RESEARCH STATEMENT

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Overview

The goal of my research is to use tools from **computational geometry**, **optimization**, and **stochastic processes** to solve challenges in **robotics and automation** in **provably efficient**, **interpretable**, and **robust** ways.

With the rapid proliferation of robots into many different domains, such as manufacturing, transportation, and services, there is a growing need for efficient and effective algorithms to solve fundamental problems such as motion planning, grasping, and decision making. The recent and remarkable successes of large-scale machine learning (ML) approaches in many domains, particularly image and language processing, is seen by many as rendering competing approaches such as analytical methods obsolete or subordinate. However, the death of analytical methods has been greatly exaggerated. While ML can indeed solve many problems which are unsolvable by analytic methods, in many other domains ML methods remain impractical or inefficient. For instance, ML often requires enormous computational resources and data to train on which may not be available, especially in settings where the robot must make use of limited on-board hardware for its computation. Other problems and settings offer opportunities for combining ML and analytic techniques. Even for problems too complex to solve with analytical techniques alone, gaining an analytical understanding of a problem often allows the creation of more efficient structured learning algorithms.

Research Areas

Motion Planning

The Traveling Salesman Problem Under Dynamic Constraints [1, 2] The Traveling Salesman Problem (TSP), in which an agent must visit (in any order) a set of target locations in the shortest possible time, is a foundational problem in computer science with numerous applications in both abstract and physical settings. While finding the exact optimal solution to the TSP is strongly believed to be intractable, it can be efficiently approximated. However, these approximation algorithms do not generalize to the *Dynamic TSP* (DTSP) where the agent must obey *dynamic constraints* in which past movements constrain future movements. Autonomous vehicles typically obey such constraints.

One question that has attracted significant attention is: if n targets are distributed randomly in the space, how does the expected length of the shortest tour grow as n goes to infinity? Previous works characterized this rate only for specific vehicle models or classes of translation-invariant vehicles.

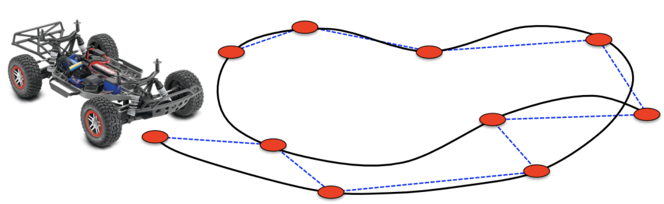

Figure 1: An instance of the Dynamic TSP. An unconstrained agent may visit the targets by following the dashed blue path; however, the vehicle must obey dynamic constraints and follow a looping trajectory such as the one shown.

In this work, we directly connected the geometric properties of the vehicle dynamics to the rate at which the length of the optimal tour grows. We found that the rate of growth depends on the form of dynamic constraints in general agents, in particular a parameter called the *small-time constraint factor*. Furthermore, for agents obeying *symmetric* dynamic constraints, we showed how the probability distribution of the target points and the parameters of constraints (which can vary over the space) interact to bound the multiplicative coefficient of the optimal tour length.

Notable techniques used in this work include sub-Riemannian geometry, various probability concentration bounds, optimization, and a probability theory analysis using exponential moments. This work was my 2023 Ph.D. thesis subject and is under review at Advances in Applied Probability (arXiv version [1]); early results from this work were also presented at ICRA 2016 [2].

Efficient Multi-Robot Motion Planning for Unlabeled Discs in Simple Polygons [3] The rise of large-scale automation for industrial tasks (in particular in warehouses) in the last decade has sparked increasing interest in the problem of *multi-robot motion planning*, in which a number of autonomous agents at given start locations must proceed to given goal locations while avoiding collisions with obstacles and each other. A common variation is *unlabeled* robots, where any (one-to-one) assignment of robots to goals is valid, which is often the case in practice when the robots are interchangeable.

In [3], we developed an efficient algorithm for unlabeled multi-robot motion planning by disc robots (or robots which require a fixed distance margin of safety) in simple polygons (despite problems of this form often being intractable). We achieved this by reducing the geometry of the workspace to a graph which represents the problem, solving an algorithmic problem on the graph, and translating back to the original problem. This work was presented at WAFR 2014, and led to significant follow-up work.

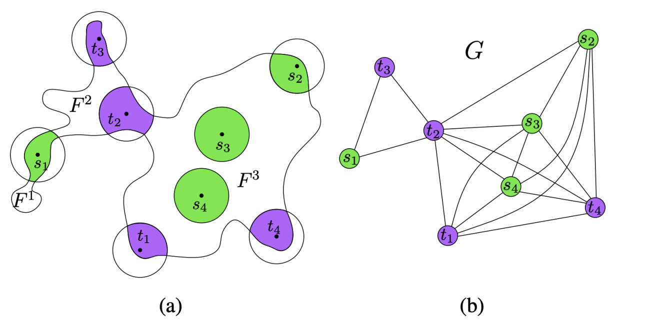

Figure 2: **(a)** An example of a simple polygonal workspace in 2D with start (green) and target (purple) configurations; disks represent the separation condition. **(b)** The graph generated by our algorithm, corresponding to the workspace in (a).

Multi-agent planning and allocation

Perimeter defense for heterogeneous agents [4, 5] Perimeter defense deals with attackers who are trying to invade a particular target area and defenders who are trying to intercept the attackers before they break into the perimeter of the target area. This is a common problem for security and defense applications and has a close relationship with pursuit-evasion games.

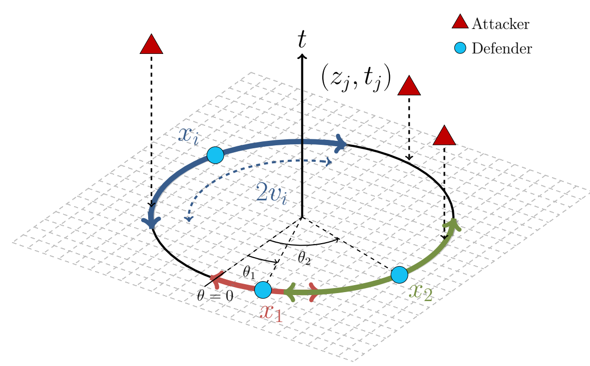

Figure 3: An instance of the perimeter defense problem with three defenders of different speeds. Attackers (red triangles) arrive at given times and locations on the perimeter; defenders (blue circles) must move to intercept them.

We study the question of how the defenders' performance is affected by *heterogeneity*: Do teams of robots with different speeds (heterogeneous) outperform teams of identical speeds (homogeneous)? For a given total speed 'budget', what is the ideal distribution of speeds to the different defenders? In [4], we gave a Dynamic Programming-based algorithm for heterogeneous defender allocation to a set of known attacks and analyzed its complexity, while studying defense against randomly-emerging attacks as a Markov

Decision Process (MDP).

In simulation, we found that heterogeneity is useful if the defenders have foreknowledge of the attacks, as they can then be allocated to different sequences of attacks based on their capabilities; however, against randomly-emerging attacks, homogeneous defenders fare better as they are more easily able to coordinate their actions. These results held under many different parameters of attack distribution. We also proved a theorem giving the exact conditions under which two defenders can be overwhelmed by carefully-placed attacks. This work was presented at WAFR 2022 [4].

We then expanded our work with a study of the case of homogeneous defenders, in order to explore the tradeoff between the speed of the defenders and the number needed to adequately defend a perimeter [5]. We reduced the homogeneous defender allocation problem to maximum matching on bipartite graphs, and found, experimentally, a stable relationship between the speed of the defenders and the number needed to adequately protect the perimeter. This extended work is to appear at IJRR.

Platooning [6] Advances in autonomous vehicles have opened up the possibility of saving fuel in autonomous transportation with *platooning*, in which a group of vehicles travels in close proximity in order to improve aerodynamic efficiency. However, in a general setting with vehicles operating on independent schedules, making efficient use of platoons requires some vehicles to wait for others. This tradeoff between time and fuel yields an optimization and queuing problem, for which we characterized the set of Pareto-optimal policies; this work was presented at WAFR 2016 [6].

Algorithms for Automation

The Teenager's Problem [7] As robots see increasing use in industrial and service roles, large (and increasing) economic gains can be made by improving the efficiency of basic tasks such moving a set of items into a bin. One promising approach is to use *multi-object grasping* (MOG) to reduce the number of times the robot must transport items to the bin. Prior work in MOG focused on rigid polygonal objects [8, 9], including using push actions to group the objects together first [10] (which I was also involved in). However, *deformable* objects, such as garments, are an equally important class of objects which require significantly different methods to deal with.

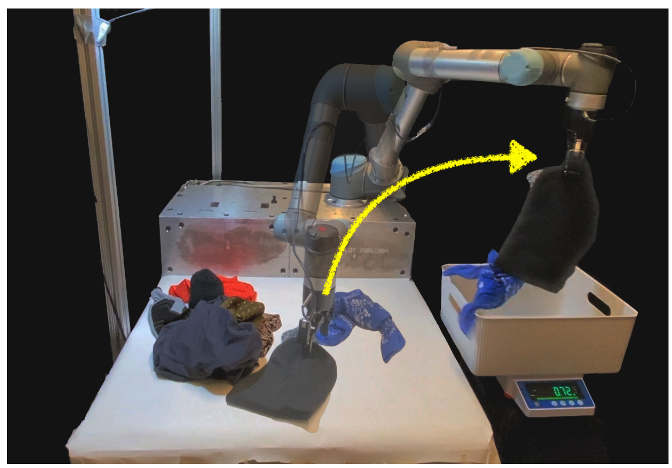

Figure 4: An action shot of a multi-object grasp executed by the robot. The robot picks up the blue bandana, black beanie, and (mostly occluded) gray sock and deposits them in the bin.

In this work we defined the problem of effectively using MOG to move a set of cluttered garments on a planar work surface to a bin, which we dubbed the *Teenager's Problem* after the tendency for teenagers' rooms to be strewn with clothes. We studied two approaches to computing grasps: *depth-based*, which relies on a depth camera to determine grasps, and *segment-based*, which does not require depth data but instead segments the image and solves an optimization problem to plan effective grasps. We found that both depth-based and segment-based approaches increases the average number of objects per transport; additionally, they have complementary strengths, allowing for even more effective *hybrid* methods. Finally, we considered an algorithm which rearranges the garments on the surface to further increase the number of objects per transport, though with additional actions within the workspace.

This work represents the first systematic study of multi-object grasping for deformable objects, and showed how efficiency gains can be made at relatively low cost by directly optimizing for multi-object grasps. It was submitted to ICRA 2024 (preprint: [7]) and is currently under review.

Complexity

Complexity of games and puzzles [11, 12, 13, 14, 15] I was also heavily involved in studying the computational complexity of certain games, puzzles, and computational problems. In particular, we showed that classic puzzle games such as Clickomania (even in the highly simplified case of only two colors and two columns) [11], Tatamibari [12], and Numberless Shakashaka [13] are NP-Hard, as well as more modern games [14]. I also studied the relationship between the game of Hex and the Jordan Curve Theorem [15]. This research area is relevant to many robotics problems, particularly in highly algorithmic and geometric topics such as multi-robot motion planning, where it is often possible to prove that the general version of a problem is NP-Hard or PSPACE-Hard (see [16], a follow-up work to [3] by my coauthors), yielding both important impossibility results and guidance on development of algorithms (generally either approximation algorithms or heuristics).

Vision and Future Research

My research vision is to use mathematical tools to efficiently solve algorithmic problems in robotics, both as a supplement to machine learning approaches and for problems for which machine learning may not be efficient or feasible.

Topological methods for representing deformable objects and their poses

One important task which remains difficult in robotics is to consistently track and represent objects in 3D. This is especially so when the objects are *articulated* (such as human beings) or *deformable* (such as bags). Articulated and deformable objects can take an infinite variety of poses that often obscure important topological features which are critical for executing a task: for example, a folded-up bag may conceal its opening or handles, greatly complicating tasks such as bagging.

Prior work on this problem has focused largely on deformable linear objects such as ropes and cables, or sought to represent garments in full from detailed point clouds or meshes using learned models. However, neither of these approaches are fully satisfactory: the first is too limited to represent the many varieties of deformable objects that industrial or service robots are likely to encounter, while the latter is unnecessarily detailed and complex. Furthermore, the representation should be stable over time, as folding or twisting an object does not alter its topology. This raises a natural question:

How can we represent and track the pose of an articulated or deformable object in a way which both represents the important topological features of the object (loops, holes, and so forth) while still being compact enough for fast computation?

A promising approach is to take the Mapper Algorithm for topological data analysis, which is used to represent the structure of datasets as graphs, and repurpose it for modeling deformable objects. Mapper is simple, requiring only basic operations on a point cloud and yielding a graph representation with relatively few nodes, yet expressive enough to represent complex topological features and structure. However, Mapper has not yet been applied to sequential data, and there remains limited theoretical understanding of its properties. The goal is to use graph theory and topology to develop a variant of Mapper designed to represent and track deformable objects with complex topologies in 3D.

Multi-Robot Algorithms

One consequence of the rapid adoption of autonomous mobile robots in many applications is the deployment of groups of relatively small and cheap autonomous systems (sometimes called *swarms*). These multi-agent applications can be seen in the fields of warehouse robotics, surveying and inspection, perimeter defense, space satellites, and many others. As these applications span a wide variety of tasks, control types (notably the spectrum between centralized and decentralized control), and agent capabilities, many different (but related) problems arise, including task allocation, teaming, motion planning, patrolling, and platooning.

I plan to extend my prior work on perimeter defense and multi-robot motion planning to encompass a broader range of objectives and settings, focusing on developing efficient algorithms for coordinating the actions of the agents. The following is an example of a problem that can be studied in this area:

Perimeter defense with strategic stochastic attacks One feature of many real perimeter defense problems is the extremely limited availability of information to the attacking agents, as modeled in [4], which often have limited sensing capabilities or insufficient time to sense defenders' actions and adjust to them. In these cases, attackers cannot react to defender actions; however, they may still have useful strategic options available to them. In particular, two types of strategy can be available for the attackers to consider. The first consists of coordinating individual attacks (which, once set, proceed along fixed routes towards the target), deciding where, when, and how many to launch in order to overwhelm the defenders (we solved an example of such a problem in [4]). The second consists of equipping each attacker with a randomized movement algorithm to make its movements unpredictable and hence make interception by the defenders more difficult. Even very simple instances of these problems exhibit interesting and nontrivial behavior.

These problems exhibit both theoretical interest from the perspective of game theory and stochastic processes, as well as practical relevance for pursuit-evasion and perimeter defense, and may be a basis for extensions for worst-case bounds in other multi-agent settings.

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