

# Teaching of bimanual skills in a compliant humanoid robot

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In contrast to standard industrial robots designed to work in predefined factory settings, humanoids are designed to share our space without the need to modify our environment. These robots create new collaborative and social interaction opportunities, but these new environments also expose the robots to various sources of perturbation and unpredictable situations. Since the range of tasks that the humanoids can carry out is infinite, it is not possible to provide a predefined database of tasks. For widespread use in homes and offices, a key requirement will be to provide user-friendly ways of programming the robot to let it acquire new skills and adapt existing skills to new situations. Robot learning by imitation offers a promising route to transfer and refine skills from demonstrations by non-expert users.

We believe that the frontier between planning and control algorithms should overlap in order to cope with unexpected situations in real-time. Our work emphasizes that skills should not only be represented in terms of the shape of the movement, but also (and maybe more importantly) in terms of the degree of variations allowed by the task and how the different movement variables are coordinated. Indeed, important information is contained in the local variation and correlation of the movement. Such variation can change over time (different phases of the movement) and can depend on situation (adaptation to changing positions of objects). This requirement is strong in the case of humanoids, where the robot is required to produce predictable human-like gestures and exploit the characteristics of the task to allow it to respond to perturbations in real-time without having to recompute the whole trajectory.

We present a learning by imitation approach based on a superposition of virtual spring-damper systems to drive a humanoid robot's movement. The novelty of the method relies on a statistical description of the springs attractor points acting in different candidate frames of reference. The proposed approach combines the practical convenience of employing dynamical systems in the humanoid's continuously changing environment with the generality and rigor of statistical machine learning. The robot exploits local variability information extracted from multiple demonstrations to determine which frames are relevant for the task, and how the movement should be modulated with respect to these frames.

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In previous work, we explored these two categories of machine learning tools in parallel. On one side, we developed a representation of movements based on a sequential superposition of dynamical systems with varying full stiffness matrices. On the other side, we developed a representation based on *Gaussian mixture regression* (GMR) to provide a statistical representation of the movement that is able to compute and retrieve movement commands in real-time, independently of the number of datapoints in the training set. We present here a method to gather these two components. From the dynamical systems standpoint, it provides a simple approach to reframe the superposition of spring-damper systems in a probabilistic framework. While from the statistical regression perspective, it provides an elegant methodology to cope in real-time with perturbations without employing an external control mechanism on top of the generated movement.

The proposed learning approach is achieved by predefining a set of candidate frames of reference, such as objects in the environment or relevant body parts such as the end-effectors of the robot. The role of the robot is to autonomously figure out which frames of reference matter along the task, and in which way the movement should be modulated with respect to these different frames. Bimanual coordination is achieved by considering the other hand as a candidate frame of reference for the reproduction of the skill. The movement of the two hands are thus naturally coupled for parts of the movement in which regular patterns have been observed between the two hands. The strength of the coupling constraint is automatically adapted with respect to the variations observed throughout the task.

The approach is tested on the new full-body compliant humanoid COMAN with skills requiring bimanual coordination (time-based and time-invariant movements are considered). This robot platform has been designed to explore how compliance can be exploited for safer human robot interaction, reduced energy consumption, simplified control and aggressive learning. The first hardware developments of COMAN targeted the legs, with several prototypes developed for the lower-body part. This paper reports the first experiment conducted with the arms and upper-body.

The results of the experiment show that the representation of bimanual gestures in humanoids can benefit from the joint use of dynamical systems and statistics, by employing a GMR approach to encode the path of virtual spring-damper systems in a set of candidate frames of reference. The proposed approach opens roads for various new developments combining the versatility of dynamical systems and the robustness of statistical methods.