Cyber-Physical Testbed for Human-Robot Collaborative Task Planning and Execution

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Abstract—In this paper, we present a cyber-physical testbed created to enable a human-robot team to perform a shared task in a shared workspace. The testbed is suitable for the implementation of a tabletop manipulation task, a common human-robot collaboration scenario. The testbed integrates elements that exist in the physical and virtual world. In this work, we report the insights we gathered through our exploration in understanding and implementing task planning and execution for human-robot teams.

Index Terms—collaborative robots, digital-twin, simulation, task planning, task execution

I. INTRODUCTION

Robots that are able to collaborate with humans represent a clear added value to the industry, as they promise to be a solution for performing tasks that are hard to fully automate or for industries that undergo frequent changes in their production line, where re-configurability and adaptability are of great importance [1]. By teaming with a human, the collaboration benefits from the decision making capabilities of the human in selecting the appropriate actions to be executed for a given task, consequently increase the overall flexibility and adaptability of the human-robot team. However counting on the human decision making skills for both the human and the robot by having the human plan for his/her own actions and the robots actions does not make the robot an efficient collaborator but a recipient of human commands. This type of interaction becomes a turn taking based which has many disadvantages towards the performance of the overall team, one apparent disadvantage is the decrease in productivity of the team.

Although collaborative robots have become safe and reliable enough to operate close to human workers, human robot teaming still lacks many aspects that makes the collaboration successful specially when compared to a human-human team when executing a shared task. Typically, when a team of two humans works together, they display a high level of action selection and coordination, and on the fly work distribution and scheduling. One aim of the HRC research community is to reach this level of coordination referred to as fluency in human-robot teams [2]. In such a team the workload is balanced between the two partners as each has the capability to plan for their own actions, coordinate their action execution with one another when they share a common goal to achieve.

Previous research in HRC believe that the transition from robots as recipients of human instructions to robots as capable collaborators hinges around their ability to select their own action and coordinate its execution with a human partner [3]. A certain amount of autonomy from the robots side is extremely beneficial in terms of efficiency of the collaboration. The HRC scenario this paper is interested in is where the human and the robot share a common workspace and the robot is expected to achieve multiple object manipulations by taking into account, at every stage, the intentions "actions" of the human partner. The robot must be able to move and act in a safe and efficient way.

The human is far superior to the robot counterpart in terms of both perception and manipulation skills. This asymmetry of skills and available information between the two partners limits the study of aspects of HRC. It is important to compensate for the unbalance of capabilities as a first step towards studying and improving any aspect in HRC scenarios. As a first step towards this goal we need to have a setup that supports studying and implementing the strategies we envision for improving task planning and execution for human-robot team. The proposed testbed is shown in [1].

The contributions of our research are: 1) Outline the main elements of an HRC testbed that enables a human and a robot to perform a shared task efficiently; 2) recommendations for design of such testbeds; 3) reporting our insights with a case study.

The remainder of the paper is organized as follows: Section

Figure 1. The physical and its virtual representation of the HRC for moving the blocks from one side of the table to the other with maintaining the same arrangement.
II provides relevant background information for this research. Section III describes the proposed approach for creating a cyber-physical testbed for human robot collaboration. Implementation of the testbed is explained in IV and a case study is presented in Section V. Conclusions are future work in Section VI.

II. BACKGROUND AND RELATED WORKS

This section provides background information and literature review of related research in task planning and execution for a human-robot team. It summarizes some of the existing practices for human-robot collaboration setups in research and industry. A brief discussion of similar and related research of HRC platforms is also presented.

A. Task Planning for Human Robot Collaboration

Task planning is a key ability for intelligent robotic systems, increasing their autonomy and flexibility through the construction of sequences of actions to achieve a final goal. However when working in a team, planning for the sequence of action with out taking into consideration the actions of the other partner is not enough specially when collaborating in achieving a common task. Therefore, adaption and flexibility of planning is crucial in such scenarios. This has been investigated extensively in previous work. Our testbed is inspired by this work [4], that offers a comprehensive system that identify and integrates individual and collaborative cognitive skills a robot should have to share space and tasks with a human. The scenario we are interested in is similar to the one investigated by [5], where a robot and a human manipulate an overlapping set of objects, without using the same object simultaneously. A key element in task planning and execution is the robot ability to anticipate the human’s actions. Similar to other work in the literature [6] [7], we track and anticipating human actions through the human arm motion to enable execution of plans.

B. HRC Testbed requirements

Several work in the literature emphasize on the need for a testbed that enables implementing and studying different aspects of human-robot collaboration [8] [9]. There are common practices within the HRC research community that are followed in creating setups for HRC scenarios. Such as having human awareness and robot intelligence elements. All the HRC referenced work in this paper contain these elements. Testing and implementing robot behaviors in simulated environment is also common, since it provide a testing method of controlled environment that help in studying and exploring one aspect of HRC in isolation [10]. What we don’t see extensively used in the HRC setups is a complete virtual model of an entire HRC scenario of the physical world. This concept is refereed to as the digital twin in industry. A digital twin is a comprehensive physical and functional description of a component, product or system virtually. It has been used for surveillance, evaluation, planning and manipulation of the production environment [11]. The work in [12], is an example where a digital twin is utilized in human-robot context. We believe combining physical and virtual information can lead to a new approach on how to implement HRC scenarios. In the approach section we will explain the added value of the virtual replica of the physical world as an element of a HRC testbed.

III. CYBER-PHYSICAL HRC TESTBED

This section presents our approach for a testbed that support human robot collaborative task planning and execution. It outlines the main elements that make efficient testbed for that purpose.

A. Perception

For the robot to be a better collaborator, it should be aware of the human partner and his/her actions and the progress of the shared task. Using sensors the robot will have a perception of these two components and through perception the knowledge will be defined in the next section.

1) Perception of the human arm trajectory: Human arm movement tracking is crucial for our HRC scenario. This information will be utilized by other parts of the testbed to calculate and define the following: (a) Human-work-pieces distances to find human goal (b) Human current arm position for safety purposes.

2) Perception of the work-pieces: For table top manipulation task, it is important to have the state of the work-pieces with respect to all other elements in the workspace at all times. The robot uses this information to efficiently locate the work-pieces to manipulate them , and define the task progress to select its action.

B. Forming Knowledge through Digital Twin

In general the fundamental elements that characterize an HRC scenario includes the following: the agents, the work environment and the work-pieces. Every element in the physical world that affects the HRC scenario has a counterpart in the virtual environment that mirrors its state in the physical world.
As seen in figure 2, the input to the virtual world is the data of the perception component, and the output of the virtual world is the integrated knowledge of the human arm, the robot and the work-pieces positions and relative distances. We believe this explicit integration of all components in a virtual platform is useful for HRC due to the following reasons:

1) Robot Reasoning for Task Planning:
   This is the main part that motivated us to build the cyber-physical testbed to support our implementation and exploration of task planning for human robot team. Taking into the consideration the knowledge gathered by the previously mentioned element, the robot is able to decide which work-piece it should manipulate and select an action to preform on the fly accordingly. This selection process will be in favor of minimizing the disruptive of the human action who is sharing the workspace and work-pieces to be manipulated. To do so the robot should have the ability to reason about which work-piece the human is going to choose to manipulate, refer to as the human goal. Then the robot should eliminate the human goal from the set of work-pieces it can manipulate, and choose the closest work-piece relative to its current end effector position. Recognizing the human goal is a key in the the robot goal selection process. In our HRC scenario it is based on the distance between the human hand position against the work-pieces on the workspace. A probabilistic approach can be used to assign probabilities on the work-pieces that needs to be manipulated, that can be utilized by the robot in its goal selection process. The robot should also reason about the safety of the human partner at all times. In our current work the robot selects to be idle when the human-robot minimum distance is below certain threshold.

2) Robot Task Execution:
   After goal selection, the robot starts autonomously executing a sequence of actions needed to place the work-piece in the location defined by the task’s end goal. During execution, the robot should still be aware of the human partner actions and location within the workspace to adapt to changes that requires the robot to change its action on the fly. To execute this behavior we utilized formalism that combine Concurrency with Hierarchical State Machines that exited since the beginning of robotics, to account for situations where interrupting the normal behavior is necessary to respond to something more important.

IV. IMPLEMENTATION

We implemented our system on a Sawyer Rethink Robotics research robot, using the Robot Operating System - ROS [13]. Suited for our HRC scenario, the robot is able to preform basic actions like pick and place of a work-piece. We have utilized Moveit - a ROS package for the robot motion planning. The perception of the work-pieces is based on ARUCO detection library, an open source library able to generate and detect fiducial markers. Each work-piece in the workspace is equipped with an unique ID associated with a specific marker. In order to cover the entire workspace with minimum occlusion of the work-pieces, we mounted a Kinect on top of the workspace as shown in figure 1. The human arm is tracked using OptiTrack 3D tracking system. OptiTrack tracks the human hand using cameras with low-latency and high precision [14]. This system requires the human partner to have an on body markers, therefore the human partner will ware a wrist band shown in Figure 1 on the hand he/she prefers to use during preforming the task. We choose the Virtual Robot Experimentation Platform (V-REP) to create our virtual HRC scenario [13].

Our testbed utilized a Python library called SMACH. SMACH provides structures based on hierarchical concurrent state machines. Figure 3 shows the plan execution levels. The pick and place execution of a work piece starts when
the BLOCK-CHOICE state receives a respond from the node responsible for the robot goal decision.

Figure 3. The plan execution that combines concurrency with hierarchical state machines for Pick and Place Tasks.

V. CASE STUDY

A testbed that enable us to study and implement task planning and execution for a human-robot team is crucial. We are particularly interested in understating action selection and coordination on the fly for such a team that share the workspace the work-pieces that needs to be manipulated.

A. Experiment Design

There are nine work-pieces that the human and the robot need to arrange in specific order based on an end goal. For this case study the participant is given a model pattern of work pieces to copy by moving similar blocks from reserve area to a new location within the workspace. This HRC scenario does not put any restrictions on the participant on which work-pieces he/she can manipulate, or create exclusive workspace zones for any of team members. This will help in creating more similar human-human team kind of interaction that we hypothesize is more efficient.

B. results

The following Figure 4 shows snippets of the collaboration using the cyber-physical testbed at different instances. The first row represent the start state and the last represent the final goal. Instances of a human picking and placing a block and concurrently the robot doing the same is portrayed in Figure 4 from the Perception i.e. overhead camera perspective, its digital twin representation and the physical world state.

C. Metrics - Evaluation of Human-Robot Collaboration

The significance of the evaluation and validation criteria are explained in detail as follows:

- **Robot Idle Time**: Robot is idle because it is unable to move, cause of predefined rules to prevent human robot collision. This reduces the productivity of the task.
- **Number of Collisions**: Between human and robot. \(\text{Collision is defined here as the event where the robot velocity is not zero when the minimum distance between human and robot is zero.}\) More number of collisions would result in less trust and comfort for human.
- **Functional Delay**: The time between the end of the humans action and the onset of the robots action.
- **Concurrent activity**: Percentage of time out of the total task time, during which both agents have been active at the same time.
- **Number of actions preformed by each agent**
- **Productivity**: Time taken to complete task, i.e. time taken to place the 9 blocks in the target location.

Similar criteria have been used to evaluate human-robot collaboration systems in state of the art works like [16] [2].

VI. CONCLUSION

In this paper, a cyber-physical testbed was created to enable human-robot teams to preform a shared task in the collaborative workspace. A digital twin of the testbed was implemented and used during a human-collaborative task of moving blocks placed in a human robot shared workspace. This setup was successfully used with a finite state machine implementation to test robot task planning and execution based on the states reported using the digital twin. Thus validating the importance of using a virtual world representation of all actors : human, robots and objects during a human robot collaborative task and its importance in task execution and planning.

Our ongoing work is performing human-subject experiments and evaluating them based on the proposed metrics. We wish to gather more insights through our explorations of understanding
Figure 4. The sequence of actions associated to the experiment of performing the collaborative task. The first column of the frames represent the Perception view form the camera of the shared workspace. The second column shows the virtual world representation i.e. digital twin of human, robot and objects, as shown in the physical world (Last Column). The last row shows the completion of the human-robot task.

and implementing task planning and execution for human-robot team.

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