On Handing Down Our Tools to Robots: Single-Phase Kinesthetic Teaching for Dynamic In-Contact Tasks

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Abstract—We present a (generalizable) method aimed to simultaneously transfer positional and force requirements encoded in a physical human skill (wood planing) from a human instructor to a robotic arm through kinesthetic teaching. We achieve our goal through a novel use of a common sensory configuration, constituted by a force/torque sensor mounted between the tool and the flange of a robotic arm. The robotic arm is endowed with integrated torque sensors at each joint. The mathematical model used to capture the general dynamic of the interaction between the human user and the wood surface is based on Dynamic Movement Primitives. During reenactment of the task, the system can imitate and generalize the demonstrated spatial requirements, as well as their associated force profiles. Therefore, the robotic arm acquires the capacity to reproduce the dynamic profile for in-contact tasks requiring an articulated coordination in the distribution of forces. For example, the capacity to effectively operate the plane on a wood plank over multiple strokes, according to the demonstration of the human instructor.

I. INTRODUCTION

In large part of traditional human manufacturing, the manipulation of materials is accomplished through the use of tools. Hence, investing some attention on the remapping of tool-mediated human skills onto robots should not strike as extravagant. Adapting or completely redesigning human tools for robotic applications is a vocational aspect of robotics. However, classical applications in robotics and automation tend to significantly override the existing human skill, often trading historically evolved, energetically efficient, dexterous interaction with the material (typical of skillful human manufacturing) for brute power.

Under a general perspective, the effective realization of such a remapping implies addressing two main challenges. On one hand, it requires the encoding of human procedural knowledge (i.e. ‘knowing how’ to do something – for example riding a bicycle [1]) into a machine, whose traditional methods require the encoding of declarative knowledge (i.e. ‘knowing what’ about something – for example having historical notions) in a formal language. On the other hand, it requires engaging in tasks where the distribution of force requirements in space and time across a physical interface tends to be the cause rather than the effect of positional specifications (in-contact tasks). In robotics, addressing these two challenges typically results in significant time and costs for software development.

Analyzing this problem with respect to current trends in robotics, we notice that several commercial robot manufacturers are currently contributing to a new generation of lightweight robotic arms provided with integrated force/torque sensing at each joint. Accurate joint torque measurements endow the robot with the capacity to estimate magnitude and direction of external forces presented at the end effector of the robot and, conversely, to deliver desired forces [2], [3]. Apparently, this class of robots is the perfect candidate for addressing the exploration of in-contact tasks. As their cost range makes them appealing even to small and medium size companies, the problem of reducing the costs for software development rises to the level of a strategic theme in contemporary society.

In this paper, we present a general method endorsing the transfer of a physical skill (i.e. the positional and force requirements encoded in wood planing) from a human demonstrator to a lightweight robotic arm, endowed with integrated torque sensors at each of its joints. Our objective is to offer the human demonstrator a general, intuitive and natural interface, minimally disrupting the fluent expression of the demonstrator’s skill. Such an interface is intrinsically built in order to avoid explicit translation of the embodied

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Fig. 1. The plane is rigidly attached to the flange of the robotic arm. Proceeding from the flange outwards: aluminum plate hosting the plane’s handles (a), force/torque sensor (b) and hand plane (c).
procedural knowledge of the skill into a declarative form. Therefore, our goal is achieved within the Programming by Demonstration paradigm (hereafter PbD [4], [5]) through kinesthetic teaching [6]. In contrast to other PbD methods (e.g. tele-operation, vision [7] and data glove [8]), during kinesthetic PbD a human demonstrator grabs the robot arm, configured to passively and smoothly follow the demonstrated motion (e.g. in a gravity compensation mode), and directly moves it while executing the task.

A mathematical model is necessary in PbD to encode the salient features of the demonstration. The model allows for the reenactment of the demonstrated task. However, its pivotal capacity is the generalization to new situations, based on single or multiple demonstrations, and for coping with contingent perturbations. In the current literature, many approaches explore the use of statistical [6], [9], [10] or dynamic models [11], [12], [13], [14], [15].

To date, the use of kinesthetic teaching for in-contact tasks has been rarely discussed in the robotic literature and is typically operated in two phases. A representative example can be found in [14], where a robotic arm is kinesthetically instructed about positional and force profile for simple in-contact tasks (ironing and opening doors). First, the demonstrator instructs the robot about the trajectory appropriate to the task. Second, the demonstrator creates and overlaps to this taught trajectory a force profile, obtained using an external haptic device.

Similar to [14], our paper describes an approach based on PbD and kinesthetic teaching. The method is used to directly transfer the dynamic of plane usage on a wooden plank from a human instructor to a robotic arm. The task requires an effective coordination between the action exerted in orthogonal and longitudinal direction with respect to the plank. Failure in achieving such a coordination likely results in the tool’s stall, as the blade might penetrate too deeply in the wood to be moved forward.

In addition to the relatively challenging task presented as our test bed, under a more general and theoretical perspective our approach offers a twofold contribution to the existing literature. First, for each demonstration, positional and force requirements characterizing the in-contact task can be simultaneously extracted through kinesthetic PbD (i.e. in a single-phase). Second, the use of the (arbitrarily chosen) haptic device can be avoided.

To achieve these results we propose a novel use of a common sensory configuration, where a force/torque sensor (hereafter F/T sensor) is mounted between the tool (plane) and the flange of the robotic arm. The demonstrator executes the task by grabbing the plane’s handles, adapted on a plate mounted just above the external F/T sensor (i.e. on side facing the robot’s flange, see Fig. 1). Force/torque and positional information can thus be simultaneously extracted. The demonstration offers to the human instructor a more intuitive and natural interaction with the robot (i.e. the demonstrator can execute the task in a more familiar form). Positional and force requirements remain intrinsically correlated in the demonstration, as during the normal execution of the task by the human. We model the demonstrated positional and force features of the task by Dynamic Movement Primitives (DMP, [11], [12]), due to the model’s flexibility, intrinsic capacity of spatial and temporal generalization and capacity to manage perturbations during reenactment.

In the remainder of this paper, we will describe the system requirements for the replication of our method, present the mathematical framework chosen for PbD and details about our proposed controller (Section II). We will then introduce our specific setup and wood planing experiments (Section III), followed by an analysis of our results (Section IV). Finally, we will discuss our results within state of the art PbD for in-contact tasks, highlighting directions for future investigations (Section V).

II. METHOD

A. System Description

The proposed method requires a robotic arm with multiple degrees of freedom and integrated torque sensors at each joint, that make it capable of programmable active compliance, gravity compensation and Cartesian impedance control. Its overall control cycle must approach 1 kHz, to allow effective force control.

Crucially, a six-axis F/T sensor with appropriate sensing range and accuracy is rigidly mounted between the robot’s flange and tool (Fig. 1). The tool consists of a small commercial plane, adapted to the F/T sensor. In order to meet the requirements for our method (i.e. the necessity to apply forces above the flange side of the F/T sensor during demonstration) the original handles of the plane are mounted on a custom-built aluminum plate that approximates the original geometric specifications of the tool handles. A standard pine plank is clamped to a table within reaching distance from the robot.

B. Dynamic Movement Primitives

The DMP model has emerged in robotics within the PbD paradigm. For a detailed treatment of the model, of its general properties and examples of applications in robotics, we refer the interested reader to the existing literature [11], [12]. In the present section we summarize the main equations of the model.

Any state space can be used with DMP. As an example, this work uses of an extended eight dimensional Cartesian space $\mathbf{y} = (y_x, y_y, y_z, y_{q_0}, y_{q_1}, y_{q_2}, y_{q_3}, y_fz)^T$. The Cartesian position is defined by $\mathbf{y}_{\text{tran}} = (y_x, y_y, y_z)^T$. The orientation is represented by the four components of the quaternion $\mathbf{y}_{\text{rot}} = (y_{q_0}, y_{q_1}, y_{q_2}, y_{q_3})^T$. The force in tool $z$ direction is given by $y_{fz}$.

The DMP model isolates and independently treats each dimension of the desired behavior (generically indicated with $y_d$ in the rest of this paper). Limiting our focus to discrete motions only (more in general, cyclic behaviors can also be modeled by DMP), the mathematical model used for each dimension can be visualized as its mechanical analogue: a spring-damper system (transformation system). Therefore, the transformation system would naturally relax
from its initial stretched position to its final steady-state point attractor. The former corresponds to the initial value for the specific dimension during the demonstration and the latter to the final value (goal). This is mathematically expressed as

\[ \tau \dot{y}_d = \alpha_z (\beta_z (g_d - y_d) - \dot{y}_d) + f_d(x), \]

where \( \tau \) is a temporal scaling factor, \( g_d \) is the goal and \( y_d, \dot{y}_d \) are current value, first and second derivative of the considered dimension (either positional or force information). The positive parameters \( \alpha_z \) and \( \beta_z \) are related to stiffness and damping of the transformation system (critically damped for \( \beta_z = \alpha_z/4 \)).

The term \( f_d(x) \) in Eq. (1) (nonlinear function approximator) acts on the transformation system, modulating the evolution of its asymptotic convergence. It is implemented as a normalized linear combination of basis functions, scaled by the term \( \xi(x) \):

\[ f_d(x) = \sum_{i=1}^{N_w} \Psi_i(x) w_{i,d} \xi(x) \]

with:

\[ \Psi_i(x) = \exp \left( -\frac{1}{2\sigma^2} (x - c_i)^2 \right). \]

Therefore, \( f_d(x) \) is the sum of \( N_w \) external forcing terms \( \Psi_i(x) \), centered in \( c_i \) and each having limited effect in time (see below for the relation between \( x \) and time) according to a Gaussian function parametrized by \( \sigma \). Each forcing term \( \Psi_i(x) \) in the sequence is scaled by a weighting factor \( w_{i,d} \), identified for each dimension in order to appropriately stretch/compress the spring-damper system over time, thus allowing accurate reproduction of the demonstrated trajectory (details about the identification process are in [16]).

The DMP model avoids the explicit use of a time variable by introducing a canonical system [11]. Its function is the synchronization of all the different components (i.e. the different relevant dimensions \( y_d \) of the task). The canonical system is implemented as a first-order ordinary differential equation:

\[ \tau \ddot{x} = -\alpha_x x + C_c. \]

Therefore, time and the phase variable \( x \) are exponentially related through the canonical system. The parameter \( \alpha_x \) modulates such a relationship.

Finally, the scaling term \( \xi(x) \) in Eq. (2) is defined as suggested by [12]:

\[ \xi(x) = A_{\text{max}} x = (\max(y_d) - \min(y_d)) x \]

Here, \( \max(y_d) \) and \( \min(y_d) \) are, respectively, the maximum and minimum value of the corresponding component of the demonstration. Rescaling of the amplitude \( A_{\text{max}} \) in Eq. (2) introduces spatially invariant properties of the attractor landscape, thus allowing for spatial scaling of the reenactment [12]. Due to its exponential decay, the phase variable \( x \) fades in time the forcing term in Eq. (2), thus ensuring the asymptotic stability of the transformation system.

\[ \text{Fig. 2.} \quad \text{State diagram of the hybrid robot control in the } z \text{ direction. The Cartesian impedance controller commands the position in the } y_z \text{ dimension and forces } y_{fz} \text{ exerted in the same direction. The value of the force requested by the DMP model, } y_{fz}, \text{ coordinates the transition between position and force control. (see text for details).} \]

\[ \text{C. Controller} \]

During reenactment of the demonstration, the DMP model is responsible for the generation of the state space vector \( y \). A Cartesian impedance controller converts the model’s output into appropriate motor commands. The controller can be formally described as:

\[ \tau_{\text{cmd}} = J^T(k_c(y_{\text{des}} - y_{\text{msr}}) + f_{\text{des}}) + D(d_c) + \tau_{\text{dy}}(q, \dot{q}, \ddot{q}), \]

where \( J \) is the Jacobian matrix of the robotic arm. The controller emulates a spring-damper-system driven by \( y_{\text{des}} \) and \( y_{\text{msr}} \), respectively the desired and measured Cartesian pose (position and rotation), through programmable stiffness vector \( k_c \). The robot can also exert an additional force/torque \( f_{\text{des}} \). \( D \) is a damping term, depending on the normalized damping parameters \( d_c \). The controller utilizes a dynamic model of the arm, represented by the term \( \tau_{\text{dy}}(q, \dot{q}, \ddot{q}) \), which allows for compensation of dynamic forces, such as gravity and Coriolis force.

We propose the following control strategy for the robot, that will be tested in the experiments presented in the next section. All positional components of \( y \), with the exception of \( y_{fz} \), are permanently position controlled by the Cartesian impedance controller. Since in our experiments contact forces are explicitly considered and controlled in the \( z \) direction only, the components in such a direction, \( y_z \) and \( y_{fz} \), are subject to hybrid control, graphically represented in Fig. 2:

When the application of a force is not required (i.e. the robot is in an aerial phase), the trajectory \( y \) generated by the transformation system is directly forwarded to the Cartesian impedance controller (\( y_{\text{des}} = y \) in Eq. 6). The desired force/torque is set to zero (\( f_{\text{des}} = (0, 0, 0)^T \)).

Conversely, when the DMP model outputs a contact force \( y_{fz} \neq 0 \), the desired force requested to the Cartesian
impedance controller in Eq. 6 is \( \mathbf{f}_{\text{des}} = (0, 0, y_{fz})^T \).

Operatively, the transition from Cartesian impedance to force controller can be forced by setting the \( z \) component of the stiffness \( \mathbf{k}_c \) to zero whenever the DMP model is demanding a force to be applied in the same direction. This causes the \( z \) direction to be only controlled by the desired force \( \mathbf{f}_{\text{des}} \). When no force needs to be exerted, the stiffness in \( z \) direction is set back to its original value.

Due to the finite precision of the calibration of the robot’s internal dynamic model (Eq. 6), the robot used for our experiments (KUKA LWR4+) typically exerts forces with accuracy in the range 1–3 N. In a related paper [17], where we present an hybrid/switch controller that extends the formulation of the controller sketched in Fig. 2, we have showed how the compensation of the desired force through a cascaded force controller becomes necessary for tasks requiring a finely controlled application of forces, e.g. writing a sequence of characters using a standard marker on a whiteboard. Compared to wood planing, such a task presents a higher geometrical complexity, but is less dynamically articulated. In fact, over the sequence of different characters to be traced, the contact between the marker and the whiteboard only needs to be repeatedly established, maintained and broken. However, the contact force is critically limited by the magnitude of the force that can be applied without damaging the marker’s tip. Conversely, despite the simplicity of its geometric requirements, wood planing imposes a careful coordination between forces applied orthogonally and longitudinally with respect to the direction of the wooden plank.

D. Handling of perturbations

We have recently presented a custom mechanism to manage external perturbations during reenactment, i.e. physical events causing the robot to deviate from its desired trajectory [17]. In case of perturbations, the function of the coupling term \( \mathbf{C}_e \) in Eq. (4) is to delay the execution, in order to allow time for the disturbance to fade and then restore the normal temporal and execution flow. For example, when \( \mathbf{C}_e = \alpha_x \mathbf{x} \), the canonical system and thus the temporal evolution of the whole system is stopped, whereas smaller (positive) values reduce the execution speed. However, although active, this mechanism has only negligible effects on the results reported in this paper. Therefore, we invite the interested reader to look for further details in [17].

III. Experiments

With the work reported in this paper, we intend to investigate the feasibility of a relatively challenging in-contact task, wood planing, according to the proposed approach. We also want to identify the minimal physical configuration of the necessary setup. In particular, we want to verify whether the basic Cartesian impedance controller proves capable of operating a plane on wood or more sophisticated control strategies are necessary.

Our experimental setup consists of a KUKA LWR 4+ robotic arm, vertically mounted on a heavy metal table. Consistently with the general requirements listed in Section II-A, the robot has 7 degrees of freedom, integrated torque sensors at each joint that make it capable of programmable active compliance, torque control and gravity compensation. Its overall control cycle runs up to 1 kHz [18].

Through the KUKA Fast Research Interface (FRI) communication protocol, the robot controller can deliver data to an interfaced standard external computer and receive commands from it [19]. The software infrastructure has been redesigned for hard real-time applications up to the robot’s nominal limit of 1 kHz. Our external computer runs a Xenomai 2.6.2.1 real-time patch for the 3.5.7 Linux kernel and RTnet 0.9.13 real-time networking. A general, robust, modular and flexible robot control framework at a relatively high level of abstraction was developed by adding components for Open Robot Control Software (Orocos) and functionalities in Robot Operating System (ROS ‘Groovy’).

A six-axis ATI mini 45 F/T sensor (sensing range: ±290 N \( F_x \) and \( F_y \), ±580 N \( F_z \); ±10 Nm for \( T_x \), \( T_y \) and \( T_z \); accuracy between: 0.75 % and 1.25 %, depending on the axis) has been rigidly mounted between the robot’s flange and tool. We have provided it with thermal insulation from the robot.

The tool consists of a small commercial plane (mass 1.121 kg.), rigidly mounted on the F/T sensor through in-house built aluminum adapters (see Fig. 1). The original handles of the plane have been mounted on a custom-built aluminum plate (Fig. 1). A standard pine plank (dimension 1000x90x20 mm) is clamped to the robot’s table in a horizontal position, one of its 1000x20 mm sides facing the plane at a minimum distance of about 450 mm from the vertical axis of the robot base (see Fig. 1).

During the demonstration, a human instructor grabs the handles positioned on the aluminum plate mounted above the flange side of the F/T sensor. After reaching for the plank, the demonstration consists of a ‘natural’ sequence of a few strokes of the plane on the plank, executed in gravity compensation mode. This limits the demonstrator’s effort in moving the system composed by the plane, the F/T sensor, adapters and the robotic arm. The robot provides an estimate of the position of the tool during the movement (pose data relative to a point located along the tool axis and laying on the tool-side of the F/T sensor are recorded), while data from the F/T sensor are received and stored for further analysis and identification of the DMP model.

Following demonstration and system identification, two experimental conditions are compared:

- **reenactment**: the robot reenacts the tasks relying on the input calculated by the DMP model;
- **reenactment with fixed orientation**: reenactment is executed after the orientation of the tool has been fixed parallel to the plank and made maximally stiff.

Observe that, due to the coupling between plank and tool, geometric and physical constraints are largely dictated by the setup. The positioning of the plank defines the target elevation for the system, and more importantly longitudinal and orthogonal directions. Exerting forces along these directions...
is critical to the task, whereas the application of transversal forces is irrelevant.

The following parameters were used: \( N_w = 500 \) for all dimensions; \( \alpha_z = 2000 \) and \( \beta_z = \alpha_z/4 \); \( k_c = 2000 \, \text{Nm/m} \) for linear movements, \( 400 \, \text{Nm/rad} \) for angular movements in the orthogonal and transversal direction and \( 300 \, \text{Nm/rad} \) for angular movements in the longitudinal direction; \( d_c = 0.7 \, \text{Ns/m} \) for linear and \( 0.7 \, \text{Nms/rad} \) for the angular movements. The exponential decay of the canonical system started at \( x_0 = 1 \) with a decay rate of \( \alpha_z = 1.1 \). The robot was configured to exert a maximum force of \( 200 \, \text{N} \) and a maximum torque of \( 15 \, \text{Nm} \) in all directions. The hard real-time control cycle was running at 500 Hz.

IV. RESULTS

In Fig. 3, the longitudinal position of the plane and its angular deviation around the longitudinal axis during demonstration, reenactment and reenactment with fixed orientation over time can be compared. The label ‘Modeled trajectory’ refers to the position and orientation encoded by the DMP model. All positional data only show limited variations with respect to each other (Fig. 3, top). For example the root mean square error (RMSE) between the demonstrated positional trajectory and that of the temporally aligned reenactment [20] is only 0.019 m.

In the two experimental conditions, reenactment and reenactment with fixed orientation, slight temporal delay is built up over time, due to the effect of the coupling term \( C_c \) (Section II-D). A small positional discrepancy derives from the finite linear stiffness of the system. In fact, finite stiffness entails that (similarly to a body dragged by a spring) the actual pose is always lagging behind with respect to the driving position, mainly due to the friction of the blade on wood (and in negligible measure to internal friction). Such a slack can be observed in different measure due to the non-homogeneous nature of the wood, although consistently larger in the case of basic reenactment, when we compare data from the two experiments.

Whereas the angular deviation during reenactment closely matches the demonstration, angular deviation during reenactment with fixed orientation of the plane is clearly displayed in the second experimental condition (Fig. 3, center). Under this condition, the system is not sufficiently compliant to dynamically adapt to the local orientation of the wooden plank. The result is the plane gliding over the plank with impoverished coupling between its blade and the wood. By direct and repeated observations, during reenactment the amount of material removed in form of wood chips is at least comparable to the demonstration, whereas when fixed orientation of the tool is maintained the removed material is noticeably less. Our observations are documented in the accompanying video and, with obvious limitations, in the snapshots taken from the same video at the end of the second stroke (Fig. 4). In particular, the sound recorded in the video support a (matching) common-sense experience interpretation of the above described dynamic. In fact, the intervals of effective coupling between plane and wood are clearly acoustically identifiable. This suggests future development of quantitative metrics based on the harmonic analysis of the sound. This approach to the characterization of the interaction during in-contact tasks would require an evidence of correlation between quality of the wood shaving (e.g. weight of the shaved material) and harmonic components.

Observe how during the forward phase of the demonstrated stroke (Fig. 3, bottom) the plane produces a rather exact repartition of the applied force between the orthogonal and longitudinal component. This is due to the inclination of its blade, close to 45 degrees.

Orthogonal and longitudinal forces are shown, individually, in Fig. 5 as a function of time and longitudinal position. The qualitative match among orthogonal forces over time proves quite tight (Fig. 5, top-left), according to the exact timing of the Cartesian impedance controller that directly generates motor commands. The RMSE for the temporally aligned demonstration and the basic reenactment is only 15.5N. However, if we consider orthogonal forces over position, we can observe a characteristic pattern due to the effect of finite linear stiffness mentioned above (Fig. 5, bottom-left) and of different coupling between blade and wood. In other words, we are considering the combined effect of linear and rotational stiffness.

In the figure, the graphs ‘loop’ around the circular markers (introduced to facilitate the reader’s interpretation) according to a specific and consistent order. From the tightest to the most loose loop drawn around the marker, we can observe the graph for reenactment, reenactment with fixed orientation and demonstration. The effect is even more noticeable once
Fig. 5. Orthogonal (left panels) and longitudinal forces (right panels) as a function of time (top) and over longitudinal position (bottom). The red markers in the bottom panels have been added to facilitate the reader in following the description of the figure (see text for details).

Fig. 4. Snapshots of the end of the second stroke from the accompanying video: reenactment (left) and reenactment with fixed orientation (right).

we consider the diagram relative to longitudinal forces (Fig. 5, bottom-right), whose curves are also ‘looping’ around the circular markers. In fact, limited stiffness entails a slack reenactment with respect to the demonstration. As already mentioned, the slack is more pronounced in the case of basic reenactment (where the blade is more tightly adapted to the plank due to the softer rotational stiffness) than in the case of reenactment with fixed orientation.

Despite its apparent deviations, the qualitative match between demonstrated and reenacted longitudinal forces displayed as a function of time (Fig. 5, top-right) is particularly interesting, for we should consider that such forces are not directly commanded, but achieved due to positional requirements. This graph also shows traces of the combined effect of linear and rotational stiffness, with the graph for basic reenactment often lagging behind the one for fixed orientation, and the latter lagging behind the graph for demonstration.

V. DISCUSSION AND CONCLUSIONS

The in-contact task presented in this paper, wood planing, is critical enough that would be (in the least) hard to implement without some form of compliant control. This is due to the possibility of ‘stall’, occurring in case strong orthogonal forces are applied to the tool, thus determining a deep penetration of the plane’s blade in the wood before sufficient inertia in the longitudinal direction has been reached. However, although a force controller could effectively back the Cartesian impedance controller to compensate for the deviations highlighted in the previous section, the Cartesian impedance controller demonstrated its ability to effectively cope with the wood planing task on its own. In other words, the task can be accomplished without the need for cascaded control compensation and for the external F/T sensor during reenactment. In [17], where the task is writing a sequence of characters on a whiteboard using a marker, we have reached the opposite conclusion. In that paper we endorse the integration of force and a velocity controllers in the system, in order to perform a fine-grained control of the exerted force during reenactment (e.g. in order to protect the relatively soft tip of a standard marker).

Therefore, the use of the F/T sensor can be limited to the demonstration, and no external feedback measurements are needed over reenactment. The number of ‘de facto’ necessary compliant dimensions can also be reduced from 6 (linear and rotational components) to four (linear in the orthogonal...
direction, linear and rotational in the longitudinal direction and rotational in the transversal direction).

Our work further contributes to current methods in robotic literature [14] by presenting a single-phase approach to kinesthetic PbD for in-contact tasks. As in [17], the method described in this paper allows the direct and simultaneous transfer of the positional and force requirements, encoded in a physical skill requiring a tool, from a human instructor to a robotic arm. However, the method trades its single-phase nature for the possibility to directly hold the tool in its original configuration. This is due to the constraint imposed by the method during the demonstration (i.e. the necessity to grab the robotic arm above the flange side of the F/T sensor). Therefore, a natural feel of the tool during demonstration can be hard to achieve. In the particular case reported in our paper (wood planing), positioning the handles of the tool sufficiently close to their original positions on the plane, while still respecting the configuration dictated by the method, could be relatively easy (see Fig. 1). By simply folding the front and back ‘wings’ of the top adapter (element ‘a’ in Fig. 1), the plane’s handles could be actually positioned only a few millimeters away from their original lodgment on the plane. However, this fortunate condition might be harder to achieve in general, or even impossible for specific tools.

Lack of a natural feel for the human instructor is aggravated by the necessity to drag around the robot during demonstration. Although operating in gravity compensation, the robot still has a significant inertia that interferes with a fluent deployment of the human skill. This will be in the future addressed by active following strategies, e.g. developing on techniques presented in [21].

Obviously, the natural function of the plane is to accomplish some goal specific task (for example regularizing the shape of the plank). Some of these problems (e.g. regularizing planks presenting a torsion) could be extremely complicated even for power machines. However, ‘wood-planing-oriented planing’ goes beyond the scope of this paper and is also left for future research.

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