# Reactive Motion Planning for Human-Robot Cooperative Tasks Under Uncertainties

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***Abstract*—Assistive robotics aims to design physically collaborative robots which are able to help human partners with cumbersome tasks; for instance, lifting a heavy plank/guard and inserting it into a frame at the ceiling. To reduce human load-share, it is expected from the robot to perform such tasks in coordination with the human partner. Uncertainty of human behavior and complex dynamics of real-world environments pose challenging problems for robotic systems. It is crucial to employ control frameworks that allow for both motion tracking and interaction/force control. Furthermore, the framework should allow for reactive and adaptive motion planning toward human behavior. To deliver these requirements, we propose a Dynamical System-based control architecture with adaptation capabilities. Our preliminary experimentation using ARMAR-6 shows promising performances to achieve such a complex task in collaboration with human users.**

## I. Introduction

Despite the recent advancements in motion planning from a learning perspective, execution and control of collaborative tasks in interaction with uncertain environments and human partners remains a challenge. In this work, we propose to use Dynamical System-based control framework for execution of such tasks. This framework leverages two key ideas. First, by using an impedance law, it allows for satisfactory control of both motion and interaction forces. Second, by using a state-dependent mapping (from the robot's current position to desired velocity) it allows for reactive and adaptive motion planning which enables the robot to react to changes in human behavior and environment and shaping the desired motions accordingly. Such a unified approach is suitable for seamless execution of task consisting of several phases, where different phases are detected based on the interaction forces and the corresponding robotic behaviors are executed [1]. In such unified approaches, all transitions are smooth as the robot utilizes one controller and only adapts the control parameters smoothly.

The goal of the Secondhands project is to provide robotic assistance for maintenance tasks in industrial settings. One of the possible tasks where the assistance of the robot is required is the "guard task". In this task, technicians are required to remove a guard which is attached beneath the conveyor belts. After maintaining the conveyor belts, they need to lift and insert the guard back. Handling such heavy guards at such uncomfortable heights makes this task hard even for two technicians. The challenge is to provide a robotic system to help the human during all possible phases: reaching for the guard, supporting the weight until the human technician unmounts it, lowering, lifting and inserting it.

In the following, we provide an overview of our control framework and present our preliminary results using ARMAR-6, a collaborative humanoid robot. This robot has been developed by KIT-H2T to perform a wide variety of complex maintenance tasks in industrial settings [2]. In this work, we primarily focus on the collaborative lifting, supporting, and insertion task where the robot plans its motion reactive to human interaction forces using Dynamical System-based impedance control.

## II. Dynamical-system based impedance control

First, let us assume the following dynamics for the gravity compensated arm of ARMAR-6 in the task-space ($x = [p, \theta]^T \in \mathbb{R}^6$) as $M_x(q)\ddot{x} = W_d + W_e$ where $W_d$ and $W_e$ represent the control and external wrenches respectively. We assume the external wrench ($W_e$) is measured using the force-torque sensor mounted on the wrist of the arm. Taking advantage of torque-control arms, the DS-based impedance controller is formulated in the task space as follows:

$$W_d = \begin{bmatrix} F_m + F_i + F_b \\ \tau_o \end{bmatrix} \tag{1}$$

Here, $F_m$ accounts for motion-planning forces, $F_i$ interaction forces with the environment, and $F_b$ bimanual coupling. Finally, $\tau_o$ represents the desired torques for orientation control. Having the desired wrench in the task space (i.e., $W_d = [F_d, \tau_d]^T$), the desired joint torques are computed as follows:

$$\tau = J^T W_d + (I - J J^{\dagger^T})\tau_{null} \tag{2}$$

In our control strategy the null-space torques ($\tau_{null}$) are computed to favor a human-like posture.

**Motion-planning**: $F_m$ is part of the control responsible for motion planning; e.g., reaching for the guard, lowering/lifting to a certain height. This part is generated using a state-dependent dynamical system (introduced in [3]) as follows:

$$F_m = -D(\dot{p} - f(p - p^* - \Delta p^*)) \tag{3}$$

where $p$ and $\dot{p}$ are the position and velocity of the end-effector. $f(.) : \mathbb{R}^3 \mapsto \mathbb{R}^3$ is the state-dependent dynamical system, generating desired velocities for the end-effector based on the current position. $p^*$ is the DS attractor which can be adapted based on the interaction; see [4] for such adaptive behavior. Furthermore, $\Delta p^*$ account for other possible adjustments. In this controller, the damping matrix $D \in \mathbb{R}^{3\times3}$ is positive definite. $f(.)$ can be designed or learned (from human demonstration) to perform specific tasks.

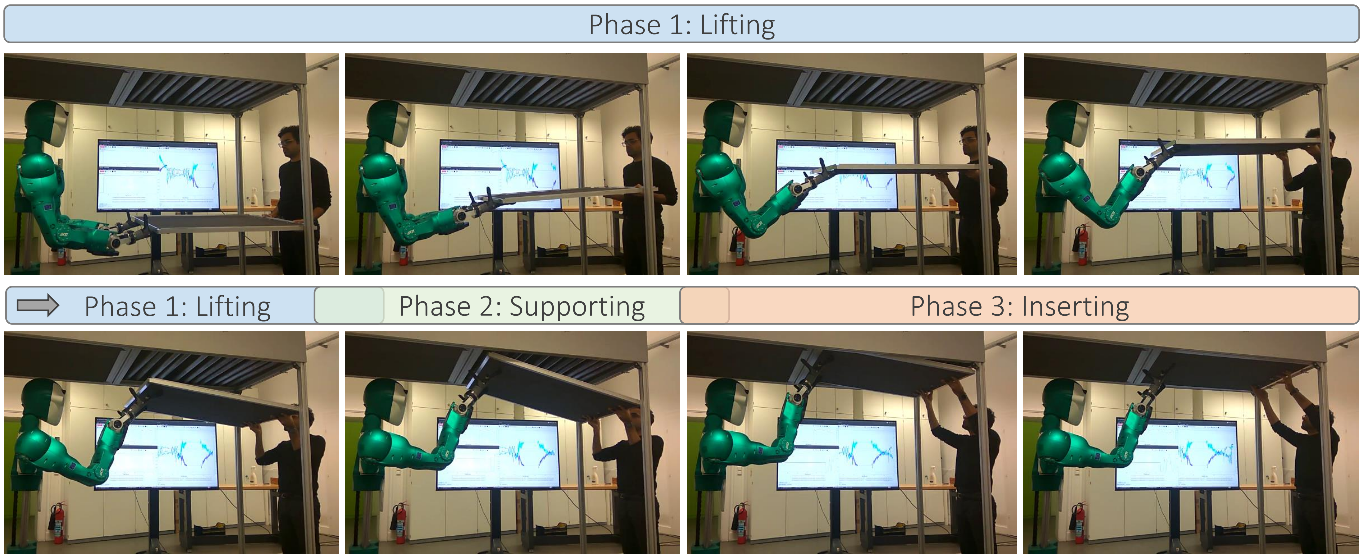


Fig. 1. ARMAR-6 lifting the guard jointly with the human technician. The robot starts performing the task by lifting the guard in a reactive fashion toward human technician inputs. The attractor of the dynamical system is adapted based on the load-share in order to generate reactive upward (or if needed downward) motion. Upon reaching, the expected height of the diverter, the robot supports the guard by maintaining the position of the end-effector. To perform the final insertion, the robot waits for the human correction. The robot recognizes the human sideways corrections by computing higher-frequency components of the lateral measured forces. Detecting high values causes the robot to slightly go down to make it easier for the human to perform the final adjustments. Measuring low values, the robot perform the final upward motion/push in order to complete the insertion jointly with the human technician.

**Orientation control**: In this specific application, we control the orientation by first computing the desired quaternion for a specific height. Knowing the desired quaternion for the heights and lowest position of the hand, we use Slerp interpolation in order to compute the desired quaternion at a given position. The orientation error is then translated into desired torque in the task space and later into desired joint torques.

**Interaction-force control**: As presented in [5], in the DS-impedance controller, $F_i$ accounts for desired interaction forces; e.g., to support or lift the guard. Let us assume $F_f$ to be the desired force to be applied to the guard. This control variable is computed as $F_i = F_f + \Delta F$ where $\Delta F$ is a correction term. This term is adapted using $\dot{\Delta F} = -\epsilon_{\Delta F}(\tilde{F} - F_f)$ to correct the error in the force application (i.e., between the measured forces $\tilde{F}$ and desired contact forces $F_f$)

**Bimanual coupling**: To couple the two arms, we consider a virtual spring connecting the two end-effectors as $F_b = k_c(p_l - p_r)$ where the $k_c$ is the stiffness of the coupling. Moreover, we limit this forces ($F_b$) to avoid generating high accelerations when the arms are farther separated due to human-interactions.

## III. Robotic performance

To lift the guard in coordination with the human technician, we adapt the DS attractor as $\dot{p}_z^* = -\gamma(F_m - F_{lift})$. This constant parameter ($F_{lift}$) is higher than the expected load-share of the robot resulting in an upward motion (since $\dot{p}_z > 0$). The lifting performance of the robot is illustrated in Fig. 1. Reaching the final desired height, the robot naturally supports the weight of the guard. To perform the final upward motion for the insertion, the robot waits for the human to finish his/her final lateral adjustments. In order to detect human adjustments, we measure the higher-frequency components of the measured forces in the $x$-$y$ plane as follows.

$$P(t) = \alpha P(t - \Delta t) + ||F_{x,y}(t) - F_{x,y}(t - \Delta)||^2 \quad (4)$$

where $P(t)$ represents the power of the higher-frequency components in the force measurement, and $\alpha$ is a positive gain smaller than 1 acting as a forgetting factor. Based on this quantification of human correction, the DS attractor is adjusted as follows $\Delta p_z^* = -\beta \Delta p_z^* - \sigma(P(t) - P_{ave})$ where $\beta \in [0, 1]$ is the forgetting factor, $\sigma$ is a scaling factor, and $P_{ave}$ is the expected threshold which is set experimentally. Measuring power higher/lower than expected leads to lower/higher values; i.e., robot moving downward/upward reacting to human corrections as demonstrated in Fig. 1.

Our preliminary results indicate that the Dynamical System-based control framework is efficient in providing both motion and interaction control to accomplish collaborative task even in the face of uncertainties induced by human and environment. By relying on the human supervision (through physical interaction) and Dynamical System-based compliant control, the robot indirectly provides a better condition for motion feasibility of the task; especially during the insertion phase which involves uncertain physical contacts with the environment. In future work, we will focus on mobile manipulation where the robot performs such tasks while maneuvering around obstacles.

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