Rule-Based Supervisory Control-Extension for Automated Manufacturing Processes

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Abstract—**Before performing a surface finishing process, human operators analyze the workpiece-conditions and react accordingly, i.e. they adapt the contact-situation of the tool with respect to the surface. This first step is ignored in most suggested automation concepts. Although their performance is satisfactory for the general process thanks to adaptive position- and force-/torque-control algorithms, they are unable to address specific problematic cases as often encountered in practice because of variations in workpiece-dimensions or –positioning. In this work, a human mimicking element is developed to overcome this limitation of current control concepts and to translate human expertise to the robotic manipulator. A rule-based system is designed where human knowledge is encoded as if-then rules. This system is integrated with a previously suggested control strategy in a hierarchical manner. The developed concept is experimentally validated on a KUKA LWR 4+-robotic manipulator.**

Index Terms—**programming by demonstration, rule-based system, human mimicry, biomimetics, supervisory system, hierarchical control**

I. Introduction

Automation or partial automation of surface finishing processes of complex freeform workpieces is of high interest to the industrial community as these processes are time- and cost-intensive. Different studies suggest shares of up to 30-50% of the entire manufacturing time and up to 40% of the total cost [1-9].

The execution of a surface finishing process is twofold. It requires 1) the following of the to be treated surface to ensure the constant contact between robot end-effector or tool and workpiece and 2) the application of an adequate manufacturing force to remove the excessive material.

For these surface finishing processes, manual work is current state-of-the-art. Not only the fact that these processes were designed by and for humans but also humans' capabilities make them the most appropriate performers for these complex tasks. The challenge in automating a surface finishing process is to mimic the human's approach to perform the considered task by translating his capabilities into robot skills and by including the worker's expertise in the control algorithm.

Programming by Demonstration, PbD and kinesthetic teaching which teach a robot by showing the desired behaviour rather than by writing commands in a programming language is a promising approach in automation research [10-17]. This supervised method enables robots to be programmed intuitively by non-experts. Programming by demonstration aims to leverage human expertise to teach robots via guided examples. Demonstrations are an opportune form of information for the unambiguous communication of a task. They do not require knowledge of a language and they are applicable also for tasks which are difficult to express in other forms like speech or programming language [18].

A control algorithm promises robustness and stability in the case of uncertainties and disturbances when playing back the desired signals recorded through kinesthetic teaching. Conventional controllers, e.g. sliding mode control in combination with bio-inspired extensions showed promising results [19-21].

Its capability to react to different situations with specific control rules, makes the human operator highly valuable for processes with varying parameters [22]. This adaptability and adjustability of the human behaviour in specific or problematic cases is not included in the previously described combination of PbD and robust controller.

In a first phase, humans apply rules of thumb in the form of 'if a then do b'. From previous experience, they deduce a rule base containing generalized guidelines about what actions to take in what circumstances, i.e. if-then statements [23-25]. The desire to mimic this human behaviour culminated in rule-based systems, one of the most straightforward forms of artificial intelligence. Knowledge is encoded into these systems as a set of rules that specify how to act in different situations. These rules are declared as an array of if-then rules: 'if a then b' or 'a => b'. They can be described as the linguistic formulation of the human's approach to achieve a goal. A rule-based system is designed to mimic the behaviour of a human expert when facing a specific challenge. The performance of a rule-based system is therefore expected to be similar to that of a human expert in the considered area and when exposed to the same data [26, 27].

A priori programmed relational condition-action statements have been implemented i.a. in behaviour-based robotics [28] and probabilistic contexts [29]. Fuzzy logic is a prominent method to express quantitative aspects of a human expert's knowledge and reasoning process with a set of linguistic rules [30]. Fuzzy rules

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have been applied for acquiring knowledge bases [31, 32], approximating unknown plant models in combination with Artificial Neural Networks [33], online task sequencing in robotic assembly in combination with Petri nets [34], extending a sliding mode control algorithm [35-38], clustering in combination with particle swarm algorithms [39], modelling trajectories [40] or machining processes [41].

Interaction and behavioural rules in social animals and insects have inspired algorithms for multi agent behaviour and clustering [25]. Reference [42] addressed a clustering problem with an algorithm inspired on ant colonies. The elements evolve according to a limited number of behavioural rules in the form of if-then statements. Other algorithms were inspired on the behavioural rules of fish swarms [43], bird flocks [44-47] and ant colonies [48, 49].

Next to the dependence on expert systems and the restriction to if-then statements, the main drawback of rule-based systems is the limitation of the number of rules for computational and complexity reasons [22, 26, 32, 38, 50] .

A combined implementation of a rule-based system and a PbD-control algorithm should fuse the advantageous aspects of all involved concepts as well as overcome their drawbacks. A PbD-set up with a control concept combining a robust sliding mode control- and bio-inspired adaptive element has been validated through simulation and experiment. Although the efficiency has been proven, this is only valid for the general case. For specific, problematic cases, additional elements are necessary in practice [51]. A rule-based system allows the encoding of expert knowledge in a narrow area of the specified problem and can also be implemented in a hierarchical way to survey a previously developed control system [25].

The rest of the paper is structured as follows: Section 2 is dedicated to the detailed description of the addressed problem: The challenge (A), requirements for the solution (B) and applied methodology (C) are presented. Section 3 develops the suggested solution. Following the analysis of the situation (A), a hypothesis (B) is emitted and a control concept (C) designed. In section 4, the results of the experimental validation on the KUKA LWR 4+-robotic manipulator of the proposed control concept are presented. The paper ends with a discussion and some concluding remarks in section 5.

II. Problem Description

A. Challenge

The general aim is the transfer of human knowledge to the robot, i.e. human mimicry in the context of automating manufacturing processes. The first step of combining Programming by Demonstration with robust bio-inspired control algorithms, does not address problematic cases like variations in workpieces or in their clamping positions. Human operators tackle these specific cases by observing the situation (if a) and reacting appropriately (then b). This step is performed before the rest of the control approach, as an outer supervising loop. The challenge consists in adding this lacking element into the control concept of the automated process. Fig. 1 shows the setup for this automated process.

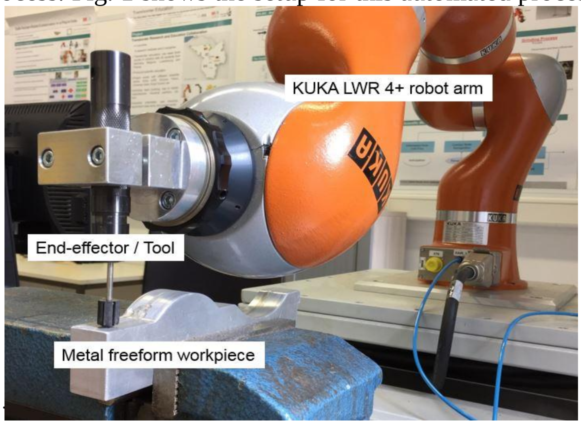

Figure 1 Setup for the automated process.

B. Requirements

The overall goal is to design an automated system with a similar performance to the human operator. The specific goal of this work is to add a control element able to deal with particular problematic situations, e.g. uncertainties in workpiece position and dimension. The requirement for the considered manufacturing task is 1) to keep contact between workpiece and tool, i.e. not to lift off and apply the manufacturing force only once contact was established 2) not to damage the workpiece through penetration of the tool, i.e. to back up once a force threshold was surpassed. The addition of the supervisory control loop should not deteriorate the results of the control algorithm qua robustness and tracking performance. An additional requirement is the human mimicry of the concept, i.e. the system should apply the same reasoning as a human operator, thereby allowing the latter to retrace the robot’s behaviour and to take over at all times.

C. Methodology

The observation of the manufacturing process performed by a human operator, noting the most important elements is the first step. In a second step, the circumstances not tackled by the control concept [52] are identified. Based on these results, a hypothesis for addressing the problematic cases is emitted and a suited rule-based supervisory control loop designed. In a final step, the developed hierarchical control concept is validated.

III. Control Concept

A. Analysis

The recurrent theme identified during the observation of the human operator is the following approach: first observe then react. Before performing any action, humans analyse and categorise the situation at hand and take a decision about the optimal approach or reaction based on their experience. This behaviour can be represented as if-then-rules: if situation a is identified then action b is chosen as optimal reaction. This becomes particularly valuable in problematic cases which deviate from the general or pre-planned case. For surface finishing manufacturing processes, these cases involve mainly workpiece-variations. Fig. 2 illustrates the effects of variations in clamping positions and presence of unexpected, intruding material.

Figure 2 Normal clamping position (left); Altered clamping position (middle); Disturbance through intruding material (right).

The suggested control concept [52] shows satisfactory performance for trajectory- and force-tracking, i.e. for position- and force-/torque-control. For a serial robot with n links, the control input is defined as $u \in R^n$ (1), a combination of inputs of a conventional PID-controller and a controller extension (3). The latter is based on a combination of feedback-signals according to (4)-(8). Both controller-parts are based on the error-signal, i.e. the difference between current and desired system-output (2).

$$u = u_{PID} - u_{extension} \quad (1)$$

$$\text{error} = \text{current} - \text{desired} \quad (2)$$

$$u_{extension} = \beta error - \int_o^T (a-b)(t)dt \quad (3)$$

$$a = \alpha error \Delta_a \quad (4)$$

$$b = \alpha error \Delta_b \quad (5)$$

$$\Delta_a = \alpha \dot{error}.\max(0, c) \quad (6)$$

$$\Delta_b = \alpha \dot{error}.((a-b)-c) \quad (7)$$

$$c = sign(error)^T.\dot{error}(error-(a-b)) \quad (8)$$

with α and β constant gain-factors.

The suggested controller can deal with uncertainties and disturbances as it adapts online, i.e. while proceeding. This online adaptation however, is not able to deal with the specific problematic situations related to workpiece-variations considered in this work and as illustrated in Fig. 2. In the case of altered workpiece-position, this control concept would either apply manufacturing forces in free space or attempting to penetrate the workpiece and therefore does not fulfil the established requirements.

B. *Hypothesis*

A superposed rule-based control element should be able to address the identified problematic cases before the other controller-elements come into effect. This new control element supervises the process controlled by the algorithm ((1)-(8)) in a hierarchical manner. This outer control loop is derived from the observations of human reasoning and implements human experience and knowledge in the form of rules.

C. *Control Concept*

The adaptation of the end-effector-position in order to achieve contact with while avoiding penetration of the workpiece-surface before performing trajectory tracking is the aim of the presented extension. A rule-based system is well suited for this purpose.

The rule-based system is developed in two steps: 1) transfer of human knowledge to the robot, i.e. development of the knowledge base and the constituting rules, 2) observations of the current situation. In general terms, the purpose of the presented extension is to avoid lifting off from or penetrating the workpiece. The knowledge which needs to be encoded includes in which conditions and how to adapt the position of the robotic manipulator in order to be able to start the general trajectory and force/torque tracking process. The analysis of the current situation is based on the online measurement of current force-signals with sensors.

When the tool risks to penetrate and damage the workpiece, i.e. if the force measured in the direction perpendicular to the work plane is above a certain threshold, the end-effector has to be moved away from the workpiece-surface.

Before a manufacturing force can be applied, contact has to be established. If there is no contact between tool and workpiece, i.e. if the force measured in the direction perpendicular to the work plane is below a certain threshold, the end-effector has to be moved into the direction of the workpiece.

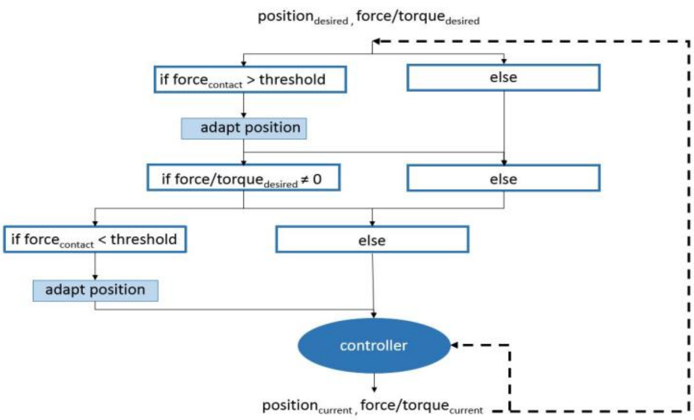

Figure 3 Hierarchical control concept.

Fig. 3 shows the integration of the rule-based control element with the previously validated control concept in a hierarchical manner. It is illustrated that the rule-based element precedes the general control algorithm and supervises the latter. The scheme includes the feedback loops (dotted arrows), the conditions, i.e. if-parts of the rule-based system (white blocks) as well as the reactions, i.e. then-parts of the rule-based system (light blue blocks).

The pseudo-code (Fig. 4) details the rules introduced above and in Fig. 3.

Code	Description
while $F_{contact}$ > threshold	risk of penetration
{	
position = position – increment	lift
}	
if a manufacturing force is desired	condition
{	
while $F_{contact}$ < threshold	no contact
{	
position = position + increment	approach surface
}	
}	

Figure 4 Pseudo-code of the suggested control concept with descriptions.

In a final step of the extension, the desired input signals need to be adapted according to the increments added.

IV. Validation

The suggested extended hierarchical control concept is validated on the KUKA Lightweight Robot (LWR), a 7DOF- KUKA LWR4+ [53]. The research of the Institute of Robotics and Mechatronics of the German Aerospace Center focussed on torque-controlled lightweight robots. One of their designs is the by the human arm inspired KUKA LWR with a payload of 7 kg and its 7 axes, all equipped with internal position- as well as force-/torque-sensors. The implementation and validation of the previously suggested control scheme requires a flexible and advanced programming environment. The LWR's possibility to connect to and communicate with an external PC though the FRI (Fast Research Interface) is used. The latter is a software-option provided by KUKA for experimental work in research-laboratories. The software configures a UDP socket communication for a binary data transfer with a cyclic timeframe in the range of 1 to 100 ms. The use of UDP socket communication is well suited for this use case due to its speed. It allows data exchange to and from the external computer, e.g. reading and writing: measurements from the robot-sensors are read by the PC and commands programmed in C++-language are sent by the PC to the robot [54, 55].

As validation of the proposed strategy, the rule-based concept is implemented together with the general control algorithm. In the considered use case the robot arm is controlled to move to a goal position which would require penetration of the surface. The encoded rule indicates the robot to back up once the measured contact force exceeds a threshold value. Fig. 5 shows the behaviour on the example of the second joint: the joint moves towards a goal position when backing up once the measured force reached the given value.

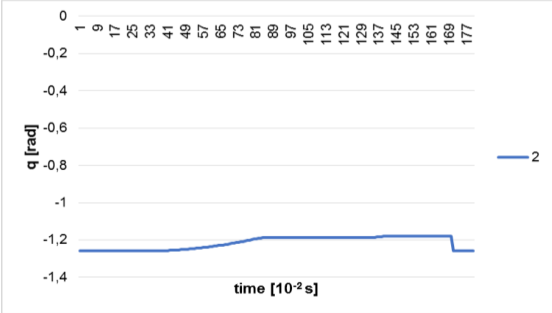

Figure 5 Position of joint 2.

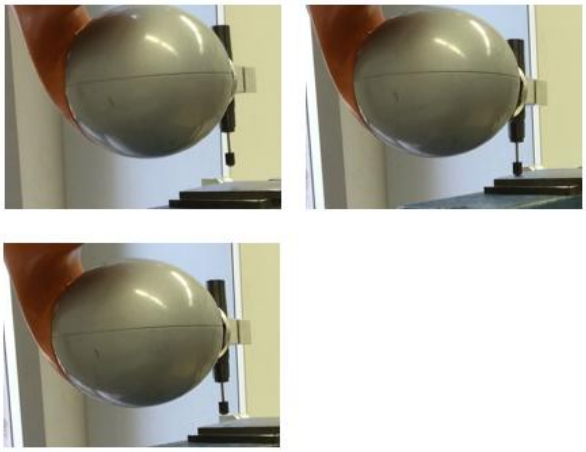

Figure 6 End-effector movement and behaviour.

Fig. 6 depicts the behaviour of the robot arm: From free space (1st row left) the robot arm is moved towards and into the surface (1st row right). When the contact force surpasses the defined threshold, the manipulator lifts off the surface (2nd row).

V. Discussion - Conclusion

This work addresses the control problem of a contact-based manufacturing operation by a robotic manipulator. A rule-based extension to a general controller for automated surface finishing processes is presented. This extension is valuable for cases that are not general and that require an adaptation step before the trajectory and force tracking. Humans are highly proficient in adapting to different circumstances based on prior experiences. Therefore human manual work is state-of-the-art for the considered manufacturing processes. This explains the choice for a human mimicking approach for the development of the control concept. The transfer of human expertise to the robot is a key element of the concept. Human knowledge is encoded as rules and human reasoning implemented as a hierarchical control concept. The developed concept is explained and illustrated in section 3 and validated on a real-life use case on a KUKA LWR 4+-robotic manipulator. The promising results satisfy the requirements established in section 2 and are presented in section 4.

The suggested concept consists in an advanced version of a hybrid position-/force-/torque-controller extended to address specific problematic situations often encountered in practice. In contrast to the general controller, the hierarchical system with the presented rule-based extension is able to deal with variations in workpiece dimension or positioning. The rule-based system therefore presents a valuable first step in the control of an automated manufacturing process. Although the suggested concept is able to address more than the general case of the process, the additional situations it can tackle are limited. Due to the nature of rule-based systems, the number of addressed situations is restricted by the complexity of the system and the situations need to be a priori planned and foreseen. Further, the performance of the rule-based extension is dependent on the human knowledge, i.e. the human input during the design phase. This dependence is a result of the human mimicry of the concept. As was pointed out above, the advantages of this human mimicry however largely outweigh this deficit.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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