Simplified Robot Programming by Kinesthetic Teaching with Limited Demonstration Data

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A new type of industrial robots, which go by the name of *collaborative robots*, have recently disrupted the market of industrial automation. While, traditionally, industrial robots are expensive, large, complicated to operate, and dangerous to human workers in their surroundings, this new breed of *collaborative robots* are cheaper and meant to work alongside humans. They are also easier to use, as they use touchscreen interfaces and graphics that allow people with no knowledge of robotics to learn to program them in a matter of hours. This has allowed smaller companies that traditionally could not afford to use robots to adopt collaborative robots in their assembly lines. However, as robots are expected to become more widespread in our society,they must be made even easier to use. This concerns especially tasks like part assembly, which even when using collaborative robots still require considerable expertise to program.

The research community has been investigating new intuitive methods for humans to interact with robots for many years. One of these methods is *programming by demonstration*, which is based on the principle of showing the robot how to perform a task by demonstrating it, after which the robot will learn how to perform it by itself. A modality known as *kinesthetic teaching* is particularly suited to collaborative robots. This consists in grabbing the robot arm, which is held loose, and guiding it through the motions needed for the task, similar to how an adult could teach a child how to draw by grabbing and guiding their hand while they hold the pencil. Ideally, the robot will not only learn how to perform the specific motion it was taught, but also how to apply similar motions in other contexts. It will get better at this the more demonstrations it is shown and the more information about the task it can gather. For instance, by placing cameras or force sensors on the robot, it will be able to use visual or touch information as part of its understanding of the task, and will be able to adapt to a wider range of situations.

However, a key challenge when trying to apply programming by demonstration techniques to industrial robots is keeping the cost reasonable for the customer. The more sensors needed for a specific method, the more expensive the system will be in both the cost of the equipment and the cost of hiring qualified personnel to set it up. It is therefore relevant in an industrial context to consider methods that use as few sensors as possible. Furthermore, because many smaller companies rely on shorter production cycles of a few customized products, before changing the whole production line to a different type of product, it is important for a programming by demonstration system to learn the task quickly. Due to this, methods that can learn from a single demonstration are particularly interesting.

In this thesis, we investigate methods for a collaborative robot to learn industrial tasks from a single demonstration, using only the sensors that are already available on the robot, and no other external sensors. We address three problems: First, we compare the ease-of-use of a programming by demonstration system with that of the graphical programming methods used on a collaborative robot. To do this, we perform a user study with people who have no previous experience working with or programming robots. Next, we focus on developing methods that allow robots to learn extremely precise part assembly tasks from a single demonstration. We consider types of tasks with similar difficulty to those found in the industry. Finally, we investigate methods where the robot not only learns the motion that the human teaches it, but also learns how to use this motion in ways not included in the demonstration. Particularly, we learn how to perform the motion both forwards and backwards. This means that the human can teach the robot how to assemble a part, and from this single demonstration, the robot will be able to both assemble and disassemble the part.