A Coordinated Search Strategy for Solitary Robots

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Abstract—Coordination without a priori information about the environment is an important problem in robotics, with applications from formation control to search and rescue. We propose a strategy based on cellular decomposition for coordinating search of solitary robots, with each robot considering cells assigned to others as soft obstacles. Simulations indicate the utility of the strategy when there is insufficient time to search the entire environment.

Keywords—coordination; coverage; cellular decomposition;

I. INTRODUCTION

This work considers coordinating a limited-time search for targets in an unknown environment by multiple solitary robots: self-interested robots without a priori knowledge about each other and with restricted communication capacity. Here, the communication range of a robot is taken to be the same as its perception range. In this setting, we use coverage as a proxy for finding targets: exploration performance is taken to be proportional to the area covered. The time limit means that robots would be unable to cover the full environment, even if the environment were known and the robots could coordinate perfectly [1].

A major challenge of search with solitary robots is interference: multiple robots searching in overlapping regions. Solitary robots only detect interference when they meet, and such meetings of solitary robots are purely serendipitous [2]. This is called an accidental rendezvous strategy. Ideally, one would like robots that are aware of each other to subsequently explore non-overlapping regions—this is termed sustainability in [3]. While strategies have been proposed to mitigate interference [1], [3], reducing interference in limited-time search remains an important research topic. The accidental rendezvous strategy (ARS) applies a greedy frontier-based approach for exploration of environments [4].

To further mitigate future interference after initial meetings, robots could schedule further meetings to share new information [1]. This method is called the periodic rendezvous strategy (PRS). However, such scheduled meetings induce interruptibility—robots cease new knowledge acquisition to travel to the rendezvous point when the rendezvous time arrives (robots travel to the rendezvous point through explored regions)—and this can consume up to half of the search time [3]. This work proposes an approach based on cellular decomposition [5] and soft obstacles to allocate largely disjoint exploration regions to robots. The approach aims to produce an interruptibility-free strategy with sustainable exploration performance: the cellular decomposition precludes the need for further rendezvous (as in PRS), and the use of soft obstacles mitigate interference when robots need to replan due to new meetings or unexpected obstacles.

II. SOFT-OBSTACLE STRATEGY

This work applies cellular decomposition to coordinate solitary robots in an unknown environment. A complication of this approach is that a robot may initially be assigned an exploration region partly outside the environment or occupied by obstacles, and only discover it later. In Figure 1, the region $X_3$ is partly outside the environment. This can lead to robots having unbalanced effective search areas, which makes interference more likely—it is unclear where a robot should search once it has completed searching its initial assignment. This is tackled by having robots remember the regions assigned to others, and treating those regions (along with regions already explored by the robot) as soft obstacles, avoiding them as far as possible.

Figure 1: Cellular decomposition with 4 robots. Solid black shapes denote obstacles, thick lines indicate the boundary of the search space, thin lines show exploration regions, and dashed lines show reserved margins.

This is further optimized by the elected leader responsible for allocating the regions also reserving margins (paths
between current robot locations and proposed exploration regions) during the cellular decomposition process. These margins are an additional novelty in our approach, and they allow robots to travel to new exploration regions along unexplored paths when necessary—typically when their exploration region is only partly accessible. The time limit is imposed to set the sizes of the exploration regions of robots involved in interaction. The maximum possible area that a robot with circular scanning region\(^1\) of radius \(r\) and maximum velocity \(\gamma\) can scan in \(\tau\) time units is

\[
A(\tau) = \pi r^2 + 2\gamma r \tau.
\]

This can be combined with a bound on the available remaining time to allocate suitably sized exploration regions for each robot during the cellular decomposition process. In addition, each allocated exploration region should be surrounded by a region of width at least \(2r\) as part of the margin.

III. RESULTS AND DISCUSSION

![Figure 2: Individual robot performance. (2a): a team of three robots. (2b): a team of four robots. (2c): a team of five robots. (2d): a team of seven robots.](image)

We compare our proposed soft obstacle strategy (SOS) to ARS and PRS. For the purposes of comparison, the robots start searching together, i.e., robots start at a rendezvous point. While various approaches to handling finer details are possible, we used a Bug algorithm [6] for obstacle avoidance, performed leader election following the approach in [7] and used a zigzag (or lawnmower) search for SOS and a frontier-based search for ARS and PRS, in exploration regions. Figure 2 plots the coverage of individual robots in different team sizes using these techniques in a randomly generated environment with obstacles.\(^2\) Here, SOS and PRS outperform ARS in sustainability, and SOS and ARS outperform PRS in coverage. SOS outperforms ARS in coverage. In Figure 2, the greater the scope of coverage line, the more sustainable a robot’s exploration performance. But horizontal segments in PRS’ lines denote interruptibility. ARS provides sustainable performance provided that scattering of robots involved in interaction is balanced [1]. Otherwise, robots’ explorations will overlap. But sustainable performance is guaranteed in PRS [3], since robots maintain collaboration through scheduled meetings. However, this approach is affected by interruptibility.

IV. CONCLUSION

We proposed a novel strategy to mitigate interference leading to unsustainable performance in situations where solitary robots search an unknown environment when there is insufficient time to search the entire environment.

Our experiments indicated that the strategy can address weaknesses of ARS and PRS. Mainly, an improvement is observed over ARS when robots have an unbalanced assignment in coordination. Going forward, we hope to develop a more theoretically grounded motivation for the approach.

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\(^1\)Alternatively shaped scanning regions should have only a minor impact on this discussion.

\(^2\)More details on https://bitbucket.org/jmf-mas/irc_2019/src/master/.

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