Behavior-Based Cooperation Among Space Robots*

João Sequeira, Pedro Lima, M. Isabel Ribeiro, João Sentieiro
Instituto Superior Técnico / Instituto de Sistemas e Robótica
IST - Torre Norte, Av. Rovisco Pais 1,
1049-001 Lisboa, Portugal
{jseq,pal,mir,jjss}@isr.ist.utl.pt

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1 Introduction

Space offers many exciting challenges for robot applications. Hostile environments and complex tasks often require complex robots with a high degree of autonomy.

Multi-robot systems have long been seen as a practical and economical way to perform complex tasks. An economical argument has been used to justify the use of multiple, low cost, robots in applications such as space exploration, [Brooks et al., 1990]. A practical argument has been that intelligence can be achieved, without using complex control architectures, through the competition/coordination among a set of basis behaviors/roles. Similarly to many biological systems, the cooperation among low complexity robots leads to the emergence of complex group behaviors, resembling a form of group intelligence, and hence to the ability to perform complex tasks.

Despite the important differences between space and terrestrial robots, the fundamentals of functional control architectures developed for land mobile robots are applicable, with suitable modifications.

This paper focuses on the past and current work on Cooperative Robotics and Micro-Satellites carried out at ISR/IST. The applications will be divided in two major classes:

1. Satellite formation and control;

2. Architectures for Cooperative Robotics with applications in planetary exploration and satellite inspection/maintenance.

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2 Satellite Formation Control

In recent years, the usage of formations of several micro-satellites to implement space telescopes and space antenna arrays has attracted increasing attention [Robertson et al., 1999]. Given a specification (e.g., the desired telescope heading), interesting control and coordination problems arise, such as:

1. what is the desired posture for each satellite of the formation that will achieve the desired telescope heading;
2. how to move each satellite of the formation to achieve the new desired posture in minimum time and without colliding with the other satellites;
3. how to minimize the energy spent by the formation, by a suitable posture distribution among the formation members - notice that satellites in the outer formation zone will usually spend more energy that their inner team mates. Therefore, depending on the requested manoeuvres, the choice of which satellite(s) will move will depend on their past trajectory and relative formation position.

ISR/IST has gained considerable experience in the past three years on micro-satellite attitude control and determination [Clements et al., 2000, Marques et al., 2000], as well as on methods for position tracking along 3D trajectories for non-holonomic robots which are part of a "follow-the-leader" cooperative scheme [Tabuada and Lima, 2000].

3 Cooperative Robotics

Robotic teams have the advantages of redundancy and robustness and incremental operability over the single robot systems. When considering the multi-robot teams, there is a broad range of scientific topics involved, from control theory (and multiple related areas, e.g., game theory, hybrid systems) to the fundamentals of functional architecture design.

Two different approaches to a general architecture for cooperative multi-robot teams are under development at ISR/IST since the mid 90's. These have in mind not only the applications to real indoors robots [Lima et al., 1999, Sequeira, 1999], but envisage as well applications to less structured environments (e.g., rescue after catastrophes, planetary exploration). Although different in several formal aspects, it is possible to identify behavioral concepts in each of the two approaches.

As a computer programming paradigm, tailored to escape the complexity of robot control in realistic applications, behavior-based control has been extensively discussed and numerous variations have been proposed, e.g., [Brooks, 1986, Košecká et al., 1997, Matarić, 1994, Parker, 1998, Sequeira et al., 1998]. Although a behavioral theory of dynamical systems has been established along the last decade, [Willems, 1991], comparatively little research has been done on behavior synthesis and analysis methodologies applied to robotics, [Colombetti et al., 1996, Sequeira, 1999].

Under the first approach, each robot will specialize in a given role (e.g., according to the different target scientific tasks), and the robotic team can be integrated by a functional architecture consisting of organizational, relational and individual layers, similar to the one described in

[Drogoull and Collinot, 1998]. Behaviors emerge from the interaction between the functionalities in the architecture and the environment. Robustness to robot losses can be achieved by a redundant role assignment to the robotic team members. The architecture also addresses resource sharing and allocation problems. An interesting framework to formalize the relational and organizational issues is based on Jennings's Joint Intentions [Jennings, 1999].

Under the second approach, the fundamental structure underlying behavior-based control of single and multiple robot systems is considered, [Sequeira, 1999]. The framework developed points out the fundamental structure underlying behavior-based control in terms of two basic operators, defined on a suitable state space, and of a supervisor controller.

The state variable is a pair composed of an action (i.e., a specialized role) and a configuration representing the initial condition for the action. Each action spans a class of trajectories contained in a bounded region of the configuration space and starting in a neighbourhood of the initial configuration. From the perspective of a mission execution, any two trajectories in such a class are equivalent and hence any of them can be chosen for the robot to follow.

Assuming that each robot in the team is equipped with an adequate set of actions, the existence of a group structure on the space of actions is a necessary condition for controllability of single, behavior controlled, robots. The first operator provides the mechanism to switch between any two states and defines a set of conditions for the existence of the aforementioned group structure. Whenever the available actions need to be adapted, aiming at preserving the group structure, due to the kinematics or the environment changes, the second operator is used.

The interactions among robots generate events that represent the way each robot perceives the surrounding environment and the other robots. Based on the events detected and on the state information the supervisor controller at each robot in the team determines the action to be executed. Cooperation among the robots in a team is thus achieved by the proper definition of the actions, the detection of the adequate events, and the exchange of state information.

The fundamental concepts involved in both approaches apply to free-flying robot teams designed for inspection and maintenance in space of satellites and space stations (e.g., parts assemblage, screw fastening, large object manipulation).

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