Task Allocation Using a Distributed Market-Based Planning Mechanism *

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ABSTRACT

This paper describes a market-based planning mechanism used for task and resource allocation within a larger distributed, multi-robot control and coordination architecture. We are developing an extension to the traditional three-layered robot architecture that enables robots to interact directly at each layer – at the behavioral level, the robots create distributed control loops; at the executive level, they synchronize task execution; at the planning level, they use market-based techniques to allocate tasks and resources. This paper focusses on the market-based planning layer, which is comprised of two main components: a *trader* that participates in the market, auctioning and bidding on tasks; and a *scheduler* that determines task feasibility and cost for the trader, and interacts with the executive layer for task execution.

Categories and Subject Descriptors

I.2.11 [**Artificial Intelligence**]: Distributed Artificial Intelligence—*multiagent systems*;
I.2.9 [**Artificial Intelligence**]: Robotics—*autonomous vehicles*

General Terms

Algorithms, Experimentation

Keywords

multi-robot control, market economy, stochastic scheduling, distributed three-layered architecture, Mars exploration

*A full version of this paper is available at `www.cs.cmu.edu/~fire/publications.html`.

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1. INTRODUCTION

We are developing a multi-robot coordination architecture [4] with the flexibility to accommodate:

- different granularities and timescale of synchronization and coordination.
- a wide range of system resources, constraints, and requirements while producing reasonable solutions.
- the strengths of both distributed and centralized approaches, allowing optimization (when required and possible) while maintaining robustness and the ability to adapt to the (changing) dynamics of the system.

The architecture is an extension of the traditional three-layered approach, which provides event handling at different levels of abstraction through the use of behavioral, executive, and planning layers. Our approach extends the architecture to multiple robots by allowing robots to interact directly at each layer. This provides several benefits, including: (1) plans can be constructed and shared between multiple robots, using a market-based approach, providing for various degrees of optimization; (2) executive-level, inter-robot synchronization constraints can be established and maintained explicitly; and (3) distributed behavior-level feedback loops can be established to provide for both loosely- and tightly-coupled coordination.

The focus of this paper is on the market-based planning mechanism for allocating tasks and resources. It is a distributed mechanism that allows for different levels of optimization in the initial allocation auctions and, if possible, during subsequent refinement auctions. The allocation process may be tailored to the system requirements with tradeoffs, such as time-to-completion versus total energy consumption, taken into account.

2. MARKET AND SCHEDULER

Our approach to task allocation and planning is based on a market economy. An *economy* is essentially a population of agents coordinating with each other to produce an aggregate set of goods. *Market economies* are generally unencumbered by centralized planning, instead leaving individuals free to exchange goods and services and enter into contracts as they see fit. Conspicuously absent from the market approach is a rigid, top-down hierarchy. Instead, individuals organize themselves in a way that is mutually beneficial. Despite the fact that individuals in the economy act only to advance their own self-interests, the aggregate effect is a highly productive society.

We have developed a market mechanism, based on our work with TraderBots [2, 3], that is flexible enough to accommodate different auction mechanisms, including single-task and combinatorial auctions. A robot/agent that needs a task performed announces that it will auction off the task as a seller. Each buyer capable of performing the task for a cost c, bids to do so for $c + \epsilon$. The seller accepts the lowest bid, as long as it is cheaper than doing the task itself. If a bid is accepted, the seller performs the task and pockets ϵ as profit. Each robot aims to maximize its individual profit (which often translates to minimizing individual cost where possible); however, since all revenue is derived from satisfying team objectives, the robots self-interest translates to global efficiency. Moreover, the robots can only increase their profit by eliminating unnecessary waste (i.e., excess cost).

The market approach has a number strengths, including: the flexibility of allowing robots to cooperate and compete as necessary to accomplish a task; its amenability to learning new behaviors and strategies during execution of complex global task; and its ability to deal opportunistically with dynamic environments.

The market works closely with the other major component of the planning layer: the *scheduler*. Following the market economy framework, a scheduler associated with each robot is responsible for maintaining the robot's current agenda of accepted and pending tasks. The scheduler plays a critical role both in the formation of bids and in the interaction between the planning and executive layers. Before a bidder can bid on a new task, it must first ascertain from the scheduler whether the task can in fact be feasibly undertaken (given resource/timing constraints and the other tasks already in the schedule) and, if so, the cost. Once a robot trader is awarded a task, it is added to the schedule and now further constrains decisions to bid on other tasks. The scheduler is responsible for subsequently sending the task to the executive so that it is executed appropriately with respect to the other tasks that the robot must accomplish. Our flexible, anytime, search algorithm used by the scheduler, is called *Whistling* [1].

The division of the planning layer of each robot into two components (the scheduler and trader) provides a clean functional separation that also highlights the flexibility of the architecture. The scheduler can incorporate a range of different search heuristics (e.g., as functions of the perceived drivers of task cost), and can be augmented to accommodate different resource constraints. The trader can be augmented with various auction mechanisms, from the distributed mechanism of trades between pairs of robots to a more optimal combinatorial exchange mechanism.

3. EXPERIMENTS AND RESULTS

We have examined the efficacy of our approach within the context of a Mars exploration scenario premised on the notion of scientific return, i.e., that a group of robots would be sent to Mars for the (potentially) valuable information they gather and return to Earth. We envision a scenario where a colony of heterogeneous robots is deployed on Mars. Scientists on Earth communicate high-level task descriptions to the colony (e.g., "find and gather data on several carbonate rocks"). We assume that the tasks given to the robots may far exceed what can be accomplished during the lifetime of the mission. In addition, communications limitations (bandwidth, delays, blackouts) necessitate highly autonomous robots, and preclude effective tele-operation of the robots or micro-managing of task execution by the scientists. The robots are therefore responsible for deciding which/how tasks are to be accomplished, based on, among other things, the tasks' relative priorities. The goal for the robots is to utilize their time, resources, and capabilities efficiently so as to provide the highest possible scientific return on the tasks they are given. Our distributed, layered architecture is designed to facilitate this goal.

In terms of the development and testing of our current system, we have focussed on a characterize-region task that will fit within a broader exploration scenario. In this task, a user/scientist specifies a region on the Mars surface, indicating that rocks within that region are to be characterized with an appropriate sensing instrument.

The goal of the experiments presented in the full version of this paper is to examine the flexibility of our market-based allocation mechanism, and specifically explore tradeoffs arising from some of the basic parameters of the system. These experiments represent the first empirical results of our system, and as such, use a fairly simple experimental scenario.

4. CONCLUSIONS

With these experiments, we have just begun to probe the parameters and possibilities of our market-based planning mechanism. It is becoming clear, however, that the approach provides immense flexibility to accommodate different problems, resource constraints, and user-level requirements. Please see the full paper for complete results.

5. ACKNOWLEDGMENTS

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