Optimizing Survivability of Robot Formation in Adversarial Environments

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Multi-robot formation is a canonical problem in robotic research, and as such has received considerable attention in the past decade (e.g., [1, 2, 3, 4, 5]). The study of multi-robot formation is wide and consists of two main problems: achieving a formation, and maintaining it. Achieving a formation requires a group of robots to create a given formation usually while minimizing time and avoiding collisions After the robots are organized in a formation, they are required to travel while maintaining it despite changes in the environment, such as obstacles, and collisions with other robots. Formation maintenance usually aims at minimizing the deviation from the desired formation during the execution.

The problem of robot formation was initially inspired by natural phenomena, from animals (e.g., a school of fish or a flock of birds [6]) or humans (e.g., a convoy or an infantry unit [7]). In these natural phenomena, the formation of birds, fish, vehicles or humans are assumed to travel in environments where the team is threatened by some adversarial existence. A school of fish may be threatened by predatory fish, a flock of birds may be targeted by a bird of prey. Similarly, a team of fire fighters need to search and rescue casualties in a wildfire, and a convoy of humanitarian aid in a disaster area may be targeted by some external parties.

Motivated by the adversarial presence in these natural examples of formations, we introduce a new problem: *robot formation in adversarial environments* (or *adversarial formation*, in short). In this problem, the team of robots travels in an adversarial environment, where possible threats exist and may harm the robots. In this novel idea the adversary and the environment influence the optimal formation that the group should be traversing in. The goal of the research is to identify possible types of threats the robots may face and the impact of the formation, in which the robots travel in, on the safety of each robot and the formation. This will give us the ability to minimize the chance of each robot to get hurt and thus maximize the formation survivability, i.e., the chances of the robots to pass through the area unharmed. To the best of our knowledge, adversarial influences have so far been ignored in robotic formation research. Note that as opposed to researches that deal with obstacle avoidance and shape transformation (e.g., [1, 2, 3, 4, 5, 8, 9]), threats are not considered as obstacles since robots can, and sometimes *must*, travel through them. In this research we would like to determine the strength of the formation rather than finding methods to avoid threats.

The Adversary and the Threats

There are different types of threats that the adversary can execute and aim at the formation. The threats are characterized using two properties: time and space. **TIME:** Different threats have different execution time, e.g., the duration of a bomb explosion is shorter than an exposure to a radiation cloud. **SPACE:** This property is characterized by traversability, concealment, spacial dimension and range of influence. Traversability (in this context) indicates whether the environment is crossable after execution. The concealment property indicates whether a robot can be concealed from the threat, either by another robot or by an object in the environment. For example, a robot that conceals its peers under a sniper threat as opposed to an earthquake where all the team is exposed to it. Spacial dimension of the threat can be of $1D$, $2D$ or $3D$. Range of influence indicates the area that the threat dominates and in which it can harm the team. It is assumed that the probability of being hit by a threat is monotonically non-increasing as the distance from the threat increases. A cartesian product between the mentioned factors will produce a wide spread of threats that needs to be handled.

Adversarial Formation: Problem Definition

A team of k robots $\{r_1, \ldots, r_k\}$ needs to traverse through an adversarial environment. The probability that a threat exists is denoted by P^E , $0 \leq P^E \leq 1$. The probability that robot r_i gets hit by the threat, denoted by P_i^H, depends on the type of the threat, its distance from the robot and other possible factors. We assume that P^E and the threat characteristics are known.

We define the *Safe Robotic Adversarial Formation* (SRAF) problem as follows:

Definition Given a team of k robots that travel through an adversarial environment **E** under given threat characteristics, find the formation in which the team should travel in, in time t, in order to maximize their safety, i.e., such that $\sum_{i=1}^{k}(1-(P^E \cdot P_i^H))$ is maximized.

Note that the optimal formation changes as the team of robots travel through the environment **E**, as the robots' position with respect to the threat changes. Therefore solving the SRAF problem optimally for time t is the main step towards solving the problem of safe traversal through the entire environment **E**, which is defined as maximizing the sum of expected survivability along the duration in which the robots are exposed to threats.

Team Survivability Characteristics

We have defined the survivability measure for optimal formation based on *individual survivability*, i.e., based on the chances of each robot in the team to get hit by the adversarial force.However, one might want to consider also measures that evaluate team characteristics, i.e., *team survivability*.

We have seen that the individual survivability measure can be relatively easily computeted, given the threat characteristics and the location of the robot with respect to the threat and to its teammates. The team survivability measure is more complex, and is composed of the following components:

Election : The cost of electing a new global leader and reorganizing the team due to a situation where the global leader gets hit.

Disconnected Components : the cost for getting disconnected components without the ability to reform again. This occurs when some robots get hit while causing their followers to become disconnected from the global leader.

Reorganization : The cost for reorganizing the team after a subset of robots got hit.

Algebraic Connectivity : A measure that indicates how well the team is connected [10]. A higher value indicates of a robust connection.

The measures are divided into two groups, *static* and *dynamic*. Static measures, such as Algebraic Connectivity, stay the same during the traversal of the team along the adversarial area. The dynamic measures values may change with each step within the adversarial environment. Those measures usually depend on the *Individual Survivability*, that is calculated as a function of the distance and the concealment with respect to the threat, which changes during the execution.

Ongoing and Future Work

This work sets the building blocks for a new problem, leaving many exciting directions for future work. First, we plan on implementing the algorithm on real robots, and solve the optimal transition from one optimal formation to another as time progresses. We would like to model other types of threats and experiment using them on different kind of formation. Additionally, the team survivability measure should be investigated in order to reduce the complexity of computing the survivability measure in different environments.

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