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Experimental comparison of offline and online compliance compensation strategies for industrial articulated robots

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Abstract

Industrial articulated robots appeal to high force processes such as material removal applications mainly due to their high flexibility and large working space. However, due to the articulated robot´s lower stiffness, significant deformations arise in the presence of process forces which reduces the robot´s positioning accuracy. To improve the positioning accuracy in tasks performed under load, offline or online compliance compensation methods are implemented.

This study presents an experimental comparison of the implementation and performance of offline and online compliance compensation strategies in a high-force application, i.e., loaded circular trajectory, characterized by the presence of quasi-static forces. The performance of the two compensation strategies was evaluated by calculating the mean deformation (comparison between unloaded and loaded trajectories). The results indicate that the performance of the online compensation strategy exceeded the offline compensation strategy performance for the case study analyzed. The limitations and potentialities of the different compensation strategies are discussed in terms of implementation and applicability for contact applications.

Keywords: Industrial robot, stiffness, compliance error compensation, loaded circular trajectory

1. Introduction

Industrial articulated robots are mainly used for handling, welding, and assembly applications [1]. Despite their higher structural compliance, which results in lower accuracy in the presence of higher process forces, there is an increasing interest in using articulated robots in contact applications due to their cost-effectiveness, flexibility, and dexterity [2].

To improve the articulated robot accuracy under load, the state-of-the-art focuses on kinematic and compliance calibration. The main strategies to achieve compliance compensation are offline and online, or a combination of them, also known as hybrid compensation [3].

The offline compliance compensation takes place during the process planning stage. In the offline strategy, the robot path is adapted based on the predicted deviations due to the external load. In fact, the articulated robot is not commanded to the desired pose but to a pose that will end as close as possible to the desired one after the compliance errors have affected the robot. Besides a kinematic description and an elastic model, this strategy requires a model to estimate the process forces [2]. The models generally grow in complexity to accurately represent the interaction between the robot, the end effector, and the work object. Its performance is highly dependent on the accuracy of the robot models and process simulations.

The online compliance compensation strategy relies on sensor signals that can directly (position sensors) or indirectly (force sensors) measure or estimate the deviations while the task is being performed. The main drawback of this strategy is the unavoidable computational delay of the correction signals, which can lead to considerable errors in the presence of high-frequency force components [3] or high trajectory velocities.

Previous research has primarily tested offline and online compliance compensation strategies separately. For instance, offline compensation has been implemented to cope with the effect of gravity on the articulated robot links and joints without considering any external load [4]. Elastic models have also been combined with other types of models, i.e., reversal error, to calculate the expected deviations and adjust the path in a circular milling operation [5]. Recently, an offline correction strategy based on a trajectory deviation measured by a 3D vision system (mirror correction principle) was proposed to improve the positioning accuracy of an industrial robot that machined composite material parts [6].

On the other hand, online compliance has been implemented mainly with optical measurement systems such as laser trackers [7, 8]. The sensor measurements have been used to compensate for the deformations due to external loads applied while moving along linear trajectories [9] and circular trajectories [10, 11].

Several efforts have also combined the two compensation strategies. In 2012, Lehman et al. [12] proposed a three-step approach: 1) selection of appropriate milling parameters, 2) offline compensation of the force-induced deviations, and 3) complimentary online compensation by comparing measured with modeled forces and updating the trajectory accordingly, though only the first two stages were validated. Lately, Hähn and Weigold [13] combined force measurements and a model-based online compensation with predicted forces from an offline simulation to instantly react to high force variations.

However, to select offline or online compliance compensation, it is necessary to understand the implementational efforts required and compare how the strategies perform when applied to the same contact application. This study proposed an experimental comparison of the application of both strategies to compensate for deformations due to the external forces applied while moving along a circular trajectory. The performance of the compliance compensation strategies was evaluated considering potential process parameter variations such as different force magnitudes and Tool Center Point (TCP) velocities.

2. Methodology

This section describes the setup used for the experiments and the procedure followed to test each compensation strategy.

2.1. Experimental setup

The setup used for the experiments is shown in Figure 1. It comprises the following equipment:

1. Industrial articulated robot IRB6700 (payload 300 kg, reach 2.7 m).
2. Three-component force sensor HBM MSC10-005-3C, connected to a NI cDAQ-9178 via a NI-9237 module for data acquisition.
3. Leica AT901-LR Laser Tracker, represented in the figure by its 0.5" Spherically Mounted Retroreflector (SMR).
4. Loaded Double Ball Bar (LDBB) with its corresponding Proportional Pressure Control Valve (PPCV) [14].
5. Rigid Table Link (TL).
6. Dummy End Effector (EE) containing the TCP.

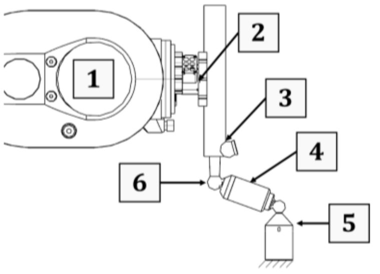

Figure 1. Experimental setup for the online compliance compensation strategy. For the offline strategy, the force sensor was removed.

The force sensor was removed from the setup for the offline compensation tests, and the EE was connected directly to the robot's mechanical interface. This step was done to ensure that both test setups reflect the actual operating conditions of the different compensation strategies.

2.2. Compensation strategies

Elasto-geometric model

The elasto-geometric model of the articulated robot comprises the kinematic and elastic models [15]. The articulated robot's kinematics (DH parameters) were obtained from the robot manufacturers' software. The robot elastic model used in this work is a lumped parameter model with flexible joints and rigid links that correspond to the one proposed by Salisbury [16]. Following this model, the deformation angles $\boldsymbol{\Delta\theta}$ can be estimated by:

$$\Delta\boldsymbol{\theta} = \boldsymbol{K}_{\theta}^{-1}\boldsymbol{J}(\boldsymbol{\theta})_{WAP}^{T}\boldsymbol{W}$$

where $\boldsymbol{K}_{\theta} \in \mathbb{R}^{nxn}$ denotes the diagonal joint stiffness matrix, $\boldsymbol{J}(\boldsymbol{\theta})$ corresponds to the robot´s Jacobian matrix, and $\boldsymbol{W} \in \mathbb{R}^{6x1}$ expresses the external wrench, i.e., the processes forces and torques. The subscript WAP (Wrench Application Point) indicates that the Jacobian matrix contains the transformation from the robot base to the TCP. The joint stiffness matrices used in the experiments were identified following a quasi-static compliance calibration procedure described by Theissen et al. [17]. This procedure is based on measuring the EE deflections due to external loads applied while moving along a trajectory.

In the case of the online compliance compensation setup, the sensor added a compliant element into the flow of forces and increased the overhang of the TCP with respect to the mechanical interface, which reduced the overall system stiffness. Therefore, the elasto-geometric model, i.e., the joint stiffness values, was again identified for the offline compliance compensation setup. Furthermore, for the compensation strategies to achieve optimal performance, the compliant robot model was calibrated in the operating space [18], i.e., creating local optima for the location of the trajectories.

Offline compensation strategy

The process followed for implementing the offline compliance compensation strategy is described in Figure 2. The offline compensation takes place within the process planning stage. Therefore, the process started by defining the desired trajectory and discretizing it in several configurations according to a convenient resolution based on the application requirements. In this work, the circular trajectory was discretized in 81 configurations to obtain an angular resolution of fewer than five degrees.

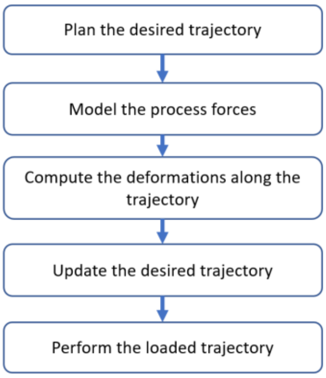

Figure 2. Steps to be followed for the implementation of the offline compliance compensation strategy for contact applications.

Then, the process forces expected to be experienced along the circular trajectory due to the loading element LDBB were estimated and expressed in the Robot Base Coordinate System (RBCS). Next, the deformations due to the external forces were computed along the circular trajectory using the elasto-geometric model and the previously estimated process forces. Finally, the trajectory is updated considering the expected deformations, and the compensated loaded circular trajectories can be performed.

Online compensation strategy

The online compliance compensation strategy requires the force measurements provided by the sensor. Thus, the forces that were originally measured in the force sensor's base coordinate system were transformed into the RBCS, considering the change of its orientation along the circular trajectory.

After this rotation, the force signals were further conditioned. First, a crosstalk compensation was implemented due to the sensing device being strain gauge-based. Second, a low-pass filter with a cut-off frequency of 25 Hz was applied to reduce the influence of noise. Third, a gravity compensation for the EE was implemented to remove the effect that all additional components mounted on the mechanical interface could have on the force components' values. Finally, lower and upper threshold values were applied to the force components', so the compensation was computed only when the process forces were significant. These thresholds also ensured that the compensation values did not change the programmed trajectory abruptly due to an error in the measurement system [19].

A combination of LabView and MATLAB was used for the compensation algorithm implementation. The former handled the data acquisition and communication with the robot controller through TCP/IP. The latter dealt with the elasto-geometric model definition and the deformation computation due to the external wrench [19]. The process followed by the online compliance compensation is described in Figure 3.

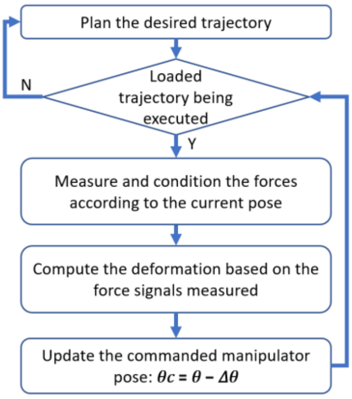

Figure 3. Steps to be followed for the implementation of the online compliance compensation strategy for contact applications.

While the trajectory was executed and based on the knowledge of the current pose, the wrench and elasto-geometric model were combined to compute the deformation angles $\boldsymbol{\Delta\theta}$ following Equation (1). This computation was done approximately every 100 ms. Then, the modified compensated configuration $\boldsymbol{\theta}_c$ was sent to the articulated robot controller to update the trajectory [19].

In both offline and online strategies, the calculated deformation $\boldsymbol{\Delta\theta}$ did not consider the deformations produced by the effect of gravity on the articulated robot links and joints. It only considered the deformations that originated from external/process forces.

3. Case study: Loaded circular trajectory

For the experiments, the articulated robot was programmed to follow circular trajectories while an external load was applied. The loads were exerted using the LDBB, a device similar to the traditional Double Ball Bar (DBB) used for circular testing of machine tools [20], with a built-in pneumatic actuator to regulate the magnitude of the applied force [14].

As shown in Figure 4, the LDBB was positioned with an inclination angle φ with respect to the XY plane to assure that the load was applied in all spatial directions and that the strategies implemented were capable of compensating for these effects. The magnitude of the loads $|Fqs|$ corresponded to 125 N, 375 N, and 625 N for the offline tests and 150 N, 400 N, and 650 N for the online tests. The load differences are explained by a maintenance and recalibration performed to the LDBB instrument between the offline and online tests.

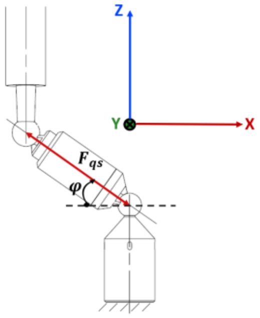

Figure 4. Orientation of the force vector applied while performing the circular trajectories.

The unloaded and loaded circular trajectories were executed in the same operational space for the offline and online cases. A complete test run of either unloaded, loaded uncompensated (UC), or loaded compensated (C) trajectories consisted of repeating three clockwise and three anticlockwise movements. Besides the load variation, the test runs were performed with three TCP velocities: 10 mm s^{-1}, 30 mm s^{-1}, and 50 mm s^{-1}, to emulate the effect of the variation of process parameters in the compensation performance.

To quantify the performance of the different compensation strategies, the Cartesian positions along the unloaded and loaded (UC and C) trajectories were measured with the LT at a sampling frequency of 1000 Hz. Then, the mean of the deformation, i.e., the distance between the loaded (UC and C) with respect to the unloaded trajectories performed at the same TCP velocity, was computed and used as an indicator for the performance comparison. The deformation calculation followed the proposal for evaluating positioning accuracy according to ISO 9283 [21].

4. Results and Discussion

The performance of the offline and online compliance compensation strategies implemented into the loaded circular trajectories can be seen in Table 1 and Table 2, respectively.

Table 1. Offline compensation: mean of the distance of the uncompensated (UC) and compensated (C1, C2, C3) points along the circular trajectory with respect to the unloaded trajectory. The compensated trajectories C1, C2, and C3 were performed at 10-, 30- and 50 mm s−1, respectively.

	UC in mm	C1 in mm	C2 in mm	C3 in mm
125 N	0.12	0.04	0.04	0.04
375 N	0.38	0.13	0.13	0.13
625 N	0.62	0.21	0.21	0.2

Table 2. Online compensation: Mean of the distance of the uncompensated (UC) and compensated (C*1, C2, C3*) points along the circular trajectory with respect to the unloaded trajectory. The compensated trajectories C1, C2, and C3 were performed at 10-, 30- and 50 mm s−1, respectively.

	UC in mm	C1 in mm	C2 in mm	C3 in mm
150 N	0.23	0.07	0.07	0.08
400 N	0.65	0.16	0.15	0.15
650 N	1.10	0.25	0.19	0.21

For both compensation strategies, the UC mean deformation values presented in Table 1 and Table 2 correspond to the average deformation considering all TCP velocities (10 mm s^{-1}, 30 mm s^{-1}, and 50 mm s^{-1}) due to its minimal variation. The maximal observed standard deviation equals 0.05 mm at 50 mm s^{-1}. For the offline compensation, see Table 1, the TCP velocity has no apparent effect on the offline compensation performance as the compensated trajectory is only conditioned by the process forces and the articulated robot's Cartesian stiffness. In the online compensation tests, see Table 2, the effect of the TCP velocities on the compensation performance was negligible, with a maximum standard deviation of 0.03 mm. A TCP velocity higher than 50 mm s^{-1} will have a more considerable effect on the performance of the online strategy due to the limited computing cycle time.

As anticipated, the mean deformation along the UC circular trajectories increased with the magnitude of the applied load. The reduction of the system stiffness due to the inclusion of the force sensor in the online setup appears evident at the hand of the approximately doubled value of the mean deformation measured compared to the offline setup while applying similar loads. However, as shown in Table 1, Table 2, and Figure 5, the performance of the offline strategy remained alike (67%

compensation) independent of the load level, while the performance of the online strategy improved at higher loads and TCP velocities (from 69% to 80% compensation). The inaccuracies in the force model or an unidentified relation between the apparent articulated robot stiffness and the velocity at which the task is performed could explain this improvement. The latter hypothesis requires further validation.

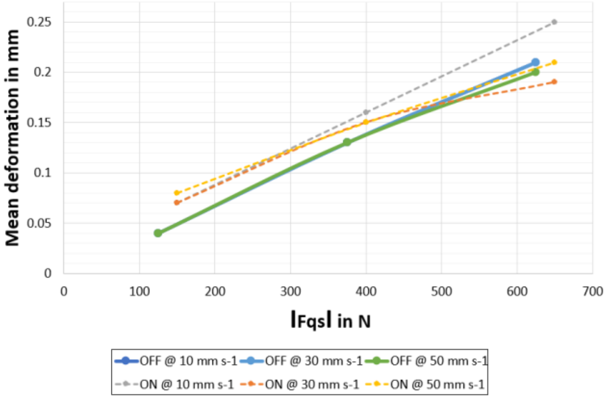

Figure 5. Comparison of the mean deformation along the circular trajectories after offline (OFF) and online (ON) compliance compensation implementation at different TCP velocities.

One of the disadvantages of the offline compensation strategy is the requirement for an accurate force model. In some applications, like the one exemplified in this work, the computation of the force vector and its transformation into the RBCS is apparently a straightforward task. However, in other contact applications, such as machining, the estimation of the cutting forces is a non-trivial task, and an erroneous estimation can result in defects that could be greater than the ones of the uncompensated task. Nevertheless, offline compensation is a compelling solution due to its resource efficiency.

Besides the additional sensor requirement, an important limitation of the online compensation strategy is the latency between the measured and the compensated signal due to the limited accessibility to the robot controller signals. Nevertheless, even if high-frequency force components cannot be compensated, most of the geometric deviations are caused by the low-frequency components of the process forces [12]. Furthermore, this compensation strategy can capture and compensate unmodeled force variations which considerably reduces the modeling effort and allows the robotic system adaptability to different contact applications.

5. Conclusions

This study presents an experimental comparison of the performance of offline and online compliance compensation strategies applied to circular trajectories executed under loaded conditions. The results indicate that the online compensation strategy could reduce to a greater extent the mean deformation for the case of circular loaded trajectories, mainly when applied to higher load levels and TCP velocities. Nevertheless, it requires additional implementational effort (hardware and software) in comparison to the offline strategy. The applicability of these compliance compensation strategies must be subjected to a thorough analysis of the requirements for the specific task and resources constraints, and their performance should be further analyzed and compared in other types of contact applications.

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