Peer-to-Peer Human-Robot Teaming through Reconfigurable Schemas

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Abstract

This position paper presents our ongoing work of developing mechanisms to facilitate human-robot teaming with a focus on peer-to-peer interaction. We have developed an approach that autonomously configures solutions for multi-robot teams based on the team capabilities and the task objective. With the success of this approach in simulation and on physical robots, we plan to extend it to address several challenging issues in human-robot teaming.

Introduction

The traditional ways of human-robot interaction through teleoperation, or supervisor-subordinate interaction have been extensively explored in the supervisory control literature. However, much work remains to be done to explicitly address the issue of human-robot teaming when humans and robots interact as true team members instead of humans treating robots only as tools. The motivation of peer-to-peer interaction rather than supervisory interaction has been presented in (Marble *et al.* 2004). On the one hand, teleoperation has the benefit of reduced danger to humans, better quality of data, etc. Such systems still have limitations such as lapses in communication, situation awareness and ability to handle failures. On the other hand, purely autonomous robot systems face problems that are extremely difficult to handle without humans' assistance. Thus, there is a great potential for humans and robots to work together as a team and for each team member to contribute to the task objective based on their capabilities. Although our approach focuses on peer-to-peer interaction, we notice that not every cooperation will be peer-to-peer, thus teleoperation will also be included when necessary.

The research on human-robot interaction issues touches many different areas, such as the various interaction modalities, cognitive models, and evaluation methods. In (Fong *et al.* 2005), the authors present a "Peer-to-Peer Human-Robot Interaction" (P2P-HRI) project, where humans and robots work as partners across a range of configurations to accomplish various space related tasks. To achieve the goal, three major components are introduced: HRI/OS, which is based on a collaborative control model (Fong 2001) that uses a dialogue system to facilitate the interaction; computational cognitive architectures that model humans to enhance the understanding between humans and robots; and a series of evaluation methods. This project is currently the most comprehensive work that deals with most of the issues in human-robot teaming. The objective of our work is to explore an alternative way of interaction based on the information that team members need to exchange to accomplish the task collaboratively.

With the premise that humans and robots interact as peers, our work is focused on the challenge of finding the optimal organization of robots to help humans in accomplishing a task that may require collective work of multiple team members. Since robots vary in their capabilities, some team members may not have the required capabilities to accomplish a task independently. Thus, it is important for the robots to work together in a tightly-coupled coalition and share information with each other as needed to accomplish a task. Humans and robots also have different capabilities, thus they can also form a coalition and share information with each other in order to accomplish a task. The ultimate goal is to develop mechanisms for building robot coalitions or human-robot coalitions autonomously as needed for the team to accomplish the task as a whole.

Many multi-robot team architectures have been developed that provide suitable assignments of tasks to robot team members (Parker 1998; Werger & Mataric 2000; Gerkey & Mataric 2002; Zlot & Stentz 2003). However, these architectures typically assume the task solutions are provided in advance and are independent of the particular team composition. We have developed an approach that enables multi-robot teams to accomplish a multi-robot task through automated task solution synthesis. Our work goes beyond the mapping of capabilities to tasks by abstracting the problem at the *schema* level, rather than the task/sensor level, and by allowing the team to autonomously configure solution strategies with schemas and sensors distributed across team members to accomplish a task. Although these robot systems work well in many situations, there are still limitations to pure autonomous robotic systems. For example, performance degrades with unexpected robot failure, or unforeseen environmental changes. Thus, human intelligence can be incorporated with such a system to increase the team's overall reliability.

The rest of paper first introduces the main idea of the task solution synthesis approach for multi-robot teams. Then it lists some challenging issues in human-robot teaming and discusses our approach to address them.

Current Work on Multi-Robot Teaming

In order to understand our human-robot teaming approach, we first introduce a multi-robot teaming approach called ASyMTRe [1] (Tang & Parker 2005a; 2005b). The ASyMTRe approach is developed for addressing the formation of heterogeneous robot coalitions that solve a single multi-robot task. More generally, this approach deals with the issue of how to organize robots into subgroups to accomplish tasks collectively based upon their individual capabilities.

The fundamental idea of ASyMTRe is to change the abstraction that is used to represent robot competences from the typical "task" abstraction to a biologically-inspired "schema" (Arkin 1987; Lyons & Arbib 1989) abstraction and providing a mechanism for the automatic reconfiguration of these schemas to address the multi-robot task at hand. To achieve this, we view robot capabilities as a set of environmental sensors that are available for the robot to use, and a set of perceptual schemas, motor schemas, and communication schemas that are pre-programmed into the robot at design time.

The ASyMTRe approach extends the prior work on schema theory by autonomously connecting schemas at run time instead of using pre-defined connections. According to information invariants theory (Donald 1995), the information needed to activate a certain schema or to accomplish a task remains the same regardless of the way that the robot may obtain or generate it. We can label inputs and outputs of all schemas with a set of information types, for example, laser range data, global position, etc. Two schemas can be connected if their input and output information labels match. Thus, schemas can be connected within or across robots based upon the flow of information required to accomplish a task. With the run time connection capabilities, task solutions can be configured in many ways to solve the same task or reconfigured to solve a new task. Additionally, more capable robots can share information to assist less-capable robots in accomplishing a task.

We have implemented the ASyMTRe approach using a distributed negotiation protocol (Tang & Parker 2005b) inspired by Contract Net Protocol (Smith 1980). We validated this approach through simulation and physical experiments and analyzed its performance in its robustness, scalability, and solution quality. With the experimental results, we concluded that ASyMTRe approach provides mechanisms for multiple robots to (1) synthesize task solutions using different combinations of robot sensors and effectors, (2) share information across distributed robots and form coalitions as needed to assist each other in accomplishing the task, and (3) reconfigure new task solutions to accommodate changes in team composition and task specification.

[1] ASyMTRe stands for Automated Synthesis of Multi-robot Task solutions through software Reconfiguration, pronounced "Asymmetry" (resembling the heterogeneity of the team).

The above results are also what we would like to generate for a human-robot team. However, humans are obviously different from robots, especially for humans and robots to work as peers. In the following section, we discuss the challenging issues in human-robot teaming and how we hope to extend the ASyMTRe approach to facilitate human-robot teaming.

Challenging Issues in Human-Robot Teaming

The problem we are addressing is: given a task that requires multiple team members working together, and given a human-robot team, how can the robots cooperate with each other to help the humans in accomplishing the task. Since team members may have different capabilities, it is essential to determine how each team member could contribute to the achievement of the overall task objective.

Usually, humans would design a special plan for a particular team to accomplish a certain task; however, the task solutions are highly dependent on the available team composition. Let us first look at this motivating example on human-robot teams. Suppose a human wants some robots to help him/her move furniture from location *A* to location *B*. The types of solutions to accomplish this task are highly dependent upon the team composition. If the robots can localize in the environment and perceive the relative position of the furniture, a straightforward approach would be to select the number of robots as required to move the furniture. However, if some robots do not have the required capabilities, an alternative approach would be for the more capable team members (robots or humans) to guide the less capable robots to fulfill the goal by providing them with the necessary information, for example, the relative position of the furniture, or perhaps, direct commands, such as "turn left", "push harder", etc. In other team compositions, alternative approaches could be imagined. The important point here is that the resulting team behaviors for accomplishing the task could be dramatically different depending upon the combination of capabilities of humans and robots. Thus, instead of redesigning the plan manually, we propose an approach that automatically synthesizes task solutions based on the current team composition. With the success of applying ASyMTRe to multi-robot systems, we plan to extend the ASyMTRe approach to ASyMTRe-HRI for human-robot applications and address the following issues.

How to represent human/robot capabilities?

We know that different team capabilities may result in different solution strategies. Thus, we need to precisely define team member capabilities. In ASyMTRe, a robot's capabilities are defined by its sensor and effector capabilities and the corresponding computational capabilities (schemas). However, as has been studied by many researchers (Fong *et al.* 2005; Sofge, Perzanowski, & et al. 2004), we also believe that to enable humans and robots to interact naturally as peers, it is necessary to model robot capabilities the same way that we would model human capabilities. The similar representation of human/robot capabilities will enhance the awareness between both parties and thus facilitate the interaction.

There are several cognitive architectures that are widely used to model human behaviors and cognitive processes, such as ACT-R (Anderson & Lebiere 1988), and the cognitive model used in (Howard 2005). In these existing models, human capabilities are represented by three branches: cognition, visual attention/perception, and motor capabilities. We also plan to explore the benefits of the above different architectures, and build a proper model to represent human capabilities. Note that the last two branches of the above architectures are very similar to the perceptual and motor schemas that are used to represent robot capabilities in our approach. It suggests that we can extend the original schema theory that has been widely used for programming robots to include cognitive representation, and thus to model robot capabilities. In addition to the general cognitive models, some researchers have also studied reasoning models for collaborative tasks in space, such as Polyscheme for perspective taking (Sofge, Perzanowski, & et al. 2004; Trafton, Cassimatis, & et al. 2005). We would like to find out the importance of perspective taking in our applications, and incorporate it into our work to improve the interaction.

How do humans and robots work as peers?

Humans and robots have different specialties, for example, humans are good at high level control and planning, while robots are precise at sensing and calculation. Thus human intelligence could be combined with robot intelligence to effectively accomplish a task. Humans and robots should not only interact at a high level, but also at a low level. We would like to implement ASyMTRe-HRI, such that humans can assign tasks to robots, and robots can negotiate with each other on how to form coalitions to accomplish the task based on their individual capabilities. If no coalitions can be formed to accomplish the task, humans will assist them by joining in the coalitions with the robots. In the same way, robots can also help humans by providing them the necessary information. For example, a robot good at global positioning can assist the human operator to arrive at a designated location, and then let the human to do the rest of the work. Humans and robots are working as peers in the sense that humans do not always command robots to perform tasks, giving specific instructions on how to accomplish the task. Instead, both humans and robots may vary their level of interactions considering the current situation.

Research in this direction is sometimes called sliding autonomy (Desai & Yanco 2005), or mixed initiative teaming (Marble *et al.* 2004). In some cases, the system is composed of discrete autonomy levels, varying from pure teleoperation to full autonomy of robots. In other cases, the system is composed of a sliding autonomy levels which can be decided by varying a set of parameters. Much work still remains to be done to determine the right level of autonomy for the system based on the team capabilities and the task objective.

What and how do humans and robots communicate?

Humans and robots exchange data depending on different levels of interaction between them. Data communication is bi-directional. At a high level, humans assign tasks to robots with task specification such as defining the goal position for the robots to achieve. Robots inform humans of their current task-execution status, for example, informing humans that they have accomplished the current task and are waiting for new assignments. At a low level, humans may teleoperate robots through direct commands, or exchange sensing or computational information with robots as needed. Additionally, robots inform humans of their possible failures so that humans can assist them in accessing or recovering from the failures. Note that in ASyMTRe, coalitions are formed according to the flow of information required to accomplish a task. We would also like to design ASyMTRe-HRI, such that humans and robots can efficiently communicate information with each other and form coalitions when necessary. For example, a human can help a robot find its way home by teleoperating it with direct commands or giving the relative goal position to the robot. However, humans and robots may have different ways of representing and interpreting the information. For example, humans tend to give abstract information, such as “the goal is to your right” instead of “the goal is at (x, y)”, which is more difficult for robots. Perspective taking also plays an important role here to enhance the communication between humans and robots.

In addition to the different interaction levels, the information exchanged between humans and robots also depends on the various interfaces with which they communicate, such as dialogue, vision, behaviors, traditional GUIs, etc. Dialogue seems to be popular and realistic in spatial applications (Fong *et al.* 2005). In our future work, we will explore these different interfaces to identify proper interfaces for different types of applications or a proper combination of interfaces to satisfy these needs.

How to evaluate team performance?

The main reason for performance evaluation is for the system to efficiently utilize the available team capabilities to satisfy the task objective. The task objective may emphasize different aspects, for example, to increase the accuracy of the result, to reduce the cost of robots or the workload of humans, to increase the success rate of the team, etc. With multiple solutions available, how these various aspects can be combined to generate an overall evaluation remains a difficult problem. In ASyMTRe, we assign a sensing cost and success rate to each schema and calculate the overall utility based on the concept of an optimization function for task allocation (Gerkey & Mataric 2004). In ASyMTRe-HRI, we plan to include more aspects in the function, and associate them with both the robot schemas and human models. We will also study the work of (Rodriguez & Weisbin 2003; Scholtz 2003) to improve our utility function.

How to adapt to changes?

Humans and robots work in a dynamic environment, thus they should have strategies for dealing with the dynamics. Team members may play different roles throughout a task to accommodate to the changes. For example, a robot can track a person and follow him/her to a goal position, but during the execution, if its sensor for tracking malfunctions, then the person would need to switch his/her role to guide this robot to the goal. This robustness can be achieved through reconfiguring schemas on robots and informing humans of the robots' new need. We would also like to incorporate the current ASyMTRe approach with learning strategies for human-robot teaming.

How does ASyMTRe fit into the picture?

ASyMTRe can be used to autonomously configure solutions for multi-robot teams by connecting schemas within or across robots based on the flow of information required to activate a certain schema, and thus to accomplish a certain task. The consequence is that coalitions are formed on the fly according to the task objective and the current team capabilities. We would also like to have the same result for human-robot teams, where each team member contributes to the task based on their individual capabilities. ASyMTRe is a promising foundation for human-robot teaming in that it provides a low-level interaction "recipe" (Zlot & Stentz 2003) that is used to autonomously generate a decomposition of multi-robot tasks. Our future work includes extending ASyMTRe for complex task scenarios and integrating it with other modules that facilitate human-robot interaction. For example, ASyMTRe is designed to solve a single task that requires the collective work of multiple robots. For more complex tasks or multiple tasks, ASyMTRe can be used as the lower level task solution generator. Other researchers have designed higher-level task planners or task allocation mechanisms, which can be combined with ASyMTRe to solve the complete problem.

Summary

This paper presents the ongoing work of extending the mechanisms of an existing multi-robot teaming approach to address several challenges in the human-robot teaming problem. Our goal is to enable humans and robot to work together as peers in accomplishing a task.

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