A METHOD TO SWARM ROBOT ESCORTING BY USING THE PROBABILISTIC LLOYD METHOD

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Abstract— The escorting task by a multi-robot team can be defined as a particular case of the dynamical environment navigation in which such team must follow a moving target agent trying to maintain a safe distance from it. Although several works present good solutions to this problem, most of them does not address the presence of obstacles other than the robots themselves. This situation is considered in this paper in order to verify the effectiveness of an escorting solution which consists of the combination of two behaviors: mainentance of a minimum distance to the target agent and an area coverage algorithm named SLACS which synergizes well with distance sensors. Experiments will be executed in the Stage simulator using two different environments: an empty place and a path which contains a corridor.

Keywords— Autonomous robotics, Voronoi diagrams, Multi-robot systems

Resumo— A escolta por uma equipe de robôs pode ser definida como um caso particular de navegação em ambiente dinâmico no qual tal equipe deve seguir um agente móvel, mantendo uma distância segura mínima ao agente alvo. Apesar de muitos trabalhos apresentarem bons resultados para a execução desta tarefa, poucos consideram obstáculos que não sejam os próprios robôs. Neste trabalho, é proposta uma solução para este problema, que consiste na combinação de dois comportamentos: manutenção de distâncias mínimas e um algoritmo de cobertura de área, que possui boa sinergia com os sensores de proximidade. Para avaliar o desempenho da solução proposta, vários experimentos são executados usando o simulador Stage, cujos resultados demonstram a eficiência do método proposto.

Keywords— Robótica autônoma, Diagramas de Voronoi, Sistemas multirrobóticos

1 INTRODUCTION

Developing algorithms to manage the navigation of a multi-robot system is often a challenging task. In multi-robot navigation, the robots must be guided to specific locations and need to avoid collisions between themselves and with the environment. Another important aspect is that the robots' coordination method must allow the system to execute various tasks (exploration, coverage, surveillance, among others) in a way that benefits from the presence of many robots. A multi-robot navigation task rarely approached is the escorting (or entrapment) task. Escorting is the act of enclosing a moving target whose trajectory is unknown for the robots in order to protect it from external actions (Antonelli et al., 2008).

The existing algorithms for escorting, in general, consider two or more combined behaviors. Antonelli et al. (2008) proposed a formulation which balances the influence of four bevaviors. They are the navigation towards the centroid of the target agent, movement on a imaginary circumference around the target agent, dispersion from other robots in the area of that circumference and obstacle avoidance. The system has enough scalability to cope with the loss of one or more robots. Such approaches, however, depend on a centralizing system that knows the position of the robots in the environment. A common trend in the multi-robot approaches is to design decentralized policies to coordinate the robots in order to accomplish a task. In this case, each robot is able to take its own decision using local information, that is, information from its neighbors, which can be obtained via wireless communication. Thus, the risk of a malfunction in a centralizing machine is reduced, avoiding a critical failure in the system. Kamano et al. (2000) proposed a fuzzy system to control robots in an escorting situation. Besides being decentralized, it can control the robots in non-linear trajectories successfully.

Many works based on decentralized navigation policies consider a special case of Voronoi tessellations called Centroidal Voronoi Tessellations (CVTs). The centroids of CVT polygons have an optimization property which is used to manage robot formations, area coverage (Tan et al., 2004) (Breitenmoser et al., 2010) (Mishra et al., 2012) and foraging (Rounds and Chen, 2009). All these methods rely on Lloyd's algorithm (Lloyd, 1982) or some variant of it to compute where the robots must be guided. In Batista et al. (2013), a decentralized area coverage solution named Sample

Lloyd based Area Coverage System (SLACS) was proposed to arrange the position of the robots such that the covered area is maximized in an environment with obstacles.

In this paper, a decentralized multi-robot algorithm for escorting task is proposed. Two behaviors have been considered and combined. The first one is maintaining a minimum distance between a robot and the target agent (to be escorted) and the second is to maximize the covered area according to the SLACS algorithm. Hence, the system proposed here allows the robots to escort an agent in a dynamic environment with the presence of obstacles. As far as it is known by the authors, few if any works consider a scenario with contains walls, and the idea of adopting an area coverage technique like proposed in this work to escorting is new. The method was built so that the advantages of swarm robotics techniques can be obtained, being scalable, robust and flexible.

This work is organized as follows. In Section 2, a brief description of the SLACS algorithm is presented, as well as how that behavior is combined with the minimum distance behavior to do escorting. The adopted robots' model is presented in Section 3 and the scenarios considered for the tests of the proposed method are shown in Section 4. In Section 5, the results obtained are presented, as well as a discussion about the relevant aspects of the proposed approach. Finally, in Section 6, the conclusions and the expectations for future works are highlighted.

2 Methodology

2.1 *Centroidal Voronoi Tessellations for Area Coverage*

In order to explain Centroidal Voronoi Tessellations, it is necessary to define Voronoi tessellations: these are polygonal constructs (V_i, $i = 1..n$) on a given space Ω that are built from generator points, denoted as x_i. The main characteristic of a Voronoi tessellation is that any sample from Ω contained in V_i is the nearest to x_i than from any other generator point. For each closed polygon (if Ω has no bounds, some polygons may be opened), a centroid may be calculated. If such centroids coincides with the generator points, a Centroidal Voronoi Tessellation (CVT) is obtained (Ju et al., 2002). In Figure 1 is shown a Voronoi Tessellation in contrast to a CVT.

CVTs have the property of optimizing Equation 1, which can be used to solve cost functions. This encourages the method to be applied in multi-robot systems. The aim of such systems is to position the robots on the CVTs' centroids in order to achieve a desired positioning. In this case, the most commonly used policy to do so is the Lloyd algorithm (Lloyd, 1982): a Voronoi tessellation is built and its centroid is calculated.

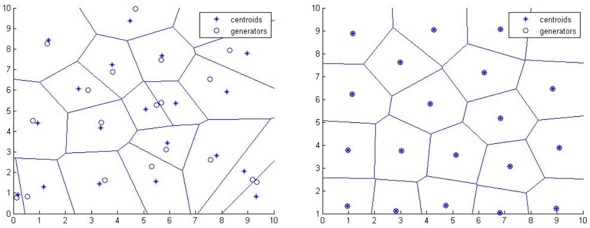


Figure 1: A Voronoi Tessellation (left) and a CVT (right) (Batista et al., 2013).

Afterwards, the generator point walks a little towards the centroid of its Voronoi polygon. In case an open polygon is considered, a bound is often used to forcefully close to the polygon. A straightforward behavior which can be implemented is the area coverage, where the robots must place themselves in an environment such that their sensors are able to cover as much region of this environment as possible, usually avoiding the connection loss. This is often achieved by positioning the robots in such a distance among themselves that sensor overlaps are diminished without losing connection due to large distances. In Tan et al. (2004), the area coverage was achieved through Lloyd's method. Each robot computes its Voronoi diagram considering its own information and information from its neighbors that are reachable by communication devices.

The system reaches an equilibrium state when the robots are in the positions (or near) that determine the maximum covered area without loss of communication among them. That process occurs elegantly, even that some robots are not visible to each other. Chao et al. (2007) applie CVTs in addition to a consensus strategy to control robots that realize a dispersion behavior.

$$K(\tilde{X}, \tilde{V}) = \sum_{i=1}^{n} \int_{\tilde{V}} \rho(x) \parallel x - \tilde{x}_i \parallel^2 dx \qquad (1)$$

Rounds and Chen (2009) proposed a probabilistic variant of the Lloyd method to compute the centroids (Ju et al., 2002): random samples are scattered in the region in Ω, and each sample is associated with its nearest x_i. All samples associated with a specific generator point are averaged, obtaining an approximated centroid of an unbuilt Voronoi region. Using such policy, there is no need to treat the closure of open polygons.

Recently, it was suggested by Batista et al. (2013) a multi-robot area coverage technique inspired by this centroid obtaining approach named Sample-based Lloyd Area Coverage System (SLACS). This technique exploits the sample-generating nature of Lloyd probabilistic and its proximity sensors by generating samples in radial-based positions, positioning these samples in the direction of a set of reading signals obtained by a laser rangefinder. A set of samples equally spaced between themselves is generated in the scanning direction of a laser reading direction. If a reading indicates that a sample will be generated after a measured obstacle distance, this sample and any other sample farther from the robot created from a specific laser reading trajectory will be discarded.

Whereas it is considered that each robot has its laser reading signals in equal radial positions, a robot r_i may only send its readings, not its samples, to the nearest neighboring (r_j) robot: the receiver robot uses these reading signals to generate its neighbor's samples acoording to its relative position. The samples that are the nearest to r_i are averaged to compute the estimated centroid (c_i). The SLACS's output is a vector that directs r_i towards c_i.

2.2 *Multi robots for escorting by using SLACS*

The objective of an escorting procedure is to maintain a team of robots covering a mobile target avoiding collisions with obstacles and trying to set a fixed distance δ to the desired target. Here, the region of the desired robots' positioning is called the δ radius region. In order to achieve this condition, SLACS area coverage and a distance mainentance behavior are combined. Both behaviors return vectors which are combined to produce the final output. The influence of each behavior is given by an influence value (α): the greater α is, the most the mainentance of the δ distance influences the output.

In Figure 2 the positioning of ten robots around an idle target using such technique is illustrated. Notice that while most robots maintained a desired distance to the target, some are positioned farther. This is an interesting result of applying a CVT based solution: the robot team acknowledges when there is no space to insert more robots in a desired distance radius, maintaining some robots outside the δ radius region. This is a desirable feature because it helps avoiding collisions, turning the system scalable. Further, this allows an easy escorting robot replacement because there are other robots in the surroundings which previously were unable to enter in the δ radius region. It is also noticeable that the difference of 0.05 in the value of α does a relevant difference in the robots' positioning. Tuning the parameter α is a critical factor. If a low α value is considered, it causes the robots to have difficulties to follow the escort target and to maintain a good number of robots in the δ radius. On the other hand, if a high α value is considered it does the robots very prone to collisions among themselves and with obstacles in the environment.

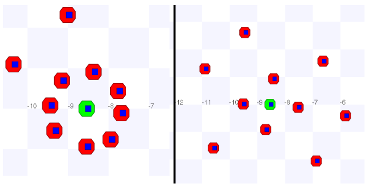


Figure 2: Escorting of a target agent (green) realized by ten robots (red) with $\delta = 0.75$. Results with (left) $\alpha = 0.5$; (right) $\alpha = 0.45$.

3 The Robots' model

The simulated robots are equipped with different sensors: an escort agent's relative position measurer, a laser rangefinder for obstacle distance calculation and a wi-fi communication device. For ideal conditions, the model of the escort target distance sensor adopted is such that robots are able to detect it at any local of an environment.

Obstacles are detected in a given sensor range R_D around the robots. This sensor is not used explicitly for obstacle avoidance, but to perform the SLACS behavior.

The communication device emits and detects messages around the robot with communication radius R_C, $0 < R_C < R_D$. The messages emitted and detected are modeled as the pair $(msg\_id, msg\_readings)$. The first term of the pair, *msg_id*, is the identification of a robot and the second, *msg_readings*, corresponds to the obstacle sensor readings. The signal's intensity can also be used to estimate the distance to a neighboring robot.

The robot model is shown in Figure 3. The robots are assumed to have omnidirectional movement and to move at a constant speed.

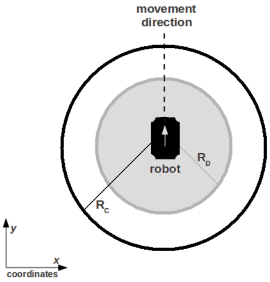
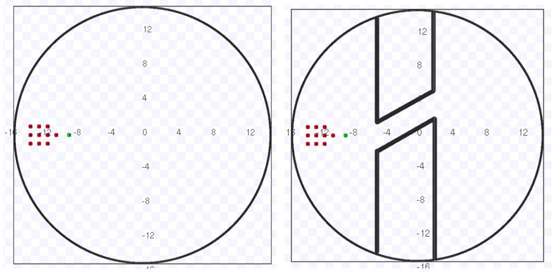


Figure 3: Robot and sensor models.

4 Considered Scenarios

Two different escorting scenarios are considered. In the first one, an empty environment is considered, i.e., an environment without the presence of obstacles. The escort target does a sinus-like trajectory, using an angular speed of $\pi/80$ rad/s until its angle be π. Then, the angular speed is inverted until the angle be π, when its angular speed



(a) (b)

Figure 4: (a) Empty and (b) Corridor scenarios.

is inverted again. The robot stops after, approximately, three oscilations in its trajectory. In the second scenario, there is an obstacle, a narrow passage (or corridor), where the escort target walks. In both scenarios, the target robot stops when it reaches the coordinate x = 7. The Figure 4 shows the empty and corridor environments.

In the next section, it will be presented the results obtained and a discussion about the efficiency of the proposed method considering these two scenarios.

5 Experimental Results

In this section, simulations are developed to evaluate the coordination strategy proposed for escorting. Experiments are carried out in the Player/Stage platform, capable of modeling various robots and sensors and of simulating simultaneously their exact dynamics. For the purpose of the experiments, the robot model used is based on the Pioneer 2DX equipped with laser range-finder SICK LMS 200.

For the evaluation of the multi-robot escorting procedure, four criteria have been adopted: the average of the robot to escort target distance; the average distances between a robot and its nearest neighbor; the number of crashed robots; the number of robots without any other robot within communication range. Each one of these data is collected after each iteration.

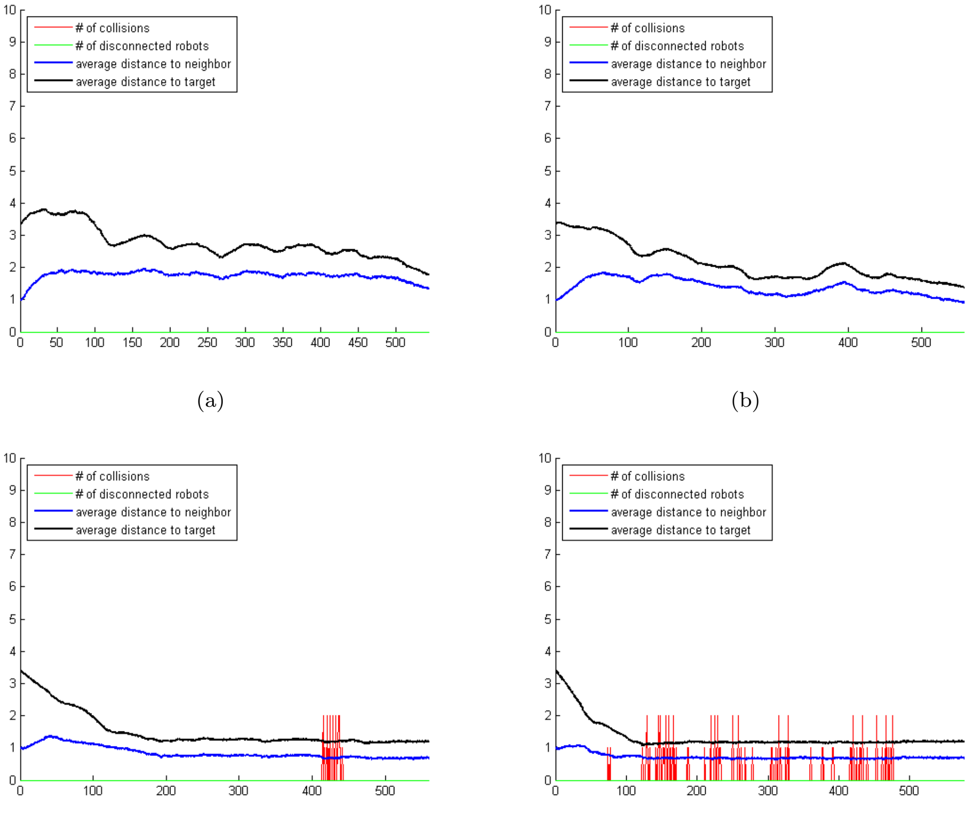
The experiments consist of changing only α, the escorting scenarios, and the escort target's angular speed in each scenario: $\delta = 1.0$; Robots' speed = 1 cm/s; Target speed = 0.5 cm/s; Number of escorting robots = 10; Number of cycles ran after the escort target finishes its trajectory = 100, where each cycle is roughly equivalent to 0.5 seconds; Laser rangefinder range (R_D) = 2.0; and Communication range (R_C) = 3.0.

In the first scenario, shown in Figure 4(a), the robots move in an empty environment in order to verify if the proposed method is capable of actually performing an escorting behavior. In Figures 5(a) - 5(d) the evolution of the proposed metrics with values for α equal to 0.45, 0.5, 0.55 and 0.6, respectively, is presented. It is possible to observe that in the two former values for α there were no collisions, but the robots were not completely into the δ radius region. In these tests, the robots were able to position themselves in a circular fashion: images are not presented in this text due to space constraints, but they share similarities to those of the left portion of Figure 2.

In the second scenario, shown in Figure fig:scenarios(b), the difficulty of escorting is increased by the presence of a corridor in the environment which the escort target navigates. Figures 6(a) - 6(d) present the results obtained with α equal to 0.45, 0.5, 0.55 and 0.6, respectively. A growth in the average distance between the robots and the escort target can be noticed. This can be explained by the loss of some robots during navigation: in all scenarios, at least a single robot is locked at the non convex entrance of the corridor. For the experiment in which the value was considered as $\alpha = 0.55$, all robots were able to escort the target properly, except for the locked one. The robots' final positions during simulation are presented in Figures 7(a) - 7(d). It is important to notice that no special collision avoidance policy was adopted other than the SLACS method itself, and this was done on purpose to identify the method's drawbacks. Despite this problem, all other robots were able to escort properly, recovering from eventual collisions.

The obtained results suggest that combining a minimum distance policy and an area coverage method as simple as SLACS was sufficient to obtain the escorting behavior. The ausence of some robots in the δ radius region observed in the empty environment scenario might be an advantage of this approach in scenarios where the robots' control present greater restrictions and when collisions are an extremely critical error, as in teams of unmanned aerial vehicles.

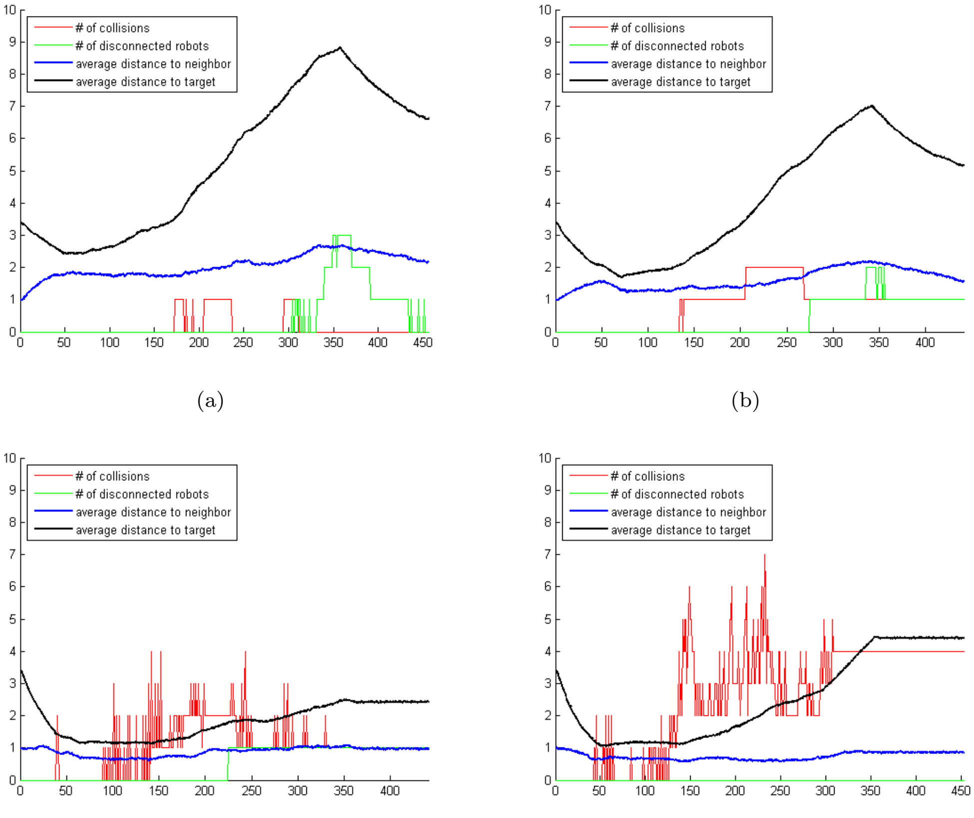
From the results of the second scenario, some interesting points can be noted. When the variable α is taken as a value relatively low (0.45), some robots were not able to go through the corridor. This was not caused by an unrecovered collision, but by a high influence of a behavior that avoids collisions (SLACS); two of the robots in the test with $\alpha = 0.5$ were to travel themselves to the corridor when the simulation stopped. Therefore, they were escaping from the navigation difficulty. The result with $\alpha = 0.55$ was clearly superior in terms of the robots got to complete the escorting travel; the likelihood of collisions when α was taken equal to 0.6 was enough to make two robots stay collided with each other despite having escaped the corridor. Thus, small variations of α were capable of changing drastically the escorting result when a non-empty scenario was presented.



(a) (b)

(c) (d)

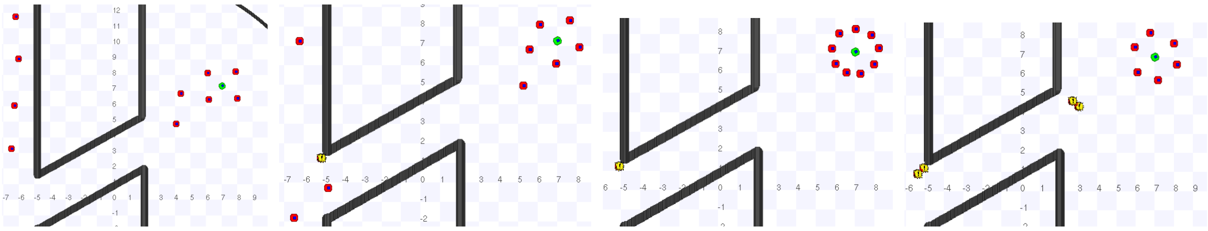
Figure 5: Empty scenario with: (a) $\alpha = 0.45$; (b) $\alpha = 0.5$; (c) $\alpha = 0.55$; (d) $\alpha = 0.6$.



(a) (b)

(c) (d)

Figure 6: Corridor scenario with: (a) $\alpha = 0.45$; (b) $\alpha = 0.5$; (c) $\alpha = 0.55$; (d) $\alpha = 0.6$.



(a) (b) (c) (d)

Figure 7: Corridor scenario's final state with: (a) $\alpha = 0.45$; (b) $\alpha = 0.5$; (c) $\alpha = 0.55$; (d) $\alpha = 0.6$.

6 Conclusion

In this paper, a multi robot escorting method for dynamic environment with the presence of static obstacles was proposed. This method consider two different behaviors: a minimum distance mainentance policy and an area coverage method that is inspired by the CVT centroid obtaining approach named Sample-based Lloyd Area Coverage System (SLACS). The proposed approach was tested in scenarios without and with walls, considering up to ten robots. In all tests, most of the ten robots used were able to effectively follow the escort target. In the empty environment, all robots succeeded using different behavior balancing parameters, while in the environment with obstacles, i.e., a corridor, some robots had difficulty to go into the corridor or to avoid unrecoverable collisions. The results show that this escorting method is viable for multi-robot escorting and that the correct adjustment of parameters is important for this method be more effective.

As a future work, machine learning methods will be applied to analyze the influence of considered behaviors. That will provide to the system described here the ability to balance properly the value of α. Assuming that the influence of behaviors is the same in the beginning of the navigation, each robot will able to improve the performance of execution of the behaviors and learn how to balance the influence of behaviors autonomously.

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