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Robot team control: A geometric approach

João Sequeira*, M. Isabel Ribeiro

Instituto Superior Técnico/Institute for Systems and Robotics, Av Rovisco Pais 1, 1049-001 Lisboa, Portugal

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Abstract

This paper describes the control of robot teams in the framework of Hilbert spaces. The paper focus are the intrinsic properties of robot control architectures, namely the conditions under which a generic mission can be successfully executed.

The proposed paradigm develops in two levels: (i) single robot control supported on a monotonic and non-expansive projection map defined over some behavioral space such as the robot configuration space or the velocity space, and (ii) team control supported on a supervision scheme over a set of neighboring relations among the teammates, accounting for their relative motion.

Each robot monitors its own neighboring relations for relevant changes and adapts its motion to the objectives of the team using a finite state automaton supervisor.

Simulation results on teams of 2D holonomic and cart robots are presented.

Keywords: Robot control; Co-operative control; Geometric approaches

1. Introduction

This paper presents an approach to the control of robot teams focused on the intrinsic properties of control architectures. These properties result from general principles on robot motion obtained using basic geometry tools for Hilbert space and lead to skeleton control algorithms. The control structure at each robot is separated in (i) single robot control in the framework of differential inclusions, (ii) team control in a discrete event systems framework. Therefore, the overall system resembles a hybrid system.

In the framework of dynamical systems, the ith robot in a team with n members, moving in a space ${}^iQ = \{{}^iq\}$, is represented by a dynamic system ${}^i\dot{q}(t) = f_i({}^iq(t), {}^iu(t))$, with initial condition ${}^iq(0) = {}^iq_0$, $i = 1, \ldots, n$, t being the time and ${}^iu \in {}^iU$ the control vector.[1] When considered isolated from the rest of the team, the synthesis of the u_i that makes the robot follow a reference path or move towards a reference configuration is a classical robot control problem that has been widely studied [6,9,14,17]. In the last years there has been an increasing interest in multiple robot problems, e.g., spacecraft and military formations,

* Corresponding author. Fax: +351 218418291.
E-mail addresses: jseq@isr.ist.utl.pt (J. Sequeira), mir@isr.ist.utl.pt (M.I. Ribeiro)

[1] Without loosing generality, this model can simply be assumed as the differential kinematics.

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for which techniques ranging from control theory to artificial intelligence were proposed in the literature.

In [12] a behavior based architecture for fault tolerant cooperating robots was proposed. This three level architecture is based on the subsumption architecture. The highest level models the motivation of a robot using performance measures such as the impatience (the attitude of the robot towards the teammates) and acquiescence (the attitude towards itself). The intermediate level contains sets of specific behaviors activated by the motivational behaviors. Each of these sets emphasizes a particular global robot behavior, e.g., find a location using a methodical behavior or a wander behavior. The lowest level contains the basis competence layers for the robot to survive.

Motor schemas (primitive motion strategies) were used in [3] to control teams of cart and car-like vehicles aiming at moving in formation. The formations considered were defined either using the distances between a robot and its neighbors, between a robot and a team leader or between a robot and some characteristic point of the formation, e.g. the center of mass. Formation specific motor schemas allow each robot to compute its motion direction so that no formation break occurs.

In [4] the formation control problem was decoupled into the planning of a reference path to be followed by a virtual leader and a tracking problem to be handled by the real robots in the team. The formation is defined by the kernel of a convex map such as the sum of quadratic errors between the position of each robot and its reference trajectory. The formation control is given by a steepest descent technique on the map defining the formation.

Formations defined by smooth functions of the relative distances of fully actuated spacecrafts were also considered in [8]. The overall system is divided into an average system, that captures the average motion of the team, and a shape system that captures the relative velocities among the robots and hence the formation pattern. PD-like laws are used to make both the average and shape systems follow their reference trajectories.

In [10] a formation is defined by a set of vectors defined after the relative positions of the robots in the team. The formation control problem is formulated as the control of a set of double integrators, acting under a leader-follower strategy. A compactness assumption on the control space of each robot allows the definition of a compact uncertainty region around its current position. The free space the team is allowed to use to avoid formation breakings is obtained by superimposing this region on the obstacles in the environment.

The approach presented in this paper differs from the ones in the current literature in that it separates the control problem into a layer that depends exclusively on the properties of the behavioral spaces of the robots, i.e., on the intrinsic properties of the space used to formulate the control problem, being independent of the particular robot, and a layer that handles the problem-dependent information.

A large variety of single robot missions neither require exact path following nor that the robot reaches a specific configuration. Instead, the robot is required to move within some bounded region in the free configuration space and/or to reach a goal region or a specific configuration. This problem, of relevance in behavioral robotics, has been considered within the Viability Theory framework [1].

Similar considerations apply to teams of robots operating either under tight or loose constraints on the distance among the team members. For example, to avoid that the distance among team members grows above a pre-specified limit, the team may be required to span a compact region in the workspace while moving towards the goal (a synthesis problem) or one may be interested in determining the region spanned by the team during a mission (an analysis problem).

In the team control problem considered in this paper the ith robot in a team must reach a goal set, $K_i \subset {}^iQ$. This set can be a priori defined to account for the mission specifications and modified either as a consequence of the data acquired by on-board sensors during the mission or as requested by the team motion. In some sense, this set defines a reference behavior for the robot to follow during the assigned mission.

The team control paradigm proposed in this paper encompasses (i) the definition of the goal sets K_i to account for the specific mission specifications (ii) a control strategy that will drive the ith robot towards K_i, and (iii) a negotiation procedure, handled by a finite state automaton (FSA) at each robot, to adapt the motion strategy to the requirements imposed by the team neighboring constraints during the motion towards K_i.

Once defined the goal set K_i, and in the absence of motion constraints, the set $\Delta_{K_i}({}^iq) = \{k - {}^iq \forall k \in K_i\}$ defines the motion directions that drive the ith robot directly towards K_i. In general, given the