Odor source localization with a multi-robot system

Linfeng Zhang, Member, IEEE, Xingguo Xiong, and Junling Hu

***Abstract*—Multiple robots with chemical sensors as a dynamic distributed system are more efficient to localize the toxic gas source as terrorist attack, while this gas source can be stationary or mobile. In this paper, the gas concentration fields at different wind speeds constructed in two dimensions and the concentration distribution can be continuous or discontinuous. At the beginning, the robots are randomly deployed in this field. Each robot estimates the location of the gas source. The search algorithm and the sensing frequency of the robot are affected by the sensor sensitivity and response time. Then, all of the information from the robots is processed by a dynamic central robot for a more precise estimation. This central robot also determines the fleet size, tasks to the other robots, and possibility of catching the gas source if it is mobile. The whole system is developed as a platform with Posix Threads programming for the research and education in the future.**

***Index Terms*—parallel processing, robot sensing system**

I. Introduction

Odor source localization is a behavioral problem that varies from animal to animal, such as moths, rats, and lobsters. Robots with sensors for toxic gas can also be used to localize the odor source for leakage detection and homeland security. Moreover, system with multiple robots is necessary for slow and low sensitive sensors and critical time requirement. The constraints are usually the energy consumption and communication rage (around 500 fts in wireless communication).

Till now, there are following algorithms for single robot system: (1) Step-by-step algorithm, the robot follows the upwind direction and toward the center of the odor plume as indicated by the concentration gradient. The robot trajectory consists of a repeated sequence of sense-move operation. The algorithm is simple to perform. However, in many cases, the location with high concentration may not the source, such as the corner of a room. For the heavy gases in 3D, they will stay in the low point. To solve this problem, a robot should walk around to check its upwind. If there is still plume, it should continue to search; otherwise, this is the odor source. Moreover, at high wind speed, turbulence causes the chemical plume to fluctuate; it is hard for a robot to determine the concentration gradient. (2) Zigzag algorithm, the robot runs diagonally across the full width of the odor plume, the robot changes direction to cut across the plume in the opposite direction once it reaches the far edge of the plume. The diagonal path is angled upwind on each sweep. (3) Male silkworm moth algorithm, the robot surges a short distance upwind at high speed, then starts casting from side to side with increasingly wide swings and finally performs a number of complete loops before stopping. This algorithm is efficient. But, the searching may be changed to localize the wind source instead of chemical source.

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In a large field and with the high wind speed, multi robot system is more efficient than the single robot system. One function of the robots at different locations can substitute the spiral search of a single robot, thus the multi robot system decreases the searching time. Also, multi robot system can change the spiral search algorithm and this will be discussed in the simulation part.

For multi-robot system, if one robot senses the chemicals, it moves toward the high concentration and this will also attract the other robots. If several robots detect the chemicals, the action depends on which stimulus is stronger [1].

In the searching, the robot senses the environment while moving. The robot accumulates the information from sensor data and constructs a map of the environment gradually. At any moment, the robot needs to determine the sequence of the locations [2]. In more detail, the decision includes of the direction and the velocity.

Other challenges include robot's dynamic joining in or leaving the multi robot system, the effect of the sensitivity and accuracy of the sensor, the determination of the fleet size.

In this paper, the objective is to construct a platform for a distributed multi-robot system, thus the search algorithms can be investigated in multi-robot system.

II. Mathematical Model

Odor source can be static at the beginning and will be mobile in the future. Each robot has one gas sensor, one wind direction sensor, GPS, and wireless communication unit. For a multi-robot system, the total number is fixed at the beginning and will be dynamic in the future. Thus, the system can be scalable. The constraints in the communication range and the power of robots are not considered here. At beginning, the odor can be detected by at least one robot. There are two cases for the odor concentration distribution, at low wind speed (laminar flow), the gas concentration is continuous in figure 1 (a); at high wind speed (turbulent flow), fluid flow breaks the plume into isolated packets, areas of relative high concentration surrounded by fluid that contains no odor in figure 1 (b) [3] [4]. In Figure 2 (a), if the wind speed induces turbulent flow, it is possible that the concentration measured by robot *a* is lower than that by robot *b*. To make a right judge, the wind direction should be considered. In Figure 2 (b), even the concentration measure by robot *a* is lower than that by robot *b*, if the wind direction is in the range showed at robot a, a judge that the concentration measured by robot a should be higher. The gas concentration distribution will affect the search algorithm, especially in the spiral search. For gas sensor, besides stable response, there are turn-on and turn-off transient responses. These transient responses may take several seconds to tens seconds due to the gas molecule adsorption, desorption, and chemical reactions in figure 3. If the limiting step in the sensor response can be determined, the quick response may be obtained through performance improvement. Otherwise, the robot has to wait for the stable response for accuracy. One algorithm to remove this effect is in the data processing, two-dimensional Gaussian weighting functions can be used to shift the center of the response [5]. Similarly, the sensitivity of the sensor also affects the search algorithm.

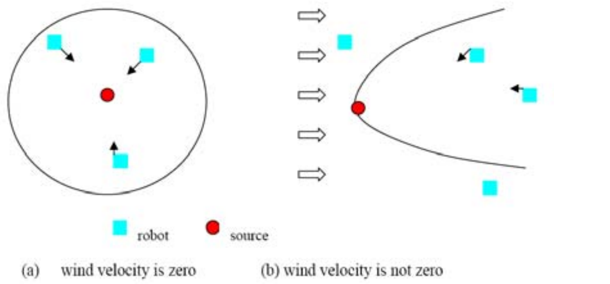

Figure 1 Distribution of the odor at different wind speed. (a) the wind velocity is zero; (b), the wind velocity is not zero and one of the robots is out of the range and can not detect the odor.

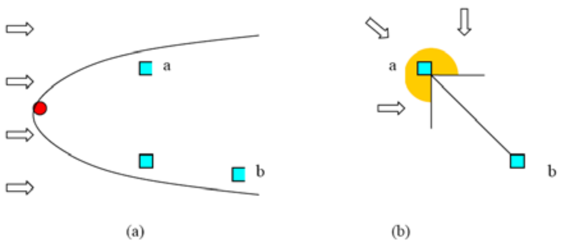

Figure 2

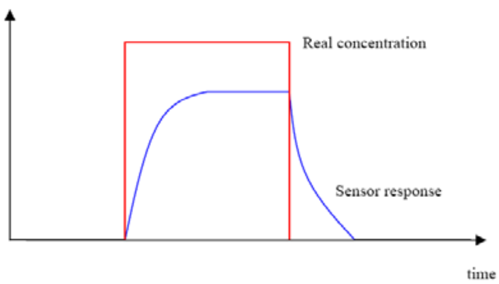

Figure 3 Typical transient response from a gas sensor

The objective is to localize the odor source at a minimum scalar value. This can be time, energy, or these two factors combined with different weighting factor. Usually, the power consumption of a robot can be divided into four parts: motion, sensing, communication, and computation. Thus, there should the models corresponding to these for parts for an optimum algorithm. In this paper, there are move and sense steps alternatively.

(1) Search algorithm for single robot system

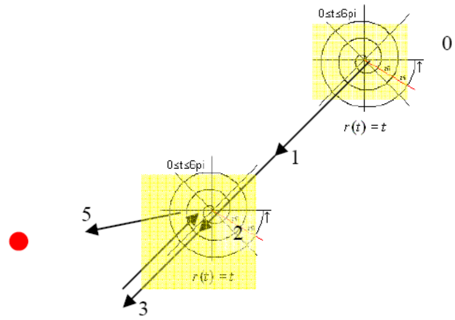

Figure 4 Search algorithm with single robot

For single robot system, the algorithm consists of spiral search-sense and move-sense processes in figure 4. The concentration gradient is determined through the spiral search, thus robot move in the direction to the high concentration area.

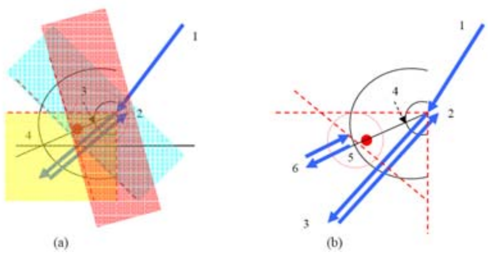

Figure 5 Two cases for the final step in the searching

In the localization of the odor source, there are two special cases as the final step of the searching. In Figure 5 (a), since the concentration is less at point “4” than at point “3”, the odor source is in area where three planes are overlapped. This area or the resolution is determined by the sensor sensitivity. Similarly, the source can also be determined in the region shown in figure 5 (b).

The following convergent condition is used in this system:

$$(Conc_{n+1} - Conc_n)^2 + (Loc_{n+1} - Loc_n)^2 < \alpha \quad (1)$$

Where:

Conc: the concentration
Loc: location of the robot
α: constant

(2) Search algorithm for multi-robot system

(a) (b)

Figure 6 Robot system to predict the source location

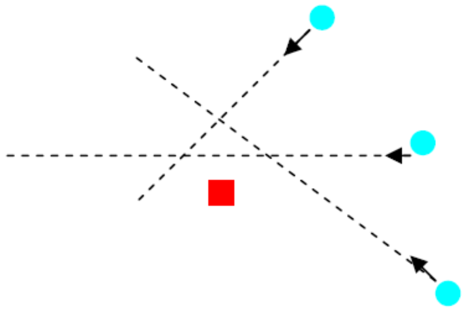

Figure 7 Multi-robot system to predict the source location

Each robot detects the source direction through the spiral search and wind direction detection as in the single robot system. In single robot system (Figure 6 (a)), robot need to measure the concentration in very small angle range to determine the direction more precisely at low wind velocity and move forward in this direction without any idea about the distance to the source. However, in a multi-robot system, the location of the odor source can be roughly predicted through the information from the two robots (Figure 6 (b)). This is a main advantage of the multi-robot system, thus the moving distance can be calculated and it saves time and power. However, when the two directions are too close (less than 10^o), the data may not be used. In this system, the accuracy in the prediction of the source is higher with more robots in the system, shown in Figure 7.

Thus, in a multi-robot system, each robot can move and sense and there is communication between the robots. After certain steps, a group decision will be made by one robot. All the robots will follow the decision to surround the odor source. If the robots are close to each other enough, only one robot will be responsible to trace the odor source, similar to the single robot system. The flow chart is shown in figure 8. The program for this simulation was done with POSIX Threads programming in Linux. The threads work as robots. A global map includes the odor source, concentration distribution, wind velocity and angle. If the wind speed is low, the concentration is continuous. If the wind speed is high, the concentration is not continuous. This can be implemented on the basis of the continuous distribution but with a probability 0 or 1.

For the convergent condition in the multi-robot system, the information in equation (1) is from the robot which is regarded as the one most close to the target.

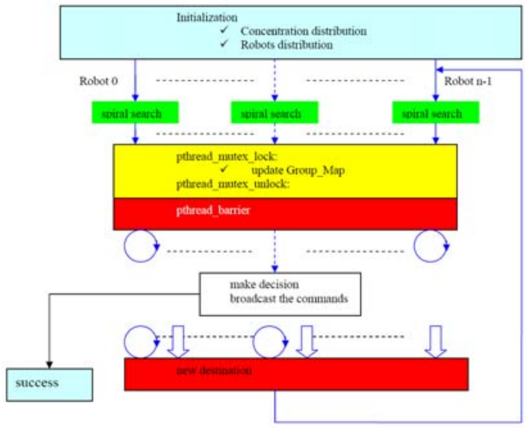

Figure 8 The flow chart of the multi-robot system platform

III. SIMULATION RESULTS AND DISCUSSIONS

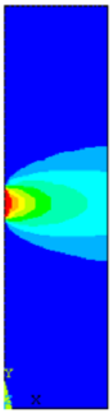

Figure 9 The concentration distribution

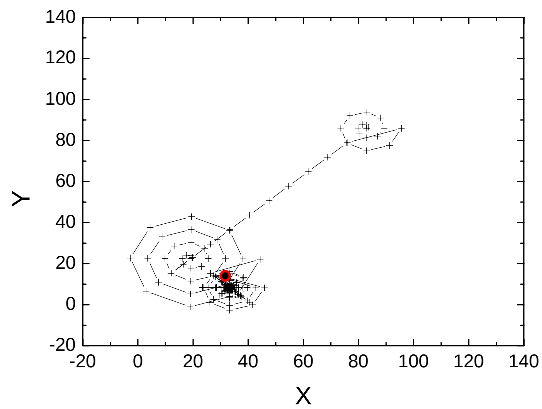

Figure 10 Simulated result of the odor source localization with single robot system

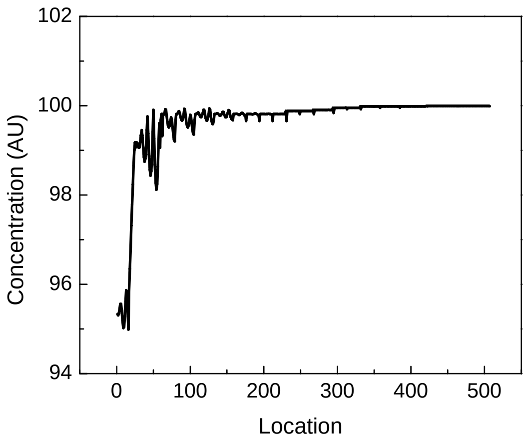

Figure 11 The concentration measured by the robot

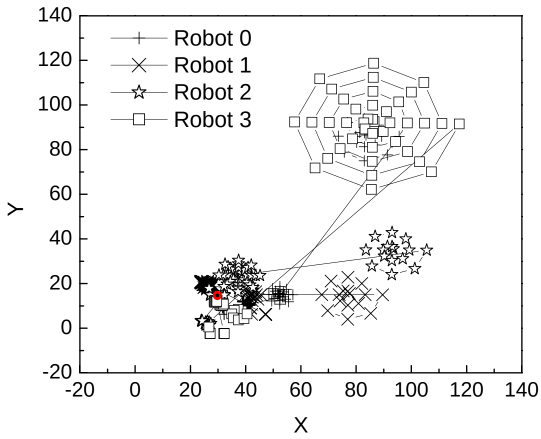

Figure 12 Simulated result of the odor source localization with four robot system

In this paper, Ansys is used to simulate the concentration distribution. Figure 9 shows a simulated distribution. Depends on the wind speed, the width of the plume will change. At high wind speed, the concentration fluctuation will appear. In the future, the boundary conditions of the wind speed and direction will not be constant.

Figure 10 shows an example of odor source localization with single robot system. The odor source is fixed at point (30, 10) and the original location of the robot is (83, 86). The whole search consists of 5 spiral search. The main problems in the signal robot system are: (1) It is impossible determine the spiral gap and the step size after the first spiral search. (2) Most of the time is spent in the final step when robot is quite close to the source. (3) This algorithm doesn't work at high wind speed with concentration fluctuation. Figure 11 shows the concentration measured by the robot in the tracing and the fluctuation of the concentration is due to the spiral search and the fluctuation of the gas concentration.

Figure 12 shows the simulation of the four robot system. For this system, all the information from each robot will be collected and processed by a robot, dynamic master. Robots periodically update the cyber global map. All the other robots, as slaves, will follow the instructions from the master to surround the source. Through this system, the time is dramatically saved since the distance to the odor source can be predicted.

Figure 13 shows the relationship between the total search time and the total number of robots in the system. The total search time includes the moving time, sensing time, and communication time. At beginning, this total search time decreases dramatically from 1301 for one robot system to 350 for four robot system. One robot can find the direction of the odor source but can not estimate the distance to the source. So, this robot takes relatively long time to approach the source. However, the distance to the source can be easily determined in the multi-robot system. It is straightforward that it is more efficient to trace the odor source with a multi-robot system in a large area. With the increasing of the total robot number, the total search time increases gradually due to the group coordination. Thus, there is an optimized robot number in the odor source search in a certain area with a specific search algorithm.

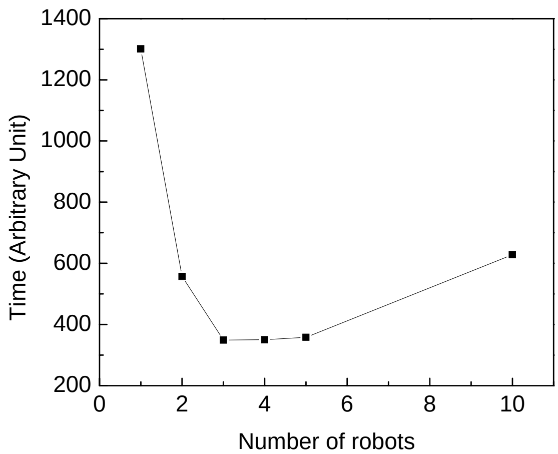

Figure 13 The relationship between the search time and the number of the robots

IV. CONCLUSIONS

In this paper, a platform of multi-robot system is developed. In the future, many issues can be discussed based on this platform, including the effect of the sensor sensitivity and accuracy, the prediction of the odor source location, the constraints of energy and communication range, scalability. The students in our university can do the projects in the nonlinear control, signal processing besides object oriented programming.

REFERENCES

[1] Russell, R.A., *Survey of robotic application for orod-sensing technology.* The International Journal of Robotic Research, 2001. **20**(2): p. 144-162.

[2] Mei, Y., *ENERGY-EFFICIENT MOBILE ROBOTS.* Ph.D. Dissertation, Purdue University, 2007.

[3] Hayes, A.T., Martinoli, Alcherio, Goodman, Rodney M., *Distributed odor source localization.* IEEE Sensor Journal, 2002. **2**(3): p. 260-271.

[4] Spears, D., Zarzhitsky, D. , *Multi-robot chemical plume tracing.* Multi-robot systems, from swarms ro intelligent automata, Springer, 2005.

[5] Achim Lilienthal, T.D., *Building gas concentration gridmaps with a mobile robot.* Robotics and Autonomous Systems, 2004. **48**: p. 3-16.