

DLR Lightweight Robots - Soft Robotics for Manipulation and Interaction with Humans

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Abstract—This demo presents the manipulation and interaction capabilities of the DLR lightweight robots. In order to act in unstructured environments and interact with humans, the robots have design features and control/software functionalities which distinguish them from classical robots, such as: load-to-weight ratio of 1:1, torque sensing in each joint, active vibration damping, sensitive collision detection, as well as compliant control on joint and Cartesian level.

I. INTRODUCTION

The Institute of Robotics and Mechatronics of the German Aerospace Center (DLR) has a long history in the design of torque-controlled lightweight robots [1], [2]. These robot arms have been developed for application areas which are fundamentally different from the ones of classical industrial robotics. The strengths of industrial robots are especially high positioning accuracy, speed, durability, and robustness, as well as the relatively low price. Therefore, nowadays industrial robots are especially used in well structured environments, in which the position and shape of the parts to be manipulated are well determined. In these, collisions with the environment and humans can be excluded in advance. High performance can then be achieved for fast tasks which are repeated numerous times. Generally, however the high positioning accuracy requires high stiffness at the price of high robot mass and energy consumption relative to the payload of the robot.

In contrast, the robotic systems developed at DLR (arms, hands, a humanoid manipulator) are designed for interaction with humans in unstructured, everyday environments.

In such applications robust and compliant behavior is crucial and cannot be realized with industrial robots. Therefore, all DLR robots are equipped with various sensors. In particular, the joint torque sensing in each joint enables compliant behavior without significantly decreasing position accuracy. Typical scenarios are:

- assembly processes for which the position estimation for the mating parts and/or the positioning accuracy of the robot is significantly below the assembly tolerance.
- applications in which the robot works in immediate vicinity of humans and possibly in direct physical cooperation with them.
- mobile service robotics applications (arms mounted on mobile platforms), for which the information about the position of the robot and the surrounding objects, as well as about the dimension of these objects is subject to relatively high uncertainty.



Fig. 1: DLR's Justin - a humanoid upper body using the lightweight robot technology.

The mentioned applications require a low robot mass compared to the payload in order to enable mobility and minimize the injury risk. Furthermore, extensive sensor usage, like the torque sensing in each joint, plays a key role for the performance of the robots. These sensors constitute an essential feature compared to most other robots: they measure joint vibration behind the gear-box, and therefore enable an active vibration damping for high positioning accuracy. These sensors are also used for the so-called soft robotics control, i.e. active compliance and force/torque control, as well as for collision and failure detection. Details about the passivity-based control strategies can be found in [3].

To make the meanwhile mature technology available for researchers around the world, a close cooperation with the German robot manufacturer KUKA has been established. The first commercial torque-controlled lightweight robot based on DLR technology is expected to hit the market in close future.

II. ASSEMBLY OF COMPLEX PLANAR PARTS

As a possible application for the DLR Lightweight Robot III (DLR-LWR III), in this section we illustrate the autonomous assembly of planar parts with complex geometry on a target movable plate. Figures 2–3 show the experimental setup arranged for this application, and detailed views of the used parts/plate. In order to realize such a task, a combination of

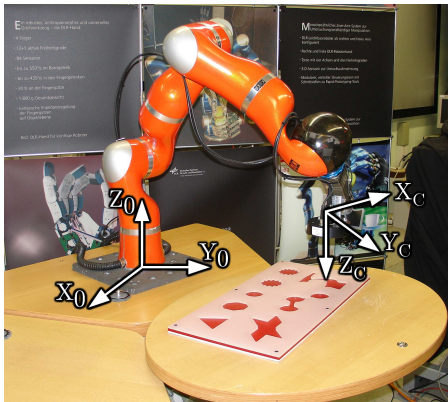


Fig. 2: The DLR light-weight robot equipped with an onboard camera.

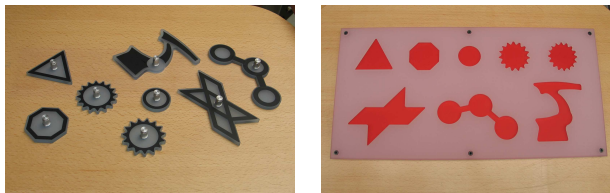


Fig. 3: The 8 parts and the plate used in our experiments.

image processing, vision and force-torque control is needed to fulfill the required steps, namely: visual object identification, fine robot positioning, and picking/insertion of the parts. Vision is used to recognize and localize the target objects, and to move the robot arm to a defined position relative to them. In our case, we adopted the *visual servoing* approach to control the robot pose with visual information [4]–[6]. In this framework the robotic task is directly specified in terms of some image features extracted from a target object. These features are then used to control the robot/camera motion through the scene until the final robot pose is reached.

After the visual positioning task over the selected hole is completed, the insertion has to be executed without vision support since, in this phase, the target hole exits the camera field of view. Due to the complexity of the parts used in this application, we adopted an off-line planning algorithm in order to generate robust insertion strategies [7], and we exploited the Cartesian impedance control framework [3] as a means to achieve an active compliance behavior during the insertion phase. The main idea of the insertion planning is visualized in Fig. 4. Consider the compliance controlled robot having inserted a corner of the part into the hole at the initial configuration x_i . For a certain set of starting configurations

(called the *region of attraction ROA*), the inserted part will converge to the desired alignment in position x_a . In Fig. 5, a complete example of an assembly sequence relative to the KUKA logo is shown.

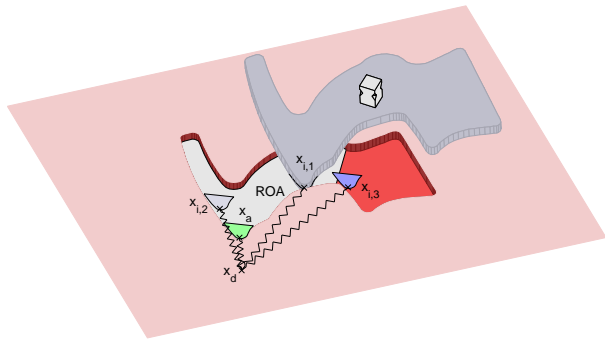


Fig. 4: A typical region of attraction (ROA) for a sample part. The inserted corner will be guided automatically to position x_a if the alignment process starts anywhere within the ROA (e.g. from $x_{i,1}$ or $x_{i,2}$). If it starts outside (e.g. from $x_{i,3}$), a successful alignment cannot be guaranteed.

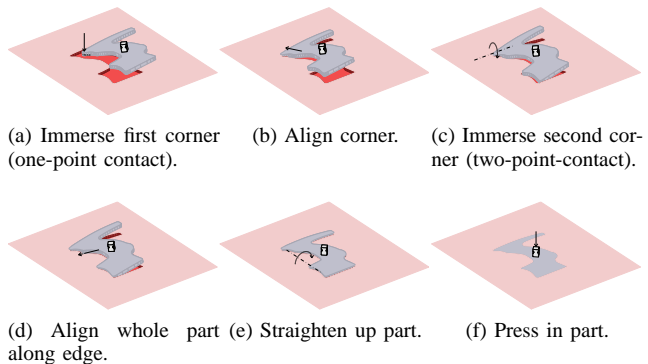


Fig. 5: Example of the presented insertion strategy.

For the complete sequence of picking/insertion, we recorded statistical data over 20 cycles, that is we collected data from 160 assemblies (see Fig. 6 for the distribution of the parts and the plate). Altogether, the robot was able to insert 154 parts successfully (96.25%). In four cases the assembly failed because the vision system was not able to detect the part or hole reliably (lost tracking during motion three times, once the part was not found initially). In the remaining two cases, visual servoing was completed successfully, but the insertion failed because the robot missed the ROA. No error recovery was implemented for these experiments, in case of errors (like lost tracking) the current part was dropped and the sequence continued with the next part.

III. SAFE PHYSICAL HUMAN-ROBOT INTERACTION

The desired coexistence of robotic systems and humans in the same physical domain, by sharing the same workspace and actually cooperating in a physical manner, poses the very

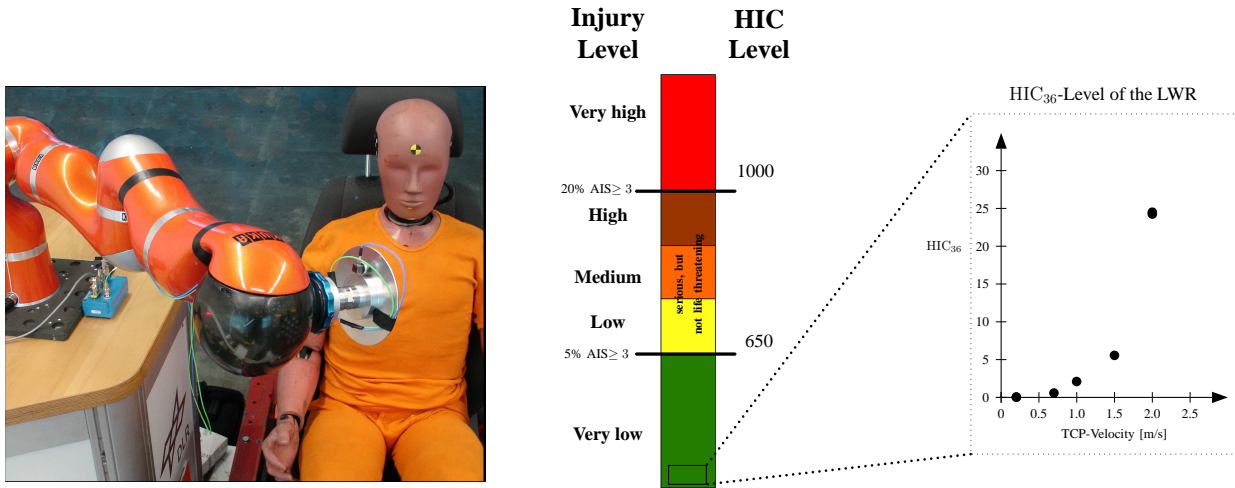


Fig. 7: Potential injury level of the human head caused by an impact of the DLR-LWRIII expressed by the Head Injury Criterion (HIC).

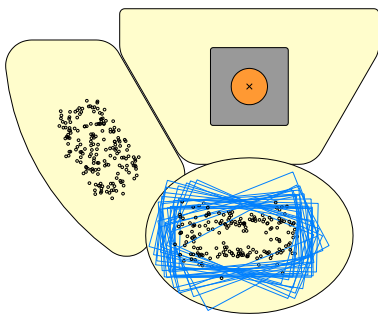


Fig. 6: Top view of the distribution of parts and plate during the statistical evaluation of the automated assembly. The small circles represent the gripping handle for parts in the starting position (left) and inserted in the plate (bottom).

fundamental problem of ensuring safety for both the user and the robot.

In order to measure the potential danger emanating from the DLR-LWRIII, impact tests at the Crash Test Center of the German Automobile Club ADAC (see Fig. 7 (left)) were conducted [8]–[10]. The evaluation of the Head Injury Criterion (HIC) indicated *very low* injury and is shown in Fig. 7 (right).

Apart from evaluating impact scenarios, fast detection of collision or failure is absolutely necessary for a robot that interacts with humans. Joint torque sensing, together with a good robot model are used to realize this.

A. Collision Detection

The principle behind our collision detection is introduced in [11], [12] and shown in Fig. 8. In the upper part the rigid body dynamics is sketched (while neglecting the joint damping), whereas the lower part represents the collision observer. This can also be interpreted as a Hamiltonian observer, since its basic concept is to observe the angular momentum $\mathbf{p} =$

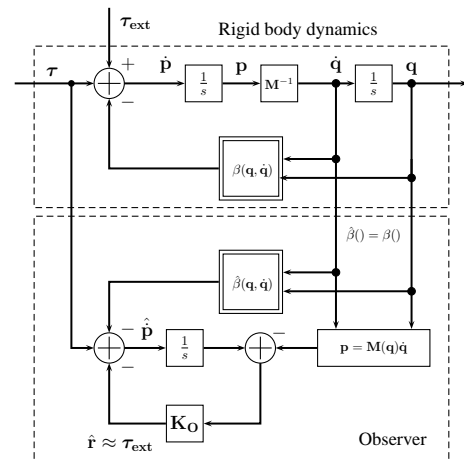


Fig. 8: Block diagram of the disturbance observer, estimating a 1st order filtered version $\hat{\mathbf{r}}$ of the external torque $\boldsymbol{\tau}_{\text{ext}}$. The nonlinear feedback term $\beta(\mathbf{q}, \dot{\mathbf{q}})$ is defined as $\beta(\mathbf{q}, \dot{\mathbf{q}}) := \mathbf{C}(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) - \dot{\mathbf{M}}(\mathbf{q})\dot{\mathbf{q}}$.

$\mathbf{M}(\mathbf{q})\dot{\mathbf{q}}$. It can be shown that the output $\hat{\mathbf{r}}$ of the disturbance observer is a component-wise decoupled and filtered version of the joint torque $\boldsymbol{\tau}_{\text{ext}}$ resulting from external collision. This signal is then used as a basis for the collision detection.

B. Collision Reaction

After a collision has been detected and isolated, an appropriate robot reaction has to be triggered. Various reaction strategies were proposed in [11], [12] which range from simply stopping the robot to switching to different compliant modes.

Certainly one of the most critical situations is an impact with sharp tools, such as knives, scissors, or scalpels. By common sense, we would expect that no robot reaction would be able to prevent serious injury in this case. However, in [13] a more

differentiated picture and very encouraging results are shown. In this demo the collision detection and reaction schemes implemented on the DLR-LWR III are presented and “hands-on” experiments will be shown, letting the visitors experience the subjective safety feeling.

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