Annual Reviews in Control 000 (2017) 1–13

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Review article

Control sharing in human-robot team interaction

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A R T I C L E I N F O

Article history:
Received 15 July 2017
Revised 28 September 2017
Accepted 29 September 2017
Available online xxx

Keywords:
Human-robot team interaction
Shared control
Human behavior modeling
Robot team

A B S T R A C T

The interaction between humans and robot teams is highly relevant in many application domains, for example in collaborative manufacturing, search and rescue, and logistics. It is well-known that humans and robots have complementary capabilities: Humans are excellent in reasoning and planning in unstructured environments, while robots are very good in performing tasks repetitively and precisely. In consequence, one of the key research questions is how to combine human and robot team decision making and task execution capabilities in order to exploit their complementary skills. From a controls perspective this question boils down to *how control should be shared* among them. This article surveys advances in human-robot team interaction with special attention devoted to control sharing methodologies. Additionally, aspects affecting the control sharing design, such as human behavior modeling, level of autonomy and human-machine interfaces are identified. Open problems and future research directions towards joint decision making and task execution in human-robot teams are discussed.

Contents

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https://doi.org/10.1016/j.arcontrol.2017.09.017
1367-5788/

1. Introduction

Human-robot team interaction describes the interaction between a human and multiple robots, which collaborate to achieve a common goal. Its envisioned benefits are superior performance in highly unstructured tasks in unknown and/or remote environments, reduced human workload, execution of tasks which are not possible with a single robot, flexibility in task execution, and robustness. Application domains of human-robot team interaction include for example search and rescue, collaborative manufacturing, logistics, maintenance, and construction.

The reduction in price, size, and operational complexity has considerably increased the availability of robotic systems, while the advancements in communication technology allow a seamless information exchange between them. These developments are enablers for *multi-robot systems*. They provide increased flexibility and robustness and are capable to conduct more complex tasks then single-robot systems (Iocchi, Nardi, & Salerno, 2000; Parker, 2008). Even though the autonomous task execution capabilities of robots have progressed rapidly in recent years, human intervention in the form of high-level reasoning and planning is still needed in a priori unknown environments. As a consequence, novel forms of human-robot interaction beyond single-human-single-robot have become a current and important topic of research covering the areas of multiple humans-single robot interaction (Malysz & Sirouspour, 2011), multiple humans-multiple robots interaction (Franchi, Secchi, Ryll, Bulthoff, & Giordano, 2012), and single human-multiple robots interaction (Cummings, How, Whitten, & Toupet, 2012).

The main scientific challenge of human-robot team interaction is to fuse the cognitive capabilities of the human and the autonomous capabilities of the robot team, while maximizing task performance, efficiency, and intuitiveness of the interaction. This leads to the consideration of suitable levels of autonomy, control sharing and human cognitive and behavioral aspects in the interaction design.

The aim of this article is to provide a survey on existing concepts and approaches for human-robot team interaction with special focus on control sharing aspects. The article is organized as follows: Section 2 concerns the modeling and control of robot teams and modeling of human behavior, Section 3 addresses the human-robot team interface design, and Section 4 reviews existing control sharing concepts. For an overview see also Fig. 1.

2. Modeling robot teams & human behavior

In this section we briefly review modeling and control approaches for robot teams and models for human behavior.

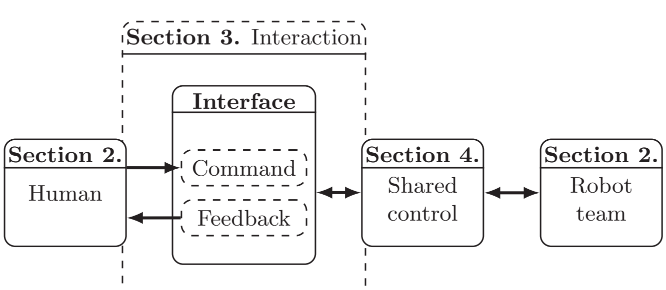

Fig. 1. Article overview in a block structure.

2.1. Robot teams

This subsection focuses on the modeling and control concepts for robot teams, which are suitable and/or used in human-robot team interaction. There are extensive reviews on multi-robot systems control in general, for example Cao, Fukunaga, and Kahng (1997), Iocchi et al. (2000), Arai, Pagello, and Parker (2002), Dudek, Jenkin, and Milios (2002), Farinelli, Iocchi, and Nardi (2004), Gazi and Fidan (2007), Murray (2007).

In this article the term *robot team* refers to a multi-robot system which cooperates to achieve a global objective. For example, robot teams can be a set of mobile manipulators (Khatib, Yokoi, Chang, Ruspini, Holmberg, and Casal, 1996; Sugar & Kumar, 2002), wheeled robots (Desai, Ostrowski, & Kumar, 2001) or UAVs (Jin, Minai, & Polycarpou, 2003; Ryan, Zennaro, Howell, Sengupta, & Hedrick, 2004). In the literature there is further the distinction between robot *swarms*, i.e. multi-robot systems with a relatively large number of "simple" and homogeneous robots, and heterogeneous multi-robot systems with more complex individual robotic agents. Under the term of robot team we will subsume both types, even though the related control problems can be quite different, see also Section 2.1.2.

2.1.1. Modeling of robot teams

Robot teams are modeled as a set of differential equations describing the models of individual robots. Most frequently used models are:

- *Kinematic* (*single integrator*) model (Tanner, Jadbabaie, & Pappas, 2003; Oh & Ahn, 2014)

$$\dot{\boldsymbol{x}}_i = \boldsymbol{u}_i \quad i = 1, \ldots, N, \tag{1}$$

where $\boldsymbol{x}_i \in \mathbb{R}^n$ is the pose of the ith robot, $\boldsymbol{u}_i \in \mathbb{R}^n$ its control input, and N the number of robots. This is the simplest of all models and often used to model robot agents in a swarm.

- *Point mass* (*double integrator*) model (Oh & Ahn, 2014; Liu, 2015)

$$\ddot{\boldsymbol{x}}_i = \frac{1}{m_i}\boldsymbol{u}_i, \tag{2}$$

where m_i is the mass of the ith robot. This model is slightly more complex than the kinematic model and also often used in the analysis of robot swarms.

- *Euler-Lagrange* model (Khatib et al., 1996; Erhart & Hirche, 2016)

$$\boldsymbol{M}_i(\boldsymbol{x}_i)\ddot{\boldsymbol{x}}_i + \boldsymbol{c}(\boldsymbol{x}_i, \dot{\boldsymbol{x}}_i) + \boldsymbol{g}_i(\boldsymbol{x}_i) = \boldsymbol{h}_i, \tag{3}$$

where $\boldsymbol{M}_i(\boldsymbol{x}_i) \in \mathbb{R}^{n \times n}$ is the inertia matrix, $\boldsymbol{c}(\boldsymbol{x}_i, \dot{\boldsymbol{x}}_i) \in \mathbb{R}^n$ the vector of Coriolis and centrifugal forces, $\boldsymbol{g}_i(\boldsymbol{x}_i) \in \mathbb{R}^n$ the vector of gravitational forces, and $\boldsymbol{h}_i \in \mathbb{R}^n$ is the vector of control wrenches. This is the classical model typically employed for an individual manipulator and for small heterogeneous robot teams.

If a robot interacts with its environment, for example touches an object, then the input $\boldsymbol{u}_i$ in (1) and (2) and $\boldsymbol{\tau}_i$ in (3), does not only contain the control input, but also the external force from the environment. Analogously, if multiple robots perform a cooperative manipulation tasks, i.e. are physically coupled through the object, then additionally the applied forces from the other robots acting through the object are contained in this input. For more details on modeling this type of systems, see for example (Erhart & Hirche, 2015; 2016).

Please cite this article as: S. Musić, S. Hirche, Control sharing in human-robot team interaction, Annual Reviews in Control (2017), https://doi.org/10.1016/j.arcontrol.2017.09.017