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Human-Robot Collaborative Assembly Planning using Hybrid Conditional Planning

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Abstract

For assembly planning, robots necessitate certain cognitive skills: high-level planning of actuation actions is needed to decide for the order of actuation actions, while geometric reasoning is needed to check the feasibility of these actions. For collaborative assembly tasks with humans, robots require further cognitive capabilities, such as commonsense reasoning, sensing, and communication skills, not only to cope with the uncertainty caused by incomplete knowledge about the humans' behaviors but also to ensure safe collaborations. We introduce a novel formal framework for collaborative assembly planning that utilizes hybrid conditional planning extended with commonsense reasoning and a rich set of communication actions for collaborative tasks. We evaluate this method by a set of experiments in a furniture assembly domain.

1 Introduction

While industries are moving towards customized products, robotic assembly tasks are getting more challenging. Flexible assembly systems need collaborations of robots with humans in order to combine the precision of robots with the dexterity of humans. To collaborate with humans safely and effectively, robots require certain cognitive skills. For instance, for assembly planning, high-level planning of actuation actions is needed to decide for the order of actuation actions; meanwhile, geometric reasoning is needed to check the feasibility of these actions. For collaborative assembly tasks that involve humans, robots need to be furnished with further cognitive capabilities, including commonsense reasoning, sensing, and communication skills. These cognitive capabilities are necessitated by collaborative tasks not only to cope with the uncertainty caused by incomplete knowledge about the humans' behaviors, but also to ensure safe collaborations.

Some of these challenges have been studied in the literature. Combining task planning and motion planning (TAMP) for manipulation planning has been studied using different hybrid methods, e.g., with search-based approaches (based on systematic search over hybrid states) [2, 9, 10] and logic-based approaches (based on formal representations of hybrid actions) [4, 8, 3]. Some studies on TAMP in service robotics have considered uncertainty due to incomplete knowledge, e.g., by belief-state planning including sensing actions [10], while some of them have utilized commonsense knowledge, e.g., by logic-based knowledge representation methods [5].

Meanwhile, human-robot interactions in natural language have been investigated, e.g., by dialogue-based approaches [13, 6, 16]. Some of these approaches [13] use conditional planning, some use branching plans [14], and some use policy generation [7] to incorporate communication actions in plans to obtain further knowledge. For instance, Petrick and Foster, Giuliani *et al.* consider queries to learn what type of drink the human wants so the robot prepares the order accordingly (here, human does not perform any actions that change the world state), Sebastiani *et al.* consider queries to negotiate which task will be done by the robot or the human (here, negotiation actions are not formalized as nondeterministic actions as part of the domain description, and thus the contingencies in communications are generated by the algorithm as execution variables), and Grigore and Scassellati consider queries to reduce state estimation uncertainty in policy generation (here, the goal is to assist the human rather than to plan for completion of a task collaboratively). Different from these related work, our goal is to plan for collaborative actions, and thus we consider a richer set of communication tasks. We formalize all the communication actions as part of the domain description, and thus utilize them as part of conditional planning.

We propose a formal method for collaborative assembly planning, using hybrid conditional planning [17], with the following contributions. The proposed formal framework allows planning of hybrid sensing actions and various communication actions, in addition to hybrid actuation actions, based on the formal logical descriptions of these actions. Unlike the sequential plans of actuation actions generated by the related work on hybrid planning, a tree of actions is generated offline. Each branch of the tree represents a possible sequence of actuation, sensing and communication actions to execute in order to reach the given goal. Note that the branching plans [14] are not guaranteed to be conditional plans, since the nondeterministic results of communication actions are not formalized as part of the domain description (e.g., ramifications and qualification constraints due to these contingencies are hard to detect). The proposed method utilizes commonsense knowledge for planning of actions that enables the robot to initiate

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collaborations by asking for confirmation, requesting help, or offering help. Unlike the related work, the relevant common sense knowledge is also formalized as part of the domain description, and thus utilized while planning rather than execution. Unlike the related work on human-robot interactions, all possible communications are planned in advance. Embedding communications in planning is advantageous, not only for providing evidence-based explanations to humans but also for safer collaborations.

2 Proposed Method

As a novel contribution, we extend hybrid conditional planning (HCP) [17] to include commonsense reasoning and a richer set of communication actions for collaborative tasks: (i) robot asking for confirmation (e.g., whether the human will assemble the part she is holding), (ii) requesting human to perform some action (e.g., human to unhold a part), (iii) asking for help (e.g., human to assemble a part that is not reachable to the robot), (iv) offering help (e.g., when the assembly part is too heavy or needs precision, or when the task is too tedious for the human), and (v) initiating/ending a conversation (e.g., greeting/acknowledging) and providing explanations. With such a general HCP framework, with sensing actions, robots can identify which assembly part the human workmate is holding; with commonsense reasoning, robots can conclude that a heavy assembly part cannot be moved by a human; and with communication skills, robots can communicate with humans in different ways for safer and effective collaborations. To the best of authors' knowledge, HCP has not been used for collaborative assembly planning.

Hybrid actuation actions and sensing actions can be formalized systematically for HCP. As a novel contribution, we introduce a systematic method for formalizing communication actions depending on their types. All communication actions have relevant preconditions to ensure that they are executed when appropriate. Requesting human to perform some action, initiating/ending conversations and providing explanations are formalized as deterministic actions. The communication actions (e.g., asking for confirmation) that require some answers/feedback from humans are modeled as nondeterministic actions. These actions serve as decision nodes in a hybrid conditional plan, similar to sensing actions. Formalizations of preconditions and effects of communications actions take into account commonsense knowledge.

3 Experimental Evaluations

We consider a Baxter robot working in collaboration with a human to assemble a coffee table. Initially, all assembly parts (i.e., table top, legs of different sizes, feet to be screwed to legs) are placed on a table in front of the robot. The goal is to build a coffee table using the relevant assembly parts.

The robot can perform actuation actions for holding/releasing a part, and attaching a part to another part. With sensing actions, the robot can gather information as to whether the human is holding some/which part, whether she is releasing the part she is holding, and where she is attaching the part to. The robot can communicate with the human as discussed in the examples above.

Unlike the existing work on constructing furniture, since the common sense knowledge is also formalized as part of the domain description, the robot can use common sense knowledge while generating a hybrid conditional plan to reach the goal. For instance, it is common sense knowledge that a table consists of legs of the same length, so when the robot aims to construct a table, it utilizes this knowledge and selects appropriate legs to assemble. Since the feet of the table require a screwdriver to be assembled to the legs, he offers help to the human for such tedious and boring tasks. If the human is holding a part that can be assembled to the part that the robot is holding, then (instead of trying to pick it from the human) he needs to confirm with the human as to whether she will assemble the part. If the human's response is negative, then the robot requests the human to release the part.

In our experiments, we have used the HCP planner HCP-ASP [17] for generating conditional plans, and RRT* motion planner [11] from OMPL [15] for the reachability checks embedded into action descriptions. All experiments are performed on a Linux server using 12 2.4GHz Intel E5-2665 CPU cores and up to 64GB memory.

We have considered instances of furniture assembly planning, that include different types of collaboration scenarios: (S1) If the robot senses that the human is holding a part that can be attached to what the robot is holding, then the robot confirms with the human about her intention of attaching the parts and safely allows her to attach the parts. (S2) If an assembly part is not reachable by the robot and he senses that the human is free, then the robot asks for help in attaching that part to what he is holding. (S3) If the robot senses that human is holding a part which is tedious to attach, then he offers help in attaching parts.

We have analyzed the effects of the following objective measures on the computation time: the total number L of leaves, the maximum length D of a branch from the root to a leaf, and the number A of actuation, S of sensing and C of communication actions in that branch, the total number DN of decision nodes that denote sensing actions and nondeterministic communication actions, the maximum branching factor BF, the total number N of nodes in the tree. The results of experiments with these objective measures are shown in Table 1.

There are several important observations. (i) The computation time of a hybrid conditional plan increases as its size increases. For Instance S3–2, a hybrid conditional plan (that consists of 523 actions in total, and 48 different hybrid sequential plans with a makespan less than 69) is computed in about 25 minutes. The increase in computation time is not surprising since, even for polynomially bounded plans with limited number of nondeterministic actions, the complexity of conditional planning is Σ_2^P-complete [1]. On the other hand, note that the plan is computed offline considering all possible contingencies, and thus no time is spent for planning during execution. (ii) The average computation time of a branch of the tree, which represents a possible hybrid sequential plan to reach the goal, is the total CPU time divided over L. This suggests that, if a hybrid sequential plan of actuation actions were computed instead of a hybrid conditional plan, then replanning would take around half a minute for

Instance S3–2. Such (re)planning times are not acceptable while communicating with a human. Therefore, computing a hybrid conditional plan in advance for collaborative assembly tasks that involve communications is advantageous.

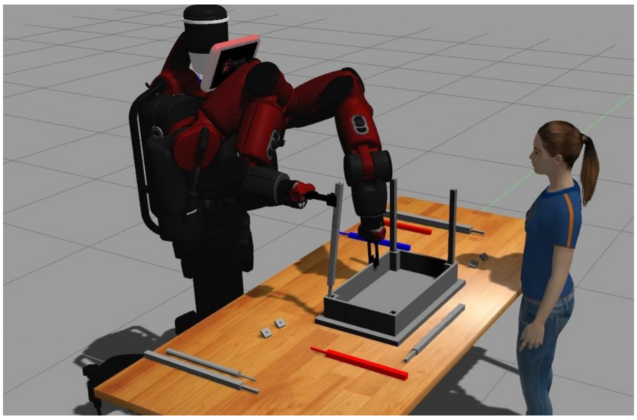

Figure 1: A snapshot from a dynamic simulation of a collaborative furniture assembly task.

4 Discussion and Future Work

When our HCP-based method is compared against plan executing monitoring with replanning, the HCP-based method spends more time on computation of a plan, as expected by the computational complexities of the problems. On the other hand, the plan execution monitoring has to do replanning to recover from failures. Along these lines, given the large number of nondeterministic sensing and communication actions in the uncertain and human-centric environments, both the number of replanning attempts and the number of executed actuation actions in the final plan, in general, are significantly higher than the length of the longest branch of the tree computed by the HCP-based method.

To demonstrate the applicability of our HCP-based method for assembly planning, the hybrid conditional plans computed by HCP-ASP have been dynamically simulated in Gazebo with ROS interface (Figure 1). A video of a sample dynamic simulation is available at `http://cogrobo.sabanciuniv.edu/demos/hri/HCP_HRI_demo_video.mp4`.

Currently, we are implementing furniture assembly scenarios with a physical Baxter robot. In connection with physical implementations, we are performing experiments with subjective measures in the spirit of [12], by means of a survey applied to a diverse group of applicants.

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Scenario	Instance	L (A+S+C)	DN	BF	N	CPU Time (sec)
S1	1	24 (5+9+6)	84	4	172	285
	2	32 (8+12+8)	144	6	201	425
S2	1	20 (4+9+6)	64	4	120	315
	2	17 (5+12+8)	70	4	130	350
S3	1	36 (15+17+12)	201	6	357	750
	2	48 (25+28+16)	325	8	523	1520

Table 1: Experimental evaluations of the three types of collaboration scenarios S1–S3.

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