A Distributed Method for Evaluating Properties of a Robot Formation

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Abstract

As a robot formation increases in size or explores places where it is difficult for a human operator to interact, autonomous control becomes critical. We propose a distributed autonomous method for evaluating properties of multi-robot systems, and then discuss how this information can be applied to improve performance with respect to a given operation. We present this as an extension of our previous work on robot formations; however, the techniques described could be adapted to other multi-robot systems.

Introduction

Applications that could benefit from a collection of robots working in formation include exploration of planets, unmanned military vehicles, crop-dusting, and Space-Based Solar Power (Mead 2008). A number of control methods have been proposed to establish and maintain robots in a formation (e.g., Balch *et al*. 1998, Fredslund & Matarić 2002, Yamaguchi *et al*. 2001); however, for robot formations to be practical, a number of issues must still be addressed. In particular, as the collective increases in size or explores places where it is difficult for a human operator to interact (e.g., underwater, in the air, or in space), autonomous control becomes critical.

Mead (2008) presents a distributed approach to formation-level control that treats each robot in the formation as a cell in a cellular automaton, referred to henceforth as CATALST (Cellular Automata for Transformations of Agents in Large-Scale Teams). The algorithm is leaderless—a human operator communicates to a *seed cell* that instigates changes within its local neighborhood, which continue to propagate in succession, causing a global transformation (e.g., formation translation, rotation, scaling, resizing, and change); any cell at any time can be designated as the seed. In the current implementation, the seed cell is directly selected by a human operator; however, the selection of the seed impacts performance with regard to various formation control commands. The position of the seed within the collective impacts how a command propagates through the formation, and consequently how a transformation manifests.

As the formation gains or loses robots, moves through an environment, or otherwise changes, it can become necessary for the network of robots to autonomously reorganize while still yielding the user-specified global structure (Mead *et al*. 2009). We propose a distributed method for evaluating properties of the multi-robot system, and then discuss how this information can be applied to improve performance with respect to a given operation. Other work uses a global monitor (Gordon 1999).

For purposes of communication and mobility, we consider the size of the collective, in terms of both the number of robots and the bounds on the formation area. The distance of a cell to the center of the collective—with respect to both the formation and the automaton—will also impact communication, stability, and control. Using this information, the collective can autonomously make changes to the structure of the formation or the automaton to improve the performance of various operations.

We present this work as an extension of CATALST; however, the techniques described in this paper could be adapted to other multi-robot systems.

Algorithm

The automaton representation used by CATALST can be viewed as a graph, where a node in the graph is a cell in the automaton and an edge indicates that two cells are next to each other or, neighbors. We refer to this as the *automaton graph*. This allows us to apply graph algorithms to the collective. Specifically, our approach utilizes a Distributed Minimum Spanning Tree similar to applications in communication networks (cf., Awerbuch 1987, Frederickson & Lynch 1984).

For a given formation operation, a cell casts a vote based on local information in the state of its neighborhood; it is an inherent property of CATALST that this process occurs from the leaf nodes to the root node. This vote is passed to the cell's *reference neighbor*, which is defined as the neighbor that with the minimum geodesic (graph) distance to the current seed cell (part of cell state defined by CATALST). Votes propagate through each successive neighborhood, eventually reaching the current seed cell, producing a branch in the minimum spanning tree with the seed cell as the root (Figure 1). Upon receiving votes from all of its neighbors, the seed comes to a consensus, and either submits this information to a human operator or uses it to execute some other operation.

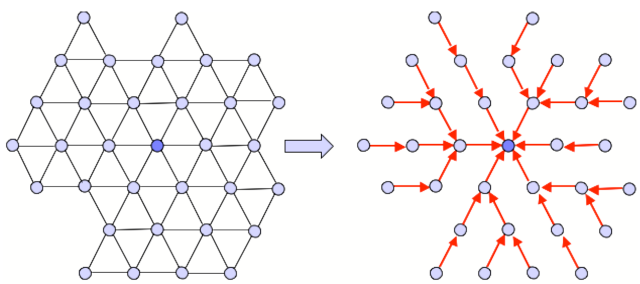

Figure 1: Each cell in the automaton graph (left) submits its vote to its reference neighbor (denoted by the arrows), producing an emergent minimum spanning tree (right) with the current seed cell (denoted in dark blue) at the root.

Properties

Using this method, we are able to autonomously determine various properties of the collective, including the *automaton size* (number of cells), *automaton center* (graph center), *formation center* (geometric center), *formation radius* (bounds the formation area), and *formation offset* (robot position with respect to overall formation). For example, to calculate the automaton size, a cell casts a vote equal to 1 plus the sum of the value of the vote submitted by each neighbor that is referencing it.

Operations

The above properties are used to perform various autonomous formation-level operations. The automaton center can be used to *select a seed based on its position in the automaton* to improve the performance of the formation with respect to communication and stability by minimizing the geodesic (graph) distance from the seed. The formation center and offset can be used to *select a particular cell*, allowing for status checks by a human operator. The same information can be used to *select a seed based on its position in the formation*, perhaps with respect to some external stimuli (e.g., a light source, an obstacle, etc.). *Formation rebalancing* uses the formation center to instigate an organized restructuring of all robots with regard to symmetry of the formation.

Details on properties and operations can be found at http://roboti.cs.siue.edu/projects/formations/props_ops.php.

Future Work

The algorithm is currently being implemented in simulation and, later, will be extended to a physical multi-robot platform, both described in (Mead 2008). Once integrated into CATALST, we will reevaluate the formation control architecture with respect to existing criteria (Fredslund & Matarić 2002, Mead *et al*. 2009).

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