Markku Suomalainen[1,2], Ville Kyrki[2]

Learning compliant assembly skills from human demonstration

***Index Terms*—Robotics, Learning from Demonstration, Compliant Assembly, Impedance Control**

The strenuousness of programming a robot to perform different tasks is a major reason holding back the widespread use of robots in industry and at people's homes. Industrial robots are mainly used only when the same product is manufactured for long periods of times. One of the next places where the usage of robots can really increase is enterprises where production batches can be small. But to enable this step, domain experts must be able to teach the robots the required task, such that a robotics expert is not required at the stage every time the robot needs to learn a new task or fails at completing a taught task.

Learning from demonstration (LfD) is an established paradigm in robotics, where the goal is easily programmable robots. In short, the idea is to show the robot an example of a skill, which the robot learns to reproduce and generalize into other locations and similar situations. However, traditional LfD techniques struggle with compliant motions, which are required in many industrial assembly tasks.

The key research question is if we can learn from human demonstrations to use compliance, contact and geometry of the task such as in Fig. 1 to mitigate pose errors with impedance controller. Humans take advantage of the environment when faced with positional uncertainties, such as inserting a screw in a poor lighting condition. The goal of my research is find methods how we can make robots learn the probing motions that humans use in uncertain situations and survive even without a vision system.

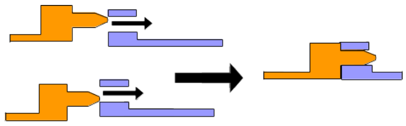
We propose to learn from human demonstration the necessary parameters of an impedance controller defined as

$$\boldsymbol{F} = K_f(\boldsymbol{x}^* - \boldsymbol{x}) + D_f\boldsymbol{v} + \boldsymbol{f_{dyn}} \quad (1)$$

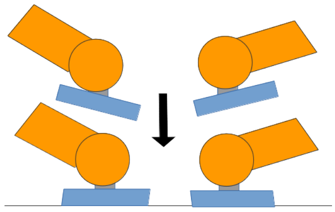
where $\boldsymbol{x}^*$ is the desired position, $\boldsymbol{x}$ the current position, K_f the stiffness matrix, $D_f\boldsymbol{v}$ linear damping term and $\boldsymbol{f_{dyn}}$ and the feed-forward dynamics of the robot. For linear dynamics, we can compute $\boldsymbol{x}^*$ from a desired direction vector $\boldsymbol{v_d}$. To reproduce a demonstrated compliant motion, $\boldsymbol{v_d}$ and K must be learned.

In [1], we learned $\boldsymbol{v_d}$ and K by assuming we can directly measure the direction of the force which the human teacher applies to the robot in kinesthetic teaching. However, we noticed that this assumption only holds true for certain force/torque sensor configurations, and hence we wanted to solve also the more general problem, where we can only measure the force between the end-effector and the environment. We solved this problem in [2], with the observation that in a compliant sliding motion there is always a certain sector of directions from which the robot can apply force to perform the observed motion. We managed to take the intersection of these sectors in a 3-D motion, over one or more demonstrations, and thus learn the parameters for a dynamically linear compliant motion. In [3] we generalized the task to work with rotational motions as well and showed how the robot can successfully learn to mitigate orientation errors when attaching hose couplers together. Furthermore, in [4] we learned how to sequence these motions to perform a full task, such as pipeline assembly, which we also showed experimentally with a real robot. Finally, to make the robots more independent even in case of changes in the environment, in [5] we looked into whether a robot could learn to search using contact forces, similarly as a human tries to fit a key into the keyhole in darkness– we showed that we can reach acceptable levels of success in this very hard task. Finally, in [6] we showed that our method can be applied to dual-arm tasks and examined the role of compliance in dual-arm assembly with a little more detail, showing that compliance in both arms increases the performance compared to single-handed assembly.

This work was supported by Academy of Finland, decision 286580.
[1] M. Suomalainen is currently with University of Oulu, Finland markku.suomalainen@oulu.fi
[2] School of Electrical Engineering, Aalto University, Finland ville.kyrki@aalto.fi



(a) Position alignment.



(b) Orientation alignment

Fig. 1: Compliant motions can be used for aligning both position and orientation of a workpiece

To show that the method from [2] is robust enough to work with systems where errors in measurements can be higher, we combined the method with a stability-guaranteed Virtual Decomposition Control- based impedance controller for a heavy-duty hydraulic manipulator with a 475kg payload [7]. In addition to this main line of work, we explored if this kind of compliant assembly could be used even in low gravity, such as space or underwater [8].

REFERENCES

[1] M. Suomalainen and V. Kyrki, "Learning compliant assembly motions from demonstration," in *Intelligent Robots and Systems (IROS), 2016*

IEEE/RSJ International Conference on, pp. 871–876, IEEE, 2016.
[2] M. Suomalainen and V. Kyrki, "A geometric approach for learning compliant motions from demonstration," in *Humanoid Robots (Humanoids), 2017 IEEE-RAS 17th International Conference on*, pp. 783–790, 2017.
[3] M. Suomalainen and V. Kyrki, "Learning 6-d compliant motion primitives from demonstration," *Robotics and Autonomous Systems*, 2018, submitted. arXiv:1809.01561.
[4] T. Hagos, M. Suomalainen, and V. Kyrki, "Segmenting and sequencing of compliant motions," in *Intelligent Robots and Systems (IROS), 2018 IEEE/RSJ International Conference on*, pp. 6057–6064, IEEE, 2018.
[5] D. Ehlers, M. Suomalainen, J. Lundell, and V. Kyrki, "Imitating human search strategies for assembly," *IEEE Robotics and Automation Letters*, 2018, Submitted. arXiv:1809.04860.
[6] M. Suomalainen, S. Calinon, E. Pignat, and V. Kyrki, "Improving dual-arm assembly by master-slave compliance," in *Robotics and Automation, IEEE International Conference on*, IEEE, 2019, submitted.
[7] M. Suomalainen, J. Koivumäki, S. Lampinen, J. Mattila, and V. Kyrki, "Learning from demonstration for hydraulic manipulators," in *Intelligent Robots and Systems (IROS), 2018 IEEE/RSJ International Conference on*, pp. 3579–3586, IEEE, 2018.
[8] S. Sharma, M. Suomalainen, and V. Kyrki, "Compliant manipulation of free-floating objects," in *Robotics and Automation, IEEE International Conference on*, pp. 865–872, IEEE, 2018.