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# Haptic and Visual Training of System Behavior – a case study for Robotic Programming-by-Demonstration

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## Abstract

*Programming-by-demonstration (PBD) is a new paradigm for programming industrial robots enabled by the development of the DLR/KUKA light-weight robot. Although the PBD approach facilitates and simplifies the generation of robot programs, the technician still needs to have skills and knowledge about the robotic system in order to produce efficient trajectories and to exploit the abilities of the robot in an optimal way. Within the EU-SKILLS project a robotic training system and protocol was developed to enable enactive learning of robotic skills and abilities. The paper presents the evaluation of the skill transfer for robotic PBD based on enactive learning.*

## 1. Introduction

In programming by demonstration a robot operator deploys his own movements in order to guide the robot to positions which can later be performed in a different location (e.g., the outside wall of a space station) or replicated many times (e.g., in manufacturing). This form of intuitive programming of robots is designed to reduce the necessity to use complex script based programming languages in the operation of robots, and to allow a more natural form of monitoring [3]. Yet its introduction has led to new challenges, which have emerged due to basic differences between the motor system of humans and robots [4], [5].

In a series of studies, we focused on two of these problems: 1) The problem of singularities – in singular configurations the robot loses a degree of freedom. While humans can exploit singular configurations of their appendages enabling them applying huge forces, singularities represent a problem for robotic system exciting uncontrolled joint movements. Thus, efficient performance involves motor paths that avoid these singularities. 2) Estimating compliance – While it is easy to convey (i.e., to demonstrate to a robot) movement paths, it is much more difficulty to convey the correct pressures with which a constraint movement is performed. The system described below attempts to train performers to excel in these two problematic areas. Our main results showed that the visual guidance based accelerator did not successfully (as a stand alone module) improve performance while the haptic based accelerator had some surprising positive effects. These findings suggest the importance of training using the enhancement of sensory interactions that are not naturally dominant.

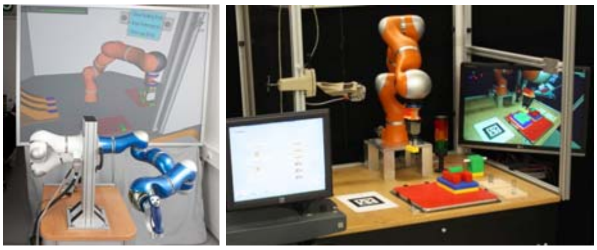

**Fig. 1: The two training platforms; left: training center setup with one LWR as haptic device and a VR-screen; right: On-Site Setup with touch screen, LWR, flexible workspace and AR-screen.**

## 2. System description

The presented studies were performed on two setups that are particularly suited for supporting skill acquisition for the two challenges addressed in this article. In both setups the KUKA/DLR light-weight robot (LWR) was the main means of both human machine interaction and training. The LWR is a revolute joint robot, with integrated electronics comprising torque and position sensors [8]. This sensory equipment enables compliant behavior and opens the door to the sensitive area of direct human interaction. In the following a brief overview of the



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technical system is given, for more detailed information refer to [6], [7], and [9].

### 2.1 Training Center Setup (VR)

In the training center setup the scope of work concerning singularities is investigated. A robot singularity is a specific robot configuration, in which the robot cannot be moved in certain direction(s) anymore [2]. The goal in this setup is to find out how to optimize skill acquisition on avoiding robot singularities.

The setup contains a virtual reality simulation of a pick-and-place task with a virtual LWR (see Fig. 1, left). Two different visual pointers are evaluated on this setup. They are integrated in the virtual simulation and presenting important information on the robot singularities. The participants can move the virtual robot by moving a real LWR that is used as haptic device. Haptic feedback is essential in this task for feeling the effect of robot singularities.

### 2.2 On-Site Setup (AR)

In a second scenario we investigated the effect of a haptic accelerator on enactively learning how to parameterize the compliance of a robot. Therefore a setup was used, where virtual (visual and haptic) information can be augmented to a real life working cell (see Fig. 1, right) with a LWR and task related equipment, and thus consequently features all the details of a real working installation. Therefore it is called On-Site Setup of the PBD-Demonstrator.

With the On-Site Setup we investigated how training to parameterize robot compliances can be improved. Robot compliances are for two reasons difficult to comprehend and therefore difficult to parameterize: First, compliance is not an attribute prevalent when dealing with machines, and secondly it is visually not apprehendable.

## 3. Skill transfer evaluation

### 3.1 Understanding of geometric properties – singularities

To explore whether we can provide effective training for avoiding robot singularities, we evaluated two types of training accelerators, based on visual guidance. Both accelerators are visual pointers which indicate whether a robot is close to a singularity, and give information as to how to prevent that singularity.

The first visual pointer (see Fig. 2, center) is a rotating arrow indicating for each joint how close it is to a singularity position, and how to avoid that singularity. The second visual pointer (see Fig. 2, right) provides the same information, but in the form of an animated transparent robot, which shows how to move the robot's elbow out of singularities.

**Fig. 2: The light-weight robot in a singular situation, and the different kinds of visual pointers; left: no pointer; center: rotating arrows; right: transparent robot.**

To evaluate the effectiveness of the accelerators we conducted a study using the virtual reality training system (see section 2.1). The study contained 60 participants which were allocated into four groups. All groups had to go through a training phase in which each participant played a pick-and-place Lego game. The goal in the game was to build a predefined Lego structure composed of five Lego bricks. The picking and placing positions were given in such a way that the direct path would lead the robot to a singularity. Therefore, to avoid singularities, a longer path was needed to be chosen. The training phase ended when the participant placed all the bricks in the correct positions.

During training, Group A didn't have any visual pointers as guidance. The participants of this group just had to complete the task without any indication when they are in a singularity position and how they can move out of it. The other groups were trained using the visual accelerators. The participants of Group B were instructed by the visual pointer of the rotating arrows while the participants of groups C and D were visually guided by a transparent virtual robot. The difference between groups C and D was that the participants of Group D were able to move the elbow of the virtual robot using a switch placed on the joystick handle of the light-weight robot. On the one hand, the addition of this feature made it harder to control the robot, but on the other hand, it enhanced the usefulness of the transparent robot, as this pointer instructs the trainee how to manipulate the elbow in order to get it out of singularity (by adding another degree of freedom).

The effectiveness of the different visual pointers was assessed using a transfer task which included a different pick-and-place Lego game. In this task there was no visual guidance. The participants' performance, with respect to avoiding singularities, was measured by the distance of the robot from singularity positions during the task. In addition, we also measured the task duration until the five Lego bricks have been placed correctly. Using one way Anova analysis we found a

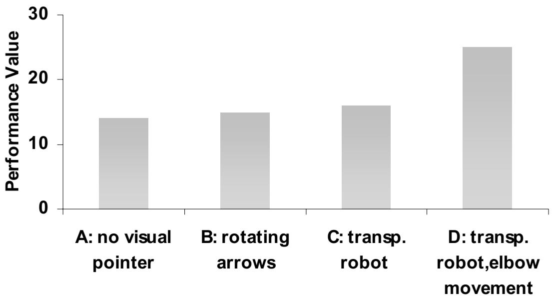



**Fig. 3: The performance in the transfer task as measured by the distance from singularity during the task.**

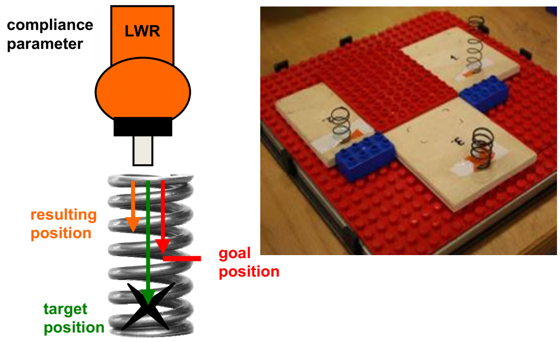



**Fig. 4: Resulting robot position of a compliant robot trying to reach a target position vs. tasks goal position (left). Training tasks setup (right).**

significant difference between the groups($F(3,56) = 3.86$, $p < 0.05$). A further post hoc (*Scheffe*, $p < 0.05$) analysis revealed that in comparison to the control group A, neither type of visual guidance was effective! Only participants of group D, where an additional elbow movement was afforded learned better how to avoid singularities as their performance in the transfer task was significantly better than the participants of the other groups (see Fig. 3). Thus, our attempts to create visual guidance that would alleviate the tendency to over-train [1] were not successful.

The findings suggest that the mere addition of visual guidance during training is not sufficient to facilitate the acquisition of singularity avoidance skill. However, utilizing a training protocol which includes a visual pointer shared with the ability of the operator to manipulate the virtual robot's elbow would be beneficial in facilitating the training of the singularity avoidance skill in PBD.

## 3.2 Understanding of behavioral properties - compliance

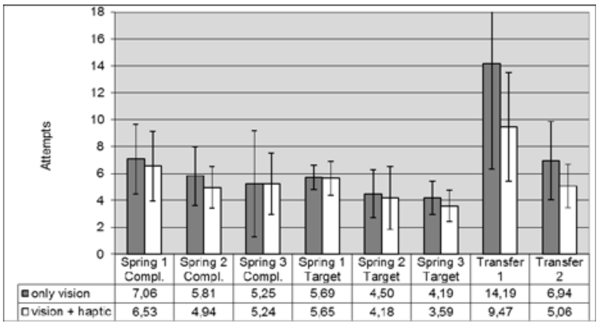
The LWR offers the possibility to control the compliance behavior of a specific point of the robot (usually the tool tip). In Cartesian space there are in total six compliance parameters – three for the translational and three for the rotational part. In a contact situation the robot creates a force that depends on these compliance parameters and the spatial difference between resulting and target position.

For the experiment the complexity of the system was reduced to a one dimensional problem in Cartesian space, which involves the parameterization of only one of the six compliance parameters. The training task was to parameterize the robot in such a way, that it compresses a spring by a specific distance (goal position). For a given spring the compression (resulting position) depends on two different factors: the compliance parameter of the robot and the selected target position (see Fig. 4). During training one of those two factors was fixed and the test subjects had two find the correct value for the other one. These two training tasks were done with three different springs leading to a total amount of six training tasks. A training session took about 30 minutes.

Each training task started with a default value for the parameterization. This value was the same for all the participants. The participants observed visually the robot movement and how far the spring was compressed with the given start value. Then they had to change the parameter by pressing +/- buttons on a screen, which changes the compliance by 25N/m steps and the target position by 5 mm steps, respectively. After finishing the parameterization the outcome could be observed again. The users had to parameterize and observe until the goal of task was reached. Participants were not allowed to touch the spring.

The training was performed by two groups with different training conditions. The control group B performed the training exactly as described above with only visual feedback during the observation phases. Group A received enactive training and thus had additional haptic feedback: They were allowed to touch the robot during the parameterization phase and directly feel the compliance of the robot with the actual set parameters. They could subsequently alter the parameters and feel the result again. After that they start the observation phase and finish a trial when they had the "feeling" that the parameters are set in a way to accomplish the task successfully.

The difficulty was increased for the transfer task. This was done by different means: First, the springs were mounted horizontal and not vertical like in the training task. Second, the springs were mounted on a fragile structure which broke when forces were too high. And most important, during the transfer task the users had to parameterize both factors – the compliance parameter and the target point – at the same time. The transfer task should show how well the participants have understood the concept of robot compliance. The conditions for the transfer task were




| | Spring 1 Compl. | Spring 2 Compl. | Spring 3 Compl. | Spring 1 Target | Spring 2 Target | Spring 3 Target | Transfer 1 | Transfer 2 |
|---|---|---|---|---|---|---|---|---|
| only vision | 7,06 | 5,81 | 5,25 | 5,69 | 4,50 | 4,19 | 14,19 | 6,94 |
| vision + haptic | 6,53 | 4,94 | 5,24 | 5,65 | 4,18 | 3,59 | 9,47 | 5,06 |

**Fig. 5: Performance of subject groups. Training tasks (left): Setting compliance parameters (Compl.) and setting target position (Target) of the robot at three different springs. Transfer tasks (right): Setting both parameters at two springs.**

the same for both groups, which means both groups had only visual feedback and touching the robot was not allowed anymore for Group A.

The statistics were conducted using t-tests and non-parametric Kolmogorov-Smirnov tests and are reported in [4] (results noted as significant had $p < .05$). Comparing the number of trials (parameterization-observation cycles) for each of the six training tasks show that both group perform similar during training. Both groups needed a similar number of trials and both group show the same training effect regarding the decrease of trials from training task to training task.

Looking at the two transfer tasks it is very interesting to see that Group A which had the haptic accelerator performed significantly better than Group B which had only visual feedback. One possible explanation of this effect is that haptic feedback was stimulating the awareness of the system's dynamic behavior and therefore has a very positive effect on learning during the 30 minutes of training. The non haptic feedback group B had a big variance in transfer task performance, which might also be explainable due to the fact that some participants were able to have the same high awareness of the system behavior without the stimulation of the accelerator.

## 4. Conclusion and future work

The evaluation study on PBD has offered an interesting contrast between the facilitating effect of visual and haptic modalities on a multi-feedback trainer. While vision is our dominant modality, there is accumulating evidence that direct guidance of vision has some negative outcomes [1]. By contrast, haptic sensations are of the least developed modalities, and were nevertheless found helpful for enhancing the comprehension of the concept of compliance. While our studies were field experiments conducted in a relatively uncontrolled environment, our findings call for more into depth experimental investigation to examine the relative contribution of strictly match information added by these two modalities.

The current findings also have important implications on the design of PBD robots, and suggest a call for enactive feedback including enhanced haptic interaction. For instance, compliance could be modified haptically. Also, haptic feedback (e.g., stiffness) may provide a natural signal for the approach to singularity positions.

## 5. Acknowledgement

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