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IFAC PapersOnLine 51-30 (2018) 430–435

Development of Mobile Robot with Sensor Fusion Fire Detection Unit

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Abstract: In this study, a mobile robot platform equipped with early fire detection unit was designed, manufactured and tested. The robot was especially developed to track virtually prescribed paths with obstacle avoidance function through obstacle avoidance and motion planning units and to scan the environment in order to detect the fire source via fire detection unit. Smoke, flame and temperature measurement sensors were used in the system to detect the fire event. A sensor based fusion system was also developed and proposed to get more reliable and highly accurate results from the fire detection unit. Partial Least Square (PLS) was used to derive the fire detection equation from the temperature, smoke and flame measurement values based on calibration and validation data sets with 200 samples. SAS/STAT (Statistical Analysis System) software was used for the development of the calibration and validation data sets. Five different distances at 100, 500, 600, 800 and 1000 mm were selected to test the fire detection capability of the system. Test results showed that the developed robot can detect the fire source up to 1000 mm distance. It can also be understood from the test results that the proposed sensor fusion system provides more reliable detection than one sensor based system with the accuracy value of 92%.

Keywords: Early fire detection, Mobile robot, Obstacle avoidance, Partial Least Square method, Robotic motion plan, Sensor fusion, Virtual path tracking

1. INTRODUCTION

As strange as it might seem there is no standard definition for a robot. However, there are some characteristics and features that can be used for counting a device or a machine as a robot. A robot has to be aware of what is happening in its environment, needs to be able to move and powered by an energy source, if it is necessary a robot has to be smart enough to satisfy the requirement.

Robots are used in wide variety of fields. Robot manipulator also known as robot arm is used to perform tasks in industry such as welding, painting, palletizing etc. due to its power, rigid body, speed and accuracy. Recently; the usage area of the robots is shifted from the classical industrial manufacturing robot to service robot. Medical robot has invaded the field of medicine. Many robotic applications have emerged in medical area such as laboratory robots, surgery and training of surgery etc. Rehabilitation robot also has been used to help people with disabilities (Gupta et al., 2006; Tajti et al., 2013).

Mobile robot is a system that able to complete tasks in different places. As opposed to fix based industrial robot, a mobile robot has its movement unlimited by its size due to its mobility. Mobile robots can be used to perform a variety of tasks that are normally carried out by humans such as surveillance, exploration, patrol, fire searching-fighting, homeland security, care taker, entertainer (A mobile robot system consists of a platform moved by locomotive elements. The locomotive system depends firstly on the environment in which the robot operates. These environments can be aerial, aquatic or terrestrial. In the aquatic and aerial environments, the locomotive systems are generally propellers or screws. The locomotive system in terrestrial environment is complicated. Wheels, tracks and legs are the typical terrestrial locomotive elements. A mobile robotic system has a set of functional parts similar to human beings. These functional parts include intellectual, actuation, mobility, sensory, communication and energy (Fig. 1). (Chen et al., 2009).

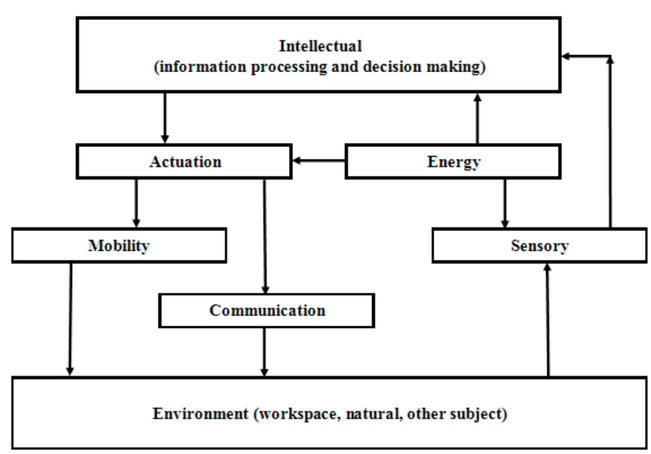

Fig. 1. Model of mobile robot's functional parts

Today's mobile robot researches deal with autonomous applications. Research topics consist of four parts as perception of the environment, self-localization, motion

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10.1016/j.ifacol.2018.11.324

planning and generation (Garcia et al.,2007; Patnaik, 2007; Valgren, 2007).

Firefighting is an extremely hard task. It is still carried by human operators so fire-fighters put themselves in dangerous situations while trying to rescue the victims and to get the fire under control before it becomes graver. After starting of a fire it is almost impossible to control it and recover the damaged area. Therefore, the better way for firefighting is to inspect and detect it, before reaching the point of no return. For this purpose, some early fire detection mobile robots have been investigated and developed (Tan et al., 2013). Luo and Su (2007) developed an intelligent security system for buildings that contains autonomous navigation, master slave operated system, supervision through internet, a remotely operated camera vision system, danger detection and diagnosis system. The multiple sensors and fuse sensory data were used in system to detect the fire and generate reliable fire detection signal. Khoon et al. (2012) investigated an AFFMP (Autonomous firefighting mobile platform) that patrols and monitors the prescribed area for searching the fire occurrence with flame sensors and extinguish it. Chang et al. (2006), developed a FSR (Fire searching robot) using task oriented design (TOD) methodology. This system was designed to operate especially for indoor fires. Kim et al. (2006), studied a portable fire evacuation guide robot system that can monitor indoor disasters. It can be used for victim detection and atmosphere observation. Roberto et al. (2013), proposed a multi sensor data fusion technique for fire detection using a mobile robot. Detection system was based on temperature, luminosity measurements and flame detection. Kumar et al. (2007), produced a gesture controlled robot with the capabilities of fire extinguishment, audio and video capturing. Robot was made up of fire extinguisher set and spy camera. Tongying et al. (2010), researched a flame detection system based on a mobile robot platform. In the system, environmental images were obtained with a camera which placed on mobile robot. An image edge detection method was proposed to suppress the noise interference and detect the flame image accurately. Martinson et al. (2012), developed a robot (Octavia) that can be used as a team member for firefighting tasks. In the system, when human team leader indicates the location of the fire using speech-gesture and clears the obstacles, robot can find the exact location of the fire with its sensors and extinguishes the fire with CAF (compressed air foam) system. Zhang et al. (2012), produced a remote controlled firefighting robot that operates based on a small multi-functional crawler hydraulic excavator. The capabilities of the robot were; walking, turning, striding, dangerous material transportation and fire extinguishment. Necsulescu et al. (2014) developed an autonomous fire detection robot equipped with two light sensors, one TIR (thermal infrared sensor) and one ultrasonic sensor for obstacle avoidance to detect potential threats of fire and find out the source while avoiding the obstacles during navigation. They also proposed "Voting Logic Fusion" approach using sensor data to get more reliable fire detection results.

In this study, a mobile robot platform equipped with early fire detection unit consisted of smoke, flame and temperature sensors was designed, manufactured and tested. The robot was especially developed to track virtually prescribed paths with obstacle avoidance function through obstacle avoidance and motion planning units and to scan the environment in order to detect the fire source via fire detection unit. A sensor based fusion system was also developed and proposed to get more reliable and highly accurate results from the fire detection unit.

2. MATERIAL AND METHOD

2.1 Fire Detection Robot Platform Configuration

The carrier board of fire detection material was manufactured using aluminum material and rigid plastic foam. Motors, power supply unit, data acquisition and control circuits were mounted to first layer of carrier board. Second layer was used to carry the pc. Ultrasonic sensors, fire detection unit and servo motor using for flamed sensor scanning motion were mounted to front side of the carrier board (Fig. 2).

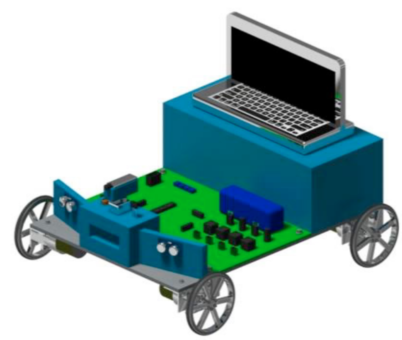

Fig. 2. Robot platform configuration

2.2 Data Acquisition and Control System

Data acquisition and control system circuits were designed and produced for special requirements of the robot. These circuits were designed using Proteus Software (Fig. 3). Data acquisition and control system was created as DC motor driver, data acquisition and communication, servo motor control and microcontrollers. Relays, 1n5822 diodes, IRF3205 power MOSFET, capacitors with the capacities of 1,000 micro farads and 25 Volts and ULN 2003 type relay driver were dedicated for DC motor drive unit. Data acquisition and communication unit was produced with L7805 voltage regulator and Max 232 integrated circuit. Servo motor for flame sensor scanning motion was driven directly with microcontroller signal and voltage regulation. Three pieces of Atmega 32 type 8 bit microcontrollers were used as the center of the data acquisition and control system.

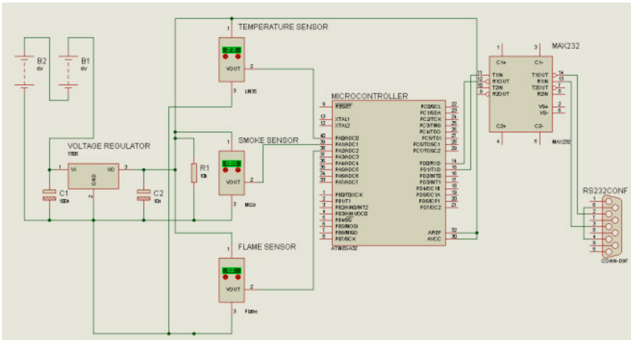

Fig. 3. Data acquisition and control system design

2.3 System Architecture

Fire detection robot was developed with the functions and units of motion planning, data acquisition and control, obstacle avoidance, fire detection and DC and servo motors drivers (Fig. 4). Motion planning task of the robot was executed by re-programmable microcontroller. The prepared route plan was programmed to microcontroller from pc via Atmel programmer. The path distances were defined to robot through motion planning program. After defining process, robot had ability to follow these lines so that it executed the patrolling task.

Data acquisition and control unit was used like a bridge between the pc and other units. It directly controlled the obstacle avoidance unit. Data acquisition and control unit was also responsible to get information from fire detection unit. It received the analog outputs from flame, smoke and temperature sensors then converted to digital data via ADC (Analog to digital converter) channel of the microcontroller. After collecting the information about the environmental situation, data acquisition and control unit transmitted fire information to the pc.

The obstacle avoidance unit was produced using two HC-SR 04 model of ultrasonic sensors. For the obstacle avoidance, control unit received data from ultrasonic distance sensors and made decision and about the path free or not and found the free path using algorithm. Fire detection unit consisted of smoke, temperature and flame sensors. Flame sensor was mounted on a servo motor. While robot was executing patrolling task, flame sensor scanned the environment for fire information. Flame sensor has 180˚ freedom of movement for scanning. All of the sensors acquired the environmental situation and each of them transmitted their own information to the pc through data acquisition and control unit dynamically.

Motor driver unit was responsible for DC motor's actions. The direction of the motor rotation was controlled by motor driver unit. By motor direction control, robot was driven forward or backward. The speed of the motor rotation was also regulated by motor driver with PWM method. As robot was steered with differential method, motor speed regulation was important for robot turnings.

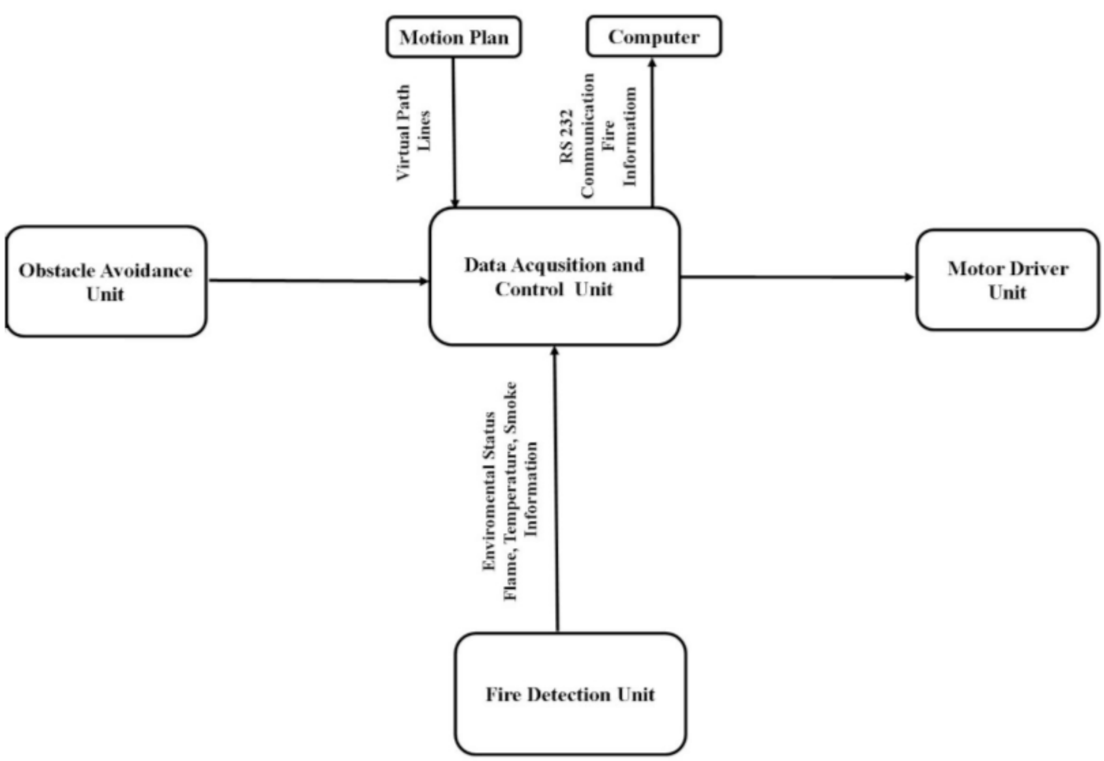

Fig. 4. System architecture

2.4 Sensor Fusion Fire Detection

Three types of sensors were used in the system to detect fire event. With the varieties of the sensor (smoke, temperature and flame) it was possible to get more reliable and high accurate results. A sensor fusion system was developed to obtain high reliable results from the fire detection unit.

In fire detection unit, the weight was a function of the P_D (probability of detection) of the sensors. Although the probability values may vary with time in real life, the optimum detection probability values determined for smoke, flame and temperature sensors through experiments. In the sensor fusion, the detection values of each sensor; temperature (X_1), flame (X_2) and smoke (X_3) were acquired by sensor fusion decision center. These values were considered and multiplied with weight values and final decision "T" was determined. The general fire detection algorithm with sensor fusion;

$$T = W_1X_1 + W_2X_2 + W_3X_3 \quad (1)$$
if $T >$ *threshold value*;
There is a fire.

Different variations have been experimented for different detection distances and fire sources to find the optimum weight values for each sensor and to get accurate fire detection information.

To derive the fire detection equation; PLS (Partial Least Square) analysis was used. To setup the analysis; number of factor was indicated as 15, Simple PLS algorithm and Split Cross Validation method were used. Analysis model was set using 200 samples for temperature, smoke and flame values. After settings, the analysis model was run using SAS/STAT (Statistical Analysis System) software. The results of the analysis are given below;

Calculated number of factor	3
Accuracy of the estimator	97%
Coefficient of regression for temperature	0.16
Coefficient of regression for flame	0.77
Coefficient of regression for smoke	0.07

Using the results of the analysis the fire detection equation was derived as;

$$Fire = (Temperature x 0.16) + (Flame x 0.77) + (Smoke x 0.07) \quad (2)$$

The flowchart of fire detection process with sensor fusion is shown in Fig. 5.

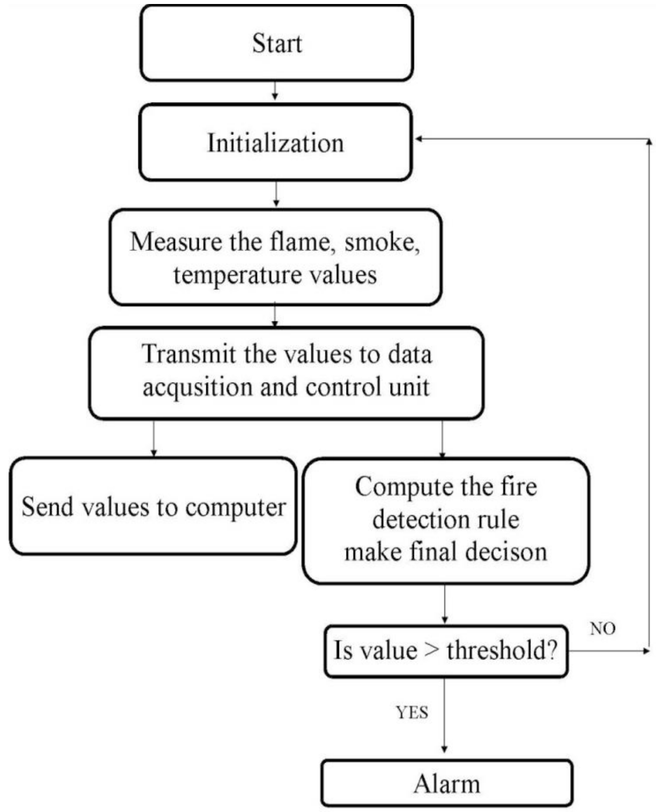

Fig. 5. Flowchart of fire detection process

2.5 Fire Detection Data Measurement

Fire data measurement was executed with the listed procedures (Fig. 6);

- Candle and firewood were used as fire sources in controlled indoor and outdoor conditions,
- A PC was mounted on the second layer of the carrier board and a serial connection was established between the data acquisition unit and pc,
- For the static data measurement robot was located at 500, 750 and 1,000 mm distances from fire source,
- For the dynamic measurement robot was driven with the speed of 0.5 m/s and 500 mm distances from the fire source,
- Temperature, flame and smoke values were measure for 180 seconds and data were saved to pc to consider and to create the fire detection algorithm.

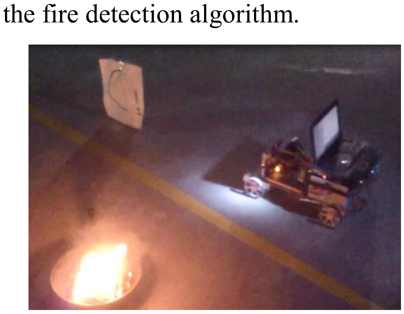

Fig. 6. Fire detection data measurement

3. RESULTS AND DISCUSSION

The performance of the sensor fusion fire detection algorithm and system was tested. Three different terms were defined for test procedure. These terms and values of them are given in Table 1.

Table 1. Terms and values of sensor fusion fire detection system

Name of Situation	Value
No fire	0-0.3
Danger	0.3-0.6
Fire	0.6-1

Three Leds (Light emitted diode) with the color of green, yellow and red were connected to fire detection unit and fire detection algorithm was programmed. The algorithm was tested five times for five different distances using a lighter. The details of the algorithm are given below;

- If the calculated fire value was in the range of 0-0.3, the green led (G) will be turned on (No fire situation).
- If the calculated fire value is between 0.3-0.6 the yellow led (Y) will be turned on (Danger situation).
- If the calculated fire value is between 0.6-1 the red led (R) will be turned on (Fire situation).

Table 2. Performance test results of fire detection system

Distances (mm)	Answer of the fire detection unit				
	Test 1	Test 2	Test 3	Test 4	Test 5
100	R	R	R	R	R
500	R	R	R	R	R
600	R	R	R	R	Y
800	R	R	R	Y	R
1000	R	R	R	R	G

As seen in the Table 2 system could detect the fire with hundred percent performances for 100 and 500 mm distances. For the 600 and 800 mm distances, system answered the lighter flame as four-time fire and one-time danger. One false alarm was shown in the 1000 mm distance. Although there was a simulated fire, system answered as no fire. The results indicated that the developed sensor data fusion algorithm could answer the fire source with hundred percent performances in the range of 100-800 mm distances. For the 1000 mm distance there was only one wrong answer. It could be understood that the data fusion algorithm was able to produce reliable results.

4. CONCLUSIONS

In this research, a mobile robot that has the ability to follow the prescribed virtual path lines and obstacle avoidance, equipped with temperature, flame and smoke sensors and sensor fusion system for fire detection was developed. The selected design and development sections and performance test results were explained. It can be concluded from the sensor fusion fire detection test that mobile robot had ability to detect the fire source up to 1000 mm distance with the accuracy value of 92%.

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