Adaptive walk-through programming for industrial applications

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I. INTRODUCTION

In the recent years, robots are becoming key elements to achieve manufacturing competitiveness, especially if they are able to collaborate with humans in a shared workspace, creating a co-working partnership. The initial paradigm for robot usage has changed during the years from an idea in which robots work with complete autonomy in a separate cell, to a scenario in which robots and humans can work together and cooperate. In this context, the safety of the human operator during the interaction must be preserved and new methods for robot programming can be exploited to ease the way the trajectory is taught to the robot. In particular, teaching techniques involving manual guidance of the robot maximize the possibilities of re-programming the robot in an intuitive and easy way, because they don’t need the knowledge of the robot programming language. Compliant motion strategies (i.e. admittance/impedance control) can be implemented to supervise the physical human-robot interaction (pHRI) and to allow manual guidance of the robotic manipulator. Thanks to this kind of controllers, the walk-through programming can be exploited: the operator becomes like a teacher that physically guides the end-effector of the robot through the desired positions. During the teaching, the robot controller records the trajectory followed by the human and it will be able to play it back thereafter. In order to create an industrial setup, the tool attached at the robot end-effector has to be considered and its dynamics has to be compensated.

The appropriate selection of the admittance parameters is crucial. First of all, they define the way the robot interacts with the user. Moreover, the choice of the admittance parameters affects the stability of the human-robot system. The causes of instabilities are identified in the contact with a very stiff environment, in the time delay of reaction of the human operator, and in the non-colocation principle. All the identified instability issues produce, as a consequence, a deviation of the robot behavior from the desired one, that is the one imposed through the admittance control. This deviation results in high amplitude and frequency oscillations of the end-effector, that render the interaction with the robot unsafe for the user. In order to restore the stability of the system, such deviations have to be first detected and then canceled (or reduced). The adaptation of the parameters of the admittance control is a common strategy for recovering the stability of the interaction.

The research focuses on a control framework with the following features:

- The process comprises:
  - A learning step, during which the operator moves the tool attached at the robot end-effector and the movements made by the end-effector are stored in the robot controller. The robot is admittance-controlled in order to guarantee a compliant behavior.
  - A reproduction step, which takes places after the learning step and during which the control system operates the robotic arm so that the end-effector substantially repeats the movements stored in the robot controller. The robot is position-controlled.

- During the learning step, where the robot is admittance-controlled, the static and dynamics components of the tool attached at the robot end-effector are detected and canceled in order to compensate the contribution of the payload to the measured forces and torques.

- Whenever high-frequency unsafe oscillations of the end-effector arise, mainly due to a stiffening of the human arm, they are detected and the parameters of the admittance control are adapted to recover the stability of the interaction.

- The whole architecture has been implemented in different setup and will be used in a real industrial setup, including an existing industrial robot that has to perform, e.g., a painting task.

II. ADAPTIVE WALK-THROUGH PROGRAMMING

The overall control framework is shown in Fig. 1. Since the dynamics of the tool mounted on the robot end-effector has to be compensated, a tool compensation algorithm is implemented. It requires the knowledge of the robot linear acceleration \( \ddot{a} \), angular acceleration \( \ddot{\alpha} \) and angular velocity \( \dot{\omega} \). These data can be estimated by using Kalman filters starting from the current pose of the robot end-effector \( x \), as suggested in [1]. Then, the algorithm estimates the contact forces and torques \( F_c \) starting from the raw measurements \( F_{ex} \) of a F/T sensor and \( [\ddot{a}, \ddot{\alpha}, \dot{\omega}] \) estimated by the Kalman filter. The admittance control, with input \( F_c \), provides the reference position \( x_{ref} \) which the position-controlled robot must follow. During the learning step, it could happen that the operator stiffens her/his arm, thus bringing high-frequency oscillations in the interaction with the robot end-effector. An heuristic based on the admittance model and depending on a threshold value \( \varepsilon \) is used to detect the rising oscillations. Whenever oscillations are detected, the parameters of the admittance control are adapted using a
passivity-preserving strategy and the desired stable behavior is restored. Finally, if the industrial controller (low-level position control in Fig. 1) does not allow to directly feed the Cartesian position/orientation setpoints, a kinematic inversion has to be performed in order to convert the outputs of the admittance control into the joint position set-points \( q_{\text{ref}} \).

During the learning phase of the walk-through programming, the robot controller records all the significant poses of the trajectory followed by the human operator, and thus it will be able to interpolate them and play the trajectory back.

A. Payload compensation

The goal of the admittance control is to establish a desired dynamical relationship between the motion of the robot and the force applied by the environment in order to force the robot to behave compliantly with the environment, according to a given mass-spring-damper system. Typically, the force applied by the environment is measured by a 6-DOF force/torque (F/T) sensor attached to the robot wrist flange. Moreover, we are considering case studies in which the end-effector is manually guided by the human to teach the robot a specific task, e.g., painting of an object. The example in Fig. 2 shows a spray gun attached to the robot end-effector, and a handle of non-negligible weight attached to the same end-effector, after the F/T sensor. In this case, the tool exerts a non-contact effect on the sensor, with both static (i.e., gravity) and dynamics (i.e., inertial, centrifugal/Coriolis) terms. Thus, the external force measured by the F/T sensor contains the sum of two terms: the non-contact wrench \( F_{nc} \) due to the load dynamics, and the contact wrench \( F_c \), arising from the interaction between the robot and the human operator or the environment. Following the strategy presented in [2], [3], the static and dynamic effects of the tool mounted on the robot end-effector can be computed and canceled, so as the remaining part of the measured F/T corresponds to the contact wrench arising from the interaction with the operator.

B. Online parameter adaptation

As described in the Introduction, the appropriate selection of the parameters of the admittance control is crucial. One of the main reason that brings the robot end-effector to unsafely oscillate is the stiffening of the operator’s arm during the interaction. Following the strategy proposed in [4], [5] it is possible to first detect the rising oscillating behavior and then adapt the parameters of the admittance control to restore the stability of the interaction while preserving the passivity of the system. Indeed, the following heuristic can be defined:

\[
\psi \left( \hat{x}, \ddot{x} \right) = \| \ddot{x}(t) + R_d(t) \dot{x}(t) \| \leq \varepsilon
\]

where \( R_d(t) \) is the damping to inertia ratio matrix, \( \ddot{x}(t) \) and \( \dot{x}(t) \) are scaled vector based on the acceleration and velocity tracking error, respectively, and \( \varepsilon \) is a specific threshold. The heuristic 1 is used for detecting online when oscillations occur. Namely, when 1 is not satisfied, that oscillations are rising. Once rising oscillations have been detected, the algorithm allows to compute the variation of the inertia that satisfies the passivity constraints derived in [5] and the stability of the system is recovered. The variation of the damping is performed according to a constant damping to inertia ratio.

III. DISCUSSION

The overall architecture presented in the work has been validated using different setup. In particular, extensive experiments on setup including a KUKA Lightweight robot 4+ and a Puma 260 manipulator have been performed. Current activities goes towards the implementation of the presented control architecture on a real industrial robot, namely the GA-2000 Gaiotto robot.

REFERENCES


