

A Distributed Framework for Real Time Path Planning in Practical Multi-agent Systems

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Abstract: We present a framework for distributed, energy efficient, and real time implementable algorithms for path planning in multi-agent systems. The proposed framework is presented in the context of a motivating example of capture the flag which is an adversarial game played between two teams of autonomous agents called defenders and attackers. We start with the centralized formulation of the problem as a linear program because of its computational efficiency. Then we present an approximation framework in which each agent solves a local version of the centralized linear program by communicating with its neighbors only. The premise in this work is that for practical multi-agent systems, real time implementability of distributed algorithms is more crucial than global optimality. Thus, instead of verifying the proposed framework by performing offline simulations in MATLAB, we run extensive simulations in a robotic simulator V-REP, which includes a detailed dynamic model of quadrotors. Moreover, to create a realistic scenario, we allow a human operator to control the attacker quadrotor through a joystick in a single attacker setup. These simulations authenticate that the proposed framework is real time implementable and results in a performance that is comparable with the global optimal solution under the considered scenarios.

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1. INTRODUCTION

The rapid advancement in the field of robotics has resulted in the development of low cost and reliable robotic platforms like quadrotors. These platforms are typically equipped with basic sensing devices for perception, and have sufficient on-board storage and processing capabilities to perform online computations. As a result, the interest in developing efficient algorithms for autonomous multi-agent systems has increased exponentially. However, one of the challenging tasks that still requires attention in developing such a system is distributed path planning under uncertain and dynamic environments in real time.

In multi-agent systems consisting of mobile robots that are battery powered, have limited processing capabilities, and communicate over noisy and shared channels, real time implementability of an algorithm has higher priority than optimal performance. In particular, for systems like quadrotors that have higher-order complex dynamics, it is extremely important to compute a feasible control action in real time. Optimality of control actions is always desirable but time complexity for computing these actions

can make them undesirable for such complex systems under practical situations.

In this work, we present a distributed framework for real time path planning under adversarial environments. The distributed algorithm is presented in the context of a motivating setup of capture the flag game, which was initially presented in (D'Andrea and Babish, 2003) for teams of robots controlled by humans. Although, a variety of setups for this game can be found in the literature, we will consider a basic setup in which there are two teams of autonomous agents, called attackers and defenders, with conflicting interests. As the name suggests, there is a flag located somewhere in the playing arena. The objective of the attackers is to capture the flag by entering into a defense zone around it, whereas the objective of the defenders is to stop the attackers from capturing the flag by defending the defense zone.

Capture the flag is popular because it is a complex game with a variety of challenges that must be addressed in a practical multi-agent system (see for example D'Andrea and Babish (2003); Earl and D'Andrea (2007); Chasparis and Shamma (2008); Huang et al. (2015)). The game

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is played under adversarial setting between two teams of autonomous robots with conflicting objectives. The players within each team collaborate with each other to achieve their objective. They compute their update actions based on the information they observe through their own sensors and the information they receive from their neighboring team members over shared communication channels. It is imperative that the update actions are computed efficiently in real time because a small delay in the computation or execution of a feasible action may result in the defeat of the entire team.

In the literature, numerous approaches have been proposed for path planning problems. One approach is to formulate the problem as a dynamic program as in Flint et al. (2002), which can guarantee optimal solution. However, except for special cases like LQR problems that have analytical solutions, dynamic programs suffer from the curse of dimensionality and cannot be solved even for a moderate size system. A computationally efficient approach is to formulate the problem as a mixed integer linear program or a linear program. However, only centralized solutions have been proposed based on these approaches (Earl and D’Andrea, 2007; Chasparis and Shamma, 2008). Another popular approach is based on model predictive control (MPC) in which each agent assumes a model for all the other dynamic agents in its environment over a finite prediction horizon and solves an optimization problem (see for example Dunbar and Murray (2002); Ferrari-Trecate et al. (2009); Müller et al. (2012)). However, these solutions typically require communication of entire trajectories among neighboring agents, which can result in excessive communication cost and latency in decision making.

In this work, we present a distributed, energy efficient, and real time implementable algorithm for path planning for capture the flag game. We start with the linear programming formulation of the problem presented in Chasparis and Shamma (2008) and propose an approximate algorithm for its distributed implementation. For the distributed implementation, each defender solves a local version of the linear program based on the current locations of its neighboring agents, and of the attackers. Since the optimization problem has to be solved over a fixed prediction horizon, each defender requires a model for the evolution of the attackers. We assume that the attackers are updating their locations based on a feedback law that moves them towards the flag.

The main contribution of this work is that we evaluate the performance of the proposed distributed framework through realistic simulations on V-REP. Typically, the algorithms presented in the existing literature are simulated in an offline environment in MATLAB in which agents are modeled as point masses with single or double integrator dynamics. These simulations are useful for analyzing the stability and convergence properties of the proposed algorithms. However, they do not provide insight about the behavior of the algorithm under actual agent dynamics and hardware constraints. Moreover, for multi-agent systems, communication among the agents over bandwidth limited shared channels also impose serious challenges because of packet loss, latency issues, and interference. To bridge this gap between theory and practice, we simulate

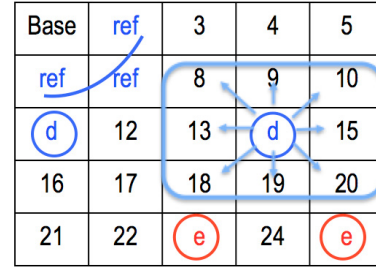


Fig. 1. Representation of the battlefield. The defense zone is $\mathcal{S}_{\text{base}} = \{s_1\}$ labeled ‘Base’ and $\mathcal{S}_{\text{ref}} = \{s_2, s_6, s_7\}$ labeled ‘ref’. There are two defenders that are located at sectors s_{11} and s_{14} . Neighborhood of the defender at sector s_{14} is represented by the arrows pointing to sectors $\{s_8, s_9, s_{10}, s_{13}, s_{15}, s_{18}, s_{19}, s_{20}\}$. Attackers are labeled as ‘e’ and are located at sectors s_{23} and s_{25} .

a multi-agent system of quadrotors in V-REP. Although our problem formulation is based on a simple linear model for defenders and a linear feedback law for attackers, V-REP uses a detailed quadrotor model as a result of which the simulations are more accurate and closer to reality than simple MATLAB simulations. Moreover, to have a realistic model for an attacker that can actively update its strategies based on the actions of the defenders, we introduce human in the loop where a human controls the attacker quadrotor through a joystick. Based on these realistic simulations, we verify that the proposed framework is real time implementable.

We start by providing a detailed description of the system in Section 2.1. Then, we formulate the problem as a centralized linear program in Section 2.3. The proposed distributed algorithm, which is the main result of this work, is presented in Section 3.2. The results of real time simulations of the system using V-REP are presented in Section 4.2.

2. PROBLEM FORMULATION

2.1 System Description

The proposed framework for distributed real time path planning is presented in the context of capture the flag game. In this section we present a detailed description of the system.

- **Battlefield:** The battlefield for the game is a grid, which is defined as a collection of sectors $\mathcal{S} = \{s_1, \dots, s_{n_s}\}$, where n_s is the total number of sectors. The defense zone is a collection of base sectors, $\mathcal{S}_{\text{base}} \subset \mathcal{S}$, that should be defended, and reference sectors, $\mathcal{S}_{\text{ref}} \subset \mathcal{S}$, that should be occupied by defenders to provide a protective perimeter around base sectors.
- **Teams:** The set of players $\mathcal{A} = \{a_1, a_2, \dots, a_{n_p}\}$ is divided into two teams, defender team (d) and attacker team (e). Each team is represented by a set

$$\mathcal{A}^r = \{a_1^r, \dots, a_{n_r}^r\},$$

where $r \in \{d, e\}$ is the type of the team, a_i^r is the i^{th} player of type r , and n_r is the total number of agents in the respective team r such that $n_d + n_e = n_p$.

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