Intelligent Mobile Olfaction of Swarm Robots

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ABSTRACT

This work presents intelligent mobile olfaction design and experimental results of intelligent swarm robots to detection a gas/odour source in an indoor environment by using multi agent based on hybrid algorithm. We examine the problem for deciding when, how and where the gas/odour sensor should be activated. Simple form of cooperation between Interval Type-2 Fuzzy Logic and Particle Swarm Optimization (IT2FL-PSO) algorithm is implemented in the olfaction strategies. The real experiments performed on smaller five mobile robots equipped with dynamic gas/odour sensor TGS2600 and three infra-red sensors. The results show that single robot-based olfaction system with 5 behaviors capable for searching source of a simulated chemical leak in unknown environment and flooking behavior can be done by 3 robots to find the source of gas/odour.

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1. INTRODUCTION

The olfaction system is widely used throughout the biological world. Animals use olfaction systems to catch information about the environment and to appropriately react to different situations [1,2]. Olfaction is fundamental for many animal species to localize a possible source of food, a mate, or to escape from possible predators [3,4]. In the early 1990s, motivated by the olfaction abilities of these animals, researchers started to try building mobile robots with similar olfaction abilities to replace trained animals [5]. Olfaction is not a common sense in the mobile robotics field, but the large number of important applications that can be solved with this sense fostered the research in this area.

Recently studies on application of robotic with olfaction technology has increased extensively. There have been several reported Implementations of odor source localization by autonomous mobile sensing system [5,6]. Mobile robots equipped with chemical sensors can be useful for a number of application areas including safety, security, and environmental inspection. Instead of humans, robots can be dispatched to areas with odor contamination for inspection, or providing continuous monitoring of the contaminated environment for specific characterization of the odor. For that purpose various approaches might be developed based on extremum seeking, gradient or hill climbing, multi-objective optimization algorithms, game theoretic strategies, negotiation based algorithms, extending single-robot search, exploration, and coverage algorithms, and others.

The ability to smell volatile chemicals provided by these sensors has lead researchers to investigate the use of gas sensors for robot navigation. The ability of robots to orientate themselves by smelling some odor has proved useful in many scenarios. Integration mobile robot with olfaction system is a new computation and behavioral application metaphor for solving real-world problems including leak in an indoor environment. It is based on the principles underlying the behavior of a natural agent consisting of an olfaction system that can simulate an animal olfaction system. The usefulness of such integration system is particularly evident when the robot needs to carry-out some chemically related task [5-7].

Therefore, algorithms developed for static environments might not perform satisfactorily in applications involving multiple contaminating sources. Moreover, studies involving only simulation might overlook the practical/experimental difficulties which might be present in applications with real contaminating chemical sources. Starting from this point this article focuses on real mobile robot search algorithms for building chemical concentration map of an unknown indoor environment contaminated by a real chemical gas. In particular, combination particle swarm optimization and interval type-2 fuzzy logic algorithm for navigation and robotic search applications is considered. The problem of deciding when, how and where the gas/odour sensor should be activated is examined by planning for active perception. In this paper interval type-2 fuzzy logic-particle Swarm Optimization (IT2FL-PSO) strategies is proposed to produce optimal results.

2. SWARM ROBOTS ALGORITHM

Swarm robotic systems are an approach for coordinating multi-robot systems. It shares information about the environment and individual members interact with each other. The main challenges for swarm robots are to create intelligent agents that adapt their behaviors based on interaction with the environment and other robots, to become more proficient in their tasks over time, and to adapt to new situations as they occur. Typical problem domains for the study of swarm-based robotic systems include foraging [8], formation control [9], aggregation and segregation [10], formation forming [11], cooperative mapping [12], soccer tournaments [13], site preparation [14], sorting [15], and collective construction [16]. All of these systems consist of multiple robots or multiple agents acting autonomously based on their own individual decisions.

For instance, most approaches rely on extensive global communication and scalable for cooperation of swarm robots, which may yield stressing communication bottlenecks. Furthermore, the global communication requires high-power onboard transceivers in a large scale environment. and the real time computation also impose significant amounts of memory and processing power. Putting significant computing resources on a robot requires both power and a certain minimal size constraint, which may be too large to allow a robot to operate effectively. Such constraints may serve to greatly limit either the operational effectiveness of simple swarm robots [17-19]. Therefore limited sensing, minimal source code and communication capability is desirable.

An alternative paradigm to tackle the scalability issue for swarm robots behavior while maintaining robustness and individual simplicity is through Swarm Intelligence (SI). This is an innovative computational and behavioral metaphor for solving distributed problems by taking its inspiration from the behavior of social insects with simple rules based on local perception such as ant algorithm, particle swarm optimization, chemotaxis algorithms and biologically-inspired algorithm [7-10,15].

In this work, simple cooperation between Interval type 2 Fuzzy Logic and Particle Swarm Optimization (IT2FL-PSO) is implemented in the navigation strategies. In this strategy IT2FL is used for navigating in safe path while PSO to search the gas/odour source in dynamic environment. The basic IT2FL-PSO algorithm is slightly modified to accommodate several tasks for gas/odour source detection application. PSO which incorporates change detecting and responding mechanisms, can be implemented with a simple algorithm in actual hardware [20]. Signal from gas/odour sensor is a direct indication of a certain chemical substance presence. When the behavior with the highest priority among those active, it transmits the commands to the motors to search the target.

The PSO algorithm which is derived from the classical PSO algorithm with formula variables as follows [21]:

$$v_{ij} = explorative + cognitive + social \tag{1}$$

The social metaphor that led to this algorithm can be summarized as three factors including, the explorative factor, cognitive factor and the social factor. PSO algorithm can be described in equations (2) and (3) as follow,

$$v_i^{k+1} = v_i^k * w_i + c_1 * rand * \left(p_i^k - x_i^k\right) + c_2 * rand * \left(p_g^k - x_i^k\right) \tag{2}$$

In simple form PSO equation (2) can be modified as equation (3),

$$v_i^{k+1} = v_i^k * w_i + \underbrace{c_1 * rand * (0) + c_2}_{\text{Cognitive}} \underbrace{* rand * \left(p_g^k - x_i^k\right)}_{\text{Social}} \tag{3}$$

One advantage of this technique is a very simple algorithms and it can be implemented in just a few lines of code. This algorithm also requires only primitive mathematical operations and it's computationally not large in terms of speed of processing and memory utilization. In this work, PSO algorithm is combined with interval type-2 fuzzy logic controller for robust implementation.

Interval type-2 fuzzy logic system (IT2FLS) constructed using interval type-2 fuzzy sets to distinguish them from the traditional type-1 fuzzy logic system (T1FLS). Interval means that the input/output domains are characterized by interval type-2 sets [22]. An interval type-2 fuzzy set $\tilde{F}$ can be written in equation (4) as follow,

$$\tilde{F} = \int_{x\in X}[\int_{u\in[\underline{\mu}_{\tilde{A}}(x),\overline{\mu}_{\tilde{A}}(x)]}(1/u]/x \tag{4}$$

In some paper, IT2FLSs singletons are used to simplify the calculation. The term singleton denotes that the fuzzifier converts the input signals of the FLS into fuzzy singletons. For each input *k* and rule *i*, the interval type-2 fuzzy set is represented by triangular membership function with uncertain mean are described in equations (5) and (6) respectively,

$$\overline{f}_A(x) = \begin{cases} 0 & x \langle l_1 \\ \dfrac{x-l_1}{p_1-l_1} & l_1 \le x \langle p_1 \\ 1 & p_1 \le x \le p_2 \\ \dfrac{r_2-x}{r_2-p_2} & p_2 \langle x \le r_2 \\ 0 & x \rangle r_2 \end{cases} \tag{5}$$

$$\underline{f}_A(x) = \begin{cases} 0 & x\langle l_2 \\ \dfrac{x-l_2}{p_2-l_2} & x \le \dfrac{r_1(p_2-l_2)+l_2(r_1-p_1)}{(p_2-l_2)+(r_1-p_1)} \\ \dfrac{r_2-x}{r_2-p_2} & x\rangle \dfrac{r_1(p_2-l_2)+l_2(r_1-p_1)}{(p_2-l_2)+(r_1-p_1)} \\ 0 & x\rangle l_2 \end{cases} \tag{6}$$

In this work the type-2 singleton fuzzifier is used and, the defuzzification layer approximates the type-reduced set using the Karnik-Mendel algorithm.

3. DESIGN AND EXPERIMENTAL SET UP

A commonly approach to control mobile robot navigation that uses behavior-based architecture. In this work the behavior-based navigation algorithms such as, obstacle avoidance behavior, wall following behavior, source checking behavior, target seeking behavior and emergency condition is used to achieve gas/odour source target, is shown in Figure 1. The integration of fuzzy logic and particle swarm optimization (PSO) technique for navigation strategy has been carried using five behaviors as follows [23];

1. Collision avoidance behavior: This behavior is always activated using fuzzy logic technique. However, it emerges only when no or olfactory signal is detected. Since its priority is the lowest, the collision avoidance behavior is suppressed whenever the other target seeking behavior is activated.
2. Wall following behavior: Mobile robot is forced by this behavior to follow the closest wall to its two sides. When olfactory signal is high, this behavior priority is lowest and the target seeking is highest priority.
3. Target seeking behavior: This behavior keeps mobile robot heading to the target and regulates the difference between the mobile robots current position and the target. The direction and distance to the object are measured by using PSO algorithm.
4. Source checking behavior: This behavior has the highest priority at 2 level. It active when the mobile robot in the junction. The mobile robot stops for a while and measures the response of the dynamic gas/odour sensor for 0.25 s. If odour with high concentration exists the search is terminated and the robot declares that a source is found. Otherwise, the mobile robot makes a turn or move to a new direction to prevent going to the same object again. The mobile robot then moving the random or target seeking behavior.
5. Emergency behavior: This behavior depends on the safest allowable distance between the mobile robot and the obstacle. This behavior has the highest priority at 1 level.

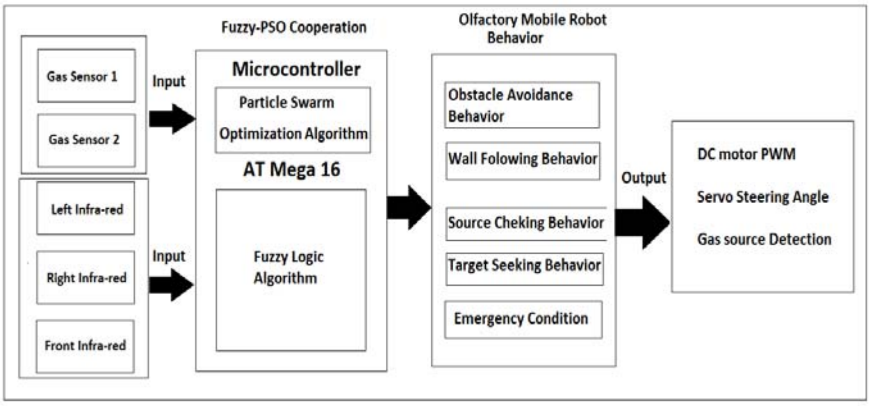
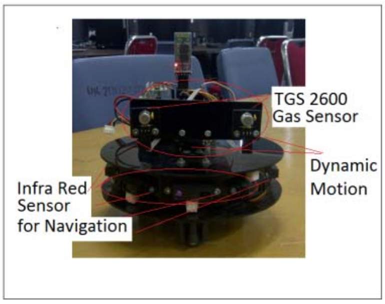


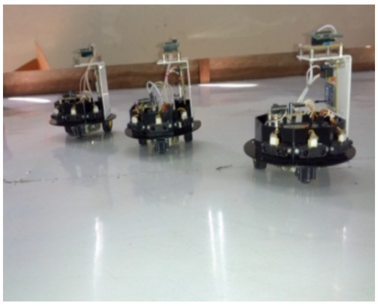
Figure 1. Intelligent mobile olfaction behavior [23]

3.1. Hadware Platform

Mobile olfaction platform are mainly applied to track plumes and to search gas sources. They provide the ability to move across in real and unknown environment. Small mobile robot is used in circular shape about 20 cm diameters and has about 15 cm of height. Mobile robot structure based on a three-wheel vehicle which is mainly composed of two driving wheels and an all-direction wheel. Two dc motors are connected to the two driving wheels respectively. Rotation direction of each motor is controlled by the direction of drive current and rotation speed is controlled by the duty cycle of pulse width modulation (PWM). The mobile robot and its onboard sensors are illustrated in Figure 2 (a). The mobile robots platform shows in Figure 2 (b) are equipped with two dynamic gas sensors TGS2600 for target seeking, with a response time is 10.3 s and a recovery time is 10.0 s. Five infrared sensors are employed for navigation system and a wireless communication X-bee is used for robots communication and data transfer. ATMega 16 microcontroller is used with two sets of high capacity rechargeable lithium polymer batteries for processing control algorithms.



(a) Single robot



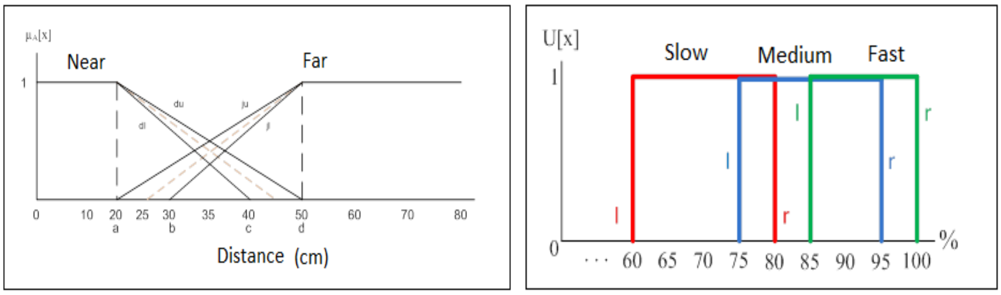
(b) Multi robots

Figure 2. Mobile robot platform [23]

The sensing systems are developed for measuring chemical plumes in the environment. This device is composed by two arrays (left and right) of two Figaro metal oxide gas sensors (TGS2600). It consists of a silicon semiconductor layer formed on an alumina substrate of a sensing chip together with an integrated heater. In the presence of a detectable odour, the voltage across the heater causes an oxygen exchange between the volatile odour molecules and the metal coating material. Electrons are attracted to the loaded oxygen and result in decreases in sensor conductivity. The main target gases of these sensors are general air contaminants, combustible gases, methane and ethanol, respectively. Besides the favoured gas, all of them show some sensitivity to other reducing gases. Using this array of sensors, it is possible to test the IT2FL-PSO algorithm with two sensing system. Gas sensors are tested in a hermetically closed box square, where a known increasing amount of methanol with a fan is included to accelerate metanol vaporization and homogeneous dispersion [23].

3.2. IT2FL-PSO Algorithm

It is obvious that the IT2 fuzzy set is in a region constructed by a principal type-1 membership functions. An IT2FLS is obtained by using the fuzzy sets to partition the input domains of the baseline Type-1 fuzzy system with footprint of uncertainty (FOU) as shown in Figure 3 (a) and (b). In this work, type-1 fuzzy system is extended to an interval type-2 fuzzy system, by adding uncertainties in both antecedent and consequent part of each rule. Therefore the membershif functions (MFs) values of the antecedent part by ±A%, and the consequent part by ±C%. The purpose of this IT2FL algorithm to perform the swarm navigation in dynamic environment from an initial point to designed goal. Linguistic for obstacle distance is represented by fuzzy set near and far as shown in Figure 3 (a) and speed of the motor are slow, medium, fast shows in Figure. 2(b).



(a) Input (b) Output

Figure 3. Membership functions

The IT2FL rule bases have the same structure as the T1FLC, the results given by T1FLC is used. The number of rules is determined by the number of the fuzzy MFs of the controller input. The rules are used to control the speed of the motor. However, if an obstacle becomes too close to the robot, it should be able to reduce speed to stop and move 270^{o} and emergency behavior is activated. When the robot is very close to the target, the attractive force between the robot and the target causes the robot seeking towards the target. Similarly when the robot is very close to an obstacle, because of repulsive force developed between the robot and the obstacle the robot must change its speed and heading angle to avoid the obstacle. There eight rules uses in IT2FL algorithm for change the heading angle are listed in Table 1.

Table 1. Rule bases

Rule	Sensor			Reference of Speed	
	S1	S2	S3	Left motor	Right motor
1	N	N	N	Slow* condition	Fast* condition
2	N	D	F	Fast	Slow
3	N	F	N	Slow	Slow
4	N	F	F	Medium	Slow
5	F	N	N	Slow	Fast
6	F	N	F	Fast	Slow
7	F	F	N	Slow	Medium
8	F	F	F	Fast	Fast

One rules cater for extreme conditions when the obstacles have to be avoiding as quickly a possible. All rules in that table have been obtained heuristically using common sense. When odour is active high in the odour sensor, PSO algorithm keeps mobile robot heading to the target and regulates the difference between the mobile robots current position and the target. PSO algorithm for gas search and IT2FL algorithm for mobile robot navigation as shown in Figure 4 and Figure 5 respectively.

```
Declaration:
        position, position_leader, motor1, motor2, s1, s2, s3: real
        du,dl,ju,jl,a1,a2,a3,b1,b2,b3,c1,c2,c3,d1,d2,d3,n=8: integer
        integer urut1[8],urut2[8],M1l[8],M1r[8],M2l[8],M2r[8]
        typedef enum {false,true} boolean
        fu[8],fl[8],f[8],ftot : real
        procedure fuzzification (input a,b,d,e,x: integer)
        procedure rulebase ()
        Procedure type reduction (input Ml[8], Mr[8]: integer , f_u[8], f_l[8], ouput *def:
real)

Description:
While (robot active)
                Read position, position_leader
                        While (position != position_leader)
                                motor 1 = 80
                                motor 2 = 90 %
                                Read posisi
                        Endwhile
                Read s1, s2, s 3
        fuzzification(15, 20, 35 , 40, s1)
        a1=du, c1=dl, b1=ju, d1=jl

        fuzzification (15, 20, 35 , 40, s2)
        a2=du, c2=dl, b2=ju, d2=jl

        fuzzification (15, 20, 35 , 40, s3)
        a3=du, c3=dl, b3=ju, d3=jl

                rulebases ()
        reduction(M1l,M1r,fu,fl,&mkiri)
        reduction(M2l,M2r,fu,fl,&mkanan)
        Endwhile
```

Figure 4. IT2FLS algorithm

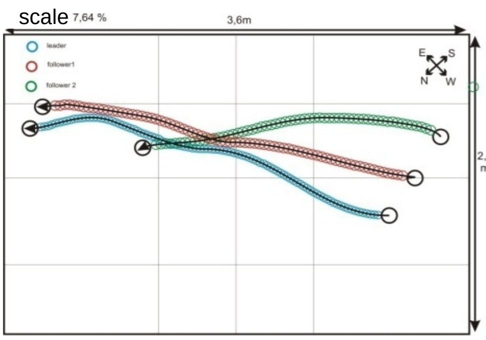
```
Start
    Declaration
            initialization distance sensor, gas sensor, servo, fpbest=0, gbest=20;
    Deskripsi
            read(distance sensor);
            read(gas sensor);
            fuzzifikasi(distance sensor);
            inferensi(near, medium, far);
            type reduction;
            defuzzifikasi_right_motor;
            defuzzifikasi_left_motor;
            if fpbest< 50
                    if left sensor< 25 and right sensor>=30
                            servo turn to right
                    else if left sensori>=30 and right sensor> 25
                            servo turn to left
                    else
                            servo in middle
                    endif

                    if targetsb>fpbest
                            fpbest=targetsb
                            robot stop
            else if fpbest>=50 and right sensor>=30
                    robot turn to right
            else if fpbest>=50 and left sensor >=30
                    robot turn to lefti

            if fpbest>=50 and intrupt=2
                    w=targetsb-fpbest
                    if targetsb>fpbest
                            fpbest=target;
                            c=1;
                    else
                            c=0
                    endif
                    if targetsb>fgbest
                            gbest=x;
                    end if
                    right_motor = right_motor*w + c(x-gbest);
                    left_motor = right motor;
            endif
End
```

Figure 5. Gas/odour search using PSO algorithm

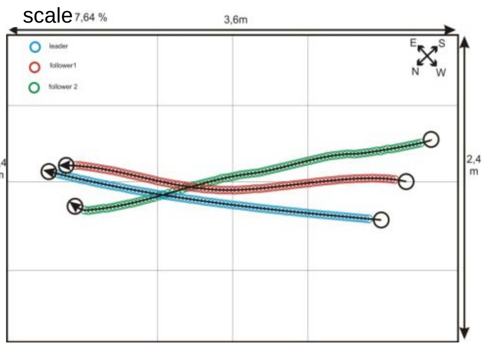
4. RESULTS AND DISCUSSION

In this works, integration of IT2FL and PSO algorithm in swarm robots has been proposed on real mobile robot. Some practical issues are expected to arise. In this section, we point out major issues in the light of some preliminary studies, with an experimental setup composed of multi olfactory mobile robot for gas/odour source detection. To investigate the effectiveness of the IT2FL-PSO algorithm, several experiment is done in a room 5 m × 5 m. During the experiments, the doors and windows of the room were kept shut. Methanol, which is a volatile and colorless liquid, is used as chemical gas source. In this experiment, five smaller mobile robots move using a random walk strategy at a maximum speed of 0.3 m/s. Whenever mobile robot is trapped in local minima or reached a goal boundary, it received a new target position chosen randomly from the workspace.

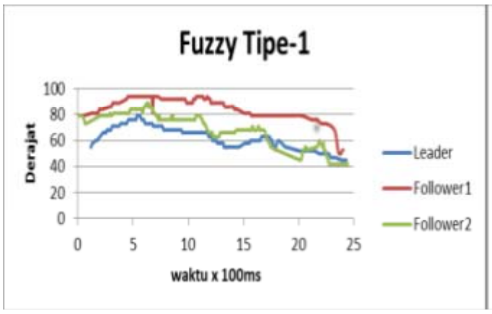
In the swarm movement, one or a few robots act as leaders which move along predetermined trajectories and other robots in the group follow while maintaining the desired relative position with respect to the leader. In Figure 6 (a) – (d) shows swarm cohesion behavior, a robot in the swarm should keep a certain distance from the swarm centre and not stray far from other robots. According to the exeperimental results swarm chesion using IT2FL-PSO produce stable movement compare to T1FL-PSO, because the propose algorithm can handles imprecise and uncertainty data from sensor and actuator to produce complex decision outcomes and minimized the effects of uncertainties.



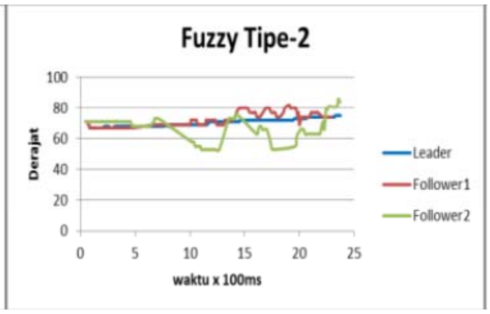
(a) T1FL behavior



(b) IT2FL behavior



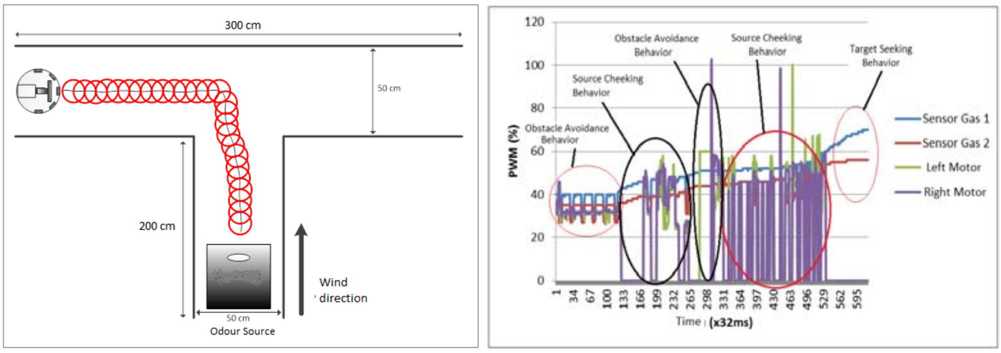
(c) T1FL Trajectory



(d) IT2FL Trajectroy

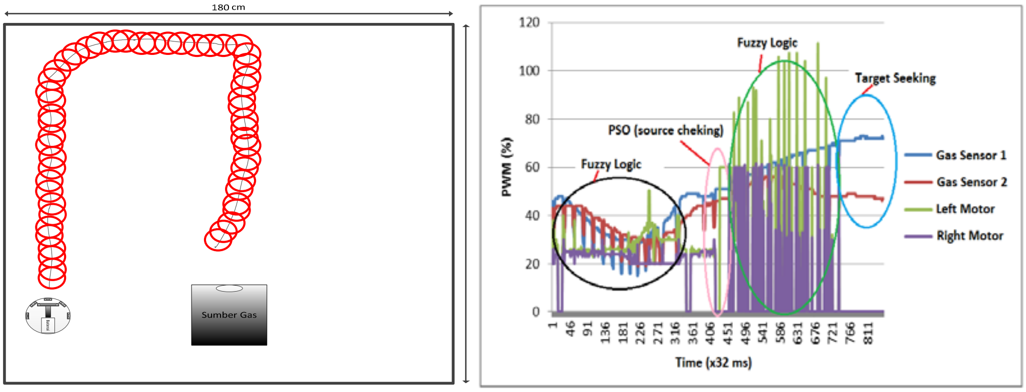
Figure 6. Swarm behavior to gas search process

From Figure 7 (a) and (b) respectivelly, it can be seen trajectory for single robot and gas search process, respectivelly. In open environment IT2FL behavior is used at 32 ms to 4.2 s when obstacle avoidance behavior active as shown in Figure 6 (b), that enabled the mobile robot to maintain its position in the middle between left and right wall. At 4.2 s to 9 s mobile robot moving randomly to check the position of the odour source, when the mobile robot meet the junction, than PSO behavior is activated. At 9.1 s to 9.8 s the mobile robot makes turn right because it detects a higher value of odour sensor readings in the right of mobile robot.



(a) Single trajectory (b) Mobile robot behavior

Figure 7 Corridor environment



(a) Single trajectory (b) Gas search activity

Figure 8 Open space environment

Figure 8 (a) and (b) shows that in open space environment single robot use proposed algorithm is able to find an odour source about 27 s. Mobile robot trajectory is smooth and moves in accordance with the target is shown in Figure 8 (a). Gas search process based on IT2FL-PSO algorithm make a single robot able to follow the wall, turn, maintain the distance to the wall and achieve the target, it can be seen in Figure 8 (b). Fuzzy behavior active when robot run in the open space environment at 32 ms to 10 s, then source cheking behavior active. In this situation Fuzzy-PSO behavior work because robot move to find the gas source direction at 11 s to 14.5 s. If the source direction are found the fuzzy behavior active in terms of obstacle avoidance and wall following behavior. Finnally, target seeking is activated when mobile robot detects a higher value of odour sensor readings and gas source is found at 26 s.

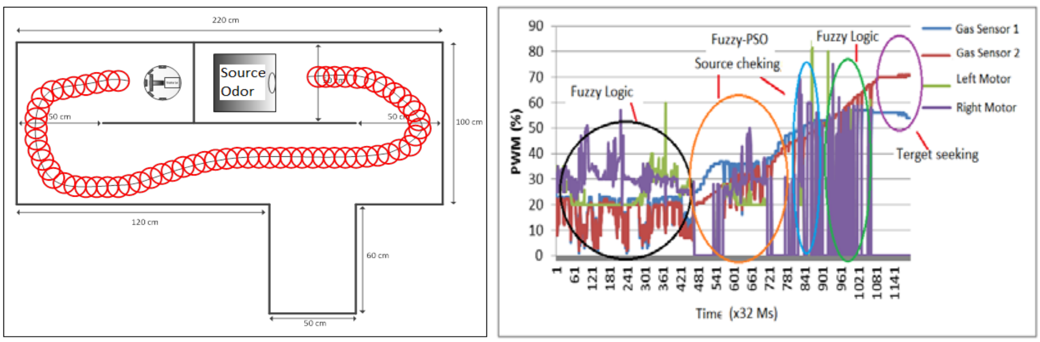


Figure 9 Complex Environment

From Figure 9, in complex environment, single robot based on proposed IT2FL-PSO algorithm capable to find the source of the gas about 38 s, due to there are some traps in the environment. Therefore, the robot must choose the best path in order not to fall into traps. In complex environment fuzzy behavior active at 32 ms to 15.5 s longer compared to open space environment. In this situation obstacle avoidance and wall following behavior alternately active. When robot meet the junction, PSO algorithm will be active to chek whether source of gas is detected. At 16 s to 25 s IT2FL-PSO is activated simulataneously for finding gas source direction. After the direction of the source of gas is found then the robot will follow the direction of the source and at that time the robot moves based on fuzzy behavior. Finnally, target seeking is found because mobile robot detects a higher value of odour sensor readings at 37 s.

5. CONCLUSION AND FUTURE WORK

The swarm robots based olfaction systems use hybrid IT2FL-PSO algorithm is considered in this research. All the robots execute the same algorithm, which will be called local interaction algorithm. The algorithm focuses on how to compute, effectively and consistently, the goal position depending on the local information gathered. It takes the positions of two neighboring robots as input, and the goal position as output. In the implementation, the input information may directly come from sensors of the robot and the direction of motion can be implemented with the actuators of the robot. Thus, the interaction algorithm, which is the core of the robot behavior, can be realized with actual robots easily.

The real experiments performed on smaller five mobile robots equipped with dynamic gas/odour sensor TGS2600 and three infra-red sensors. The experimental results show that by using proposed IT2FL-PSO algorithm, the swarm robots could successfully use olfaction system to achieve gas/odour source in unknown environment. Mobile robot capable of locating the source of a simulated chemical leak in an environment while detecting and avoiding obstacles along its path. As future work we would like to consider the extension to the problem of classification in environments where more than one substance is present and validate the algorithms searching gas/odour sources in a large real testing setup.

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REFERENCES

[1] Sandini, G., G. Lucarini and M. Varoli. (1993). Gradient driven self-organizing systems. in *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems*. Yokohama, Japan: IEEE.

[2] Consi, T.R., et al. (1994). AUV guidance with chemical signals. in *Proceedings of IEEE Sympsium on Autonomous Underwater Vehicle Technology*. Cambridge, MA, USA: IEEE.

[3] Russell, R.A., D. Thiel and A. Mackay Sim. (1994). Sensing odour trails for mobile robot navigation. in *Proceedings of IEEE International Conference on Robotics and Automation*. San Diego, CA, USA: IEEE.

[4] Ishida, H., et al. (1994). Study of autonomous mobile sensing system for localization of odor source using gas sensors and anemometric sensors. *Sensors and Actuators A: Physical*, 45(2): 153-157.

[5] Loutfi, A., Broxvall, M., Coradeschi, S., and Karlsson, L. (2005). Object recognition: A new application for smelling robots. *Robotics and Autonomous Systems*, 52:272–289.

[6] Taylor, B., Willis, M., and Quinn, R. (2010). Integrating olfaction, vision and touch to locate fluid-borne odors in diverse and dynamic environments. International Conference on Applied Bionics and Biomechanics (*ICABB-2010*) *Venice, Italy October 14-16.*

[7] Marques, L., Nunes, U., and A. T. de Almeida. (2006). Particle swarm-based olfactory guided search. *Autonomous Robot*, 20:277–287.

[8] Krieger, M.J.B., Billeter, J.B., and Keller. L. (2000). Ant-like Task Allocationand Recruitment in Cooperative Robots. *Nature*, 406:992-995.

[9] Barca, J.C. Lee, E.E., Sekercioglu, A. (2013). Flexible Morphogenesis based Formation Control for Multi-Robot Systems. *International Journal of Robotics and Automation*. 2(1):26-34.

[10] Martinoli, A., Ijspeert, A.J., and Mondada, F.(1999) “Understanding CollectiveAggregation Mechanisms: From Probabilistic Modeling to Experiments with Real Robots”, *Robotics and Autonomous Systems*, Vol. 29, pp. 51-63, 1999.

[11] Balch, T., and Arkin, R.C. (1999). Behavior-based Formation Control for Multi-robot Teams. IEEE Trans. on Robotics and Automation.

[12] Yamauchi, B. (1999). Decentralized Coordination for Multi-robot Exploration. *Robotics and Autonomous Systems*, 29(1):111-118, 1999.
[13] Special Issue on Advances in Multi-Robot Systems, T. Arai, E. Pagello, and L. E. Parker, Editors, *IEEE Trans. on Robotics and Automation*, 18(5): 685-699, 2002.
[14] Weigel, T., Gutmann, J.S., Dietl, M., Kleiner, A., and Nebel, B. (2006). "CS Freiburg: Coordinating Robots for Successful Soccer Playing", C.A.C. Parker and H. Zhang, Collective Robotic Site Preparation. *Adaptive Behavior*. 14(1): 5-19.
[15] Holland, O.E., and Melhuish, C. (1999). Stigmergy, Self-Organization, and Sorting in Collective Robotics. *Artificial Life*, 5:173-202.
[16] Stewart, R.L., and Russell, R.A. (2006). A Distributed feedback mechanism to regulate wall construction by a robotic swarm. *Adaptive Behavior*. 14(1):21-51.
[17] Meng, Q.H., Yang, W.X., Wang, Y., and Zeng, M. (2011). Collective Odor Source Estimation and Search in Time-Variant Airflow Environments Using Mobile Robots. Sensors, 11(11): 10415–10443.
[18] Ishida, H., Nakamoto, T., and Moriizumi, T. (1989). Remote sensing of gas/odor source location and concentration distribution using mobile system. *Sens. Actuat. B 49*, 52-57.
[19] Mc. Carty, K., and Manic SR., M. (2009). Adaptive Behavioral Control of Collaborative Robots in Hazardous Environments. HSI 2009, Catania, Italy, May 21-23, pp 10-15.
[20] Jatmiko, W. Fukuda, T., Matsuno, T., Arai, F., and Kusumoputro, B. (2005). Robotic Applications for Odor-Sensing Technology: Progress and Challenge. WSEAS Transaction on System 7(4).
[21] Kennedy, J., and Eberhart, RC. (1995). Particle swarm optimization. in: Proceedingsof the 1995 IEEE International Conference on Neural Networks, Perth, Australia, pp. 1942–1948.
[22] Mendel, J., and John, R. (2002). Type-2 fuzzy sets made simple. IEEE Trans. On Fuzzy System, Vol. 10, PP 117-127, April, 2002
[23] Nurmaini, S., Tutuko, B., and Rahman, A. (2014). A New Navigation of Behavior- based Olfacory Mobile Robot. *Applied Mechanics and Materials,* 446-447:1255-1260.