Internal Agent States: Experiments Using the Swarm Leader Concept

Mohamed H. Mabrouk, Craig W. Murray, Kevin Johnstone and Colin R. McInnes

Abstract — **In recent years, an understanding of the operating principles and stability of natural swarms has proven to be a useful tool for the design and control of artificial robotic agents. Many robotic systems, whose design or control principals are inspired by behavioural aspects of real biological systems such as leader-follower relationship, have been developed. We introduced an algorithm which successfully enhances the navigation performance of a swarm of robots using the swarm leader concept. This paper presents some applications based on that work using the simulations and experimental implementation using a swarming behaviour test-bed at the University of Strathclyde. Experimental and simulation results match closely in a way that confirms the efficiency of the algorithm as well as its applicability.**

I. INTRODUCTION

Research activity on autonomous robots has witnessed a surge, especially in the field of artificial robotic systems that inspire ideas from real biological systems due to their important commercial applications [1]. Swarms of self-organizing agents that exchange information have a greater functionality than single robots [2]. In these systems, large numbers of identical autonomous robots are controlled using architectures that are inspired from natural systems such as insect swarms, bird flocks and fish schools [3]–[6].

We use a model designed to simulate the motion of a swarm of robots, which consists of N agents. The i^{th} agent is represented with mass m_i, position $\mathbf{r}_i$ and relative distance $\mathbf{r}_{ij}$ between the i^{th} and j^{th} agents. The generalized Morse potential, which decays exponentially at large distances and represents a comparatively realistic description of natural swarming agents, is used to define the interactions amongst the swarm agents $V_{interaction}(\mathbf{r}_i)$, the attraction potential of the goal $V_{goal}(\mathbf{r}_{ig})$ and the repulsive potential of the N_o obstacles $V_{obstacles}(\mathbf{r}_{io})$. Unit mass agents are considered for simplicity. To prevent the agents from reaching large speeds, a dissipative frictional force with coefficient β_i for the i^{th} agent is added.

The potential is characterized by attractive and repulsive interaction potential fields of strength C_a and C_r with ranges l_a and l_r respectively, while C_g, l_g, C_{oz} and of l_{oz} are the attraction potential strength and range the goal point and the repulsive potential strength and range of the z^{th} obstacle point, respectively. The equations of motion for N agents that contains N_o obstacle points and a goal point at position G, are then defined for the i^{th} agent as

$$\mathbf{v}_i = \dot{\mathbf{r}}_i \quad (1)$$

$$m_i \dot{\mathbf{v}}_i = -\beta_i \mathbf{v}_i - \nabla_i V_{global}(\mathbf{r}_i) \quad (2)$$

$$V_{global}(\mathbf{r}_i) = V_{interaction}(\mathbf{r}_i) + V_{goal}(\mathbf{r}_{ig}) + V_{obstacles}(\mathbf{r}_{io}) \quad (3)$$

$$V_{global}(\mathbf{r}_i) = \sum_{j \neq i}^{N} \left(C_{r_j} e^{-|\mathbf{r}_i - \mathbf{r}_j|/l_{r_j}} - C_{a_j} e^{-|\mathbf{r}_i - \mathbf{r}_j|/l_{a_j}} \right) + \sum_{z=1}^{N_o} C_{o_z} e^{-|\mathbf{r}_i - \mathbf{r}_{o_z}|/l_{o_z}} - C_g e^{-|\mathbf{r}_i - \mathbf{r}_g|/l_g} \quad (4)$$

In earlier work [7], we introduced sets of first order differential equations to describe the free parameters of the potential field (internal state) to solve the local minimum problem. For artificial potential field based navigation, there have been several attempts to solve the local minimum problem. The problem for a swarm of agents attracted to a goal point at position G is defined such that an artificial potential field at G induces motion towards the goal. However, in order to prevent collision with a static obstacle, an additional repulsive potential field is required. In general, a local minimum may form due to the superposition of the goal potential and that of the obstacles, resulting in the agent, or swarm of agents, becoming trapped in a state other than the goal G. Considering this problem, the entire swarm, or part of the swarm will be trapped at the obstacle since the agents trapped inside the obstacle will experience two virtual opposite forces, as shown in Fig. 1. We introduced three new concepts; the swarm leader concept [7], the swarm aggregation concept [8],[9], and the swarm vortex-like behaviour concept [10] to enhance the performance of the internal state model for agents behaviour that allows them to effectively solve this key problem. In this paper, we introduce applications using the internal state model enhanced with the swarm leader concept through simulation and test-bed facility.

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M. H. Mabrouk is with the Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK. (phone:+44 (0) 141 548 4851; fax: +44 (0) 141 552 5105; e-mail: mohamed.mabrouk@ strath.ac.uk).

C. W. Murray is with the Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK (e-mail: craig.murray@ strath.ac.uk).

K. Johnstone is with the Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK (e-mail: kevin.johnstone@ strath.ac.uk)

C. R. McInnes is with the Department of Mechanical Engineering, University of Strathclyde, Glasgow, UK (e-mail: colin.mcinnes@ strath.ac.uk)

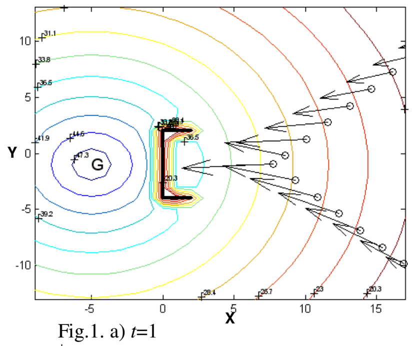

Fig.1. a) *t*=1

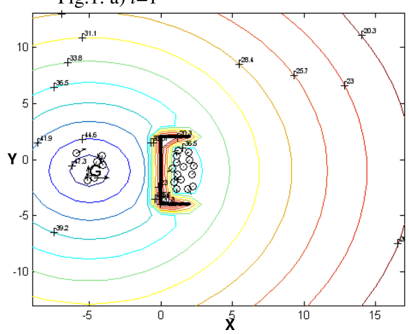

Fig.1.b) *t*=26

Fig.1. Classical reactive problem for a swarm of agents

II. AGENT INTERNAL STATE MODEL WITH SWARM LEADER CONCEPT

There is a considerable body of research concerning building artificial systems inspired by swarm leaders phenomenon in real biological systems. In [11]–[12], the authors introduced dynamic models based on the distance and the angle between leaders and followers, which indicates that the agents must know who and where their leaders are. Different leader roles were discussed in Wang and [13] and a convergent condition, in which the followers need to have the leaders' states by sharing global information, was constructed by using contraction theory. In [14], the swarm members know which members are the leaders in a leader based control strategy. Similarly, the followers need to know who the leaders are in [15] where the leader-follower systems are investigated in terms of controllability and optimal control. In [16], the authors discuss the importance of updating the follower information concerning the leader position. Experimentally, much research work focuses on leader-follower relationship in multi-agent systems. In [2], the author tested a set of communication techniques and a library of behaviors, among which follow-the-leader behaviour is programmed, on a swarm of 100 physical robots.

From this background it can be seen that although local information can be used to control the relative distances and angles amongst swarm members, the followers must know which members are their leaders. In addition, the followers need to share global information about the updated position of their leader. In the algorithm used in this paper [7], the agents have information about the leaders by sharing global information, which is the agents potential parameters that are employed to express the leader-follower relationship. The swarm leader concept enables the swarm in Fig. 1 to efficiently solve the problem by making the agents follow the agent that finds a clear way to the goal, as shown in Fig. 2.

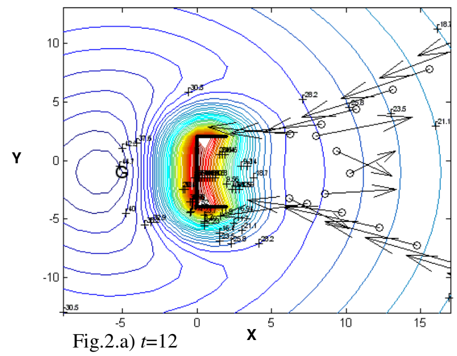

Fig.2.a) *t*=12

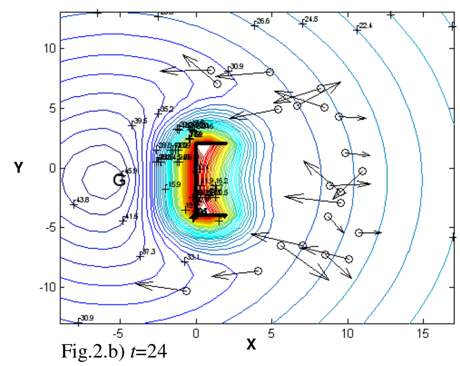

Fig.2.b) *t*=24

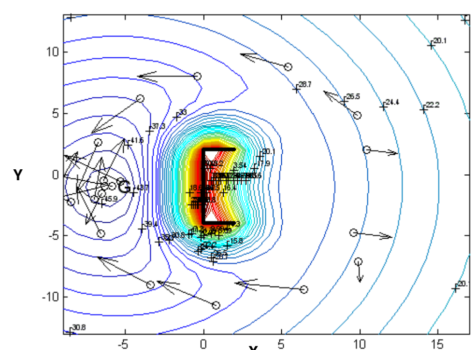

Fig.2.c) *t*=48

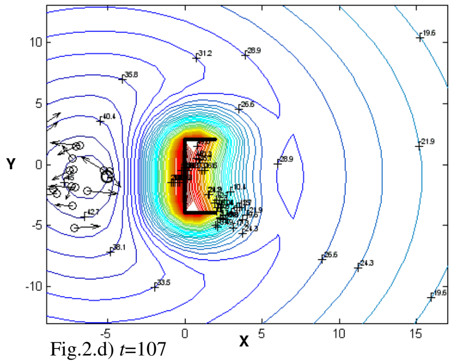

Fig.2.d) t=107

Fig. 2. Behaviour of a swarm using the internal state model and swarm leader, t =12-107 [7]

III. RESPONSES TO A TEMPORARY LEADER

For a complete understanding of the role of the leader in a free system and how it affects the swarm behaviour using the artificial potential approach for the agents interactions, the motion of a free swarm whose agents experience an attraction to one of them will be considered. For a swarm of agents, let agent (h) be the temporary leader that has higher C_a and l_a than the other agents of the swarm. Recalling Eq. (1-4) for obstacles and goal free environment and using V_{ij} instead of $V_{interaction}$ for simplicity, the global potential equation for i^{th} agent is

$$V_{global}(\mathbf{r}_i)=V_{ij}(\mathbf{r}_i)=\sum_{j\neq i}^{N_p}\left(C_{r_j}e^{-|\mathbf{r}_i-\mathbf{r}_j|/l_{r_j}}-C_{a_j}e^{-|\mathbf{r}_i-\mathbf{r}_j|/l_{a_j}}\right) \tag{5}$$

Defining the swarm center velocity as $\mathbf{r}_c=\frac{1}{N_p}\sum_{i=1}^{N_p}\mathbf{r}_i$ and noting that $\nabla_i V_{ih}(\mathbf{r}_{ih})=V'_{ih}(\mathbf{r}_{ih}).\hat{\mathbf{r}}_{ih}$, the equation of motion of the swarm center will be

$$\ddot{\mathbf{r}}_c=-\frac{1}{N_p}\left(\sum_{i=1}^{N_p}\beta\mathbf{v}_i+\sum_{i=1}^{N_p}\sum_{\substack{j\neq i\\ i\neq h\\ j\neq h}}^{N_p}\nabla_i V_{ij}+\sum_{i=1}^{N_p}V'_{ih}(\mathbf{r}_{ih}).\hat{\mathbf{r}}_{ih}\right) \tag{6}$$

where V_{ih} is the interaction potential that affects i^{th} agent by the leader agent (h). Since $\hat{\mathbf{r}}_{ij}=-\hat{\mathbf{r}}_{ji}$, the double summation in Eq. (6) will cancel to yield

$$\ddot{\mathbf{r}}_c+\frac{\beta}{N_p}\dot{\mathbf{r}}_c=-\frac{1}{N_p}\sum_{i=1}^{N_p}V'_{ih}(\mathbf{r}_{ih}).\hat{\mathbf{r}}_{ih} \tag{7}$$

which represents a damped oscillator with a forcing term generated by the lead agent. It can therefore be concluded that the agents will be attracted to any agent considered as a temporary goal if it has a larger attraction interaction parameters according to some task; for example a scout agent finding something of interest for the swarm.

IV. SIMULATION RESULTS

A. Escaping a trap I

To show the swarm leader concept, Eq. (1) – Eq. (4) are now used to simulate the agents' motion for N_p identical agents which are trapped behind a barrier that consists of N_o identical obstacle points, as shown in Fig. 3, where G is a goal point which has an attraction potential of low interaction range l_g such that it does not extend to the region inside the trap.

The challenge in this situation is that the agents are stuck inside a trap whose only exit is located away from the goal position and they are not strongly attracted to the goal. In this situation, a condition is defined such that if one of the agents finds its way through the exit, it will gain a higher attraction potential coefficient C_a and higher attraction potential range l_a. These conditions now make any succeeding agent a temporary leader for the rest of the agents and the swarm center therefore accelerates to the leader position, leading them out of the trap. Then, the leader and subsequently the swarm are attracted to the goal. Figure 3 shows the agents randomly moving inside the trap until one agent succeeds in escaping and so becomes a temporary leader leading the rest of the agents out of the trap.

B. Escaping a trap II (a 'rescue' mission)

We now consider another application of internal states using communication through interaction between swarm members. The application is a 'rescue' mission that has been given to one of the team members, which uses the internal state model with the swarm leader concept, to assist other team members that use fixed internal states and fail to reach the goal according to the local minimum that forms behind a C-shape obstacle (which has not been prior known).

The key idea is that the rescuing member gains leadership characteristics as it realizes it has a clear way to the goal. This application has the advantage of using the internal state model with only some agents in the swarm whose task will be to act as 'leaders/scouts' for the rest of the swarm, mimicking the behaviour in real biological systems [17].

The scenario, shown in Fig. 4, demonstrates a swarm that uses fixed internal states in two groups. The first group has a clear path to the goal while the other group is trapped in a local minimum formed behind a C-shape obstacle. The agents that successfully reach the goal clearly did not lead the individuals of the swarm, which are trapped in the local minimum.

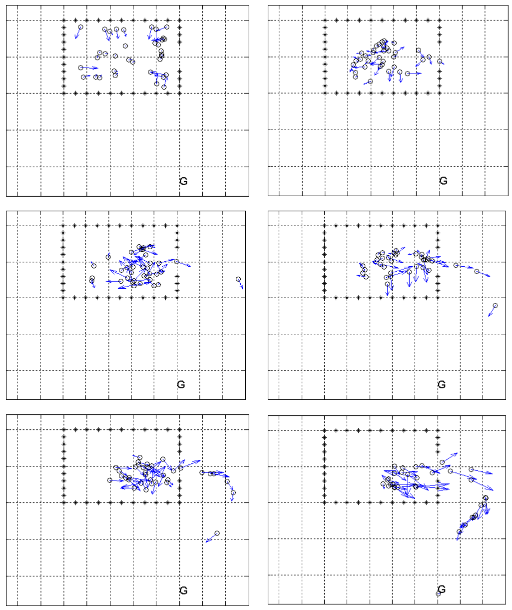

Fig. 3. Swarm leader concept in a trap application, t=0.5, t=9, t=12, t=15, t=18, t=22.3

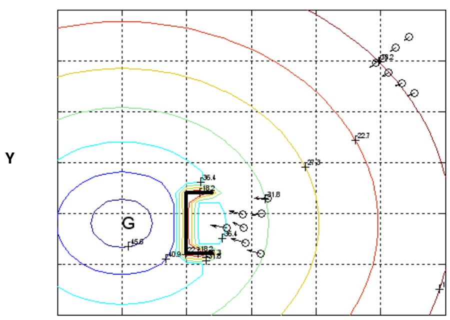

Fig.4.d) t=2 X

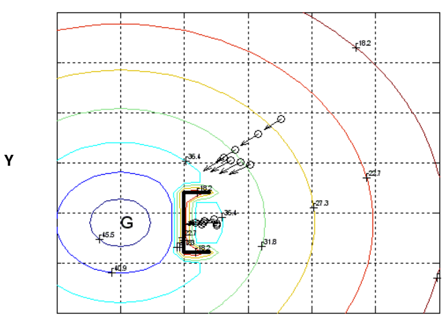

Fig.4.d) t=30 X

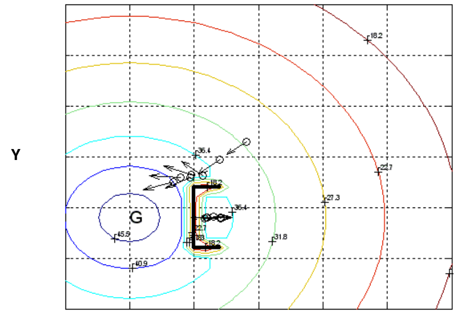

Fig.4.d) t=35 X

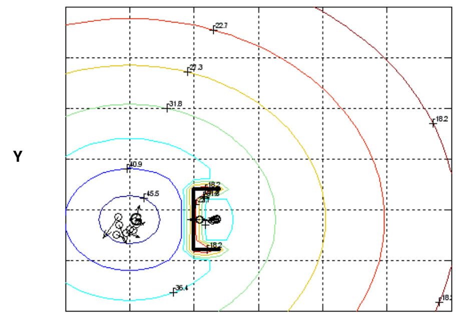

Fig.4.d) t=70 X

Fig. 4. Behaviour of a swarm using conventional fixed internal states, t =2-70

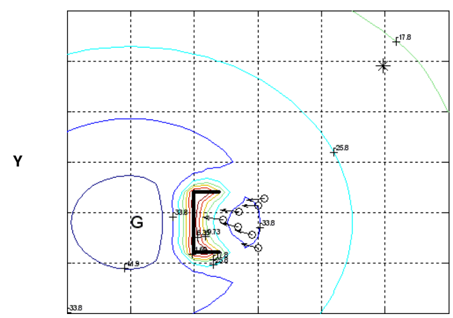

Fig.5.d) t=1 X

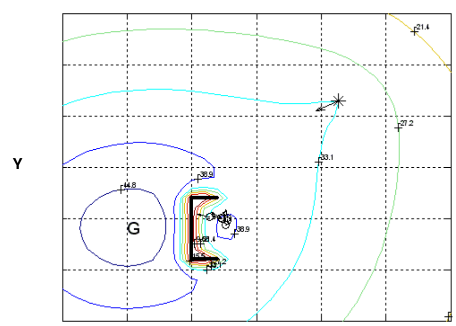

Fig.5.d) t=10 X

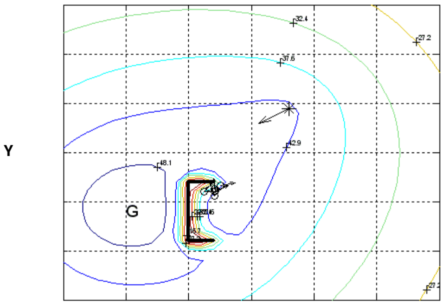

Fig.5.d) *t*=19

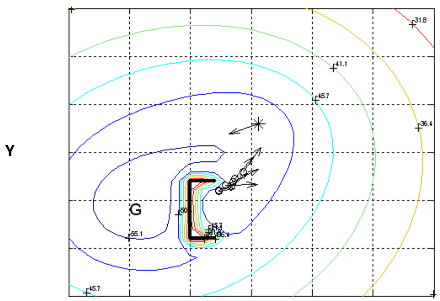

Fig.5.d) *t*=25

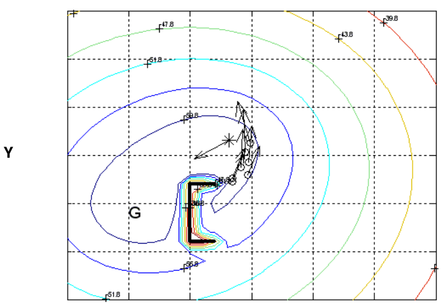

Fig.5.d) *t*=33

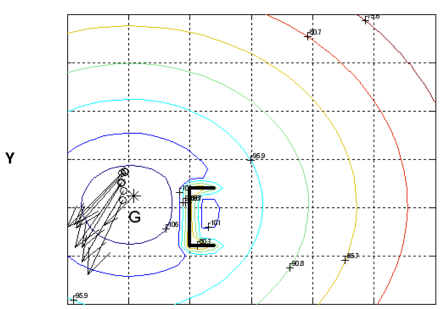

Fig.5.d) *t*=44

Fig. 5. Behaviour of a swarm using the internal state model and swarm leader, *t* =1-44

We now compare this scenario with another scenario through which one of the agents is assigned the rescue task by using the dynamic internal state model with the swarm leader concept, as show in Fig. 5. As the leader agent has a clear way to the goal, it gains leader properties (large C_a) according to the internal state model with the swarm leader concept. This will enable the leader agent to manipulate the potential in the workspace such that the individuals trapped in the local minimum are attracted to it rather than to the goal, as shown in Fig. 5, resulting in successful escape from the trap.

V. EXPERIMENTAL RESULTS

The 'rescue' mission application is implemented in a swarming behaviour test-bed; University of Strathclyde. The test-bed has been built to test the behaviour of agents, which interact via pair-wise interactions of short-range repulsions and long-range attraction. Every agent, as shown in Fig. 6, is equipped with an external source of light, a short-range touch sensor to implement the repulsion type forces, and long-range light sensors to implement the attraction type forces. The same procedures in the rescue mission application are implemented using only 3 agents for simplicity.

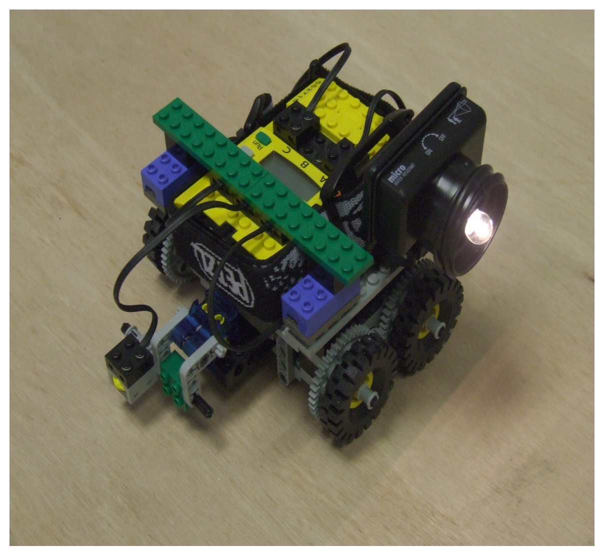

Fig. 6. One of the agents used in the test

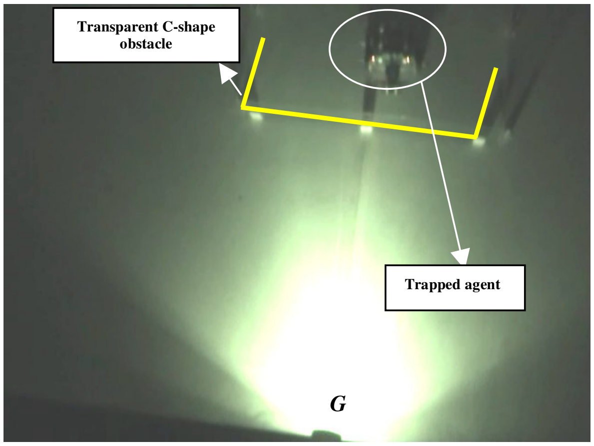

Fig.7.a) t=2 sec (agent trapped in local minimum)

Fig.7.b) t= 18 sec (leaders approach)

Fig.7.c) t=23 sec (trapped agent is attracted to the leaders)

Fig.7.d) t=26 sec (trapped agent follow the leaders)

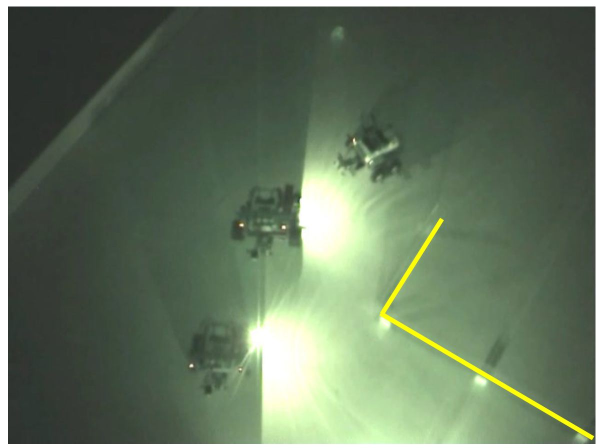

Fig.7.e) t=29 sec (trapped agent escapes)

Fig.7.f) t=36 sec (trapped agent reaches the goal)

Fig. 7. Swarm leader concept implementation, t = 1- 36 sec

The scenario of the local minimum problem is implemented using an agent that is attracted to a visible goal (light source located at the goal position) through a transparent barrier. When the agent reaches the barrier, it is repelled according to the function of its touch sensor. However, as the agent moves away from the barrier it is attracted again according to the function of its light sensor and then tries again to reach the goal through the barrier, as shown in Fig. 7.a-b). In this case, the agent gets stuck in a position away from the goal position defining the local minimum problem. In the simulation, using the internal states model enables the stuck agent to solve the problem by following another agent 'the leader' that has a clear path to the goal. This idea is implemented through a modification of the leader agents such that their external light source becomes brighter as they have a clear way to the goal (they gain leader properties which is represented by higher C_a according to the internal state model with the swarm leader concept). This enables the leader agents to attract the trapped agent more than the goal such that the individual trapped in the local minimum is attracted to the leaders rather than to the goal, as shown in Fig. 7.c-f).

VI. CONCLUSIONS

This paper presents some applications based on earlier work which aimed to enhance APF based navigation performance of multi-agent systems using one of the most common swarming behaviours in natural systems; the swarm leader concept. Two applications are introduced using simulations. The first application is escaping a trap application, through which if one of the agents finds its way through the exit, it will gain a higher attraction potential coefficient C_a and higher attraction potential range l_a becoming a temporarily leader to the rest of the individuals inside the trap to help them escape. The second application is a 'rescue' mission application to use the internal state model with only some agents in the swarm whose task will be to act as 'leaders' for the rest of the swarm, mimicking the behaviour in real biological systems. The implementation of the second application using a swarming behaviour test-bed confirms the applicability of the used model as well as its ability to enhance the performance for a real swarm of robots.

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