplied by external power supply is stated as 2A, its actual current to Arduino's input is limited to 500 mA by the Arduino's PTC self-resettable protection fuse. Power consumption of the robot is 37.44Wh.

5.2 Sensor Unit

Flame sensor module (Fig. 12) is sensitive to the flame and radiation. It also can detect ordinary light source in the range of a wavelength 760nm-1100 nm. The detection distance is up to 100 cm and it has detection field angle of 60 degree [8]. It has four pins. (i) VCC: Positive voltage input: 5V for analog 3.3V for Digital, (ii) A0: Analog output, (iii) D0: Digital output, (iv) GND: Ground. It takes the input from the environmental data and gives an analog output. If there is a significant change of IR wavelength, it detects it as flame and decreases the analog output.

5.3 WIFI Module ESP 8266

ESP 8266 is a WIFI module that is compatible with Arduino Uno. To interact with ESP-8266, AT command will be used, it is an instruction to control modem. All the AT command start with "AT" and "AT" is the abbreviation of attention (White, 1998). For example, "AT+RST" is to restart the ESP-8266 and "AT+CWMODE" is to select the mode of ESP-8266 (Rakib and Sarkar, 2016). If the AT command is successfully executed by ESP-8266, it will return a result code of "OK" and information response to Arduino UNO. If the AT command is executed failed, only a result code of "ERROR" will be returned to Arduino Uno to indicate that the command is not executed successfully [11]. Fig. 13 shows the hardware structure of ESP 8266.

To interface ESP 8266 with website, application program interface (API) will be used. API is like an intermediate between two people who interact with each other using completely different languages. API is used in software so that 2 different kinds of software package can communicate [12].

ESP8266 is programmed to link to an IOT application website (thingspeak.com). The IOT application website receives control data and information data from ESP 8266 and post the alert about fire detection to user social website (Twitter). However, the data transmission (Fig. 13) from ESP 8266 to websites sometimes might be lost [13]. To handle this situation, the ESP8266 is programmed to resend the data if not receive acknowledgment from the website after timeout.

Fig. 11 - Hardware sturucture of flame sensor

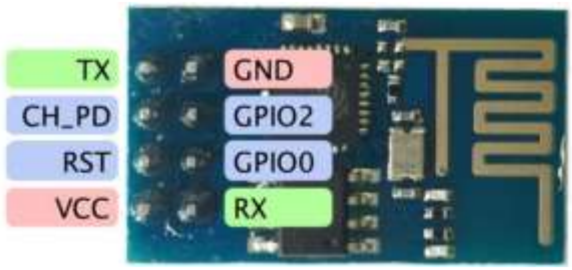

Fig. 12 - Hardware sturucture of ESP-8266

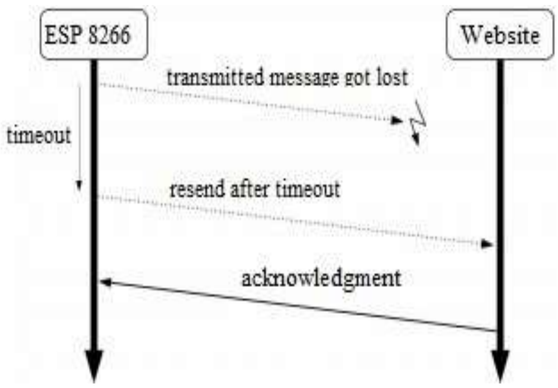

Fig. 13 - Communication protocol between ESP 8266 application layer with the target website

6. Results and Discussion

The results on the flame sensor stimulus response to sunlight during the day and night time are to be presented. In addition, the sensor reading in these two occasions are mapped in relation to the relative distance between the sensor and the fire source.

6.1 Effect of Infrared Rays from Sunlight on Sensitivity of Flame Sensor at Day and Night

Sensitivity of flame sensor is tested at day and night. To compare the sensitivity of flame sensor, it is tested for case of without fire source and case of from 50 cm distance away from the fire source. Fig. 15 shows that the sensitivity of flame sensor at day. From Fig. 15, it is observed that with or without fire source, the reading from flame sensor is the highest during the period of 8am-9am and 6pm-7pm. This is due to the disturbance of infrared rays from sunlight is the minimum during that periods. During period of 10am-12pm, the intensity of sunlight starts increasing, flame sensor is affected and reading from sensor keeps falling. The sensor reading for both cases is the lowest during the period of 12pm-5pm because the intensity of sunlight is the highest during that time. It is also observed that sensor reading is almost equal for both cases during 12pm-5pm because the effect of infrared rays from sunlight become dominant during that time. From the graph, the gap between the case of with fire source and without fire source is small. It is hardly can set a threshold to distinguish between case of with fire source and without fire source at day.

Fig. 15 shows that the sensitivity of flame sensor at night. It is observed that for the case of without fire source, the sensor reading is high and remain constant because there is no other source of infrared rays affects the sensor reading. For the case of with fire source, the sensor reading is in the range of 380 to 600 units. From the graph, the gap between these two cases is high. A threshold is programmed to distinguish between the case of with fire source and without fire source at night.

6.2 Flame Sensor Reading Versus Distance from Fire Source at Day and Night

Fig. 14 shows the graph of flame sensor reading at 11pm and 11am versus distance of robot from fire source. When the robot starts moving towards the fire source, the reading from flame sensor decreases gradually. From the graph, it is observed that sensor readings at 11pm is always higher than sensor readings at 11am when the robot is at distance further than 45 cm from fire source. It is also observed that the change of sensor reading when the robot starts moving towards the fire source is much dramatically at 11pm than at 11am. It is due to the disturbance from infrared rays of sunlight at 11am. When the distance between robot and fire source is shorter than 40 cm, both the sensor readings at 11pm and 11am are almost equal and remain constant, it is because the flame sensor is near to the fire source, the effect from fire source become dominant and the flame sensor is saturated.

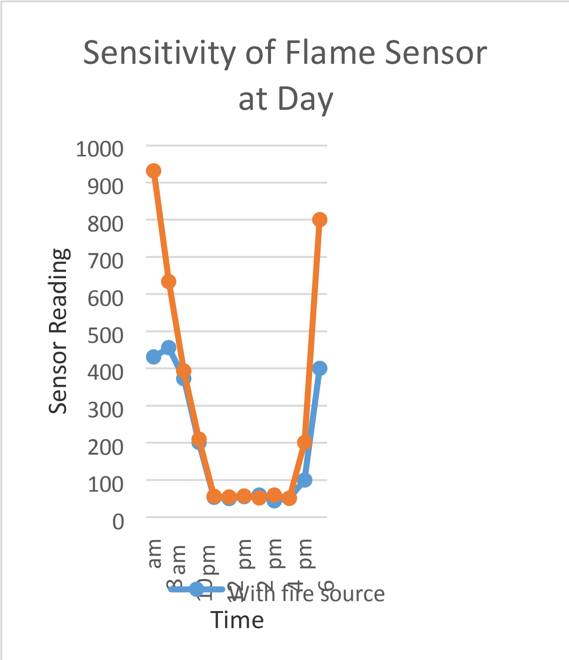

Fig. 14 - Sensitivity of flame sensor at day

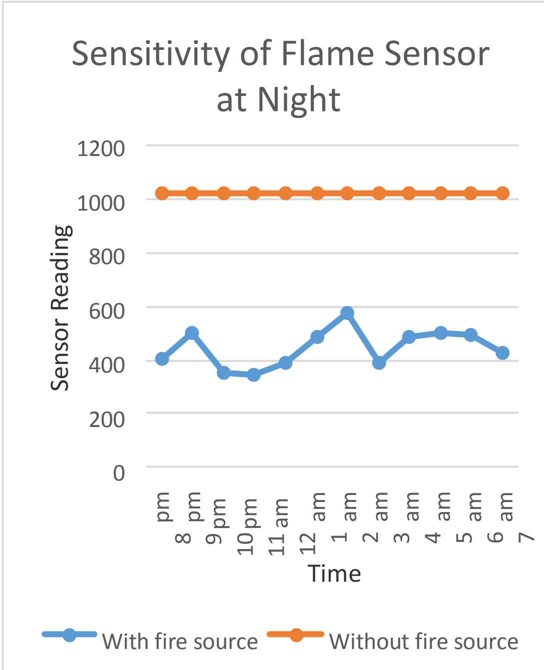

Fig. 15 - Sensitivity of flame sensor at day

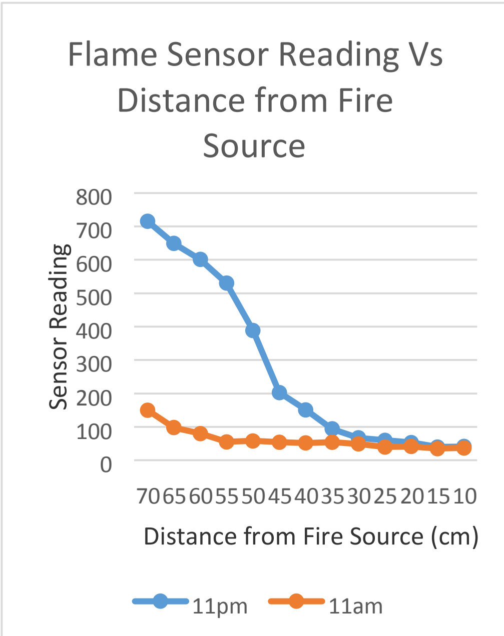

Fig. 16 - Flame sensor reading at 11pm and 11am versus distance from fire source

7. Conclusions

The Fire Fighting Robot is developed with readily available materials and some tests are done to observe its effectiveness at different situation. The robot is able to detect flame and dispense sand to extinguish it at exact location autonomously. Fig. 17 illustrates a screenshot demonstrating fire fighter robot in action which sensed the flame and consequently moved to the fire source to dispense sand to put out a fire. Further improvements can be made in order to deploy this fire-fighting robot into real life situation:

- Printed Circuit Board is to be further developed to minimize the wiring connections.
- Better robot wheel design to achieve tracking.
- A bigger sand reservoir to put out bigger fire and multiple fire source as well as ease the flow of the sand.
- ABC fire extinguisher powder is preferred over sand.

The fire fighter robot is effective in fighting against flame on a small scale. It can sense fire flame better at darker places. As it can detect fire instantly and can extinguish it before spreading, this robot may be a solution to many fire hazards. The substantial benefits gauged from this rather simple proof of concept is that, water was not used as part of medium to put up fire. Certain fire flame which is oil-based may not be able to be eradicated with a mere water fountain. Moreover, using water to putout fire may create other potential electrical hazards in the vicinity of fire source causing harm to the building occupants. Other methods of advanced *non-contact* fire eradication method to be considered in the future is through sound waves which is beyond the scope of this research.

Fig. 17 - Fire Fighter Robot moved to fire source to pour down sand

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