Combining Virtual and Physical Guides for Autonomous In-Contact Path Adaptation*

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Abstract. Several approaches exist for learning and control of robot behaviors in physical human-robot interaction (PHRI) scenarios. One of these is the approach based on virtual guides which actively helps to guide the user. Such a system enables guiding users towards preferred movement directions or prevents them to enter into a prohibited zone. Despite being shown that such a framework works well in physical contact with humans, the efficient interaction with the environment is still limited. Within the virtual guide framework, the environment is considered as a physical guide, for example, a table is a plane that prevents the robot to penetrate through. To mitigate these limits we introduce and evaluate the means of autonomous path adaptation through interaction with physical guides, which essentially means merging virtual and physical guides. The virtual guide framework was extended by introducing an algorithm which partially modifies the virtual guides online. The path updates are now based on the interactive force measurements and essentially improves the virtual guides to match them with the actual physical guides.

Keywords: Human-robot physical cooperation · On-line path adaptation · Virtual guides.

1 INTRODUCTION

A typical strategy for programming an industrial robot involves an expert which makes a program based on a defined task. Such a process is commonly very costly and time-consuming. To decrease the programming time one alternative is to use the Programing-by-Demonstration (PbD) approach which can be used also by skillful personnel, that has no knowledge about robot programming but knows how to perform a given task. PbD is typically performed with kinesthetic teaching which allows the user to easily demonstrate a given task to the robot. Programming such motion on a classic way would, on the other hand, require many programming hours [1]. Clearly, novel robot coaching methods would enhance the application of robots in new domains ranging from our daily home-environments to small and medium-sized enterprises.

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One possibility is the kinaesthetic teaching and programming which relies on the measured interaction forces between the user and the robot. Typically it can be implemented by either using impedance or admittance control [11]. While the impedance control is more suitable for interacting with the stiff environment, the admittance control is more applicable when interacting with more compliant environment [6]. This characteristic has to be taken into account when used in PHRI framework. Regardless of the chosen control approach, it is crucial to defining the control parameters such that they ensure safe operation in physical contract considering also the characteristics of human arm [8].

However, when the task requires physical interaction the virtual guide framework is not directly applicable. Since virtual guides have similar behavioral properties as real physical guides, an algorithm that can effectively adapt virtual guides to the physical guides is needed. Only a few papers investigated the online adaption of the virtual guides using a physical feedback. Kinesthetic teaching with motion refinement tubes was used for iterative updates in [4]; a motion adaption based on a supervised learning using psychological affective feedback was used in [3]; user feedback was used for learning high-level task representations in [5]; verbal instructions as a learning feedback was used to modify movements in [10]; a framework for physical and visual coaching for altering robot behaviors was introduced in [2]. Despite the fact that all the above-proposed methods are able to alter robot motion based on user feedback or environmental constraints, they are not directly applicable for the use in the unified virtual guides framework.

To merge the physical guides with the virtual guides into the unified virtual guide framework we merged the coaching algorithm [2] with our recent work on virtual guides using admittance control for redundant robots[13]. The novelty in this paper is the ability of on-line path adaptation based on the physical constrains. Using the path Jacobian the measured fore is decomposed into the tangential component and perpendicular component with respect to the desired path. While the tangential force component is used to move back and forth along the path, the perpendicular force component is used to adapt the virtual guides to match the physical guides.

The paper is organized as follows. In section 2 we give a brief introduction of the virtual guides framework based on virtual admittance control. In section 3 we introduce an algorithm for on-line adaption based on physical interaction. In section 4 we show experimental results on robot arm adapting to the physical path while preserving physical contact in the vertical direction. In section 5 we discuss the possibilities and the impact of our work.

2 Virtual Admittance Control and Virtual Guides

Here we first give a brief overview of the virtual admittance controller [13, 12, 7], which is then followed by a methodology for an online path adaption through physical interaction.

Note that here we assume that the robot will not be in contact with a very stiff environment, therefore admittance control with accurate position control can be used. Consequently, the tracking error can be negligible and the flowing assumption holds

$$\boldsymbol{q} \approx \boldsymbol{q}_d. \tag{1}$$

Under this assumption, the control scheme shown in Fig. 1 was used. Here, the virtual admittance control generates motion based on the desired end-effector motion $\boldsymbol{x}_d$ and external force $\boldsymbol{F}_{ext}$.

In general, the virtual robot dynamics can have any dynamic properties. In our case, we propose to use a virtual robot dynamics as an ideal system represented by a single integrator system, where the input is the desired velocity and the output is the position. Block scheme on Fig. 1 shows that the only feedback loop from the robot to the virtual robot is over the external force $\boldsymbol{F}_{ext}$. Note that by assumption the virtual robot and the robot subsystems are both stable and further on when in contact with a non-stiff environment we can assume that the overall system is stable. Similar can be assumed when the robot is in contact with a human, although humans are not passive per se, they are capable to adapt and tend to be passive [9].The inverse kinematics can be given as

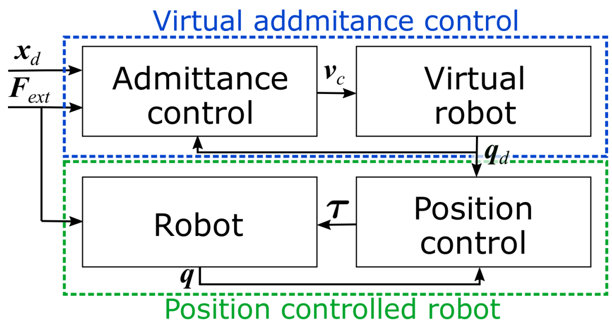

Fig. 1. Implementation of the admittance control on the virtual robot that generates the desired motion for the position controlled robot.

$$\dot{\boldsymbol{q}}_d = \mathbf{J}^{\#}\boldsymbol{v}_c + (\mathbf{I} - \mathbf{J}^{\#}\mathbf{J})\dot{\boldsymbol{q}}_n \ , \tag{2}$$

and the following admittance controller as

$$\boldsymbol{v}_c = \boldsymbol{v}_d + \mathbf{D}^{-1}(\mathbf{K}\boldsymbol{e}_x + \boldsymbol{F}_{\text{ext}}) \ . \tag{3}$$

Here the parameters $\mathbf{K}$ and $\mathbf{D}$ define the virtual robot dynamics. Without loss of generality, the flowing derivation was limited to position part of the Cartesian space. The end-effector error in Cartesian space is therefore given by

$$\boldsymbol{e}_x = \boldsymbol{p}_d - \boldsymbol{p} \ , \tag{4}$$

where $\boldsymbol{p}_d$ denotes the desired Cartesian end-effector position and the path $\boldsymbol{f}$ is defined as a parametric curve given by

$$\boldsymbol{p} = \boldsymbol{f}(s), \tag{5}$$

$$\boldsymbol{v} = \mathbf{J}_s\dot{s}, \tag{6}$$

$$\dot{\boldsymbol{v}} = \mathbf{J}_s\ddot{s} + \dot{\mathbf{J}}_s\dot{s}^2 \ . \tag{7}$$

Note that the path is dependent only on the path parameter s, where $\mathbf{J}_s \in \mathbb{R}^{3\times 1}$ is the path Jacobian. Parameter s can be chosen arbitrary if the following holds, $\boldsymbol{f}(s)$ is a continuous function for all s. A suitable candidate for s is the path length, $s \in [0,\, s_l]$, which when moving along the path is given as

$$\ddot{s} = \frac{1}{m_s}\left(b_s(\dot{s}_d - \dot{s}) + k_s \boldsymbol{F}_{dir}\right), \tag{8}$$

$$\boldsymbol{F}_{dir} = \mathbf{J}_s^T \boldsymbol{F}_{\text{ext}}, \tag{9}$$

where the tangent projection on the path of the external force $\boldsymbol{F}_{\text{ext}}$ is used to guide the robot. Note that the k_s is a scaling constant and parameters m_s and b_s are the proxy inertia and damping constants, respectively. Further on, the desired path velocity $\dot{s}_d$ can be used to define the velocity profile along the path. It is given as

$$\dot{s}_d(s) = \frac{\sum_{i=1}^{m} \boldsymbol{w}_i^s \Psi_i(s)}{\sum_{i=1}^{m} \Psi_i(s)}, \tag{10}$$

where $\boldsymbol{w}_i^s \in \mathbb{R}^{1xm}$ are weights that define the desired velocity profile. Note that the desired velocity will be achieved only when no external force is present. When the external force is applied, the system will respond based on Eq. 8, which allows constant human-robot interaction.

The path for the virtual guide can also be encoded with parametric description as

$$\boldsymbol{f}(s) = \frac{\sum_{i=1}^{m} \boldsymbol{w}_i \Psi_i(s)}{\sum_{i=1}^{m} \Psi_i(s)} \tag{11}$$

where $\boldsymbol{w}_i \in \mathbb{R}^{3xm}$ are now weights that define the path. If not stated otherwise all radial basis kernel functions Ψ_i in this paper are given as

$$\Psi_i = \exp\left(-\frac{(s-c_i)^2}{2h_i}\right). \tag{12}$$

Here c_i and h_i define the centers and the widths of kernel functions, respectively. We set the parameters to: c_i, $i = 1, \ldots, m$. They were equally spread along the path $c_i \in [0,\, 1]$. Parameter m was set to $m = 30$.

To encode an arbitrary path we define $\mathbf{\Phi}(s) \in \mathbb{R}^m$ as

$$\mathbf{\Phi}_i(s) = \frac{\Psi_i(s)}{\sum_{i=1}^{m} \Psi_i(s)}, \tag{13}$$

which combined with (11) yields

$$\boldsymbol{f}(s) = \boldsymbol{\Phi}(s)\boldsymbol{w} \; . \tag{14}$$

Here we assume that along the path $\boldsymbol{f}(s)$ the path values p are known and the corresponding wights $\boldsymbol{w}$ are computed by solving (14) as

$$\boldsymbol{w} = (\hat{\boldsymbol{\Phi}}^T \hat{\boldsymbol{\Phi}})^{-1} \hat{\boldsymbol{\Phi}}^T \hat{\boldsymbol{f}} \; . \tag{15}$$

Here $\hat{\boldsymbol{f}} \in \mathbb{R}^{r \times \dim(\boldsymbol{f})}$ are path values, $\hat{\boldsymbol{\Phi}} \in \mathbb{R}^{r \times m}$ is the basis vectors and r is the number of path steps, respectively. Note that multiple trajectories can be used to compute the weights $\boldsymbol{w}$. In this case, the resulting path will the best fit for a set of given data.

3 Path Adaptation

To combine virtual guides with physical guides (physical constraints) in the proposed framework it is crucial to ensure that the virtual guides follow the exact path of the physical guides. This can be achieved by accurately modeling the physical guides or accurately recording the path of the physical guide. The latter can be achieved by adapting the initial virtual guide to the exact physical path/guide. To perform the path adaption we propose a method which is based on the active support of virtual guides. Here we assume that the initial path, i.e. corresponding weights $\boldsymbol{\omega}_0$ are known, is given in advance or recorded with kinesthetic teaching using (15). The initial path is then used to compute the path Jacobian and corresponding path updates for s (see Eq. 9). Note that without knowing the initial trajectory in advance the (8) will not integrate properly if immediate local updates are used. Therefore, we propose to use the Jacobian computed based on the initial path in (8) and (9), which yields

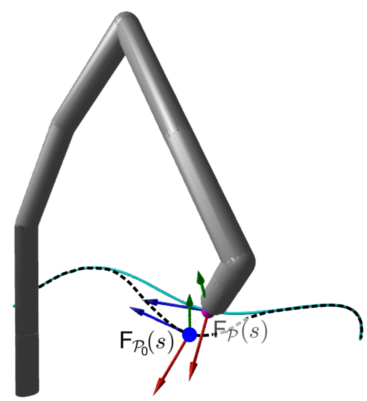

Fig. 2. Illustration of coordinate systems and corresponding path Jacobians for the initial path $F_{p0}(s)$, and the locally updated path $F_p(s)$.

$$\boldsymbol{F}_{dir} = \mathbf{J}_{s0}^T \boldsymbol{F}_{\text{ext}}. \tag{16}$$

Note that here the path Jacobian $\mathbf{J}_{s0}$ depends on the initial weights $\boldsymbol{\omega}_0$, i.e. the initial path. The initial path and locally updated path are illustrated in Fig. 2.

For on-line adaption of virtual guides, we transform the Eq. (15) into a locally weighted regression given by

$$\boldsymbol{\omega}_{n+1} = \boldsymbol{\omega}_n + \boldsymbol{\Phi}_i(s)\boldsymbol{e}_u^T, \tag{17}$$

$$\boldsymbol{e}_{\boldsymbol{u}} = k_u \boldsymbol{F}_{nor}. \tag{18}$$

Here, k_u is the scaling constant and $\boldsymbol{F}_{nor}$ is the projection of the external force $\boldsymbol{F}_{\text{ext}}$ perpendicular on the path. It is given by

$$\boldsymbol{F}_{nor} = (\mathbf{I} - \mathbf{J}_s \mathbf{J}_s^T)(\boldsymbol{F}_{\text{ext}} - \boldsymbol{F}_d), \tag{19}$$

where $\mathbf{J}_s$ is the path Jacobian. Note that the learning session can always be re-activated and the newly learned weights become the initial weights. If not stated otherwise, we re-activated the learning after each pass of the path, i.e. form $s = 0$ to $s = s_l$.

4 Results

To validate the behavior of the proposed path adaptation algorithm we have selected a task where the robot end-effector has to slide into the groove of a given object. Sliding into the groove requires to know either a precise path of the environment in advance or a method that can adapt the environmental constraints online. It is a typical path following task that can not be easily programed. Alternatively, PbD could be used to program such task, however when PbD is used it is not possible to specify also the exact contact forces without using additional external force/torque sensors. Note that case of PbD force/torque sensors are used to interact with the user and therefore can not be used for measuring contact forces or torques.

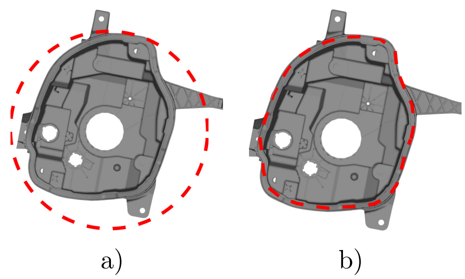

Fig. 3. Top view of the experiment: a) initial trajectory, b) final trajectory. Note that the path is three dimensional. All three path components can be seen in Fig. 4.

The experimental results of autonomous path adaptation to the physical constrains are shown Figs. 3 and 4. In Fig. 3 we can see the groove on the object, initial path and final path after autonomous physical adaption. To demonstrate the path adaptability of the proposed algorithm we chose ellipsoid as the initial path, as seen on left plot in Fig. 3. Both Figs. 3 and 4 shows that the on-line adaption was able to adapt the virtual guide path to fit perfectly with the actual physical constraints of the groove.

There are several advantages of the proposed approach. The main advantage of the proposed approach with respect to the PbD approach is that here we can also easily specify the desired vertical force to which the system needs to adapt. Another advantage is that the initial path which is not accurate can be used, and the path corrections are only at the points where needed. Thirdly the measured force is also decoupled with the path Jacobian to the tangential and perpendicular component in relation to the path. This allows only changes in the path when the perpendicular force in relation to the current position on the path is present. This implicitly, without any additional changes, makes the system useful for PHRI. Note that when the additional external force is present the system will adapt the path only in the perpendicular direction, while the tangential component will translate into the increase or decrees of the path parameter s integration, see (8). As such the user can also interact during the path adaption process by adding additional force with physical contact.

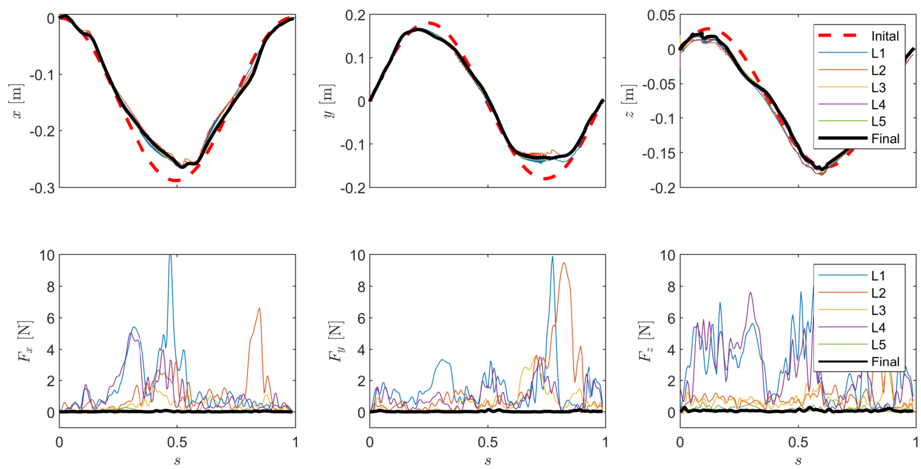

Fig. 4. The adaption of the path for all three Cartesian coordinates. The red dotted line denotes the initial trajectory, black line denotes the final trajectory and colored lines denoted the intermediate trajectory updates during learning phases. Each learning iteration is denoted with a different color by the legend.

5 Discussion and Conclusion

This paper presents an algorithm for the on-line adaption of the path based on interactive forces. As such the system is able to autonomously adapt the path to the environmental constraints, i.e. essentially merging together virtual and physical constraints. Since measured force is decomposed on tangential and perpendicular components it is as such inherently applicable, without any changes to the algorithm also for PHRI. In addition, the proposed approach for adapting path components within the virtual guides framework is also suitable for learning complex paths. Since the path adaption is local, the path can be adapted or learned at any time.

The proposed approach is the incremental advance of our virtual guides framework with virtual admittance control [13, 7]. From where it follows that these methods can be used with any robot as long as it is equipped with a force/torque sensor. The only limitation of such control concept is that the admittance properties of the controller need to be taken into account when interacting with the stiff environment. In the future, we plan to investigate how to use hybrid robot impedance with virtual admittance controller to improve the robot performance when in contact with the stiff environment.

Despite the limitations, we have shown that the autonomous adaption of the path to the environmental constraints is possible within the given virtual guides framework. Preliminary experimental results have confirmed that virtual guides can be merged with physical constraints by using the on-line path adaption algorithm.

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