Human-Robot Handovers with Signal Temporal Logic Specifications

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***Abstract*— We present a formal methods based approach to human-robot handovers. Specifically, we use the automatic synthesis of a robot controller from specifications in Signal Temporal Logic (STL). This allows users to specify and dynamically change the robot's behaviors using high-level abstractions of goals and constraints rather than by tuning controller parameters. Also, in contrast to existing controllers, this controller can provide guarantees on the timing of each of the handover phases. We replicate the behavior of existing handover strategies from the literature to illustrate the proposed approach. We are currently implementing this approach on a collaborative robot arm and we will evaluate it's usability through human-participant experiments.**

I. INTRODUCTION

Object handovers are a central aspect of human-robot collaboration in both industrial and domestic environments. Examples include collaborative assembly, surgical assistance, housekeeping and rehabilitation assistance. These tasks require a robot to take objects from a human or give objects to them. The importance of this fundamental action enabling physical human-robot collaboration has resulted in a large body of work on robot controllers for handovers.

Most of the prior work on human-robot handovers has focused on offline controllers [1]–[9] in which the robot's motion is planned before the start of a handover. These approaches do not take into account the observed behavior of the human during a handover, and thus, lack adaptabilitly to the human's behavior. Some have proposed online controllers for human-robot handovers that take into account the observed human motion [10]–[13]. Though these approaches enable the robot to adapt to the human's motion, they require tuning non-intuitive controller parameters (e.g., the weights of DMP terms [11] or the velocity-tracking gain [12]) to achieve a specific robot behavior. Also, none of these provide timing guarantees on different stages of a handover. Such timing guarantees may be crucial in productivity oriented industrial tasks and fast-paced life-critical scenarios like surgery. Finally, although several human-inspired strategies have been proposed in the literature for human-robot handovers, there is no unified framework to easily switch between those strategies. Our proposed approach, shown in Fig. 1, tries to address these limitations.

A human-robot object handover consists of three phases: "reach" phase in which both agents move to the handover location, "transfer" phase in which the object is transferred from the giver to the receiver, and "retreat" phase in which both agents move away from each other. We use Signal Temporal Logic (STL) [14] to specify the robot's behaviour in a handover in terms of timing constraints on these phases. STL is a suitable formalism for modeling Human-Robot handovers since it can specify real-time and real-valued constraints.

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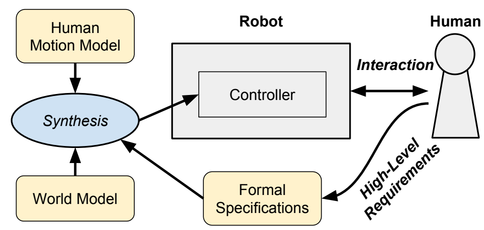

Fig. 1: Our approach to human-robot handovers uses the automatic synthesis of a robot controller from formal specifications written in Signal Temporal Logic. Users can change the robot's behavior with high-level requirements. The controller is then synthesized online based on given human-motion and world models.

Almost all the prior work on handovers discusses a single robot behavior. Although it is conceivable to write a program with different robot behaviors and allow the user to switch between them, the approach in this paper proposes a more unified view of this central aspect of HRI. It also allows end-users to specify the handover in terms meaningful to them.

II. FORMULATION OF HANDOVERS IN SIGNAL TEMPORAL LOGIC (STL)

Several formalisms have been proposed in the literature for the automatic synthesis of robot control [15]. We use Signal Temporal Logic (STL) [14] to formulate human-robot handovers, as it allows specification of the robot's behavior in terms of distances, timings and object states.

A. System Representation

We model the robot's end-effector's motion as a linear system with the state consisting of robot end-effector's 3D position $\mathbf{p_r}$ and orientation $\mathbf{q_r}$ (jointly called "pose") along with the gripper's state $g_h \in [0,1]$ (0 for fully closed and 1 for fully open). We choose velocity as the control input u as it enables control over the timing of the pose trajectory. Also, velocity control is the most suitable choice for reactive trajectory modification and online motion planning [16]. u is constrained by $u_{min} \leq u_i \leq u_{max}$, indicating the safety cap on the robot's speed.

We represent the state of the environment in terms of the pose of the human's hand $[\mathbf{p_h}, \mathbf{q_h}]$ and that of the object $[\mathbf{p_o}, \mathbf{q_o}]$. To simplify the specification formulae, we create sets of robot, human and object states and represent them using the discrete variable $o \in \{o_r, o_h, o_s, o_g\}$, corresponding

TABLE I: STL Specifications for Human-Robot Handovers

Robot's Role	Phase	Specification
Receiver	Reach	$\square(e \Rightarrow \lozenge_{[0,t_1]}(\|\|\mathbf{p_l}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_l}-\mathbf{q_r}\|\| < \varepsilon_q))$
	Transfer	$\square((\|\|\mathbf{p_o}-\mathbf{p_r}\|\| < \varepsilon_p \wedge (o == o_h \vee o == o_s)) \Rightarrow \lozenge_{[0,t_2]}(\|\|g_r - g_*\|\| < \varepsilon_g))$
	Retreat	$\square((o == o_r) \Rightarrow \lozenge_{[0,t_3]}(\|\|\mathbf{p_r}-\mathbf{p_d}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_r}-\mathbf{q_d}\|\| < \varepsilon_q))$
		$\square((\|\|\mathbf{p_r}-\mathbf{p_d}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_r}-\mathbf{q_d}\|\| < \varepsilon_q \wedge o == o_r) \Rightarrow \lozenge_{[0,t_4]}(\|\|g_r - 1\|\| < \varepsilon_g))$
Giver	Pick-up	$\square((o == o_g) \Rightarrow \lozenge_{[0,t_5]}(\|\|\mathbf{p_o}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_o}-\mathbf{q_r}\|\| < \varepsilon_q))$
		$\square((\|\|\mathbf{p_o}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_o}-\mathbf{q_r}\|\| < \varepsilon_q \wedge o == o_g) \Rightarrow \lozenge_{[0,t_6]}(\|\|g_r - g_*\|\| < \varepsilon_g))$
	Reach	$\square(e \Rightarrow \lozenge_{[0,t_7]}(\|\|\mathbf{p_l}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_l}-\mathbf{q_r}\|\| < \varepsilon_q))$
	Transfer	$\square((o == o_s) \Rightarrow \lozenge_{[0,t_8]}(\|\|g_r - 1\|\| < \varepsilon_g))$
	Retreat	$\square((o == o_h) \Rightarrow \lozenge_{[0,t_9]}(\|\|\mathbf{p_r}-\mathbf{p}_\eta\|\| < \varepsilon_p \wedge \|\|\mathbf{q_r}-\mathbf{q}_\eta\|\| < \varepsilon_q))$

TABLE II: STL Specifications for Reach-Phase Strategies

Robot's Role	Strategy	Target	Specification
Receiver	Proactive	Predetermined	$\square(\neg(o == o_r) \Rightarrow \lozenge_{[0,t_1]}(\|\|\mathbf{p}_*-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q}_*-\mathbf{q_r}\|\| < \varepsilon_q))$
		Towards Human	$\square(\neg(o == o_r) \Rightarrow \lozenge_{[0,t_1]}(\|\|\mathbf{p_h}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_h}-\mathbf{q_r}-\mathbf{q}_\delta\|\| < \varepsilon_q))$
	Reactive	Predetermined	$\square((\neg(o == o_r) \wedge \|\|\mathbf{p_h}\|\| \leq l_h) \Rightarrow \lozenge_{[0,t_1]}(\|\|\mathbf{p}_*-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q}_*-\mathbf{q_r}\|\| < \varepsilon_q))$
		Towards Human	$\square((\neg(o == o_r) \wedge \|\|\mathbf{p_h}\|\| \leq l_h) \Rightarrow \lozenge_{[0,t_1]}(\|\|\mathbf{p_h}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_h}-\mathbf{q_r}-\mathbf{q}_\delta\|\| < \varepsilon_q))$
Giver	Proactive	Predetermined	$\square((o == o_r) \Rightarrow \lozenge_{[0,t_7]}(\|\|\mathbf{p}_*-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q}_*-\mathbf{q_r}\|\| < \varepsilon_q))$
		Towards Human	$\square((o == o_r) \Rightarrow \lozenge_{[0,t_7]}(\|\|\mathbf{p_h}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_h}-\mathbf{q_r}-\mathbf{q}_\delta\|\| < \varepsilon_q))$
	Reactive	Predetermined	$\square((o == o_r \wedge \|\|\mathbf{p_h}\|\| \leq l_h) \Rightarrow \lozenge_{[0,t_7]}(\|\|\mathbf{p}_*-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q}*-\mathbf{q_r}\|\| < \varepsilon_q))$
		Towards Human	$\square((o == o_r \wedge \|\|\mathbf{p_h}\|\| \leq l_h) \Rightarrow \lozenge_{[0,t_7]}(\|\|\mathbf{p_h}-\mathbf{p_r}\|\| < \varepsilon_p \wedge \|\|\mathbf{q_h}-\mathbf{q_r}-\mathbf{q}_\delta\|\| < \varepsilon_q))$

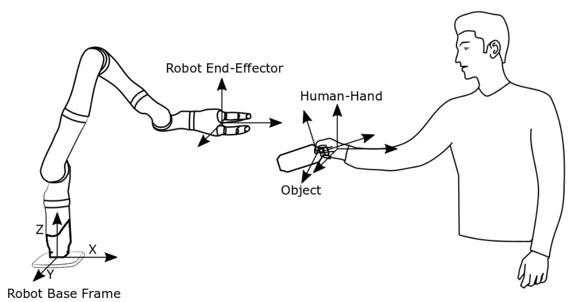

Fig. 2: Human-Robot object handover reference frames. All poses are expressed in the frame attached to the base of the robot.

to "object with the robot", "object with the human", "object shared by both" and "object on ground" respectively.

Assumptions: We represent all the poses in the frame attached to the base of the robot, as shown in Fig. 2. We assume that the human-hand always remains in the dextrous work-space of the robot. We consider that the human is ready for the handover if the human-hand is within a region of radius l_h centered at the robot's base, which we call the *handover zone*. For human-to-robot handovers, we assume that the human-hand contains the object at the start of the handover, and also assume that the object's drop-off (or target) location is in the dextrous work-space of the robot. For robot-to-human handovers, we assume that the object is initially in the dextrous workspace of the robot. For simplicity, we consider that there is only one object in the workspace, but the formulation can be easily extended to multiple objects.

B. *Specifications for Human-to-Robot Handovers*

In Human-to-Robot handovers, the robot receives the object from the human. From a receiver's perspective, a handover consists of three phases: a reach phase, a transfer phase and a retreat phase. When the robot is the receiver, we specify its behavior in terms of timing constraints on these three phases (Table I top).

- Reach: The robot should reach the handover location $[\mathbf{p_l}, \mathbf{q_l}]$ within t_1 seconds after the handover signal e.
- Transfer: The robot should grasp the object within t_2 seconds after it reaches the object's location.
- Retreat: The robot should retreat to the object's drop-off (or destination) location $[\mathbf{p_d}, \mathbf{q_d}]$ within t_3 seconds after it has the object and release the object in t_4 seconds after reaching the object's drop-off location.

C. *Specifications for Robot-to-Human Handovers*

From a giver's perspective, a handover consists of four phases: a pick-up phase, a reach phase, a transfer phase and a retreat phase. When the robot is the giver, we specify its behavior in terms of timing constraints on these four phases (Table I bottom).

- Pick-up: The robot should reach the object's location within t_5 seconds and grasp the object within t_6 seconds after reaching the object's location.
- Reach: The robot should take the object to the handover location $[\mathbf{p_l}, \mathbf{q_l}]$ within t_7 seconds after the handover signal e.
- Transfer: The robot should release the object within t_8 seconds after the object is shared by both.
- Retreat: The robot should retreat to a home position $[\mathbf{p}_\eta, \mathbf{q}_\eta]$ (pre-defined) within t_9 seconds after the human has received the object.

D. *Specifications for Different Handover Strategies*

To illustrate the flexibility of our approach, we list specifications for four different handover strategies, three of which are found in the literature. For each of these strategies, the specification in Table II replaces only the reach phase specification in Table I, all other specifications remain the same.

- Proactive, Predetermined: The robot should reach a predefined or offline computed handover location $[\mathbf{p}_*, \mathbf{q}_*]$ without waiting for the human's hand to enter the handover zone. This behavior is similar to the robot's behavior in [3] and the "proactive" strategy presented in [17].
- Proactive, Towards Human: The robot should reach the human's hand without waiting for the human's hand to enter the handover zone.
- Reactive, Predetermined: The robot should reach a predefined or offline computed handover location $[\mathbf{p}_*, \mathbf{q}_*]$, only when the human-hand is in the handover zone. This is similar to the "reactive" strategy presented in [17].
- Reactive, Towards Human: The robot should reach the human's hand, only when the human's hand is in the handover zone. This behavior is similar to the behaviors in [12] and [13].

E. Implementation

For control synthesis, we use the algorithm presented in [18], which converts the STL specifications into mixed integer linear programs (MILP) and solves them iteratively in a receding horizon manner (or "Model Predictive Control (MPC)"). The receding horizon control synthesis from the STL specifications depends on the predicted behavior of the human. At each time-step, we predict the motion of the human by a Linear Dynamical System (LDS) $\dot{\mathbf{p_h}} = \mathbf{A}\mathbf{p_h}$. Similar to the approach used in [13], we use the pose data of the human for a pre-defined time interval before the current time-step and estimate the matrix $\mathbf{A}$ using least squares approximation. Then the predicted motion of the human is given by:

$$\mathbf{p_h}(t_0 + t) = \mathbf{p_h}(t_0) + (t\delta_t)\mathbf{A}\mathbf{p_h}(t_0) \;\forall\; t \in [0, H] \qquad (1)$$

where H is the prediction horizon and δ_t is the sampling time. We update this estimate at each time-step using the position of the human hand and generate the control input for the next time-step. If no feasible control input is found, the robot stops. More details on implementation along with simulation results are available in [19].

III. Ongoing Work

We are implementing the approach presented in this paper on a collaborative robot arm with a motion tracking system to monitor the human and the object. We will conduct human-participant experiments with naïve users to study the quantitative and qualitative outcomes of human-robot handovers with our approach and compare them with other state-of-the-art approaches from the literature. We will use the criteria presented in prior works such as [7] and [3] to compare different controllers for human-robot handovers.

As the human-motion prediction model is an integral part of the controller synthesis, we are developing and testing other online human-motion prediction models. We are exploring different optimization criteria for MPC synthesis from the specifications, for example, minimum jerk or minimum velocity, which will change the robot's trajectory while obeying the timing constraints. Also we plan to develop an intuitive user interface so that users can modify the STL specifications presented in this paper. In the interface, users will be able to change the timing values of handover phases and switch between different strategies. The default values of the timings will be provided based on a public dataset of human-human handovers [20].

IV. Conclusion and Future Directions

We formulated the human-robot handover scenario using STL formulae and provided candidate specifications of eight different robot behaviors for bi-directional human-robot handovers. To the best of our knowledge, this is the first work to use the automated synthesis of robot controllers from formal specifications for human-robot handovers. Most existing research in HRI does not use formal representations and specifications to describe the desired behavior of a collaborative robot. Conversely, existing research on formal methods in robotics does not model physical human-robot collaboration, neither does it have models for collaborative human behavior in the form of high-level specifications. Our ongoing and future research will bridge this gap by providing such models and methods for human-robot handovers and other HRI domains like social navigation and non-verbal behavior.

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