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A model for using self-organized agents to visually map environmental profiles

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ABSTRACT

In this work, we investigate the possibility of using inspiration from the self-organizing property of organisms in nature for providing visual representation of an invisible pollutant profile. We present a novel mathematical model of the bacterium and use it to find pollutants in the environment. This model has the capability of exploring the environment to search for sparsely distributed pollutants or food sources and then subsequently exploiting them upon discovery. We also combine the bacterium model in a bacterium–flock algorithm for the purposes of preventing collisions between robots or organisms in addition to providing coverage to a pollutant. By adjusting the velocity of individuals, we show that we are able to control the coverage provided by the population as a whole. Furthermore, we compare the bacterium–flock algorithm with a novel gradient-ascent-flocking algorithm and the well established Voronoi partition algorithm. Results show that bacterium–flock algorithm and the Voronoi partition algorithm are capable of adapting the distribution of the individuals of a population based upon the underlying pollutant profile while the gradient-ascent-flocking algorithm is not. This shows that the bacterium–flock and the Voronoi partition algorithms can potentially be used to track a spatiotemporal function. On the other hand, the gradient-ascent-flock algorithm has a faster convergence time in some cases with the Voronoi partition algorithm having the slowest convergence time overall.

1. Introduction

In the event of an accidental leakage or deliberate release of an invisible hazardous substance as a result of the act of terrorism, human casualties could be reduced by making the invisible hazardous substance visible. In such situations, a visual reference is possibly the only clue that humans can use to keep away from contaminated areas. Such invisible hazardous substances could include Nuclear radiation as was the case in the recent 2010 Japanese Tsunami Nuclear disaster (Dauer et al., 2011) when nearly 60,000 people had to evacuate areas close to the affected Fukushima reactor (Matanle, 2011); Nerve gas as in the 1991 Gulf War (Kang and Bullman, 1996) and carbon dioxide as in 1986 when the Lake Nyos in Cameroon released its underground storage of carbon dioxide. This led to the asphyxiation of both animals and unsuspecting 1700 humans in the surrounding areas (Baxter et al., 1989). A similar event occurred two years earlier when Lake Monoun released carbon dioxide resulting in the death of up to 37 people (Kling, 1987). According to Kling (1987), the month that these events occur can be predicted as both occurred in August. However, due to the invisible nature of the gas, it is presently not possible to know when a release event actually occurs. A similar event is likely to occur in Ethiopia around the Lake Kivu in the near future with potentially greater consequences (Schmid et al., 2005). The above cases indicate a humanitarian challenge that calls for a solution.

In order to meet this challenge, a swarm of robots could be used to provide a visual reference so that a previously invisible substance becomes visible. Providing this solution could lead to a reduction in human casualties. Furthermore, providing a visual representation of such biological hazards would reduce the pressure on emergency services who might be overwhelmed with dealing with the already injured. In such cases, communication of hazardous areas to the population would be instantaneous as opposed to relying on state of the art robots to collect information, relay it to a base station in order to build an electronic map, before communicating the situation to the population via the emergency crew. This cycle would result in unnecessary delays resulting in more causalities. The possibility of using this proposed visual

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approach to provide information to a population is becoming more feasible as devices get smaller and cost less as a result of technological advances. This is especially true with the continuing advance in nano-technology. In the near future, nano-bots could be deployed as a means to visually represent invisible spatio-temporal quantities. However, presently, implementing a flock of flying agents outside the lab is still a challenging issue to be solved. Nevertheless, progress is being made in this area as in Kushleyev et al. (2013).

In robotics, providing a solution to the problem raised above, could be viewed as a coverage or optimal resource allocation task (Cortes et al., 2004). Researchers in robotics have investigated various methods of solving this problem. This includes the use of virtual springs in which the distance between individual robots in the swarm are controlled using virtual forces. The virtual springs generate virtual forces which are used to keep the agents from each other (Shucker et al., 2006, 2008). By varying the length of the spring in accordance to the concentration level of the pollutant in the vicinity, the agents can be used to represent the distribution of the pollutant. Their approach however needs to track individual points in the pollutant and in addition, requires a heavy communication requirement. Another approach is the use of deterministic annealing which involves the use of the theory behind metal annealing to find the optimal configuration of the position of agents with respect to a pollutant's distribution (Kwok and Martínez, 2011). Metal annealing involves heating a metal to a very high temperature and then slowly cooling it. The high temperature phase makes the metal's atoms vibrate vigorously in order to escape their present state which might not be the most optimal. This phase could be termed as an explorative state in which the search for an optimal state takes place. This phase is followed by a slow cooling phase which makes the metal's atoms settle into low energy configurations that is representative of the optimal configuration. The deterministic annealing algorithm also makes use of these phases in order to make the agents explore their environment and then settle into configurations representative of the pollution distribution. However, the algorithm requires a heavy communication requirement in order to synchronize the agents.

The most commonly used approach in robotics for multi-agent coverage as evident from literature (Cortes et al., 2004; Schwager et al., 2007, 2008, 2009) is the Voronoi partition method. This method aims to minimize a cost function represented by the pollutant with respect to the agents' positions. It does this by using robot positions to divide the area containing the pollutant into Voronoi cells. The mass density of the Voronoi cells are then calculated followed by the centre of mass of the cells. The robots are then moved to the positions of the newly calculated centre of masses at the next iteration.

The problem with this approach is that it relies on unrealistic sensor constraints that could only be satisfied by using a machine learning paradigm. It requires that a robot's sensor has a radius of pollutant perception beyond the immediate position of the robot so that the mass density and then the centre of mass of the corresponding Voronoi cell can be calculated. This is not possible as the robot can be in only one place at a time. As a result, in order to obtain this information, a machine learning paradigm is often used to estimate the pollutant data beyond the immediate position of the robot. As a result of the use of the machine learning paradigm in addition to the computation of the mass density of the Voronoi cell, a heavy computational cost arises. Furthermore, it does not have an exploratory behaviour for the initial search of the environment for a spatiotemporal quantity of interest and is consequently prone to local maximum traps (Cortes et al., 2004; Schwager et al., 2007, 2009).

Due to the heavy computational or communication costs required by the methods discussed above, it becomes difficult to make use of these approaches in providing visual representations of an invisible hazardous substance especially if the substance is dynamic and time is of essence. As a result, this paper investigates the possibility of using an alternative technique by taking inspiration from nature. Organisms in the natural environment have undergone evolution over million of years resulting in robust, efficient and cost effective mechanisms for carrying out their everyday activities. This paper investigates the possibility of using the self-organizing properties of natural organisms in order to provide a solution to the visual representation of invisible hazardous substances as discussed above.

The phenomena of self-organization has been observed in the brood sorting of honey bees, termite hill building, the emergence of dead ant clusters among other phenomenon. Self-organization relies on multiple interactions between agents, a balance of exploitation and exploration with a feedback mechanism (Bonabeau et al., 1999).

Bonabeau et al. (1999) discussed that the emergence of patterns or structures by self organization is not always predictable. However, a way of making it predictable is through the use of templates. Templates are predefined structures or commands that agents follow during the construction of a structure. For example, it has been shown that the termites of the specie *Macrotermes subhyalinus* use the queen's pheromone as a template to build the royal chamber (Bonabeau et al., 1997). Templates make it possible to predict self organization and Johnson (2009) was able to use templates to obtain biological plausible results of honey bee nest construction. In addition, Jost et al. (2007) showed that ant cemetery clusters are actually dependent on wind direction templates. By controlling the wind direction or flow, it is possible to change the structure of the cemetery clusters. It was observed that when the wind was flowing longitudinally through the nest, ants arranged their dead longitudinally into the direction of the flow. However, without wind flow, the ants made a nearly circular heap in the centre of the nest (Bonabeau et al., 1999). From this observation, it can be seen that the cemetery cluster shape formed by ants is dependent on wind flow direction in the nest.

Collectively, bacteria too are known to exhibit self organization as is evident when they form rings or other various shapes around food sources in the environment depending on the type (Shapiro, 1998; Ben-Jacob, 2003; Marrocco et al., 2010). When food is found, it has been observed that the swarm of Bacteria move towards it while maintaining their self-organization (Shklarsh et al., 2012).

Individually, bacterium use chemotaxis to navigate up chemical gradients in the environment (Brown and Berg, 1974; Segall et al., 1986). However, due to noise in the environment caused by turbulence, internal mechanisms and so on, individual estimates might be wrong. In order to increase accuracy, it has been shown that animal groups including bacterium often school in order to collectively improve their individual estimates and navigate up gradients (Simons, 2004; Shklarsh et al., 2011). However, Berdahl et al. (2013) argued that flocking could emerge as a result of interactions between individuals and not just for the purpose of improving individual estimates. In experiments, they showed how individual golden shiners were affected more by the group in which they were placed compared to the environmental gradients they individually experience. They came to a conclusion that the gradient tracking capabilities of schools were better than an individual's gradient tracking capability. Nevertheless, the above observations have led to the study of the swarming capabilities of organisms including bacteria for various purposes including micro-cargo transporting (Shklarsh et al., 2012), micro-assembly (Martel and Mohammadi, 2009), air turbine inspection (Correll and Martinoli, 2009), and so on.

In this paper, we investigate how the emergent phenomenon of bacteria self-organization can be used to achieve the visual