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Robot skills for manufacturing: From concept to industrial deployment

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ABSTRACT

Due to a general shift in manufacturing paradigm from mass production towards mass customization, reconfigurable automation technologies, such as robots, are required. However, current industrial robot solutions are notoriously difficult to program, leading to high changeover times when new products are introduced by manufacturers. In order to compete on global markets, the factories of tomorrow need complete production lines, including automation technologies that can effortlessly be reconfigured or repurposed, when the need arises. In this paper we present the concept of general, self-asserting robot skills for manufacturing. We show how a relatively small set of skills are derived from current factory worker instructions, and how these can be transferred to industrial mobile manipulators. General robot skills can not only be implemented on these robots, but also be intuitively concatenated to program the robots to perform a variety of tasks, through the use of simple task-level programming methods. We demonstrate various approaches to this, extensively tested with several people inexperienced in robotics. We validate our findings through several deployments of the complete robot system in running production facilities at an industrial partner. It follows from these experiments that the use of robot skills, and associated task-level programming framework, is a viable solution to introducing robots that can intuitively and on the fly be programmed to perform new tasks by factory workers.

1. Introduction

In order to remain competitive in a globalized environment, manufacturing companies need to constantly evolve their production systems and accommodate the changing demands of markets. Currently, production is experiencing a paradigm shift from mass production to mass customization of products. The impact of this trend on production systems is that they should adapt to handle more product variation, smaller life cycles, and smaller batch sizes – ideally batch size 1. Today, robot-based production is an essential part of the industrial manufacturing backbone. However, the concept of an industrial robot statically placed in a cell and continuously repeating a carefully predefined sequence of actions has remained practically unchanged for many decades. Not surprisingly, typical industrial robots are not flexible and thus such a degree of *transformable production* [1–3] is beyond the capabilities of current systems.

A simplified illustration of the situation is shown in Fig. 1. Traditional manufacturing systems are automated to a large degree, but can only be reconfigured with great difficulty. On the other hand, traditional manual labor is very flexible, but not economically viable for large scale production, especially so in high-wage countries. In the future, mass customization will make it necessary to combine high reconfigurability with a large degree of automation. This goal can be achieved in two distinct ways: workers can either be equipped with better automation tools, such as intuitive on-the-fly programming of robots, thereby increasing their productivity, or the reconfigurability of traditional automated production lines can be improved, e.g. through the use of multi-purpose robots.

Robotics is expected to be one of the main enablers of this transition to the transformable factory of tomorrow. To reach the demanded level of flexibility robots, or more generally mobile manipulators, need to be able to move autonomously, cope with uncertainty in interactions with humans and partially known environments, handle a variety of different tasks, and be able to be reprogrammed fast by non-robot experts when a new task in the factory arises.

So, the question emerges: What should be the characteristics of a framework that would allow robots to be flexible enough to handle uncertainty and changing production tasks, while being intuitive enough to be used and re-programmed by non-robot experts? We argue that the answer lies in the tight integration of

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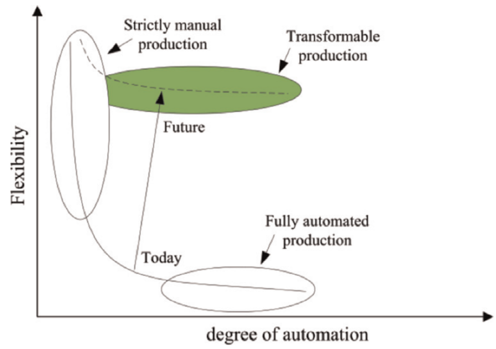

Fig. 1. A clear requirement for the factories of tomorrow is that of a *transformable* production system, showing a high degree of flexibility, while still applying a high degree of automation.

sensing and action within a small set of modular and parametrizable *"robot skills"*. Contrary to traditional robot macros, our skills are characterized as being general, in that they can handle a variety of objects, and self-asserting, in that they contain pre- and postcondition checks. Finally, this set of skills for a given industry can be naturally extracted from a careful analysis of industrial standard operating procedures (SOP).

In this work we present a conceptual model of the "*skills*" and how this concept can be implemented and successfully applied in real-world industrial scenarios. The conducted experiments show that a small set of skills can be intuitively parametrized by either kinesthetic teaching, pointing gestures, or automatic task planners to solve different industrial tasks, such as part feeding, transportation, quality control, assembly, and machine tending.

The main contributions of this paper are that

- We propose a conceptual model of robot skills and show how this differs from traditional macros.
- We show how this approach can enable non-experts to utilize advanced robotic systems by encapsulating advanced capabilities, implemented a priori by experts, inside each individual skill.
- Concrete applications of the approach are presented, in which advanced robot systems have been applied in several real industrial scenarios.

The rest of this paper is organized as follows: in Section 2.1 we discuss how the list of skills can be extracted for a given industry and how the concept of skills can be formalized. In Section 3 we present a series of experiments where robots powered by skill-based software architecture were deployed in real industrial settings. We discuss the outcomes of our work and possible future directions in Section 4 and finally we conclude with Section 5.

1.1. Related work

The goal of achieving easy and quick reprogramming of robots by non-experts has been consistently pursued using the task-level programming paradigm. Task-level programming constitutes a higher abstraction level than traditional robot programming. It specifies a given task as a sequence of actions, but avoids describing each action in full detail. The sequence of actions leading to the fulfillment of this task can either be planned or specified by an operator. Such an approach is similar to the symbolic representation of tasks of the Shakey robot that used a STRIPS planner to reason about which actions may lead to accomplishing a goal [4], or the concept of Object-Action Complexes (OACs) [5] that allowed cognitive robots to identify possible actions based on object affordances.

Task-level programming is based on lower level entities, usually called *robot skills*, that instantiate actions. Various representations of robot skills that would be suitable for task-level programming have been pursued during the last decades [6–14]. What most of the aforementioned attempts have in common, is that robot skills are, in turn, composed of primitive sets of robot motions, called action or motion *primitives*. These skill primitives are simple, atomic robot movements that can be combined to form more complex behaviors [15–21]. A systematic survey of the rich relevant literature reveals how fragmented the concept of skills is, lacking a widely accepted, strict definition.

In contrast to the skills themselves, the *skill primitives* [13,10,11] are rather well defined in the robotics community; although several different descriptions exist, most of them loosely follow Mason's work on compliant controllers [22], which paved the ground for the Task Frame Formalism (TFF) introduced by Bruyninckx and De Schutter [23,24]. Recent work has expanded upon this idea, for instance enabling the use of any sensor and controller in the same task frame (e.g. visual servoing combined with force control), and operating in a dynamic task frame [25–27].

Our definition of skills integrates pre- and post-conditions checks in the execution, which makes the interconnection of skills into tasks an intuitive and controlled process. In that sense, our approach is comparable to the *manipulation primitive nets*, described best in [26]. However, this approach requires low-level parametrization of the manipulation primitives, making it accessible only to robot experts. Another concept, similar to our notion of skills, is that of Action Recipes as defined in the RoboEarth project [28,29]. Different to our skills though, Action Recipes keep sensing and acting separate and mainly focus on knowledge sharing between robots with similar capabilities. All the aforementioned approaches require a robot expert to program and use the system. This is also one of the reasons why these works, in contrast to ours, were never deployed in a real industrial setting.

Easy programming of industrial robots requires, apart from the underlying concepts, intuitive Human–Robot Interaction (HRI) mechanisms. HRI in industrial settings focuses on offline programming by using CAD models [30–32] or online programming using augmented reality (AR) [33–35]. The apparent limitation of such methods is that they assume the presence of an expert for reprogramming, which makes them unsuitable for the envisioned transformable factories. In contrast to the majority of publish works and similar to our approach, the authors of [36] combined skill primitives and speech recognition for programming grasping tasks by speech, with other work presented in [37,38]. This work incorporates task-level programming, however, the programming is a combination of primitives, with no higher-level skills between these and the task layer. In general, the literature of HRI in industrial settings is rather limited. One possible reason is that industrial robotics applications traditionally focused on accuracy and speed without the need for external sensors. However, lately this trend is giving way to more intuitive and user-friendly interfaces that largely rely on sensing [39]. Furthermore, given the nature of factories of the future, that are only semi-structured, there is a high need for accurate, external sensors as well as intuitive HRI.

Apart from HRI that allows human instructions to define a task, another possibility is to consider use of automated task-planers. Industrial robots have been endowed with task-planning capabilities, starting with the STRIPS planner [4], and many other algorithms that followed, based on the same ideas, in that they act on a set of actions that alters the current world state [40,41]. This includes breaking down assembly tasks into some form of manipulation primitives the robot can interpret [42]. Simple robotic scenarios, as in GOLEX [43], have been succeeded recently by more advanced ones [44], resembling to some of the capabilities of our work presented in the paper at hand.

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