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Hybrid Insect-Inspired Multi-Robot Coverage in Complex Environments

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Abstract. Coordination is one of the most challenging research issues in distributed multi-robot systems (MRS), aiming to improve performance, energy consumption, robustness and reliability of a robotic system in accomplishing complex tasks. Social insect-inspired coordination techniques achieve these goals by applying simple but effective heuristics from which elegant solutions emerge. In our previous research, we demonstrated the effectiveness of a hybrid ant-and-bee inspired approach, HybaCo, designed to provide coordinated multi-robot solutions to area coverage problems in simple environments. In this paper, we extend this work and illustrate the effectiveness of our hybrid ant-and-bee inspired approach (HybaCo) in complex environments with static obstacles. We evaluate both the ant-inspired (StiCo) and bee-inspired (BeePCo) approaches separately, and then compare them according to a number of performance criteria using a high-level simulator. Experimental results indicate that HybaCo improves the area coverage uniformly in complex environments as well as simple environments.

1 Introduction

Recent years have seen a rapidly growing interest in distributed multi-robot systems for automatically exploring and surveilling environments of different sizes, type and complexity. Multi-robot systems (MRS) consist of multiple interacting robots, each executing an application-specific control strategy, which is not centrally steered. Coordination is a key challenge when deploying teams of distributed multi-robot systems as these systems are often limited in resources (e.g., on-board processors, batteries, controllers). Lightweight interactions among robots (e.g., facilitated by wireless communication) are not only a desired feature for such platforms, but also necessary to overcome practical deployment issues stemming from inconsistent network connectivity. Simple yet effective heuristics that avoid complex, heavy computation and establish lightweight interactions are therefore highly desirable for MRSs. Biologically inspired, or bio-inspired, solutions for the challenging problem of multi-robot coordination are gaining traction.
Swarm algorithms, like ant colony optimisation [10], rely on pheromonal knowledge for communication between agents. Such insect-inspired multi-agent research has also opened the possibility of applying some of these techniques to robotic systems, i.e., swarm robotics [11, 16]. Swarm robotic systems are motivated by a wide range of application areas, such as surveillance and patrolling, where mobile guard robots are considered an alternative and improved mechanism over fixed security cameras and even humans. Other application areas include exploration and identification of hazardous environments (e.g., nuclear plants and fire detection), mobile sensor networks, wireless sensor and robot networks, and space exploration.

Previous research, StiCo [13], investigated ants’ stigmergic behaviour in an attempt to address the coverage issues in multi-robot systems using self-organised coordination techniques. Another approach, BeePCo [4], used bee pheromone signalling processes to solve the same multi-robot coverage problem. Both StiCo and BeePCo rely on pheromone substances for coordination and communication between agents. Based on these approaches, a hybrid ant-and-bee inspired technique was developed, HybaCo [2], in an attempt to further improve multi-robot coverage. This included a comparative study of the StiCo, BeePCo and HybaCo algorithms and identified their strengths and weaknesses. The environment used in the experimental scenarios in [2] was a simplistic, obstacle-free square arena. In this paper, we extend this work and introduce more complex environments that contain obstacles, in order to represent more realistic scenarios. We demonstrate the effectiveness of HybaCo and compare it with StiCo and BeePCo on multiple complex environments.

2 Related Work

Many bio-inspired techniques have been examined to address multi-robot coverage by establishing lightweight coordination principles based on the behaviour of social insects. Ants [8, 9] and bees [1, 12] are the two main families of social insects that have inspired approaches within the fields of robotics and distributed systems as a means to improve self-organisation and autonomous coordination characteristics.

In [13, 14], Ranjbar-Sahraei et al. developed their first stigmergic approach using a simulation environment to address coordination issues in multi-robot systems. Extensive experimental results on both simple (obstacle free) and complex (with static and dynamic obstacles) environments showed that the stigmergic approach (StiCo) applies (almost) uniform coverage. Later in [17], Ranjbar-Sahraei et al. extended their research deployed on a physical robot swarm, which validated the correctness of the simulated results. The mathematical model of this approach is shown in [15] that derives a probabilistic macroscopic model for ant-inspired coverage by multi-robot platform.

In previous work on pheromone signalling (PS) based load-balancing, [5, 7] presented a dynamic technique for wireless sensor networks (WSNs) that is applied at run time in the application layer of a communication network.
PS is inspired from the pheromone signalling mechanism found in bees and provides distributed WSN control that uses local information only. [6] extend the initial PS technique by introducing additional network elements in the form of robotic vehicles for wireless sensor and robot networks (WSRNs). Different subclasses of cyber-physical systems are merged together to increase the area coverage effectively, which directly increases the service availability and extend the network lifetime by benefiting from their heterogeneity. The same pheromone signalling principle is applied to multi-robot systems in [2, 3] and explained in detail in the next sections.

3 Background: Comparison Between StiCo and BeePCo

This section provides some background information about the StiCo and BeePCo techniques separately, which is essential for later describing our hybrid HybaCo in Section 4.

3.1 StiCo Principle

The StiCo approach follows the principle of indirect, stigmergic coordination to establish efficient coverage of an environment by simple means. Classic stigmergic coordination in an ant system (AS) is characterised by two properties: (1) agents have a tendency to move straight with minor deviations, and (2) traces (signal trails) act as sources of attraction. In contrast, StiCo robots orbit in circles (instead of moving straight), and their traces have repulsion characteristics (instead of attraction). These two key differences transform the path-finding characteristic of an AS into the efficient area coverage provided by StiCo.

In StiCo, robots are equipped with two simple sensors (pointing in the front-left and front-right directions like ant antennae), capable of detecting immediate traces. Each robot rotates in a circle with a predetermined radius. Based on the circling direction (clockwise, CW, or counter-clockwise, CCW), one sensor is considered as the interior sensor and the other as the exterior one. When the interior sensor detects pheromone (virtual substance marking the trace of a robot), the robot changes its circling direction immediately. Otherwise, if the exterior sensor detects pheromone, the robot continues rotating in the same direction until it no longer detects any pheromone. For a more detailed description we refer to [13].

3.2 BeePCo Principle

The BeePCo approach follows the principle of pheromone-signalled coordination found in bees to establish direct, lightweight communication between agents and can address multi-robot coverage problems. The BeePCo algorithm consists of four parts, which are executed on every robot in the MRS: two parts are time-triggered (differentiation cycle and decay of pheromone), whereas the other two (propagation of pheromone and motion direction and magnitude) occur in
parallel invoked by one event-triggered process. During the propagation, robots send pheromone to their neighbours within direct communication range. If a robot receives pheromone, it makes a decision to move and selects a target destination in the opposite direction of the pheromone received. The movement decision is based on vector addition; further description can be found in [4].

3.3 Comparison Between StiCo and BeePCo

Here we characterise the strengths and weaknesses of StiCo and BeePCo. Three key differences between these two techniques are illustrated in Table 1. The first difference between StiCo and BeePCo lies in how pheromone is used for communication. In the StiCo approach, communication between agents is implemented using indirect pheromone trails, where pheromone signals are deposited in the robots’ environment without knowing which or whether another agent will receive the signal. In contrast, in the BeePCo approach, pheromone signalling is implemented by directly sending signals to robots within a specific range.

The second difference between StiCo and BeePCo lies in the type of movement effected by the robots. When robots run StiCo, their motion is applied in a circular fashion and only the direction of circling changes. When robots run BeePCo, their motion is guided by vectors which influence the straight-line direction and distance for each move.

The difference between indirect and direct communication methods, taken in combination with the different motion methods, have significant impact on the speed with which these algorithms converge. The duration from the moment of deployment until the robots reach a stable configuration and until their energy is depleted varies significantly. BeePCo produces faster convergence in comparison to StiCo, and this is one of the strengths of BeePCo. However, because robots in BeePCo use direct communication based on transmission range, the robots stop moving once they are not in each other’s communication range; and this is the main weakness of this approach.

4 HybaCo: Hybrid Bee-Ant Coverage Algorithm

In [2], we proposed HybaCo, which combines the effectiveness of the two pheromone-based approaches (StiCo and BeePCo) detailed above while overcoming the major weaknesses of each approach taken alone. In this section, we describe HybaCo briefly once again before we evaluate it in complex environments. The most important performance bottleneck of the BeePCo occurs when the robots move far apart from each other and lose their communication network. This prevents pheromone exchange and, as a result, robots do not move any more. The
biggest problems with the StiCo approach are the extended time to converge and the lack of coverage redundancy—which is a desirable feature when considering practical deployment. In order to solve these issues, our hybrid approach begins with BeePCo but changes dynamically to StiCo when the communication network between the robots is lost [2]. Robots apply the BeePCo technique when the communication network is still active; but as the robots move further apart from each other, the communication network dies. When the robots lose connectivity (communication links) with all of their neighbours (i.e., others within transmission range), they assume that the BeePCo technique is no longer effective and so they switch to StiCo. After some time using StiCo, the robots will again get close enough to transmit pheromones to each other, at which point they will switch back to BeePCo. It is important to underline that the ANT and BEE pheromones are different, and are thus declared separately in the algorithm.

5 Experimental Evaluation

We evaluated three main algorithms (StiCo, BeePCo and HybaCo) using custom-built abstract simulators. The original StiCo [13, 14] was developed in C++, which is extended for the HybaCo experiments described here. The set of experiments presented in this section compare three important evaluation metrics:

1. the area covered by the robots;
2. the distribution of robots in their environment; and
3. the time it takes to converge (or stabilise).

In this study, area coverage is defined as the maximum of the total non-overlapping area covered by the sensors of the involved robot(s), as defined in [17]. The distribution of robots in the arena shows that the robots are moving around without leaving unattended gaps in the environment. This is measured by overlaying a grid of 160,000 cells (1cm × 1cm) on the environment and calculating how many cells are unattended at any moment in time. For the entire environment, all cells that are “attended” (or covered) by one or more robots are summed and divided by the total number of cells, resulting in the percentage of coverage. This metric indicates how evenly the robots are distributed in the arena and what the level of redundancy is for the different algorithms. The result is illustrated in the heatmaps shown in Figures 2, 4 and 6. The lighter the colour of the arena’s in the arena, the higher is the percentage of the area being covered over the total time of the experiment. The more evenly the total area is coloured, the more uniform is the distribution of the robots’ positions over time.

Finally, the time it takes to converge is the duration from the moment of deployment of the robots until they achieve a stable configuration (i.e., the moment the algorithm performs nearly optimally before resources are depleted). The experiments were carried out with sets robots which allow maximal coverage of ≈ 75% (depending on the environment this number is between 56 to 60 robots), each robot having a sensing and communication radius of 25cm. The robots’ environment (arena) size is 400cm × 400cm. Initially, the robots are deployed randomly in the central square region of size 5cm × 5cm.
We consider the following five algorithmic variations of StiCo and BeePCo in our comparisons:

- **StiCo**: The robots execute the stigmergic principle for coordination [14], as described in Section 3.1.
- **BeePCo**: The robots execute the bee-pheromone signalling principle [4] for coordination, as described in Section 3.2.
- **BeePCo-with-rotation**: The BeePCo algorithm is extended with a rotational move. This is an intermediate algorithm between BeePCo and HybaCo in which the robots execute the BeePCo approach until they lose communication links with each other. Once communication is lost, the robots apply the rotational move described in [2].
- **HybaCo**: The robots execute the bee-and-ant inspired coordination principle as introduced in [2] and described in Section 4.
- **MaxCo**: This represents the optimal case where the robots’ transmission range does not intersect with each other. This scenario is a benchmark for the maximum possible coverage of deployed robots with zero surveillance area overlap. This can also be referred to as potential coverage.

These five different algorithms are evaluated over three different environmental setups (topdown, L-shaped, floor plan) as Fig. 1 illustrates. The experimental results presented in this paper is average of five individual runs over each environmental setup for all five algorithms.

![Fig. 1: Three environment setups used to evaluate the performance.](image)

Figures 2 and 3 illustrate the experimental results of an MRS of 56 robots in an arena containing four blocks of square obstacles in the corners and two walls comparing the performance of the StiCo, BeePCo, BeePCo-with-rotation and HybaCo approaches against each other. Fig. 2 shows the heatmap images of this arena containing a number of static obstacles and our observations are as follows. StiCo robots had difficulties passing the walls and the square obstacles, therefore, focused on the middle of the arena, as shown in Fig. 2a with darker corners. In BeePCo, the robots stop spreading after communication links with the other robots are broken, because they are outside of the inter-robot transmission range.
Therefore, in Fig. 2b, a white circle represents an area covered by a robot after it stopped moving and did not receive further pheromone from other robots. This results in entirely uncovered areas in the arena, because the robots are not able to move. The BeePCo-with-rotation and HybaCo approaches provide more even distribution than BeePCo, where BeePCo-with-rotation distinctively
focuses more around the obstacles. This behaviour is less obvious in *HybaCo* and thus makes *HybaCo* more uniformly distributed than *BeePCo-with-rotation*.

Figure 3 shows the percentage of the area coverage with all four techniques. The maximum possible area coverage is shown by *MaxCo*. Among the four techniques, *StiCo* provides the lowest percentage of covered area, whereas *BeePCo* outperforms and achieves the highest percentage of covered area. The difference between *BeePCo-with-rotation* and *HybaCo* is not significant, although *HybaCo* distributes robots more uniformly.

Fig. 4: The distribution of robots in the arena using an MRS of 60 robots on *BeePCo*, *StiCo*, *BeePCo-with-rotation* and *HybaCo*.

Figures 4 and 5 show experimental results on an MRS of 60 robots in the arena which contains L-shaped obstacles (e.g., separators or boxes in a room). Figure 4 illustrates the distribution of the robots in this environment on *StiCo*, *BeePCo*, *BeePCo-with-rotation* and *HybaCo*. *StiCo* performs uniformly distributed coverage, although the corners of the arena are slightly less covered, whereas the robots had no issues getting around the L-shaped obstacles, nor providing coverage around the obstacles. In *BeePCo* approach, the robots stop spreading after communication links with the other robots are broken because they are outside of the inter-robot transmission range. The white circles in Fig. 4b show the robots’ non-overlapping coverage within the experimental arena. Because the robots do not move for a long time, the percentage of area coverage in
BeePCo is higher and more unevenly distributed, as opposed to the other three techniques. Figure 4c and 4d illustrate that BeePCo-with-rotation and HybaCo have a more uniform robot distribution over the environment in comparison to StiCo and BeePCo. The distribution of the robots is remarkably high around the obstacles in BeePCo-with-rotation which shows that robots struggle to get away from the obstacles. This situation is not applicable in HybaCo, therefore, HybaCo shows more uniformly distributed robots, as Fig. 4d illustrates.

![Graph showing area coverage over time](image)

Fig. 5: The percentage of area coverage using MRS of 60 robots on different techniques.

Furthermore, Fig. 5 shows the percentage of the covered area in the environment containing L-shaped obstacles. The maximum possible area coverage of 60 robots is represented by MaxCo, which is \( \approx 75\% \). StiCo achieves the least area coverage, whilst BeePCo gives the most among these four techniques, although it does not allow robots to move any further once the transmission connection between robots has stopped. The difference in the percentage of the covered area is very small between BeePCo-with-rotation and HybaCo, as the figure shows. In terms of the time the algorithms take to distribute robots in the period between \( 10^0 \) and \( 10^1 \) seconds, StiCo initially scatters the robots faster than BeePCo and converges faster, unlike our expectations, because StiCo has a more gradual manner of moving outwards, i.e., circling, whereas in BeePCo robots move outwards in a direct line. Later, in the time period between \( 10^1 \) and \( 10^2 \) seconds, BeePCo robots benefit from the direct communication exchange and spread out much faster than StiCo, BeePCo-with-rotation or HybaCo.

Figures 6 and 7 illustrate an MRS of 60 robots on an arena representing floor plans. In Fig. 6, heatmap images represent the distribution of the robots using StiCo, BeePCo, BeePCo-with-rotation and HybaCo approaches individually. The bottom left corner represents a room where all four sides of the room are surrounded by walls, apart from a small doorway gap close to the middle of the arena. Although StiCo and BeePCo have some coverage in this room, both BeePCo-with-rotation and HybaCo provide better coverage and improve the robot distribution as well. The top left corner in the arena is the least cov-
Fig. 6: The distribution of robots in the arena using an MRS of 60 robots on BeePCo, StiCo, BeePCo-with-rotation and HybaCo.

ered area for all four approaches due to the long wall stretching across the arena from side-to-side, apart from the little doorway gap. Because the doorway is small, robots struggle to find the gap and pass through the wall, especially covering the upper left corner. *BeePCo* has no coverage on the left corner above the wall, whereas *StiCo* has brief coverage of the same corner. *BeePCo-with-

Fig. 7: The percentage of area coverage using MRS of 60 robots on different techniques.
rotation and HybaCo visibly improve coverage of the same corner as a result of the advantages of the combined approaches. Similar to Figs. 2 and 4, BeePCo-with-rotation has more coverage around the walls, whereas HybaCo uniformly improves the coverage of the arena, mostly beneath the long wall.

In terms of the percentage of the area coverage, as shown in Fig. 7, BeePCo outperforms in this set of experiments too. The maximum possible area coverage of 60 robots is represented by MaxCo, which is ≈ 75%, similar to the L-shaped arena. The difference in the percentage of the area coverage in BeePCo-with-rotation and HybaCo is very small, whereas StiCo is considerably lower than the other three techniques. In terms of the time for the robots to converge, StiCo takes the longest to stabilise, whereas BeePCo has the steepest hill in the time period between $10^1$ and $10^2$ seconds and stabilises fastest among the four techniques compared in this study. A significant performance improvement can be observed in BeePCo-with-rotation and HybaCo in comparison to StiCo and BeePCo. Specifically, the experiments show that merging the strengths of both StiCo and BeePCo leads to superior results with respect to uniform distribution of the robots in the arena.

6 Conclusions

This paper compares four social insect inspired multi-robot coverage approaches, namely stigmergic behaviour of ants (StiCo), the pheromone signalling process of bees (BeePCo), a derived method based on BeePCo (BeePCo rotation), and an ant-and-bee inspired hybrid approach (HybaCo) in realistic, complex environments. We have shown the performance of all four approaches with respect to a number of criteria, including area coverage, uniformity of distribution and speed of convergence, with a particular focus on our hybrid bee-and-ant inspired approach that merges the strengths of StiCo and BeePCo into one algorithm. The advantages and disadvantages of these two techniques have been highlighted. In the experimental analysis, we evaluated the effectiveness of the proposed hybrid bee-and-ant inspired approach, i.e. HybaCo in MRSs with 56 and 60 robots in a number of different complex environment each containing numerous static objects and reported our observations.

StiCo moves at all times and applies (almost) uniform coverage over the arena. BeePCo achieves a higher percentage of area coverage in comparison to StiCo; however, it produces non-uniform coverage because the robots stop moving when they step outside of each others’ transmission range. The experimental results show that BeePCo-with-rotation, which is an extension of BeePCo, improves the distribution of the robots, but does not provide the same percentage of area coverage as BeePCo. Finally, our experiments confirm our earlier results [2] and show that HybaCo merges the strengths of the StiCo and BeePCo algorithms.
References