Vibrotactile Feedback for Aiding Robot Kinesthetic Teaching of Manipulation Tasks

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***Abstract*— Kinesthetic teaching is a viable solution for programming robots in the execution of new tasks thanks to the human-mediated mapping between the task objectives and the robot joint space. Redundant designs and differences from human kinematics pose challenges in the efficient execution of the teaching task. In this work we employ vibrotactile feedback letting operators understand specific kinematic constraints such as reaching joint limits and singularities. The experimentation with a Baxter robot and a four-motor vibrotactile bracelet is reported showing the effectiveness of the proposed enhancement to the kinesthetic teaching task.**

I. INTRODUCTION

In learning-by-demonstration teachers use their own body to give demonstrations to the robot. It is more natural and intuitive. However, mapping demonstrations from the user to the robot creates a correspondence issue. Collecting these demonstrations also requires to track and estimate accurately the user's pose. Kinesthetic Teaching (KT) overcomes several of these issues: the teacher physically manipulates the robot to provide a demonstration recorded by the robot's sensors. Hence, there is no correspondence problem. However, many users struggle to provide good demonstrations due to their inexperience in manipulating complex robots featuring several Degrees of Freedom (DOF) [1].

Feedback can easily be given to the teacher to help refine demonstrations. Feedback is typically provided either during the demonstration or after the end of the demonstration. Haptic feedback is often provided when users are physically manipulating or teleoperating the robot to make it easier to control [2]. Other systems provide feedback by playing the completed demonstration back to the teacher, so they can evaluate its success [1]. This, however, involves many playbacks that are time consuming.

The human operator has to avoid paths where the robot loses degrees of freedom, such as along the boundaries of the robot workspace or in singular configurations. Thus, the robot's performance is still linked to the quality of demonstration. In this regard, the use of vibrotactile feedback is versatile and useful to increase the level of intuitive perception and interaction with the environment. Vibrotactile feedback is generated by devices applying vibratory stimuli to the human skin. During last years, vibrotactile devices have not only been used to support visually impaired users, but also to develop more and more applications, for assisting sighted persons.

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In this work, we explore the use of a haptic vibrotactile bracelet to enhance the awareness of the human operator during KT with the objective of improving the quality of the demonstrated trajectory. In particular the paper adopts two vibrotactile feedbacks presented to the user while he's manipulating the robot. These feedbacks have been chosen with the objective to minimize corresponding qualities of the resulting trajectory.

We performed tests on the Baxter Research Robot. These tests aimed to verify the efficacy of using vibrotactile feedback during the demonstration of a manipulation task by KT. The paper is organized as follows: next section introduces the related works, then follows a section that describes the overall framework and system setup. Section 3 presents the vibrotactile device, the proposed feedback, and the planned feedback strategy. Following sections are on the description of experimental evaluation and the achieved results.

II. RELATED WORKS

Compliant and redundant robotic arms have improved the application possibilities but this also means that these systems face new situations in which they have to be programmed, taking into account task and environmental constraints. Among the different demonstration based approaches to robotic programming [3], KT involves the physical contact with the robot thanks to compliant kinematics. KT deals with the demonstration of the activity in task space and/or specific motion trajectories in situation on redundant solutions. User studies in KT have shown the effectiveness of KT for teaching environmental constraints [4], [5], while other works have investigated supporting techniques for improving KT. Cha et al. [6] combined KT with a simulation based interface for supporting the programming of motion models based on dynamical systems. Others have investigated the information flow from the human to the robot by means of tactile sensors on the robot body [7].

In this work we are interested in exploring augmented feedback for improving the KT task, in particular by means of vibrotactile devices, as a specialized form Human-Robot Interaction [8]. Other types of feedback have been experimented such as table-top projective interface [9] or possibly wearable devices [10].

There is a wide spectrum of uses of vibrotactile devices in the literature: collision feedback [11], guidance [12], [13], [14], force feedback in telemanipulation [15], remote control and teleoperation [16], [17], [11]. This spread is basically due to the following reasons [18]:

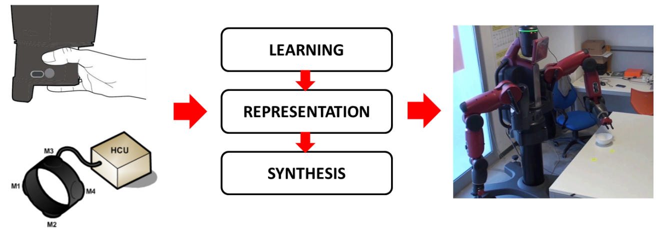

Fig. 1. The proposed framework: kinesthetic teaching and vibrotactile feedback used to teach the Baxter robot.

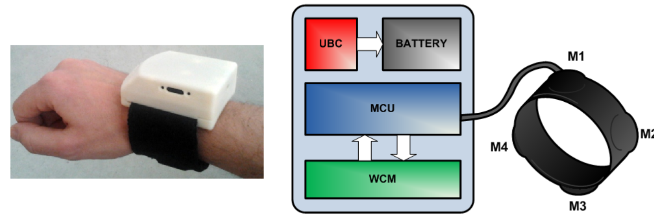

Fig. 2. The HB worn on the user's wrist (left). Schematic representation of the HB (right) composed of: the MicroController Unit (MCU), the USB Battery Charger (UBC), and the Wireless Communication Module (WCM).

- The tactile channel is less overloaded. In fact, visual and auditory channels may be overload with information, thus resulting in a rapid error increase and in a consequent reduction in overall user performance.
- Vibrotactile stimulation allows for displaying information in an unobtrusive way.
- Finally, it is also a quite intuitive form of feedback because the stimuli are directly mapped to body coordinates (e.g., the user simply follows the direction of vibrotactile stimulation).

Studies have demonstrated that vibration is best on hairy skin due to skin thickness and nerve depth, and that vibrotactile stimuli are best detected in bony areas [19]. In particular, wrists and spine are generally preferred for detecting vibrations [20].

III. Framework and System

A. Framework

Figure 1 shows the framework overview. The Haptic Bracelet (HB) aids the human operator during the kinesthetic teaching of manipulation tasks of the Baxter robot. To encode the robot motion, we employ motion representation of the end-effector decomposed in action primitives [21] and represented with splines in SE(3). This representation allow to preserve the shape representation and easy re-targeting. Splines also feature a good accuracy of evaluation and a good capacity to approximate complex shapes. In the end we execute the playback of the representation on the Baxter robot to evaluate the result of the demonstration. The target task is a manipulation task consisting of a pick-and-place operation executed on a table.

There are a lot of possibilities of what feedback could be provided to improve the quality of the demonstration (see [22] for a discussion about feedback modeling in general). We considered to use feedback to let the teacher avoid paths where the robot loses degrees of freedom, such as along the boundaries of the robot workspace or in singular configurations. Due to these considerations, we use two vibrational feedbacks: (1) to indicate when the robot is close to the limit of a joint and (2) to indicate when the robot is close to a singularity.

For both these feedbacks we need to introduce a metric that is then used to generate the stimuli. For the joints we'll employ the joint limits from the robot kinematics. For the other feedback we choose to adopt the following index of manipulability ω [23]:

$$\omega = \sqrt{det\left(JJ^T\right)} = \prod_i s_i \tag{1}$$

where J is the task Jacobian and s_i are its singular values.

IV. Vibrotactile Device

Although more complex bracelets have been recently proposed in the literature, e.g., [24], in this work we employ an inexpensive and mechanically simple device designed in previous work for navigation purposes [25]. The haptic device, called HB and employed for providing vibrational feedback to the teacher, was designed starting from our previous research results on haptic devices. In Figure 2 we show our bracelet, the idea is similar to the one presented in [16].

The vibrating motors are distributed over the wristband in order to be in contact with the center of the dorsal (top - motor M1), ventral (bottom/palm - motor M3), inner and outer lateral sides of the wrist (motors M2 and M4). This configuration results in a minimum distance between the actuators of about 4 cm that is higher than the two-point discrimination threshold [19], allowing a reliable subjects spatial detection. Such a low spatial information density around the wrist has a beneficial effect both on the information transfer and on the level of attention in the primary task.

Among the possible approaches for the transmission of the mechanical vibration to the skin the HB employed is based on a rotary cylindrical motor with an eccentric mass mounted on its shaft, then placed in a custom-designed frame manufactured with rapid prototyping. Each frame can be easily anchored to the stretchy fabric.

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A. System Setup

The data flow can be summarized as follows. The external PC sharing the ROS environment with the Baxter robot, receives the position information of the robot end-effector. Depending on the feedback strategy the software maps the robot state to commands for the HB for each of the 4 vibration motors. The HB is controlled via Bluetooth at a maximum rate of 100Hz.

Joint Naming Convention

- **S0** - Shoulder Roll
- **S1** - Shoulder Pitch
- **E0** - Elbow Roll
- **E1** - Elbow Pitch
- **W0** - Wrist Roll
- **W1** - Wrist Pitch
- **W2** - Wrist Roll

Fig. 3. The diagram of the Baxter's joint names.

Joint	Min limit (deg)	Max limit (deg)	Range (deg)
$S0$	-97.494	+97.494	194.998
$S1$	-123	+60	183
$E0$	-174.987	+174.987	349.979
$E1$	-2.864	+150	153
$W0$	-175.25	+175.25	350.5
$W1$	-90	+120	210
$W2$	-175.25	+175.25	350.5

TABLE I

THE RANGE OF MOTION FOR EACH JOINT OF THE BAXTER'S ARM IN DEGREES.

B. Kinesthetic Teaching and Vibrotactile Feedback

Kinesthetic teaching exploits the Zero-G mode of the Baxter robot. In the Zero-G mode the controllers are disabled and the arm can be freely moved across the workspace. This mode can be enabled by grasping the cuff over its groove as shown in Figure 1. Learning consists in recording the trajectory of the end-effector with the gripper states and in obtaining a representation of this trajectory.

Baxter robot has two seven DOF arms. A labeled diagram of the Baxter's arm joints can be found in Figure 3.

We have chosen vibrotactile feedback types to help the teacher during the kinesthetic demonstration. The first feedback type indicates that any joint of the robot arm is close to its limit. In Table I is presented the range of motion for each joint in degrees.

The second feedback indicates when the robot arm is close to a singularity thanks to the manipulability measure 1.

For the proposed tasks two main strategies of feedback can be identified: proportional stimulation and symbolic. Both depends on the association between the stimuli and a target measure. In the former approach the vibration is triggered progressively when the target measure exceeds a threshold and the vibration is increased in energy as the measure grows. This approach is similar to the one of haptic guidance and it has been used both for robots [26] and human training [13]. The other approach is based on the creation of distinctive vibrotactile patterns that define an alphabet.

In this work we opted for the symbolic approach due to the fact that both the joint limits measure and the singularity measures are not naturally associated to a linear function as occurs with distance metrics.

Pattern name	T (sec)	D (sec)	n
$attention$	1	0.08 $\Rightarrow$ 8%	255
$alarm$	0.5	0.2 $\Rightarrow$ 40%	255

TABLE II

THE VALUES OF THE FOUR PARAMETERS OF THE VIBRATION PATTERNS USED IN THE KINESTHETIC TEACHING.

In the following, we describe the type of indication which we give to the teacher for each feedback in the two conditions:

- `joint attention`. It's a continuous wave which we use when the teacher is starting to be close to a limit. It's just a warning, so the duty cycle is small. For the joint limits we give this feedback when any joint of the Baxter's arm is in the range of 10 degrees close to the limits presented in Table I.
- `joint alarm`. It works similar to the previous signal, but here the duty cycle is higher to have a more intense wave which indicates that we are very close to a limit. For the joint limits we give it when a joint of the Baxter's arm is in the range of 5 degrees close to the limits presented in Table I.

The singularity measure is a non-negative value and for this reason it is sufficient to identify two positive thresholds: 0.07 for attention and 0.04 for alarm.

All the values for the feedback have been chosen by preliminary experimental trials.

Finally in Table II we report the two vibration patterns that we use for the feedback using the convention: T is the pulsing period of the square wave (seconds), D is the duty cycle (seconds) and n is the number of pulses.

We send the feedback of the joint limits to the motors $M1$ and $M3$ (see figure 2) and the one of the singularity on the motor $M2$, to avoid the overlap of the signal.

There are two potential issues with the fact that we convey multiple joint limits to a single stimulus and that there is no indication of the directionality of the joint limit. This is a general problem of disambiguation but in practice with kinesthetic teaching the operator has some physical indication of the moving joints and their direction. The missing information could be provided by means of multimodality (e.g. visual stimulus) or separating the effects of the two motor $M1$ and $M3$ although this would require someunderstanding of the orientation of the bracelet in space.

V. EVALUATION

For the evaluation of the concept we employed a manipulation task consisting of a pick-and-place operation executed on a table. The task environment is reported in Figure 4: take an object from the table and put it in a bowl with a small wall created purposely for letting the user reach possible situations of joint limits or singularities.

Each experiment consists of four parts: introduction, training, demonstration, interview. In the introduction, we explained to the users the task to teach to the robot, and

Fig. 4. The task workspace for the experiment: the Baxter robot, a bowl and an object inside the bowl.

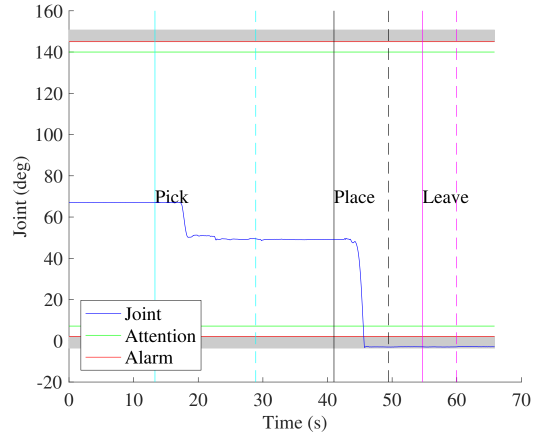

Fig. 5. Example of user demonstration, showing left wrist motion with the attention/alarm boundaries (green and red respectively), and the segmentation in the three phases.

the users signed the consent form for the execution of the experiment. At training session the participants were allowed to learn to use the system and the vibrating stimuli, in case of demonstration with HB. If the subject was struggling with the system, we offered participants some advice. The demonstration consisted of teaching the task to the robot, with or without the HB. After the experiment, we interviewed each participant. We adopted a within-subject design where each user provided two demonstrations: one with the HB on the wrist and the other without it. The ordering of the demonstrations was counterbalanced to negate ordering effects.

For the quantitative analysis we collected data of each execution for performance assessment at 100Hz: robot joint values (7 joints), manipulability index and activation level of the bracelet. The actions of each subject has been segmented in the three phases of robot motion: pick, place and leave.

We defined the following target metrics to be analyzed:

- task duration
- percentage of time spent in one of the attention or alarm regions for both joint and singularity (4 measures in total).

In addition to the quantitative analysis, the users answered 6 questions taken from the NASA Task Load Index (NASATLX) [27] and the System Usability Scale (SUS) [28] on the 5-point Likert scale.

1) The system required low mental and perceptual activity (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.).
2) The system required low physical activity (e.g. pushing, pulling, turning, controlling, activating, etc.).
3) I was successful in accomplishing the goals of the task set by the experimenter.
4) I thought the system was easy to use.
5) I would imagine that most people would learn to use this system very quickly.
6) I felt very confident using the system.

Finally we asked general demographic information such as their age, gender and their knowledge about kinesthetic teaching, joint limits and singularity concepts and implications.

VI. Results and Discussion

We report first the quantitative assessment then the qualitative. We recruited 10 participants, ranged in age from 25 to 43 (average = 32) years old. They were 80 % male and 20 % female, and all signed the consent form for the execution of the experiment. Almost all the participants knew the concept of joint limits and singularity, except one. Three of them have used kinesthetic teaching with robots before.

A. *Quantitative Assessment*

Each demonstration by the user lasted 1 minute in average (avg 62s, dev ±68s). The order effect due to the within-subject design has been tested using ANOVA over the three target variables duration, joint maximum distance, and joint mean distance. Order effect between groups was significant only for the duration ($p < 0.05$): in particular subjects using the HB in the first session performed quicker in the non-HB session, without affecting the other target variables.

In Figure 7 we show the statistics of the scores by condition: it results that joints feedback is affected by HB, while manipulability is not. Due to the fact that the attention level (L) is included in the alarm level (H) we report both the exclusive case L or H (disjoint) and the inclusive case LH (both attention and alarm).

In the end, we examined the graphs of joint and manipulability trajectories, as the one shown for example in Figures 5 and 6. The graphs indicated that people that used the bracelet in the first demonstrations performed better and cleaner demonstrations in the second ones when they had not bracelet respect people that started the first demonstrations without the bracelet.

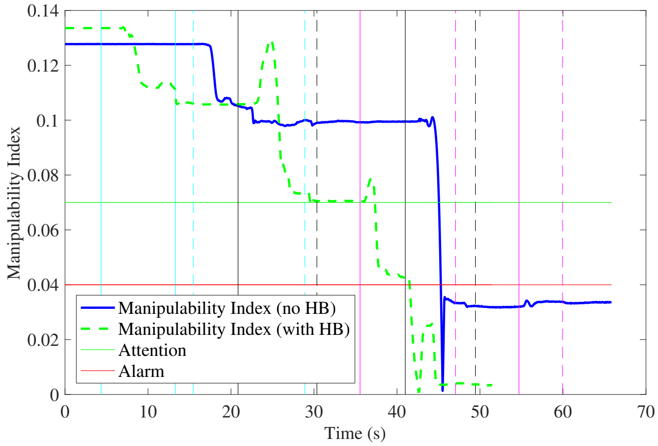

Fig. 6. Example of user demonstration, showing the left arm manipulability index in the case with bracelet (dashed) and without (solid). The attention boundary is shown in green, while the alarm is in red.

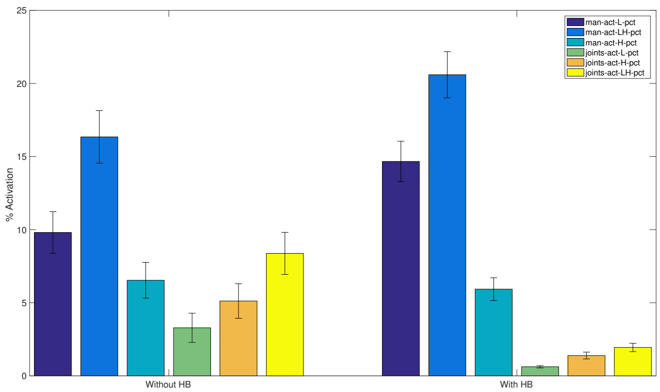

Fig. 7. Percentages (over duration) of exceeding of condition: high-low level for manipulability and joints. First group is without Bracelet, second group is with bracelet.

B. *Qualitative Assessment*

In Figure 8 we report the scores for the 6 questions answered by the users after the demonstrations. Level 5 means *Strongly agree* and level 1 means *Strongly disagree*. We expected the demonstration to be rated the most mentally demanding. However, participants rated the demonstration not mentally demanding. Instead, we discovered a more physical demand about the demonstration. Their comments indicated it was due to the difficulty in manipulating the robot.

Overall, participants rated the demonstration easy to use and with success. Participants felt they could learn to use the system quite quickly. Their ratings of confidence is little less than the easy to use and success. We interviewed the users also about their preferences and thoughts about the system. Participants preferred to use the system with the HB.

They commented that when using the system without the HB they were unsure whether the robot would be able to fit through the demonstration. Their comments indicated that it was due to two reasons: the first reason is that 7 people never used kinesthetic teaching with robots; the second reason is that they were not confidence about which direction to follow to move the arm out of a limit, after they have received an attention feedback. This work has focused on the event triggering while additional work is required for introducing directional feedback [14]. In our previous work [13] directional feedback was supported by the fact that the position and orientation of the wrist was provided by the task, in this case we should introduce a form of wrist tracking either based on cameras, inertial devices, eventually combined with touch sensitive surface on the robot body.

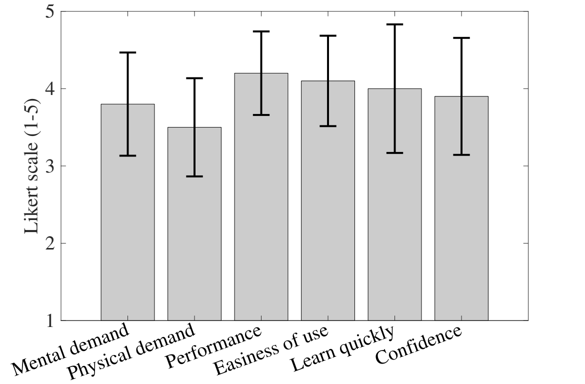

Fig. 8. Questionnaire results on a 5-point Likert scale. We report the average and the 95% confidence interval.

VII. Conclusion and Future Works

In this work we explored the use of vibrotactile feedback in combination with kinesthetic teaching. We have seen that the vibrotactile feedback can help the human operator who teaches the robot. It indicates problems during the demonstration like operating close to joint limits and singularity that influence the quality of the demonstration and which the human operator cannot see just with the eyes. We presented the results of the quantitative and qualitative analysis.

The next iteration of this approach is to see if this type of vibrotactile feedback can let people learn singularities and manipulability for improved kinestetic teaching without feedback.

Future research works will extend the framework to cope with more complex workspaces and feedback, thus to help the confidence of teachers. We will improve the system with other motion models as the time-invariant representation investigated in [29]. We will also try switching the kinesthetic teaching in the articular space [30] or using damped least squares in the neighborhood of singularities [31], [32] to get improvements. Finally this type of feedback could be integrated in the Augmented Reality wearable tele-operation we have experimented with the Baxter [33].

Additional material about this work is available on the website `https://github.com/eruffaldi/paper_vibroteach`.

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