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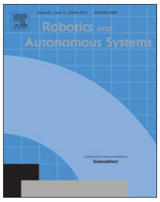

On the manipulation of articulated objects in human–robot cooperation scenarios

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HIGHLIGHTS

- Articulated and flexible objects constitute a challenge for robot manipulation tasks, but are present in different real-world settings, including home and industrial environments.
- We propose a novel reactive/deliberative architecture for the manipulation of articulated objects using action planning to sequence a set of actions leading to a target articulated object configuration, and allowing humans to collaboratively carry out the plan with the robot.
- We introduce two representation and planning models for the specification of articulated object configurations and the sequencing of manipulation actions.
- We discuss how robot perception and object representation impact on action planning and execution in human–robot cooperation scenarios.

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ABSTRACT

Articulated and flexible objects constitute a challenge for robot manipulation tasks but are present in different real-world settings, including home and industrial environments. Current approaches to the manipulation of articulated and flexible objects employ *ad hoc* strategies to sequence and perform actions on them depending on a number of physical or geometrical characteristics related to those objects, as well as on an *a priori* classification of target object configurations.

In this paper, we propose an action planning and execution framework, which (i) considers abstract representations of articulated or flexible objects, (ii) integrates action planning to reason upon such configurations and to sequence an appropriate set of actions with the aim of obtaining a target configuration provided as a goal, and (iii) is able to cooperate with humans to collaboratively carry out the plan.

On the one hand, we show that a trade-off exists between the way articulated or flexible objects are perceived and how the system represents them. Such a trade-off greatly impacts on the complexity of the planning process. On the other hand, we demonstrate the system's capabilities in allowing humans to interrupt robot action execution, and –in general –to contribute to the whole manipulation process.

Results related to planning performance are discussed, and examples with a Baxter dual-arm manipulator performing actions collaboratively with humans are shown.

1. Introduction

The introduction of the Industry 4.0 paradigm is expected to redefine the nature of shop-floor environments in many directions, including the role played by robots in the manufacturing process [1,2]. One of the main tenets considered in Industry 4.0 is the increased customer satisfaction via a high degree of product personalization and just-in-time delivery. On the one hand, a higher level of flexibility in manufacturing processes is needed to cope with such diversified demands, especially in low-automation tasks. On the other hand, skillful robots working alongside humans can be regarded as a valuable aid to shop-floor operators, who can supervise robots' work and intervene when needed [3], whereas robots can be tasked with difficult or otherwise stressful operations.

Human–robot cooperation (HRC) processes in shop-floor environments are a specific form of human–robot interaction (HRI) with at least two important specificities. The first is related to the fact that the cooperation is targeted towards a well-defined objective (e.g., an assemblage, a unit test, a cable harnessing operation), which must be typically achieved in a short amount of time. The

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second has to do with the fact that humans need to feel (at least partially) in control [4,5]: although grounded in the cooperation process, their behaviors could be unpredictable in specific cases, with obvious concerns about their safety [6,7]; they may not fully understand robot goals [8]; robot actions may not be considered appropriate for the peculiar cooperation objectives [5,9].

As far as the cooperation process is concerned, two high-level directives must be taken into account:

D_1 *cooperation models* (and robot action planning techniques) enforcing the prescribed objectives must be adopted [10,11];
D_2 the robot must be flexible enough to adapt to human operator actions avoiding a purely reactive approach [12,13], and to make its intentions clear [14,15].

These two directives lead to three functional requirements for an HRC architecture. The robot must be able to:

R_1 (at least implicitly) recognize the effects of human operator actions [16];
R_2 adapt its behavior on the basis of two elements: human operator actions themselves and the whole cooperation objectives;
R_3 employ planning techniques allowing for a fast action re-planning when needed, e.g., when planned actions cannot be executed for sudden changes in the environment or inaccurate modeling assumptions [17].

Among the various tasks typically carried out in the shop-floor, the manipulation of flexible or articulated objects, e.g., cable harnessing operations, is particularly challenging [18–21], as can be seen in Fig. 1: on the one hand, it is usually beneficial to accurately plan the expected cable configurations on the harnessing table *in advance*, thus confirming the requirement R_3; on the other hand, it is often necessary to keep a cable firm using more than two grasping points and to re-route the wiring pattern, which – when done collaboratively with a robot, for instance to place bundle retainers or junction fixtures – leads to the requirements R_1 and R_2 above.

In the literature, the problem of determining the 2D or 3D configuration of flexible or articulated objects has received much attention in the past few years [22,23], whereas the problem of obtaining a target configuration via manipulation has been explored in motion planning [24–26]. However, in the context of HRC, perception and manipulation are only part of the challenges to address. Conceptually speaking, the outcome of such approaches is a *continuous mapping* in 2D or 3D space from an initial to a target object's configuration [25,27–29], subject to a number of simplifying hypotheses as far as object models are concerned [30–34]. This observation leads to two further functional requirements. The robot must be able to:

R_4 represent object configurations adopting suitable modeling assumptions, and then segment the whole manipulation problem in simpler actions to *appropriately* sequencing and monitoring, each action operating in-between two intermediate configurations;
R_5 represent the actions to perform using a formalism allowing for plan executions that are robust with respect to unexpected events (e.g., the human operator suddenly intervenes), and modeling errors (e.g., not modeled objects to be removed from the workspace).

In this paper, we consider articulated objects as suitable models for flexible objects [24], and we address the following challenges: (i) we provide two representation and planning models for the classification of articulated object configurations and the sequencing of manipulation actions, using an OWL-DL ontology-based formalism and the Planning Domain Definition Language (PDDL) [35], and we test them using two state-of-the-art PDDL planners, namely Probe [36] and Madagascar [37], as well as with the VAL plan validator [38]; (ii) we embed such models in a reactive/deliberative architecture for HRC, referred to as PLANHRC, which takes human operator behaviors into account and is implemented on top of the ROSPlan [39] and MoveIt! [40] frameworks; and (iii) we discuss how perception assumptions and representation schemes impact on planning and execution in HRC scenarios. The PLANHRC architecture has been deployed on a dual-arm Baxter manipulator, which is used in all of our experiments.

The paper is organized as follows. Section 2 discusses relevant approaches for the work described here. Section 2.2 introduces more formally the problem we address, as well as the scenario we consider. The PLANHRC's architecture is described in detail in Section 3, where the overall information flow, the representation and reasoning challenges, and the planning models are discussed. Experiments to validate the architecture are described in Section 4. Conclusions follow.

2. Background

2.1. Planning techniques in human–robot cooperation

A number of studies have been conducted to investigate the role and the acceptability of automated planning techniques in HRC scenarios. As highlighted in a field study by Gombolay and colleagues, two factors are important to maximize human satisfaction in HRC [41]: on the one hand, humans must be allowed to choose their own tasks freely, i.e., without them being assigned by an algorithm, subject to the fact that the cooperation is successful; on the other hand, the overall system's (i.e., the human–robot team's) performance must be at high standards. It is noteworthy that these two factors may conflict in case of a *lazy* or *not focused* human attitude. However, when required to trade-off between them, humans show a strong preference for system's performance over their own freedom. This study well fits with the requirements R_1, R_2 and R_3 outlined above, and opens up to an idea of a collaborative robot as a device not only able to *aid* human workers, but also capable of *keeping them in focus* and steering the cooperation towards its objectives if deviations occur.

As a follow-up of the work discussed in [41], a study about the actual amount of control a human worker would like to have when collaborating with a robot has been reported in [42]. The main finding of this study is that human workers tend not to prefer a total control of the cooperation process, rather they opt for partial control. This is confirmed by the fact that the overall team's performance seems higher when the robot determines what actions must be carried out by the human. As a consequence, a key factor for the acceptance of collaborative robots is finding a sensible – yet efficient – trade-off between performance and human control.

In order to determine such trade-off, which may depend on the peculiar emotional or physical status of the human worker, one possibility is to encode in the planning process her/his preferences as far as tasks and operations are concerned [43]. In a first series of experiments, the use of human preferences in the planning algorithm led to an overall *decrease* in performance, correlated with human subjective perceptions of robots not in line with the main cooperation objectives. This suggests that a subjective assessment of the HRC process tends to attribute major inefficiencies to robots, and confirms that this is a crucial aspect for the applicability of collaborative robots in industrial scenarios.

Techniques for HRC available in the literature target these issues only to a partial extent, positioning themselves at different levels in the trade-off scale outline above. It is possible to identify two relevant trends for our work.