Leader-Follower Formation System of Multi-Mobile Robots for Gas Source Searching

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Abstract. Currently, robots are used to help dangerous human activities, including monitoring and searching for sources of toxic and flammable gases. One of the characteristics of a gas leak is that the direction of the gas changes easily due to wind. Therefore, when using a mobile robot, it will easily lose the direction of the gas plume which results in the longer time needed to find the gas source. In this study, the method of searching for gas source has been developed with the leader-follower formation system. This formation aims to make the multi-mobile robots not easily lose the direction of the gas plume. A simple Particle Swarm Optimization (PSO) algorithm is used to configure V-shaped formation and keep the distance among the robots. The XBee module is used to transmit the data and measure the distance of each robot using the Received Signal Strength Indicator (RSSI) value. The Fuzzy Logic Control (FLC) method is applied to mobile robot navigation to track the gas plume. The PSO algorithm and the FLC method are implemented in the Arduino Mega 2560 microcontroller. The experimental results show that the mobile robot team can maintain a distance of 1 to 2 meters between each robot.

Keywords – Formation system, Gas sensor, Mobile robot, PSO, FLC

1. Introduction

The automatic mapping and searching system for a dangerous or explosive gas source is a challenge needed in many applications, especially in the industrial and environmental fields. Currently, robots are being developed to help with hazardous works including the search for gas leak locations. One of the characteristics of a gas leak is that the direction of the gas changes easily due to wind. Therefore, when using a mobile robot, it will easily lose the direction of the gas plume which results in the longer time needed to find the gas source.

In the case of solving problems, a team has the ability to solve complex problems more easily than other individuals in the same species. As a team, a little information could lead the team to the desired destination more efficiently in time than the individual itself [1]. Collaboration between each individual in the team can be applied on a mobile robot platform. Therefore, in order to find gas sources quickly, it is used more than one mobile robot.

When searching for gas source locations, there are several problems that must be addressed. The large space will result in a long process of finding gas sources. Artificial intelligence is an important requirement so that the process of finding gas sources becomes more optimal [2]. Multi-mobile robots require cooperation and coordination between members to get to the same target. The mobile robot team works by determining the group leader. The requirement to be a team leader is to have the
highest gas sensor response. The robot team then moves with a certain formation. The collaborative procedures in mobile robot group can use the swarm intelligence algorithm. One concept of the swarm intelligence algorithms is Particle Swarm Optimization (PSO). In the PSO algorithm, each mobile robot can represent a potential solution [3][4]. Mobile robots using the swarm algorithm can learn both from other robots and personal experiences.

In this study, multi-mobile robots are used to find gas source. The PSO algorithm is used to form a leader-follower formation. The mobile robot team will configure a V-shaped formation so that when there is a change in the direction of the gas plume, the team can follow changes in the direction of the plume by comparing the response of the gas sensors of each robot. If there is a change in the direction of the gas plume, the mobile robot will make changes to the formation to follow the direction of the gas plume. In addition, the Fuzzy Logic Control (FLC) method is used to move the mobile robot to the gas target. The response of the two gas sensors determines the speed of the two mobile robot wheels.

2. Method

2.1. Mobile Robot

Mobile robot is a robot that can move generally using wheels in its application [5][6][7]. Figure 1 shows the mobile robot to find the gas source used in the experiment. The configuration algorithm of the mobile robots uses the PSO method to maintain the V-shaped formation. The FLC method is used to steering the mobile robot towards the source of the gas source. The PSO algorithm and the FLC method are implemented in the Arduino Mega 2560 microcontroller as the control processing unit of the robot. Three mobile robots are used for this study.

Figure 1. The Multi-Mobile Robots used in the experiments.

Figure 2. The overall block diagram of the system for the formation of multi-mobile robots.
The mobile robot is equipped with two gas sensors located on the front left and right side of the mobile robot, three ultrasonic distance sensors on the front side of the robot and one Xbee module with a 2.4 GHz frequency. Figure 2 shows the overall block diagram of the system for the formation of multi-mobile robots.

The gas sensor is used by mobile robots to follow the direction of the gas source. The output of the gas sensor is a change in material resistance represented by analog voltage [8]. The ultrasonic distance sensors are used to detect objects in front of the robot so that there are no collisions of each robot. This sensor is also used as a stop criterion when the mobile robot is very close to the gas target. The XBee module is used to transmit data and measure the distance of each robot using the Received Signal Strength Indicator (RSSI) value.

2.2. The Received Signal Strength Indicator (RSSI)

Equation 1 is the signal strength equation that is widely used in wireless signal transmission [9].

\[
\frac{P_r(d)}{d_{dBm}} = \frac{P_r(d_0)}{d_{dBm}} - 10n \log \left( \frac{d}{d_0} \right) + X_{dBm}
\]  

(1)

where, \( P_r(d) \) is the signal strength received by the receiver (dBm), d is the distance from the transmitter to the receiver in meters, \( d_0 \) the distance of the reference when the transmitter and receiver are within one meter, \( X_{dBm} \) is a Gaussian random variable whose average value is 0, and n is the path loss index. The equation can be simplified as follows:

\[
\frac{P_r(d)}{d_{dBm}} = \frac{P_r(d_0)}{d_{dBm}} - 10n \log \left( \frac{d}{d_0} \right)
\]  

(2)

For \( d_0 = 1m \), the RSSI distance measurement equation is obtained as follows:

\[
\text{RSSI[dBm]} = \frac{P_r(d)}{d_{dBm}} = A - 10n \log d
\]  

(3)

\[
d = 10^{\frac{A - \text{RSSI}}{10n}}
\]  

(4)

with A is the signal strength received in a distance of 1 meter in dBm. After overcoming the influence of environmental factors such as diffraction and obstacles that affect wireless signal transmission, the RSSI can be used in indoor and outdoor localization and can measure distances.

2.3. Leader-Follower Formation System

The use of leader-follower formation is to expand the range of mobile robot while searching the leakage of gas. The leader-follower configuration for multi-mobile robots is V-shaped formation. The leader-follower formation is used to keep the robot team moving to keep up with changes in the direction of the gas. The selection of leader from the mobile robot team is conducted by comparing the gas sensor responses from each mobile robot. Mobile robot that have the highest value from all members will be chosen as the leader of the team.

2.4. Particle Swarm Optimization

The PSO is a part of swarm intelligence which is defined as a population-based algorithm where each solution is the individual itself that moves in the search space. Each individual can determine the movement itself by considering several aspects of the best position before [2]. The PSO was first introduced by Kennedy and Eberhart as a new methodology in computational intelligence analogous to social interaction.

PSO is based on a group of birds or ants, where if an ant finds the best way or a shortcut to a food source then another group will follow that path even though it is far away [5]. Therefore, the behavior of animal group or swarm is influenced by individuals and other groups. Each individual is assumed to have two characteristics, namely position and velocity. A team leader will send information about its position to the others and adjust the value of its position and velocity. In the PSO algorithm, each individual in swarm represents a potential solution. By knowing the position of other individuals in the
swarm, each individual can adapt to the search pattern. The PSO algorithm in this study is expressed as follows:

1) At the beginning, each robot is in a parallel position.
2) Evaluate the voltage value of the gas sensor from each mobile robot based on its position.
3) Determine the mobile robot based on the highest voltage value of the sensor as the global best (leader) and other robots configured as followers.
4) Update the position and velocity of each robot.
5) Configuring a V-shaped formation with the distance of each robot is 1 - 2m.
6) Evaluate the gas sensor voltage values of each individual.
7) Check the stop criteria, if the distance of the mobile robot to the gas source is less than 9 cm and the gas sensor voltage is more than 1.62 volts, then the mobile robot team stops. If not, go to the step 2.

2.5. Fuzzy Logic Control
Fuzzy logic works with linguistic rules of reasoning and decision making from uncertain information [10][11]. Fuzzy logic steps are divided into three stages, namely fuzzification, inference, and defuzzification. The FLC block diagram is shown in Figure 3, while the control design applied to the mobile robot is shown in Figure 4. The stages in designing fuzzy logic control are as follows:

1) Fuzzification is the process of converting crisp inputs into fuzzy inputs. There are two gas sensors, namely the left and right gas sensors used to determine the orientation of the mobile robot. The input membership function of the gas sensor is shown in Figure 5.
The output of a gas sensor is an analog voltage converted into digital values by 10-bit analog to digital converter. The input data is the current value subtracted by reference. The reference value is a gas sensor response to clean air in 40 seconds.

2) **Inference** is a fuzzy rule that is used to logically control a system to correlate between fuzzy input and output in the form of "if-then" logic expressed by:

$$\text{if } X_1 \text{ is } A_1 \text{ and } ... \text{ and } X_n \text{ is } A_n \text{ then } Y \text{ is } B$$ \hspace{1cm} (5)

In this study, the fuzzy rules are divided into two parts, rules for moving the right and left motors shown in Table 1. Decision making uses the max mechanism to make the appropriate fuzzy output expressed by

$$\mu_B(y) = \max \left[ \min \left[ \mu_{A_1}(\text{input}(i)), \mu_{A_2}(\text{input}(i)), ... \right] \right]$$ \hspace{1cm} (6)

3) **Defuzzification** is the process of converting fuzzy output to crisp values. The output membership functions are singleton of the PWM value used to drive the motors on the mobile robot. In this design, the Mamdani method is used to define the output value. The defuzzification method used in this experiment is the Center of Area (CoA) expressed by

$$Z_0 = \sum_{i=1}^{n} \frac{\mu(Z_i).Z_i}{\mu(Z_i)}$$ \hspace{1cm} (7)

$$\text{Motor PWM} = \text{constants} + Z_0$$ \hspace{1cm} (8)

**Table 1. The fuzzy rule used to drive the motors.**

| Gas Sensors | Right | Left | Right Motor | Left Motor |
|-------------|-------|------|-------------|------------|
| Low         | Low   |      | Big-        | Big-       |
| Low         | Medium|      | Big+        | Big-       |
| Low         | High  |      | Small+      | Big-       |
| Medium      | Low   |      | Big-        | Big+       |
| Medium      | Medium|      | Zero        | Zero       |
| Medium      | High  |      | Small+      | Small-     |
| High        | Low   |      | Big-        | Small+     |
| High        | Medium|      | Small-      | Small+     |
| High        | High  |      | Zero        | Zero       |

**Figure 6.** The output membership function of the FLC.
3. Experimental Result

3.1. The Gas Sensor Response to Distance
In this study, the MQ-2 gas sensors are used to detect the presence of gas and determine the distance of the robot to the gas source. Figure 7 shows the gas sensor response to the distance. The experimental result shows that the greater the distance of the sensor to the gas source, the smaller the sensor voltage. This can be used as a stop criterion for mobile robot when approaching gas sources whose values range from 1.5 V and 1.6 V.

3.2. The Measurement of RSSI to Distance
The mobile robot uses two distance measurement data, namely the distance data of the ultrasonic sensor and the RSSI value. The RSSI is provided by the XBee module in the dBm unit. As data for the control system, RSSI is converted to PWM using the following equation:

\[ PWM\ counts = (41 \times RSSI_{\text{unsigned}}) - 5928 \]  

Figure 7. The gas sensor response to the distance.

Figure 8. The measurement of the RSSI to the distance.

Figure 9. The distance measurements using the RSSI value.
Distance measurement with RSSI aims for each mobile robot to realize the distance from each other. When a robot moves to form a formation, the robot must adjust the distance between the leader and the follower to keep the configuration. Figure 8 shows the measurement of RSSI values to the distance, while Figure 9 shows distance measurements using the RSSI value.

3.3. The FLC Implementation for the Mobile Robot Navigation

This experiment aims to control the movement of the robot in finding gas source. The evaporated liquid fuel is used as a target in a certain direction and a distance of 1.3 meters in front of the robot. Figures 10 and 11 show the response of the mobile robot in the search for gas source location in the direction of 45° and -45°, respectively. The time needed for a mobile robot to find a gas source is about 180 seconds. If the gas sensor voltage is less than 0.049 volts, the mobile robot will stop because there is no gas detected. FLC will be activated if the sensor voltage is more than 0.049 volts. The motor speed will be updated until the mobile robot reaches the gas source indicated by the maximum response of the gas sensor. Figures 12 and 13 show a snapshot of the mobile robot experiments when searching for gas source location in the direction of 45 and -45°, respectively.

Figure 10. (a) The gas sensor response, and (b) the motor speed when the robot is searching the gas source at the direction of 45°.

Figure 11. (a) The gas sensor response, and (b) the motor speed when the robot is searching the gas source at the direction of -45°.

Figure 12. The robot in searching for the gas source at the direction of 45°: (a) the initial position, and (b) the track of movement.
3.4. The Leader-Follower Formation System of the Multi-Mobile Robots

Leader-follower formation aims to expand the reach of mobile robots when searching for gas source. In addition, the leader-follower formation also serves to keep the team from losing the direction of the gas plume. In Figure 14 (a) shows the initial state of the mobile robots which are parallel to the others. When one of the robots detects a gas, the robot will inform the others. Then the robot team begin to configure a V-shaped formation with the leader in the front. In Figure 14 (b) shows the configuration formed during the search for gas sources. The robot team will form a distance of 1 to 2 meters from one another. The robot team always keeps the formation until it finds the location of the gas source. Mobile robots still communicate with each other to provide information about the environment. Figure 15 shows the response of the mobile robot team in the search for gas source location, in which the distance between the mobile robot team and the gas source is 2.5 meters.

![Figure 13](image)

Figure 13. The robot in searching for the gas source at the direction of -45°: (a) the initial position, and (b) the track of movement.

![Figure 14](image)

Figure 14. (a) The robot trajectories (b) the formation reconfiguration of the multi-mobile robots in searching for the gas source.

![Figure 15](image)

Figure 15. The snapshots of the multi-mobile robots in the search for the gas source location.
4. Conclusion
In this study, the method of searching for gas source has been developed with the leader-follower formation system. This formation aims to make the multi-mobile robots not easily lose the direction of the gas plume. A simple PSO algorithm is used to configure V-shaped formation and keep the distance among robots. The XBee module is used to transmit data and measure the distance of each robot using the RSSI value. The FLC method is applied to mobile robot navigation to track the gas plume. The PSO algorithm and the FLC method are implemented in the Arduino Mega 2560 microcontroller. The experimental results show that the mobile robot team can maintain a distance of 1 to 2 meters between each robot. The time needed for a mobile robot to find a gas source with a distance of 1.3 meters is 180 seconds.

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