Model-Based Coordination of Robotic Networks

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The Problem: Robotic systems are being created that must act together to robustly achieve elaborate missions within uncertain and sometimes dangerous environments. To achieve this robustness we must go well beyond current programming practice. How do we program these teams of robots or vehicles to carry out elaborate missions, while offering them a breadth of options for dealing with the unknown? How will these robotic networks generate and adapt coordinated plans on the fly, while distributing the decision making amongst the robotic components in an effective manner? How will these robots best deal with the uncertainty of communication as well as uncertainty of the environment? How do we give these robots enough autonomy to perform agile maneuvers?

The challenge is three fold. First how do we extend programming languages to express contingencies, critical timing constraints, uncertainty and reward. Second, how do we develop planning and execution languages that can handle real-world problems in real-time. Finally, how do we perform planning and replanning in a distributed manner, while being robust to communication delays and communication lossage.

Motivation: With the success of individual land, space and aerial robots, research is increasingly turning towards tasks that involve networks of robots. For example, in the future teams of autonomous airborne helicopters and ground vehicles will work together to put out a fire, or to search a flood area for humans in need of rescue. In the future networks of remote sensing satellites will be able to quickly reconfigure, in order to accurately characterize a weather event that might turn into a hurricane. In the future a collection of orbiters, balloons and ground rovers will work in concert to discover the source of water on Mars, lending insight into the age old question about life on Mars. In the future ubiquitous computing environments will disseminate information and commands in order to ensure that the desired information is readily at hand, office environments are comfortable, highways avoid congestion and power grids are working at maximum efficiency. Each of the above scenarios requires a new programing practice for creating cooperative systems that are agile, coordinated and long-lived.

Previous Work: This research thrust of the Model-based Embedded and Robotic Systems group (MERS) builds upon work on reactive programming of embedded systems, temporal planning, distributed algorithms, and kinodynamic path planning. We introduce a language for describing the behavior of teams of robotic vehicles that builds upon work in reactive programming languages, such as Esterel [Berry; Halbwachs], and on time-concurrent constraint languages [Gupta & Saraswat]. Using these descriptions we generate plans for team behavior based on a unification of work on Simple Temporal Networks [Meiri & Dechter], graph-based planning [Blum & Furst; Kautz & Selman] and temporal planning [Dean & Boddy; Muscettola; Chien]. We distribute this planning process by building upon algorithms for distributed network flow analysis, most notably a distributed auction algorithm for solving shortest path problems [Bertsekas]. Finally, the behaviors we generate include agile stunt maneuvers for vehicles, and is based on kinodynamic path planning algorithms [Frazzoli, Feron & Dahleh].

Approach: There exists a wide range of approaches to coordinating collections of robotic sytems, including those that are purely emergent, and those that are strictly top down. The focus of this project is on cooperative robotic tasks that involve a clear, but possibly changing set of mission goals, that involve time pressures during critical mission phases, and that involves interactions with the environment that are highly uncertain. Teams of human-piloted vehicles achieve complex missions under uncertainty, such as search and rescue, by having at their disposal a rich set of game plans and tactics. The same is true for astronauts in space and sailors at sea.

A set of plans and tactics consist of a range of alternative methods for performing activities and contingencies for responding to novel events. In order for a team of vehicles to autonomously perform the set of activities necessary to complete a mission it needs to continuously make decisions. Whenever a team encounters an activity that allows for several alternative methods, it must decide which one is best to employ. If the team has control over the time and duration of activities, then it must also decide when each activity should be performed and for how long. These decisions may lead to failure, for example, if they exhaust non-renewable resources, if overlapping activities conflict, or if too little time is left to complete all the necessary activities. Cooperative planning, therefore, is an essential capability to avoid these failure situations.

Multiple-vehicle mission planning presents the following major challenges. First, as with most planning systems, the plan representation must be flexible enough to handle variations in plan execution due to exogenous factors. A plan could be represented as a fixed set of time-stamped commands that indicate exactly when each activity must commence and complete, but this type of plan is brittle to small variations in execution time. Flexibility is achieved by specifying only relevant temporal constraints, and by expressing contingencies for handling uncontrollable factors. Second, each mission plan must be expressive enough to fully describe complex coordinated behaviors, that go well beyond traditional planning languages. For example, the plan must be able to express the coordination of concurrent behaviors, such as two vehicles meeting at some location and then proceeding together, or the constraint that multiple vehicles should not be transmitting messages on a single communication channel at the same time. Finally, the planner must support reactive on-board re-planning over execution horizons ranging from hours to seconds. This efficiency goes well beyond the performance of current temporal planning systems. Hence expressivity and efficiency, combined with distribution are the defining characteristics of the task.

This MERS research thrust introduces a model-based reactive programming language that enables autonomous vehicles to create and adapt coordinated mission plans on the fly, by reasoning from models of individual vehicle behaviors and a range of team strategies. First, we introduce the Hybrid Activity Modeling Language (HAML), which extends reactive programming languages, such as Esterel, to allow for the expression of complex concurrent behaviors, metric time constraints, multiple contingencies and continuous dynamics. Second, we introduce the Hybrid Temporal Planning Network (HTPN), a simple, compact encoding of HAML programs that we will use to support efficient decision theoretic planning under uncertainty. An HTPN is a hierarchical encoding of a discrete hierarchical semi-Markov decision process coupled with continuous dynamics. Finally, we are developing a distributed planning system that draws upon distributed algorithms for network search, dynamic programming, conflict resolution, and hierarchical decomposition to perform real-time multiple-vehicle mission planning, resource allocation and execution on HTPNs.

To achieve efficiency, our planning algorithm operates in the spirit of recent work on graph-based planning [Blum & Furst], with the important novel feature that the HTPN representation supports a least commitment planning paradigm. In particular planning is viewed as a process of searching through the set of possible concurrent executions within the HTPN, for one that minimizes expected cost. This search process is framed as a variant of a multi-edge shortest path problem.

Impact: Increasingly computer systems are being designed to continuously interact with their environment, and are being designed to function over long periods of time. Such systems will interact with other systems and their environment in ways that are impossible for their designers to explicitly anticipate, nevertheless the systems must be prepared to handle these novel circumstances. If our project succeeds, it will revolutionize the way such systems are designed and implemented.

Future Work: To date our research has concentrated on a centralized approach to generating a coordinated plan for a team of air vehicles. We are developing distributed planning capabilities, by generalizing the distributed auction algorithms for shortest path by Dimitri Bertsekas. We are also generalizing our approach to support kinodynamic path planning of vehicles that are able to perform agile stunt maneuvers. To accomplish this we are currently generalizing our approach to optimal planning of hybrid systems, in which robust hybrid automata are used to describe a range of possible agile maneuvers that each vehicle can perform. Finally we are exploring the interplay between planning and communication. The planner will be tested in simulation on search and rescue and Mars exploration scenarios, and will be tested in hardware using a collection of four RWI rovers.

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