A Comparison of Types of Robot Control for Programming by Demonstration

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Abstract—**Programming by Demonstration (PbD) is an efficient way for non-experts to teach new skills to a robot. PbD can be carried out in different ways, for instance, by kinesthetic guidance, teleoperation or by using external controls. In this paper, we compare these three ways of controlling a robot in terms of efficiency, effectiveness (success and error rate) and usability. In an industrial assembly scenario, 51 participants carried out peg-in-hole tasks using one of the three control modalities. The results show that kinesthetic guidance produces the best results. In order to test whether the problems during teleoperation are due to the fact that users cannot, like in kinesthetic guidance, switch between control points using traditional teleoperation devices, we designed a new device that allows users to switch between controls for large and small movements. A user study with 15 participants shows that the novel teleoperation device yields almost as good results as kinesthetic guidance.**

Index Terms—**teleoperation, kinesthetic guidance, learning from demonstration, interface design**

I. Introduction

Programming by Demonstration (PbD),[1] also referred to as Learning by Demonstration or Learning from Demonstration (LfD) [1]–[3], is a common way of programming new behaviors into robots [4], [5] and thus addresses "the problems of skill and task transfer from human to robot, as a special way of knowledge transfer between man and machine" [6]. Teaching a robot new behaviors in this way is time effective, intuitive and it can be done by naïve users so that costs for expensive programming experts can be saved [7].

In PbD, the robot is moved by the user while the robot is recording the trajectories or states presented; Chernova & Thomaz [4] refer to this approach as "learning by doing". When the teaching process is complete, the robot generalizes over the different trajectories or recalls the target positions and calculates the connections between the different positions itself (see [2]). PbD is often carried out using kinesthetic guidance, during which the robot's joints are moved by hand into the position desired. Another possibility is to operate each joint by itself; most robots come with an interface, such as a control panel, to do this. A third possibility is teleoperation, where the robot is controlled remotely and where the postures and /or trajectories demonstrated are recorded based on the joint positions (cf. [3]). In this paper, we compare these three possibilities - kinesthetic guidance, direct control via control panel, and teleoperation - with each other in a controlled study. In particular, we are interested in the advantages and disadvantages of the different modalities by means of which the robot is controlled during PbD regarding efficiency, effectiveness and accuracy, as well as usability. The results show that kinesthetic guidance is superior to the other two control options in terms of efficiency and effectiveness, yet that there are usability issues. In a second study, we therefore explore whether the disadvantages of teleoperation can be compensated for. While potentially many aspects of remote robot control could cause the problems observed with robot teleoperation (it could be lack of visual access, for instance; cf. [8]), our hypothesis is that the lack in efficiency and effectiveness in teleoperation is mostly due to the fact that in kinesthetic guidance tutors can choose which point of the robot they want to control. We therefore developed a teleoperation device that allows tutors to switch between control points. In a subsequent user study we compare the results of PbD with the new device to that of the other options. The results show that teleoperation can be almost as good as kinesthetic guidance when tutors can switch between control points.

[1]While we focus on robot control for a programming by demonstration application in our study, issues of robot control also arise in other remote control scenarios, for instance, in the shuttle remote manipulation system (Canada arm), deep water submarines or during keyhole surgeries.

II. Previous Work

Few studies have compared the efficiency of different control options for PbD directly; Chernova & Thomaz [4] compare kinesthetic guidance with teleoperation in terms of the correspondence problem [9], i.e. the problem that humans and robots differ regarding their sensing abilities and physical embodiment. They argue that in kinesthetic guidance the correspondence problem is eliminated because users operate the robot directly (p. 20); in contrast, in teleoperation the robot's morphology needs to be mapped onto the controls available to the user. Furthermore, Chernova & Thomaz [4] suggest that kinesthetic guidance supports error avoidance since the

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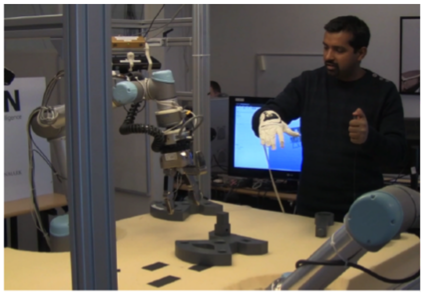


Fig. 1: Workspace with data glove

demonstrations are naturally constrained to fit the robot's abilities. Muxfeldt et al. [10] however argue that kinesthetic guidance does not allow a direct transfer of human skills to the robot, either; they compare four tasks carried out by the human hand, the object to be assembled connected to a handle and kinesthetic guidance and find considerable differences in the ways the tasks are carried out. Thus, also kinesthetic guidance suffers to some extent from the correspondence problem.

Another study that directly compares different control modalities is by Akgun and Subramanian [11], who test lay users' demonstrations of tasks to the PR2. They find that demonstrations by means of kinesthetic guidance are faster and more successful than teleoperation, yet that the learned skills do not perform better afterwards. They also asked participants for their opinion and find that participants prefer kinesthetic guidance because it is easier and more accurate.

Another criterion for the comparison of the control modalities is the usefulness of the different control modalities in different types of situations and with different robots [4]. For instance, if the robot is highly complex, there are limits to direct control. A disadvantage of kinesthetic guidance can be if the setting is dangerous or if objects are large, far apart or dangerous to handle [4]. Furthermore, as Wrede et al. [12] show, kinesthetic guidance can be problematic in narrow spaces. Tung & Kak [13] furthermore argue that visual access plays a big role, which could be an argument for teleoperation since this allows users remote access to the robot whereas kinesthetic guidance requires human and robot copresence.

Regarding teleoperation, several different devices are in use; the data glove in Fig.1 is a common teleoperation device, which is equipped with sensors to track the user's movements, used, for instance, by [6], [13]–[15]. Pardowitz et al. [6] use the data glove to teach a robot household tasks. Savarimuthu et al. [16] use the same data glove as in the current study to perform a quantitative and qualitative analysis of human peg-in-hole operations in industrial assembly tasks. Besides the data glove, joysticks are also widely used as teleoperation devices, for instance, for flying helicopters [17] or for operating humanoid robots [18]. Akgun and Subramanian [11] use PhantomOmni, yet without the haptic feedback, for the teleoperation of a PR2. In an industrial application, Kukliński et al. [19] integrate a trackSTAR sensor in one of the objects from the Cranfield set [20], which they then use to teleoperate the robot, which produces better results than the data glove. In general, the employment of teleoperation devices depends crucially on the degrees of freedom of the respective robot (e.g. [3]).

Previous work on the usability of the different control modalities is rare (see [4]); usability issues in PbD addressed concern, for instance, how naïve users can best be instructed to operate the robot during PbD; in particular, [21] find that instruction by video prepares participants best for PbD sessions.

In this paper, we compare three different types of robot control: The first method is direct control of each joint using a control panel; while this is a remote form of controlling the robot, and thus could be referred to as teleoperation, it is different from the other remote forms of control by the fact that each joint is controlled separately. The second method is kinesthetic guidance, where the robot is moved by the user, who is free to choose where to touch the robot to bring it in the desired position. The third method is teleoperation by means of a data glove - here, in contrast to the control panel, the user controls only one point (the tool center point) while the joints are moved in accordance. The data glove is a common teleoperation device, but also others, for instance, joystick or phantomOmni, share the fact that a single point on the robot is controlled, in accordance with which the robot joints are moved. Comparing these three methods thus allows us to identify the effects of a broad spectrum of different types of robot control.

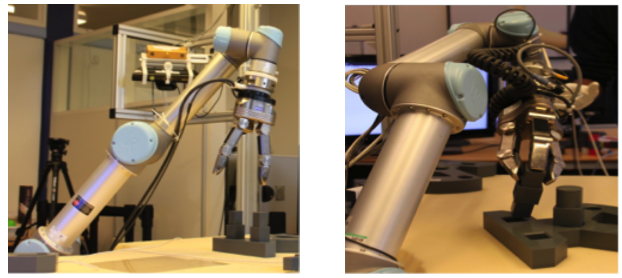
III. Technical Set-Up

The robot used is an industrial assembly robot equipped with a Universal Robot arm (see [16]). The robotic platform comprises two 6DoF robot arms UR5 by Universal Robots equipped with the three-finger gripper SDH-2. The three fingers can be brought into three different positions in order to grasp objects with different shapes: the two-finger pinch grasp, the three-finger pinch grasp and the three-finger ball grasp. A force-torque sensor is mounted between the robot and the gripper. It returns the force vector measured in the wrist of the gripper. The platform is equipped with three pairs of kinect- and stereo cameras and the workspace on the platform is covered with a 10cm layer of foam to avoid damage caused by applying too much pressure on the robot gripper's fingers.

The **data glove** is a glove with a trackSTAR sensor mounted on top to track the user's movements (see Fig.1). The robot picks up the movement of the sensor in the data glove only as long as the dead man's button is pressed (left hand). When the user wears the glove, the sensor is on the back of his or her right hand. Inside the glove's index finger, a second sensor enables the user to open and close the fingers of the gripper by opening and closing his/her own hand. In order to select the grasping mode, the participant needs to communicate with the robot engineer.

When the user controls the robot arm by means of **kinesthetic guidance**, he/she guides the robot by hand. To move the robot, the user pushes a button on the control panel in order to release the breaks of the robot's joints. The user needs to holds on to the robot when the breaks are released since otherwise

Fig. 2: Robot operation via control panel



Singularity Self-collision

Fig. 3: Common errors during PbD

the gripper will fall down onto the foam, which can harm the robot or the user. The user can then guide the robot into the position he/she wishes.

The **control panel** is the official control modality provided by Universal Robots with their industrial robot arms ([22], see Fig.2). It provides controls to operate each joint separately.

IV. Study I

The first study compares the three control modalities kinesthetic guidance, teleoperation and direct control via a control panel.

A. Participants

The experiments were carried out between subjects and took place at different days; 15 participants interacted with the robot via the data glove (ten male, five female; average age 27.8, range 21-57). The questionnaire given to them at the beginning of the sessions shows that they have an average experience with robots of 2.6 on a scale from 1-4. Similarly, participants rate their familiarity with video games with 2.2 on average, again on a scale from 1 to 4.

18 participants used the control panel (17 male and one female; average age is 22.4, range is 18-26). Participants rate their experience with robots as 1.3 and with video games as 2.6 on a scale from 1-4.

Further 18 participants used kinesthetic guidance (15 male and three female with an average age of 22.1 (range 18-28)) to demonstrate new behaviors to the robot. They self-report an experience with robots of 1.8 and with video games of 2.5 on a scale from 1-4.

B. Methodology and Procedure

Participants were recruited by means of flyers and word-of-mouth at the technical faculty of the University of Southern Denmark. Upon arrival, they were asked to fill out a consent form and a brief questionnaire addressing their previous experience with robots and other technologies. Then, following [21], they were shown a video that introduced them to the task, the robot, to common errors (singularity, self-collision and too much pressure) and how they can be avoided, and to the respective control modality (see Fig. 3).

Then participants were led into the room with the robot platform, where they were introduced briefly to the equipment and the task. The task in all experiments reported on in this paper consists in the assembly of certain parts of the Cranfield set [20], a benchmark set for industrial peg-in-hole tasks. Participants had 20 minutes to finish the task. which consists of inserting a square peg and a round peg into a faceplate and adding a separator on top.

During the experiments, we automatically logged for how long the robot was operated. Furthermore, the demonstration path was recorded. These data serve as the basis for the quantitative analysis below. In addition, the experiments were carried out using think-aloud protocols [23]. The task to verbalize one's cognitive processes can however be quite awkward since traditional think-aloud methods emphasize the passive role of the researcher during usability testing [24]. However, speaking aloud to oneself while being observed is neither common nor socially very accepted [25], [26]; it can easily create an unnatural and awkward atmosphere, which can influence the results negatively [27]. Boren & Ramey [26] therefore suggest to turn the experimental situation into a dialog between participant and experimenter. For that reason, participants were told that the robot operator needed to remain informed about what was going on during the demonstrations, and three facilitators kept the dialog going during the experiments. In particular, when a participant stopped verbalizing his or her thoughts, neutral and open questions were asked like "What are you thinking?", "What is going on?", "What would you tell the robot?", "Did you expect this?". When a participant produced non-verbal signals like laughing, sighing or frowning, or short verbal cues like "oh" "ah," one of the three facilitators asked the participant to explain the situation and what exactly caused this reaction. Especially non-verbal cues happen unconsciously and reflect the participants' opinion in an honest way [25]. At the end of the sessions and during waiting times (e.g. during system restarts due to error), the facilitators asked the participants open questions like "How do you like the speed of the robot?", "What do you think of the shape of the control device?", "Which part of the robot do you think you control?" and "Which part of the robot would you like to control?" (cf. [28]). In addition, methods from participatory design were used to inspire users to express what they would like a control device to be like. In particular, we handed users tangible prototypes' [29] such as toys and a handheld gaming device to address their perceptual motor skill and senses and to generate design ideas with regards to a variety of properties such as size, shape, weight, material, and technical functionalities, thereby inspiring comments and reflections on multi-sensory aspects of the prototype.

C. Data Analysis

The analysis concerns whether participants fulfill the task (success rate), how fast they perform it (efficiency), and how many mistakes they make during their performance (effectiveness). A task is complete when all three objects are placed correctly within 20 minutes. The level of efficiency is determined by how quickly a user can complete a task [25], which means that only completed actions (i.e. inserting the pegs and the separator) are included in the calculations. In order to measure the timing equally for every participant, we apply two measures: interaction time, which consists only of the time the robot was being moved, and total time, which includes the time to choose a grasp mode, which comprises either the communication with the robot engineer or the operation of the numpad. Not included are situations in which the robot needed to be restarted or when the participants stopped in order to answer a question.

To determine the error rate (effectiveness) for each modality the following rules applied: A participant makes a mistake whenever s/he moves the robot in a position that can lead to damage to the robot arm. These positions are a) too much pressure applied to the gripper's fingers, b) singularity and c) self-collision. When participants apply too much pressure on the fingers this is indicated by the fingers or the faceplate being pushed into the foam. The robot is moved into singularity if the base, the shoulder and wrist 1 are aligned (Fig. 3). Self-collision occurs when two parts such as the robot gripper and the elbow of the robot collide with each other (Fig.3). Most of the times when the robot arm is moved in one of these positions, a security stop occurs.

Moreover, as a measure for data quality for learning from demonstration, we compare the lengths of the trajectories demonstrated; Fig.4 illustrates the demonstrated paths (reconstructed from the video) – they were automatically logged and measured. The qualitative analysis concerns the verbal statements uttered by the participants during or after the testing gathered from the video recordings of the experiments. The statements are collected and categorized according to their content.

D. Results

The three control modalities produce very different success rates for the task, which consists in the placement of two pegs and a separator within a time frame of 20 minutes. Participants employing kinesthetic guidance had a 100% success rate. Participants using the control panel succeeded in the completion of the task 93% of the time. In contrast, participants using teleoperation by means of the data glove have a success rate of only 79%. In the teleoperation condition, three participants succeed in placing only the two pegs, two participants succeed in placing only a single peg within the time frame given, while one participant does not succeed in placing a single peg.

The three demonstration techniques differ also regarding the number and type of errors occurring: In all 18 interactions via kinesthetic guidance, there is one problem regarding singularity and one problem regarding too much pressure. In the

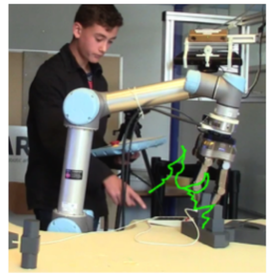


Fig. 4: Paths demonstrated (reconstructed from video)

TABLE I: Results on the efficiency for the three modalities

	Mean path length in m (sd)	Mean interaction time in sec (sd)	Mean total time in sec (sd)
Data glove	2.14 (1.46)	52.55 (38.5)	121.02 (104.54)
Kinestethic guidance	1.27 (0.76)	18.35 (10.82)	37.17 (22.55)
Control panel	1.18 (0.37)	40.13 (20.24)	117.34 (115.57)

interactions via the control panel, there are two instances of singularity and three instances of too much pressure. Finally, in the interactions via teleoperation, there are nineteen instances of singularity, six instances of too much pressure, and in addition five instances of self-collision or twisted arm (see Fig.3).

Regarding efficiency, the three control modalities differ according to interaction time, total time and length of demonstration path as seen in table I.

An ANCOVA reveals a significant effect of the control device on total time of demonstration after controlling for the effect of type of object (i.e. square peg, round peg and separator), $F(2,118)=24.637$, $p<.01$, partial $\eta^2=0.29$. Tukey post-hoc testing reveals that this effect is due to significant differences ($p<.01$) between kinesthetic guidance and the other two control modalities. In addition, the difference between the control panel and the data glove is marginally significant ($p<.06$).

Regarding interaction time, the ANCOVA reveals a significant effect of the control device (after controlling for the effect of type of object), $F(2,118)=13.58$, $p<.01$, partial $\eta^2=0.19$. Tukey post-hoc testing reveals that this effect is due to significant differences between the data glove and kinesthetic guidance ($p<.01$), and between the control panel and kinesthetic guidance ($p<.01$).

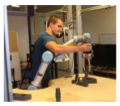
Finally, we find a significant effect for the length of the demonstrated path: $F(2,118)=14.010$, $p<.01$, partial $\eta^2=0.19$. Tukey post-hoc testing reveals that this effect is due to significant differences between the data glove and the other two control modalities.

Table II exemplifies the participants' comments about the usability of the respective robot operation modalities.

E. Discussion

The comparison of the three different control modalities has shown that kinesthetic guidance is superior to the other two

TABLE II: User statements about the three control modalities

	✔	✘
 teleoperation via data glove	"it feels natural" "it's fun" "it feels like an extension of my own arm, quite easy" "it's easy for big movements" "rotation is easy"	"I thought it would be easier, but it is really hard to control" "I can't seem to control it" "the robot is not exactly doing what I want" "placing the peg is difficult" "I feel zero in control" "it's illogical" "it's very sensitive"
 operation via control panel	"good when you have bad motor skills" "rotation is easy with just one joint" "I am sure what I am doing" "not afraid of destroying anything"	"the hardest problem is which button does what" "it is getting on my nerves that it takes so long" "I have to think about what I'm doing, I cannot do it by instinct" "I don't know how the robot will translate my actions" "the down adjustment is difficult" "it is just very very hard"
 kinesthetic guidance	"when you move it with your hand, you know exactly what will happen" "it is pretty easy to rotate it" "the positioning is easy" "you can be exactly in control" "the big movements are quite ok"	"it was too heavy and too uncomfortable" "I was afraid it could fall" "I am really not strong enough" "my arms are not quite long enough" "this is hot" "I don't think this is good for high precision work" "when you do these small movements it is difficult"

kinds of PbD in terms of number of errors, success rate and speed, yet it is about equal with the control panel regarding accuracy (as measured by the length of demonstrated path). Regarding usability, participants felt in control when using kinesthetic guidance and found it easy to position the robot in the ways desired, even though they were more content with larger movements than with finetuning, complained about the robot becoming hot and found it heavy to hold onto especially during the demonstrations of smaller movements. Thus, while kinesthetic guidance is the fastest and least error-prone way of teaching the robot, the large size (and hence weight) of the robot arm as well as its temperature make it less comfortable to use.

The control panel, which allowed users to move each joint separately, turned out to be easy to use, and it gave the participants the feeling of having precise control over the robot's movements. This corresponds to the very good results on accuracy (in terms of length of paths demonstrated). However, the control panel was also slow, and the participants complained about the interactions being tiresome and exhausting since it involved a lot of planning.

Finally, teleoperation by means of the data glove was the slowest, and the demonstrated paths were significantly longer than those of the control panel and kinesthetic guidance. Many participants using the data glove comment positively on the intuitive handling of the robot, yet there are as many comments stating that handling is actually unintuitive, suggesting that the apparent ease of teleoperating the robot by means of the glove is actually misleading. The most important negative comment concerns the feeling of not being completely in control.

Furthermore, teleoperation by means of the data glove was significantly less effective in terms of errors produced and longer in terms of time necessary for each demonstration. Participants also report that larger movements and rotation are easy, yet that control is very sensitive and that fine movements are difficult.

The results on the different control modalities thus show that kinesthetic guidance yields the best results; the advantage of kinesthetic guidance over teleoperation in terms of speed and usability was also noted by Akgun & Subramarian [11]. However, kinesthetic guidance shows some usability issues – some of which may be due to the particular robot version we used;[2] nevertheless, teleoperation would still be useful in circumstances in which the robot is unreachable or which involve dangerous goods (see [4]). The question thus arises whether the shortcomings of teleoperation identified can be overcome.

We take the comments from our participants during the experiment as a starting point for the improvement of teleoperation; what participants liked best about the control panel and kinesthetic guidance was that they have a good sense of control with these two operation modalities. As the demonstrated paths show, this sense of control must be independent of the number of joints controlled at the same time; while participants liked the control panel for its transparency ("they know what they're doing"), the amount of planning necessary to make certain types of movements when they could only rely on one joint at a time proved time-consuming and counterintuitive. Participants' sense of control must thus result from something else than the number of joints moved simultaneously. We suggest that it is the free choice of control point that makes kinesthetic guidance so much more accurate, intuitive and usable. A post-hoc analysis of the kinesthetic guidance teaching sessions shows that participants switched the ways in which they hold their hands 39.86 times on average, ranging from 18 to 65 times when handling all three Cranfield items. For the round peg, for example, participants switched their holds 4-24 times, and 10.79 times on average, for the separator the range is 8-26 with an average of 17.64 times. Thus, participants controlled

[2]The gravity compensation in the UR arm used in this paper is implemented without torque sensors in the joints, but using measurements on the motor currents. This resulted in a rather stiff robot with high friction in joint 1 to 3. This problem can be avoided by using a different robot or even with a newer version of the same robot.

the robot from many different control points; in contrast, in teleoperation the robot uses only a single point, which is usually the tool center point.

What participants liked about the data glove was that it felt a bit like self-extension, given the similar morphology of the robot arm and the hand in the glove, as well as the ease with which the robot can be operated. Regarding the types of movements, participants had problems with fine movements with all three operation modalities. The only device that allowed users to make large horizontal movements easily was the control panel; in general, paths demonstrated by kinesthetic guidance and especially the control panel are significantly shorter than those of teleoperation with the data glove.

In the following, we investigate whether the shortcomings of teleoperation, especially the lack of control users were experiencing with the data glove, disappear if users can switch between control points as they can in kinesthetic guidance. For that purposes we designed a novel teleoperation device to replace the data glove.

V. Device Design

Given the results from Study I, the following design criteria for teleoperation emerge:

- it should be possible to switch between control points;
- there should be different control options for large versus small movements;
- it should be intuitive when to use which control point;
- the similarities between robot morphology and human morphology should be exploited.

In order to provide users with the possibility to switch between control points, we created a novel teleoperation device in which the dead man's switch is integrated into the teleoperation device in such a way that the user implicitly informs the robot which control point to use. The device thus provides two kinds of signal: First, the 6D pose of the trakSTAR sensors, which is sent to the trakSTAR control unit; second, the information which button is pressed is sent to the phidgets board, allowing the robot to choose the intended control point. The device thus allows users to switch between the control of large versus small movements by choosing two different control points on the robot (see Fig.6).

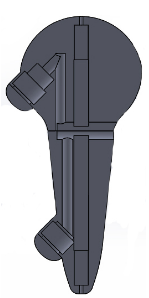


Fig. 5: Techical drawing of new device)

To make the choice of the appropriate button intuitive, the device was shaped in a way that suggests intuitively two different holds that correspond to two different activities: The hold for large movements exploits the similarity between the human arm and the robot arm. That is, in order to press the upper button, the user has to hold the device in a way that naturally invites large movements (see Fig.6). In order to press the lower button, the participant has to hold the device like a pen, thus inviting small, finetuning movements (see Fig.6). Each of the buttons is connected with one of the trakSTAR sensors and has its own control frame on the robot: the tool center point for the large movements and a control frame around the insertion zone (see Fig.6 and [19]).

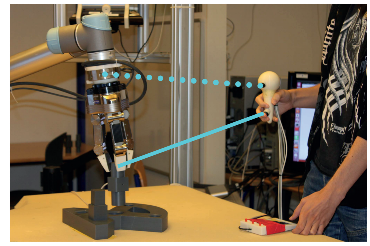


Fig. 6: New device with two buttons corresponding to two robot control points (tool center point and finger-level)

We pilot tested the device in the same scenario in which the other studies were carried out and found that if participants believe that the two buttons just constitute alternative ways for operating the robot, they do not switch between the two holds (only 13% used both buttons). Unfortunately our initial introduction video seemed to suggest this interpretation. We thus redesigned the video in such a way that we let participants know that their choices mattered. The analysis of this trial shows that users indeed switch between the control points for large versus small movements, and that in only 8.8% of all actions, the wrong button was used. While it would be desirable that users chose the buttons correctly even without an introductory video, we can still conclude that the device is effective in the way it was designed to function.

VI. Study II

To test whether the novel device can make up for the problems with teleoperation observed in Study I, we elicited a comparable set of interactions.

A. Participants

Sixteen students and staff from the technical faculty at the University of Southern Denmark (fourteen male, two female) between 18 and 39 years old participated in this study. On a scale from 1 (little experience) to 4 (much experience), they report an average experience with robots of 1.94 and with games of 2.87.

B. Technical Set-up

The technical set-up was identical to the one used in Study I, as was the material used (four items from the Cranfield set).

C. Procedure

The introductory video explained to the participants not only what errors to avoid (singularity, self-collision, too much pressure), but also how the device was used and that the upper and lower button correspond to large and small movements respectively.

D. Results

The results show that the new device is significantly better than the data glove on all measures; in particular, when we compare all four operation modalities, it turns out concerning the length of the demonstrated paths that the new device

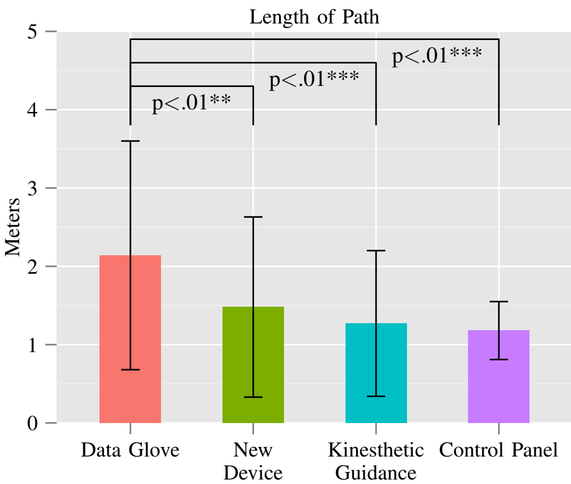


Fig. 7: Length of demonstrated paths of all four control modalities

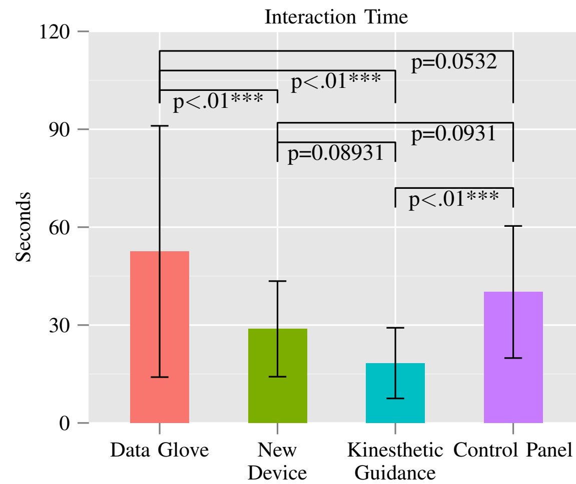


Fig. 8: Interaction times of all four control modalities

is significantly better than the data glove, while not being significantly less accurate than the other two operation modalities (F(3,162)=10.42, p<.01, partial η^2=0.16 (controlling for the effect of type of object, i.e. round peg, square peg and separator), see Fig.7).

Regarding interaction time (Fig.8) there is a significant difference between the data glove and the new device (F(3,162)=21.676, p<.01, partial η^2=0.29). Tukey post-hoc testing reveals that this effect is due to significant differences (p<.01) between the data glove and the new device, the data glove and kinesthetic guidance, and the control panel and kinesthetic guidance. In addition, there are marginally significant differences between the control panel and the data glove (p<.06), the new device and kinesthetic guidance (p<.09), and the new device and the control panel (p<.09).

Finally, regarding total time (Fig.9), the new device is faster than teleoperation by means of the data glove and faster than the control panel. An ANCOVA reveals a significant effect of the control device on total time after controlling for the effect of type of object, F(3,162)=11.809, p<.01, partial η^2=0.18. Tukey post-hoc testing shows that the general difference between conditions is due to significant differences between the data glove and the new device (p<.01), the data glove and kinesthetic guidance (p<.01), the control panel and the new device (p<.05), and the control panel and kinesthetic guidance (p<.01).

Regarding the number of errors, users generally produce 1.2 errors on average, while one exceptional participant produces 12 errors..

In general, the number of errors is thus much lower than during teleoperation with the data glove. The analysis of users' comments shows that users have a good sense of control: "very responsive and easy to control;" "pretty intuitive once you get to know it:" "like a pencil." Negative comments concern mostly the relatively clumsy design of the device, for instance, the fact that users have to use both hands to switch between the two holds and the cables in the middle.

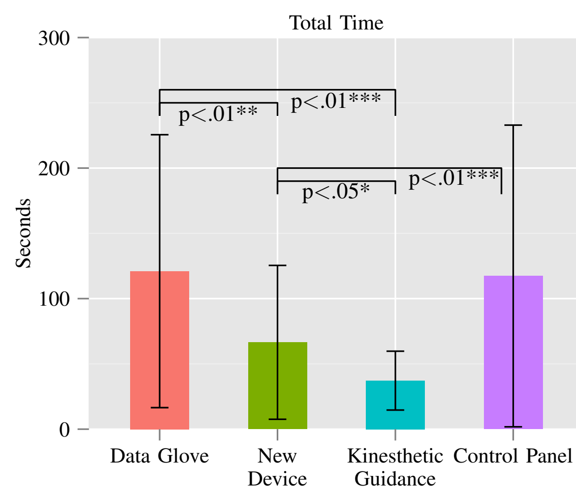


Fig. 9: Total time of all four control modalities

VII. Conclusion

The two studies presented show that the type of control used during PbD has a considerable impact on efficiency, effectiveness and the quality of the data for LfD in terms of the length of paths demonstrated. Furthermore, the different control modalities differ with respect to usability and their usefulness in different situations. Moreover, the results of Study II show that the device by means of which the respective robot is teleoperated matters, especially concerning the opportunity to choose between different control points on the robot, similar to the possibility to choose different handholds during kinesthetic guidance. Here our results indicate that by allowing users to switch control points, the previously identified shortcomings of teleoperation can be compensated for, rendering teleoperation almost equally efficient and accurate as kinesthetic guidance. The comparison reveals in particular:

- **kinesthetic guidance**: is fast, produces few errors, and is intuitive; presented paths are slightly, yet not significantly longer than those from demonstrations via the control panel; users have a good sense of control; the usability of kinesthetic guidance is compromised if the robot is large and/or heavy (or remote, dangerous etc.);

- **control panel**: allows for remote control and produces few errors, yet is very slow; it is mostly intuitive to use, yet requires careful planning; paths presented are the shortest of all modalities compared; regarding usability, users have a good sense of control and robot behavior is transparent, yet the interactions are tiresome and exhausting since they involve considerable cognitive effort;
- **teleoperation**: depends on the device
  - with the data glove, teleoperation is slow and produces many errors; its apparent intuitiveness is partly misleading; presented paths are longer than in any other control modality;
  - with the new device, teleoperation is almost as fast as kinesthetic guidance; it is intuitive and fun; efficiency and presented paths are almost as good as those from kinesthetic guidance.

VIII. Limitation and Future Work

While the new device increases the efficiency and effectiveness of teleoperation for PbD, its design still needs to be improved; the participants mentioned several usability issues, such as the placement of the cables and the shape and weight of the device, and there were still 8.8% of actions in which participants overused the upper button This will thus be the next task to address. Furthermore, there are many other possible operation modalities, such as joysticks or haptic devices, whose usefulness in comparison to the demonstration modalities investigated is sill open. Finally, different types of robots and the effect of robot complexity should be investigated.

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