Transferring Physical Skills From Humans to Robots: Multimodal Programming by Demonstration for In-Contact Tasks

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New opportunities requiring new methods

A new generation of industrial quality robotic manipulators is currently being released on the international market. State of the art over-actuated manipulators are now starting to be flanked with a significant proprioceptive capacity (i.e. force/torque sensing at each joint). Joint proprioception can be further extended by force/torque sensing at the robot's wrist and multi-fingered robotic hands provided with torque and tactile sensing. Therefore, although still fulfilling the key properties of traditional industrial robots in their motor actuation (i.e. accuracy, high performance, control, reliability and durability), a new class of commercial robots can now receive significant sensory feedback, enhancing their potential for adaptive dexterous manipulation. Against a relatively limited financial investment (starting from approximately 20.000 US dollars), manufacturers can now easily deploy this novel option in their workshops. The manufacturing process can integrate unprecedented possibilities in form of low cost, flexible, industrial quality manipulators under extended proprioceptive monitoring.

However, in contemporary robotics, major hardware improvements require the balanced coupling with comparably efficient soft methods. Unfortunately, when trying to exploit the full potential of the new robots for a broad range of industrial applications, the current unbalance between hard and soft methods emerges. Nowadays, the deployment of true, skillful and flexible manipulation can only be achieved in front of significant costs due to the rather delicate and complex process of dedicated software development.

Nevertheless, the current generation of robotic manipulators seems ready for major advancement in the field of HRI, in particular for the transfer of physical skills from humans to robots. Over the last decade, a significant body of work has focused on the generation of trajectories, reproducing at the level of the robot's end effector the ones demonstrated by a human instructor, and on the system's capacity to generalize these trajectories to novel situations (e.g. coping with obstacles or other constraints). This approach, namely *programming by demonstration* (hereafter PbD [1]), can be implemented as a general architecture for flexible use. In kinesthetic approaches, the end effector is physically grabbed by the human demonstrator, and moved in space to directly offer one or multiple examples of the required behavior. Practical methods can be deployed in order to minimize the mechanical interference due to the robot's inertia during the demonstration [2]. Obviously, the kinesthetic form of PbD is more natural to human instructors than explicit programming of complex movements in partially uncertain scenarios. Recent work has integrated the reproduction of the trajectory with the associated force profile of the interaction between the robot's tool and its environment for simple tasks such as ironing [3].

Transferring in-contact skills from humans to robots

We believe that robotic systems with enhanced proprioceptive capacities can be effectively used for the transfer of physical skills from humans to robots, particularly for skills requiring non trivial sensorimotor coordination.

Kinesthetic teaching for *in-contact tasks* is a promising way to capture the actual dynamics of mechanical interaction between an expert human demonstrator and a material substrate. By in-contact tasks we mean tasks for which the ability to skillfully distribute a spatial and temporal profile of mechanical forces at the interface between the arm and the material plays a crucial role. Kinesthetic teaching can be combined with multi-modal sensory inputs (e.g. tactile, visual, auditory) in order to facilitate more natural and effective human robot interactions. For example the auditory modality can carry vocal information used by the instructor to modulate the intensity or amplitude of the robot's movement. Furthermore, sound produced by the interaction between the robot's tool and the manipulated material can carry useful information.

As mentioned above, most recent studies in PbD aimed for the reproduction of demonstrated trajectories (e.g. [4], [5], [6]). During dynamic interaction, trajectory is directly accessible to our visual senses and its salience to human observers can be easily predicted. Nevertheless, in order to actually encode human skills for in-contact tasks we are mostly interested in capturing the actual dynamics of mechanical interaction between the human agent and the object under manipulation, as in the spirit of [7]. Such an interaction is physically characterized by a partly uncertain scenario, due to several parameters that cannot be directly controlled, and requires continuous adaptation to the current factual conditions. From this point of view, the generation of trajectories might be considered merely functional to the establishment of the proper agent-material dynamics, while respecting physical and geometrical constraints (i.e. desired shapes, geometrical boundaries, etc.). Once the constraints

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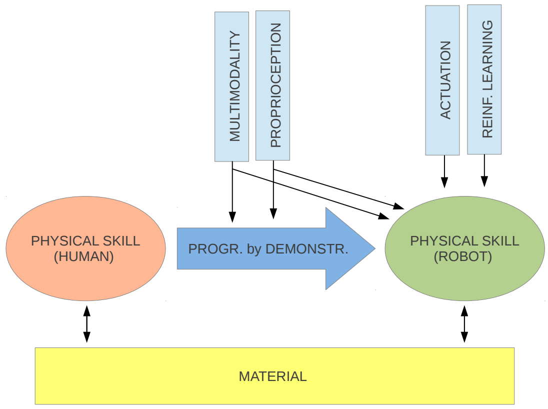

Fig. 1. In a PbD scenario, proprioception and multimodal sensing feed the adaptive mechanism, facilitating the transfer of skills for in-contact tasks from humans to robots. The material, rather than being an accessory entity, acts as the substrate that makes this transfer possible. Reinforcement learning, coupled to the capacity for action, completes the transfer by adapting the acquired skill to the robot's specific embodiment.

are relaxed, the trajectory only traces the necessary movement as a result of maintaining appropriate agent-material dynamics.

Interweaving perception and action via the material

The new class of robots, endowed with enhanced proprioception, also seems ready to reduce the ability gap between human craftspersons and technological manufacturing. In traditional robotics, the robot is the active agent. It typically injects relatively high levels of mechanical power at the mechanical interface between its tool and the processed material, often with little regard for the intrinsic mechanical response of the material itself. In this sense, the manufacturing process could be qualitatively described as a static (although non stationary) chain of unidirectional events. However, robotic manipulators with increased levels of proprioceptive capacities, while maintaining their traditional role as an active agent (thus acting in the same direction as before), would also be able to assess the material's response to the given mechanical stimulation (in the opposite direction). In other words, the proprioceptive robot would at once evoke and listen to the specific material's response, interweaving perception and action through the material as they occur. This might open an opportunity for groundbreaking development in the field of robotic manufacturing, advancing it by means of robots that could physically operate in ways more similar to human artisans, shaping and revealing at the same time the hidden mechanical properties of the materials, and thus broadening the traditional scope of industrial robotics.

High sensitivity in the proprioceptive capacity is a key factor in the broad range of applications that can be foreseen for the methods here described. For example, a current socially critical problem is the insufficient availability of experts in physical rehabilitation for several classes of patients (e.g. orthopedic, post-strokes, etc.). We can easily imagine scenarios where the human expert offers the robot kinesthetic instruction. The robot can then execute similar manipulations on the patient, and focus on the passive response of the manipulated tissues and on the active response of the patient.

Conclusions

Of course, this position paper is increasingly venturing toward the realm of open research questions and speculations. Nevertheless, we are convinced that such speculations and questions can now start to be addressed with the necessary technical resources in hand. The above does not imply that the answer will be trivial or even feasible. For example, transferring skills for in-contact tasks from a human instructor to a robot opens an obvious problem regarding the different embodiment. Humans are characterized by strong lower limbs, that can provide relatively high levels of force at low frequency. Upper limbs are more suitable to deliver lower forces at higher frequency and with increased accuracy with respect to our lower limbs. The magnitude of proprioceptive sensitivity, limited in our lower limbs, increases dramatically from shoulder to fingertips. Our trunk seems to mechanically couple and modulate these two components for skillful physical action. Can a skill that is encoded in the human-like kind of embodiment be directly ported, for example, to a robotic arm with seven degrees of freedom (and therefore to some extent representative of the human arm in isolation)? Is there a limit to this kind of porting? Can it be quantitatively or qualitatively characterized? The introduction of more sophisticated adaptive strategies in parallel with the traditional methods of PbD could facilitate this mapping. For example, recent work has highlighted the beneficial effects of reinforcement learning in PbD [8], [9]. After initial training, the robotic system could autonomously search for more efficient solutions according to its specific embodiment.

The territory briefly sketched in this paper covers a significant part of the research space that we intend to explore in our future work.

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