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*autonomous assembly and disassembly,
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Steffen IHLENFELDT¹, Marcel LORENZ^{*2},
Uwe FRIEB², Rayk FRITZSCHE²

AUTONOMOUS ASSEMBLY AND DISASSEMBLY – KEY TECHNOLOGIES AND LINKS FOR THE ADAPTIVE SELF-OPTIMIZATION OF FUTURE CIRCULAR PRODUCTION

European industry and beyond, faces the challenge of becoming carbon neutral within an unprecedented short timeframe. An important approach to achieve this goal is the transformation of the current economy to a circular economy. In this context, the reuse of technical products as well as their recycling are in the foreground. Flexibility and adaptability are crucial for the competitiveness of companies. Therefore, adaptive and autonomous assembly and disassembly systems are the key. Classically automated assembly systems are inflexible due to a mostly rigid and predefined sequence control and are mostly strongly oriented towards economic criteria. Existing autonomous production cells, with their focus on autonomy and failure-free operation, also reach their limits in terms of adaptivity. For this reason, intelligent systems are needed that are able to act autonomously and without interference, as well as to cope with complex and cognitively demanding situations and tasks.

1. INTRODUCTION

The European as well as the global product market, in particular the technical one, is exposed to a multitude of social, economic and environmental challenges (Fig. 1).

One of the global environmental challenges is climate change. The circular economy plays a key role in countering these. This aims to preserve the value of products, materials and resources for as long as possible by returning them to the product cycle at the end of their use, while minimizing waste generation. The focus of the 5-stage waste management hierarchy is on the preparation of waste for reuse and recycling [1, 2].

Efficient and economical assembly and disassembly systems are the key to this. Furthermore, a wide range of economic and social requirements can be observed. These challenges may vary in severity and importance depending on the region or country. In the European Union, for example in Germany, demographic change and a changing labour

¹ Fraunhofer Institute for Machine Tools and Forming Technology IWU, Germany

² Body Construction, Assembly and Disassembly, Fraunhofer Institute for Machine Tools and Forming Technology IWU, Germany

* E-mail: marcel.lorenz@iwu.fraunhofer.de

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market are causing a shortage of skilled workers in various fields [3]. Due to the advancing globalization of the last decades, partly one-sided dependencies have emerged. Current global shock events (Covid-19, conflicts, ...) have revealed the fragility of the European product market in the face of such dependencies, e.g. in the form of interrupted supply chains [4].

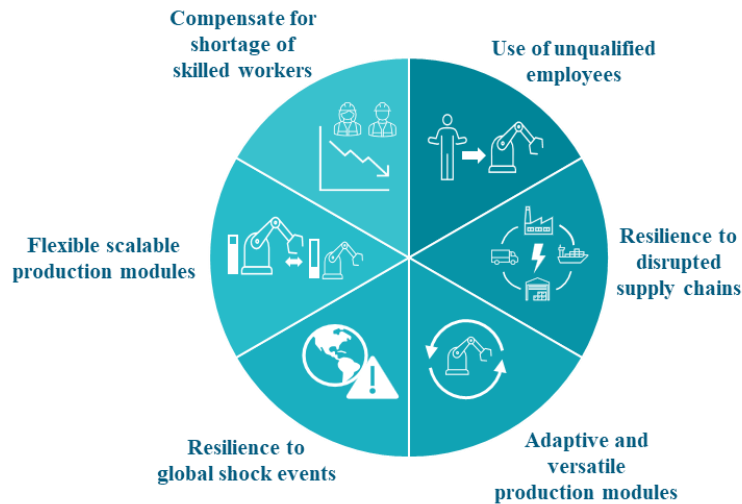


Fig. 1. Exemplary current and future challenges for product markets, based on [3-6]

To counteract this vulnerability and meet these challenges, a competitive and resilient European market is needed. This means that production systems must become more flexible and adaptable. In this context, it becomes apparent that »classical automation« is too inflexible, since it usually has a static and predefined sequence control. For this reason, autonomous production systems are needed that are highly adaptable and flexible. In addition, they are capable of taking on complex tasks that were previously performed by humans [3, 7]. Autonomous production system in the form of autonomous production cells is state of the art, such as autonomous milling systems and autonomous laser welding systems. The focus here is on a certain degree of independence, i.e. without human intervention, and failure-free operation. [8]. With regard to adaptivity, e.g. in the case of unexpected events, intelligent production systems are needed. This requires the use of artificial intelligence. Additionally, depending on the complexity of the task, decision-making power can be delegated to the system [6, 9]. Depending on the task at hand and according to the desired level of autonomy, these characteristics can be pronounced differently.

2. APPLICATION FIELDS OF AUTONOMOUS SYSTEMS

Numerous application areas are currently emerging that pursue the goal of autonomization. Table 1 lists seven fields of application, which in turn are subdivided into further fields of application. Each of these application areas is characterised by special requirements and must be adapted to their place of use. A specialisation of an autonomous system with regard

to its field of application is necessary. Table 1 lists some exemplary areas of application. Of particular interest for this article is industrial production with the application area of assembly and disassembly. Disassembly is a key technology for the circular economy in terms of reuse and recycling and is particularly well suited to participate in autonomous enabling features such as situational adaptive process execution.

Table 1. Application fields of autonomous systems, based on [10]

Application fields	Application areas
Mobility	<ul style="list-style-type: none"> ▪ Passenger traffic ▪ Freight traffic
Industrial production	<ul style="list-style-type: none"> ▪ Manufacturing ▪ Assembly
Smart home	<ul style="list-style-type: none"> ▪ Service robots ▪ Smart building
Harmful environments	<ul style="list-style-type: none"> ▪ Maintenance systems ▪ Search and recovery systems
Health	<ul style="list-style-type: none"> ▪ Medicine ▪ Nursing
Energy	<ul style="list-style-type: none"> ▪ Energy production ▪ Energy distribution
Agriculture	<ul style="list-style-type: none"> ▪ Harvesting systems ▪ Transport systems

3. AUTONOMY IN INDUSTRIAL PRODUCTION – AN INTERSECTION FOR PRESENT AND FUTURE APPLICATIONS

Cognition and automation are interdisciplinary terms and are used very differently in the respective specific and overarching fields. For the application area of assembly and disassembly, the concept of cognition follows the approach of recording, processing and storing process information that can also be used for decision-making. The term “recording” refers to sensor-based input data that can then be processed and stored using information technology. In distinction to human cognition, artificial cognition is meant to information-based decision making and process control based on sensorics input and contrary to pure »process execution« based on static control programs. The use of artificial intelligence algorithms, especially machine learning, is of particular importance in this context [11].

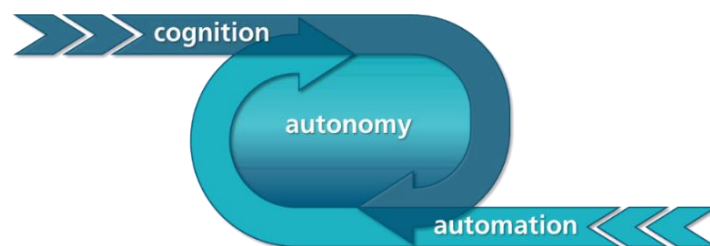


Fig. 2. Autonomy as intersection between cognition and automation

Automation here refers to the automation technology of systems and devices used in industrial production, especially assembly. This can be, for example, the use of industrial robotics, as well as individual devices that can carry out sub-processes independently. Automation technology is characterised by mostly rigid and predefined action sequences in which economic goals are prioritised. In addition, the higher the degree of automation, the greater the adaptation to the products to be manufactured and their respective requirements. In the event of product and connected processes changes or adaptations, highly automated systems can only be reconfigured with great effort, if at all [12]. To meet the current and future challenges of assembly and disassembly, autonomous systems that combine elements of cognition and automation are needed. With recent developments in robotics and cyber-physical systems, it is possible to meet these challenges. By combining »cognitive capabilities« with automation (Fig. 2) based on robotic systems, autonomous systems (assembly and disassembly) become possible. These are characterised by a high degree of adaptability to changing system conditions (e.g., internal faults and error states) and flexibility in the case of product variation and changing batch sizes. Another important aspect is the handling and assumption of complex tasks and situations that previously required human cognitive abilities. Partially independent of humans, these systems can self-organise within their system boundaries, for example by adjusting the sequence and process parameters of assembly processes. These autonomous systems are characterised by the fact that they adapt assembly and disassembly based on cognition.

4. AUTONOMY LEVELS - POSSIBILITY OF DIVISION AND DIFFERENTIATION

For the classification and comparison of autonomous systems it is necessary to establish a taxonomy. This allows to classify the current state of the system and to define goals for a transition to a higher level. For example, a 6-level taxonomy is used in automotive (autonomous driving), a 4-level taxonomy is used in aeronautics (UAV), and a 5-level taxonomy is used in rail technology [7, 13]. One possibility for differentiation of autonomy levels, inspired by autonomous driving, is shown in Fig. 3. Here, the general capabilities of autonomous systems, related to applications in industrial production, are divided into six levels. As the autonomy level increases, general system characteristics such as decision-making power, control, monitoring and the activities of programming and project planning are successively handed over to and carried out by the technical system. The »cognitive capabilities« of the technical system (artificial intelligence, machine learning) are decisive for the assumption of decision-making and monitoring activities.

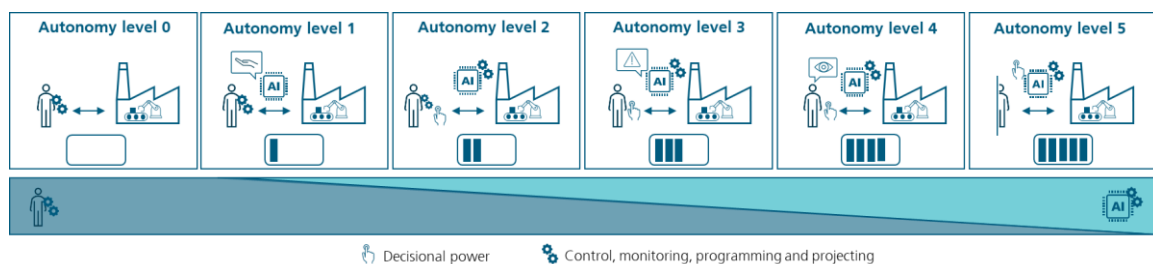


Fig. 3. Autonomous levels, based on [7, 9]

Depending on the area of application and requirements, capabilities can be prioritised and needed differently, i.e. specific use cases can have different defined levels of autonomy. The following Table 2 shows the respective autonomy levels.

Table 2. Autonomous levels, based on [7, 9]

Autonomy level	Description
Autonomy level 0	Autonomy level 0 describes classical automation and control technology. The processes are predefined and therefore static during execution. In this autonomy level, no artificial intelligence is used; the human being takes control of the overall process. This »human control« may be limited to starting and stopping a whole automation line but nonetheless no adaptive control exists. The same applies to the responsibility of maintaining operation and reacting to unforeseeable events.
Autonomy level 1	As in autonomy level 0, the robot is programmed or projected by the human. However, an assistance system, e.g. based on artificial intelligence or machine learning techniques is used, which suggests certain advantageous options for the process execution. The decision whether to choose a certain option lies with the human. The assistance system provides support in the form of assistance for the operator, optimisation of the process flow and interpretation of complex and ambiguous information. The goal is the reduction of complexities in the overall process.
Autonomy level 2	In autonomy level 2, programming and project planning are still largely determined by humans. In contrast to autonomy level 1, artificial intelligence is allowed to improve itself and its goals within predefined system limits. For example, parts that are not exactly positioned can be recognised and picked up. Simple tasks are automated or delegated to automation systems within set system boundaries. More complex tasks remain with the operator. In defined areas, the system can take over control to the desired extent. However, the monitoring and control of results as well as the decision-making power remain with the human operator. The operator sets the objectives and supports them with experience and knowledge.
Autonomy level 3	In autonomy level 3, programming and project planning are only partially taken over by humans. Within system boundaries, the system itself can plan adjustments to its actions and also implement them. To fulfil this task, the system is additionally equipped with sensors for environmental sensing. This enables the perception of the environmental context, the adaptation to movements and the learning of skills. The semi-autonomous system is capable of monitoring the manufacturing process and executing learned actions autonomously to a limited extent. The operator's task is to set the system boundary, observe the system decision and intervene in case of unforeseen problems or emergency.
Autonomy level 4	In autonomy level 4, in contrast to autonomy level 3, the robot works autonomously. Here, it is equipped with all the necessary sensors for sensing the environment, which enable a complete perception of the environmental context. The robot acts autonomously and adaptively within the system boundaries specified by the human. The artificial intelligence is able to optimise itself and adapt its behaviour to changing goals. The control is left to the system, the human being only takes over a monitoring function and acts in emergency situations.
Autonomy level 5	In autonomy level 5, the robot acts completely autonomously within the specified system boundaries. The system always cooperates with other autonomous subsystems of the overall system. The overall system works out adaptive solutions through self-organisation and through communication with other manufacturing cells. The strategy plan can be dynamically revised in real time as working conditions change and communicated to participating machines. Human presence is not required, as the system can drive itself to a safe state. The possibility of human intervention in an emergency situation remains.

5. ASSEMBLY AND DISASSEMBLY – CRUCIAL FOR REUSE AND RECYCLING

In industrial production, assembly and disassembly generally refer to any process of assembling or disassembling a product. This can be done from or into all individual parts or smaller assemblies, which are essential tasks for reuse and recycling. However, this is strongly dependent on the respective industry (e.g. automotive, aviation, electrical devices) and also on the respective product, with its various requirements and boundary conditions. In addition, the concretization of the respective task is enormously important. For example, a product can be completely reused and thus no assembly/disassembly activities would be necessary, or individual assemblies or individual parts could be reused (e.g. removal of engine from vehicle). This also applies to recycling, depending on the level of detail of the task, a wide variety of complexities can occur, for example in the form of complex processes such as the loosening of material bonds (e.g. welded joints). However, the definition of the respective product is of enormous importance. This results in its design and structure as well as the number of all elements, as well as its necessary connection concepts (e.g. screwing, welding, clamping ...).

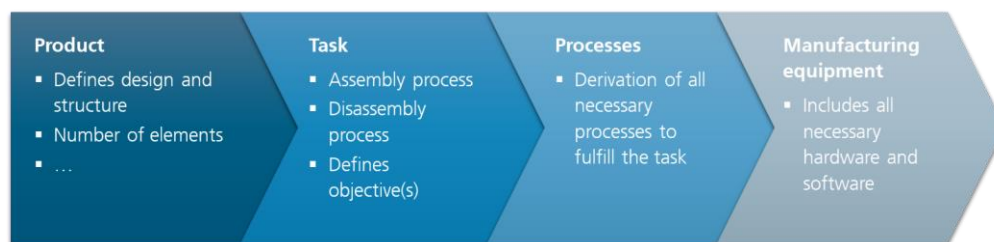


Fig. 4. Dependencies in assembly and disassembly systems

A general description of an assembly or disassembly system is very complex. Therefore, Fig. 4 is only intended to show the basic interdependencies in assembly and disassembly systems. Based on the individual tasks with their respective goals, all necessary processes for the fulfilment of the individual tasks can be derived. Hardware and software resources are required to carry out the processes. Depending on the state of the art, as well as research and development, a wide variety of technologies can be used. Due to the wide variety of dependencies, assembly and disassembly systems offer a huge number of configuration options. The individual subsections in Fig. 4 can have a very different degree of complexity, which will be summarized in the following.

Product:

The complexity of the respective products can vary greatly. The complexity is already evident in the large number of different product areas, e.g. automotive engineering, the aviation engineering and battery systems. Each of these product areas has its own specific requirements and applications. These are decisive for the respective product design and structure, as well as the number of individual parts and their connection concept. For example, the challenges for assembling or disassembling an aircraft are significantly higher than for a motor vehicle.

Process:

Are the sum of all necessary processes for the fulfilment of a task. The complexity of the individual processes can also vary greatly. The number of processes and their specific requirements is highly product dependent. Depending on the product areas and possible environmental conditions, the boundary conditions for a specific process can differ greatly. Basically, there are three process categories for assembly and disassembly: setting (includes the necessary manufacturing processes to produce a connection), handling and checking.

Manufacturing equipment:

Hardware and software resources are needed to carry out the respective processes. Here, too, there is a huge range of options or possible combinations, e.g. sensors and actuators. Which specific resources are needed or used is again strongly dependent on the type of process and its complexity. The suitability must be checked in the respective application. Criteria for the different resources would be, for example, compatibility and integration capability, which in turn limit the selection options.

6. AUTONOMOUS LEVELS IN ASSEMBLY AND DISASSEMBLY

As described above, a taxonomy can be used to classify the current state of an assembly and disassembly system and to derive targets for increasing the autonomy level.

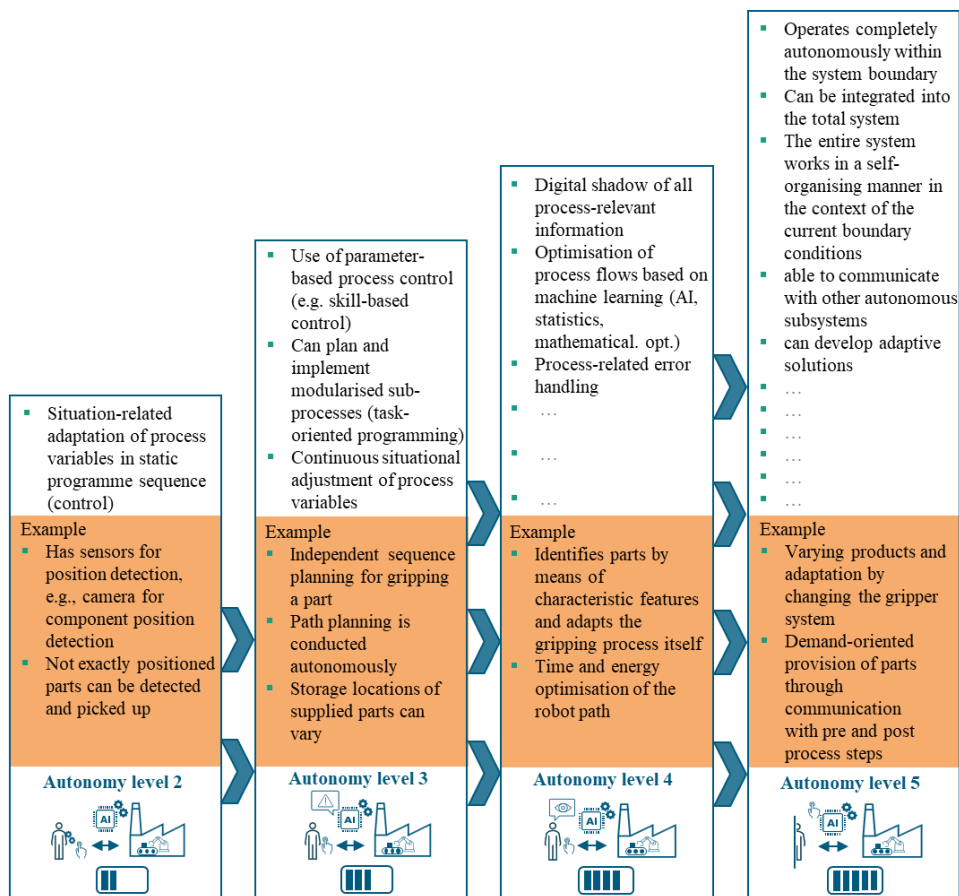


Fig. 5. Exemplary derived taxonomy for assembly and disassembly systems, detailed with handling-robot example

The taxonomy of autonomous systems presented above is only applicable to assembly and disassembly systems to a limited extent. The general description above lists features, such as environmental sensors, that are not directly required for assembly and disassembly systems. For this reason, an exemplary taxonomy for assembly and disassembly systems is shown in Fig. 5. Characteristic properties and technologies are listed for each of the four stages shown. Each level is characterized by different properties of the system, e.g., different use of »cognitive capabilities« and automation technology such as AI, machine learning, robotics, and sensors. With each increase in level, the system becomes more »intelligent« and thus increases the degree of autonomy. The above complexities also exist for autonomous assembly and disassembly systems. Due to the above complexities in assembly and disassembly, additionally using the example of a pick-and-place application using a handling robot, the task and resources are partially defined and constrained. With increasing level, the pick-and-place station is able to take over further tasks and to adapt to changing situations independently, i.e. it increases its adaptivity and flexibility. Successively, the system can handle more and more complex situations, from compensation of inaccuracies to sequence planning to identification and optimization activities. Depending on the product, the task, the necessary processes and the structure of the system, i.e. the hardware and software resources used, the characteristics and capabilities can vary greatly and be pronounced differently.

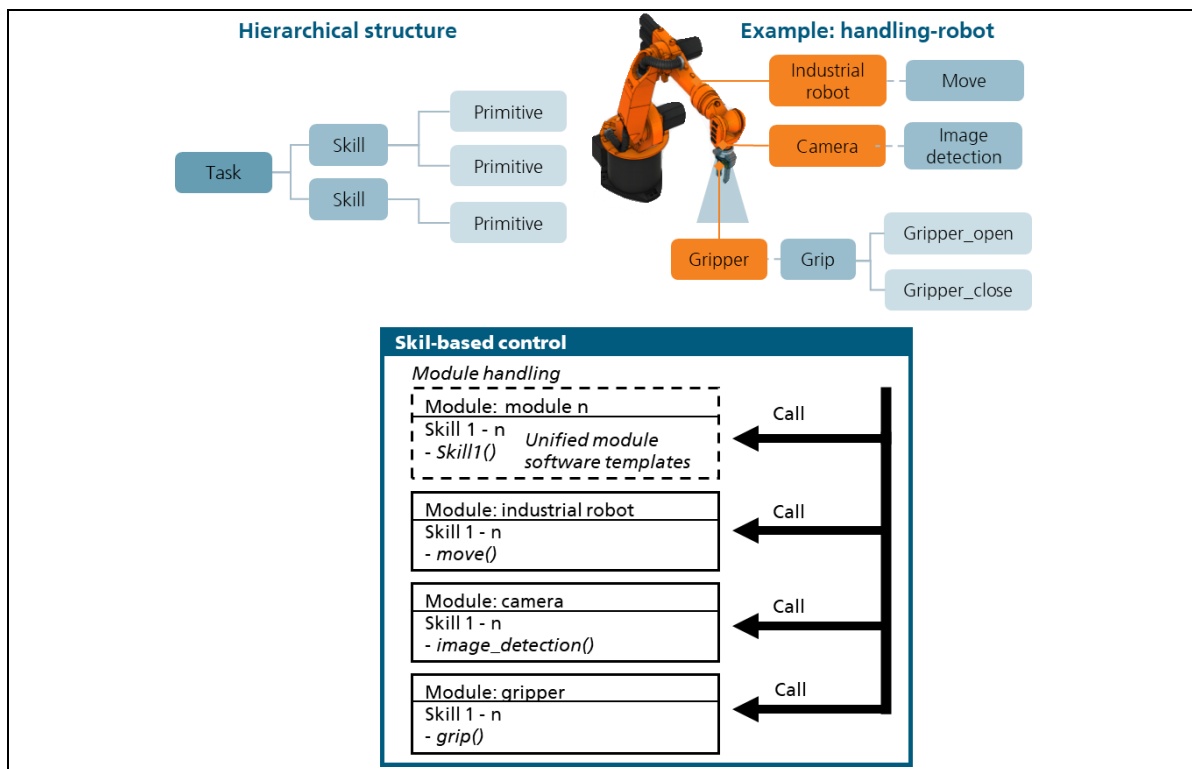


Fig. 6. Parameter-based control (skill-based control)

For example, in a screwdriving process using a robot. Not every system is necessarily suitable for an increase in the autonomy level, i.e. when reaching a higher level, an »intelli-

gent« system does not hold any further advantage. For example, in processes with constant requirements and boundary conditions or if the system is subject to rather low variability. As shown in Fig. 5, autonomy level 3, parameter-based control (e.g., skill-based control) is an important capability that enables flexible sequence control and planning. Building on this, other important capabilities can be integrated in subsequent stages, e.g., situational error handling. The principle of parameter-based control is illustrated in Fig. 6. Basically, tasks are divided into skills and these in turn into primitives. A primitive describes a skill that performs an elementary function, e.g., opening a gripper. Skills are composed of one or more primitives. They can be used to perform simple tasks, such as pick-and-place applications. As shown in the example in Fig. 6, each resource is assigned its specific skills and primitives. This creates a direct relationship between hardware and capabilities. Complex processes can thus be broken down into their elementary subprocesses. Based on this, more specific requirements and thus suitable hardware and software can be determined.

7. USE CASES FOR AUTONOMOUS APPLICATIONS IN MANUFACTURING

In the following, two examples are shown that are already autonomous applications. Both examples are developments of the Fraunhofer IWU. Here, they differ significantly from each other in their application areas and their requirements.

Figure 7 shows the Robo Operator, which is a development of the Fraunhofer IWU in Dresden. This is a flexible and mobile robot cell that automates operator tasks on machine tools. The aim is to automate all operator tasks by means of trained skills. These are, for example: pick and place tasks, post-processing (deburring, blowing off lubricant ...), interaction with the machine tool (starting, closing the door) and error detection. With the help of 2D/3D image detection, the robot movement is parameterised. The Robo Operator is able to communicate interface-free with the machine tool. An autonomous error handling system enables a situation-appropriate ability to act in the event of malfunctions. By means of a skill-based control, the operator tasks are programmed in skills [14].

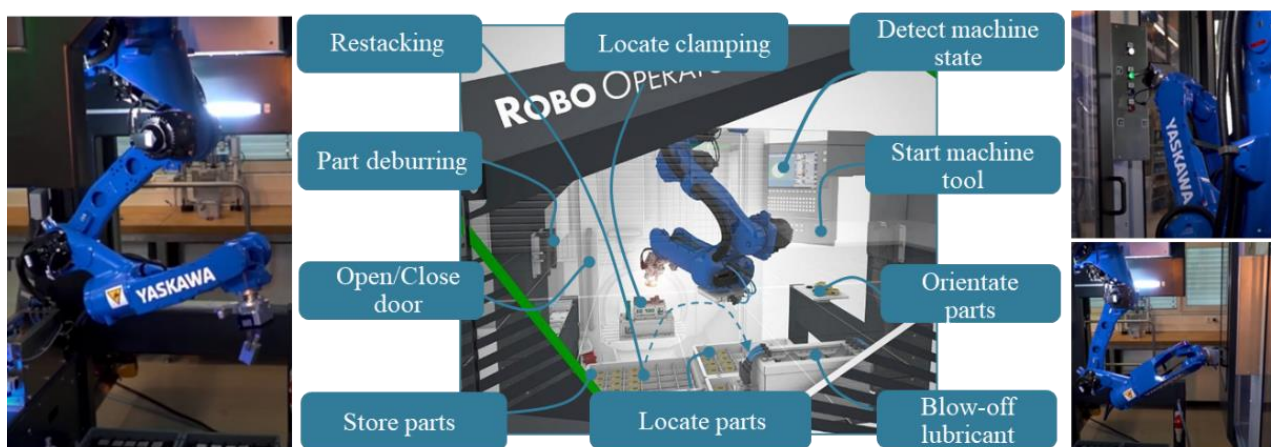


Fig. 6. Robo Operator [14]

Figure 8 shows a method for autonomous straightening processes, which is currently being developed by Fraunhofer IWU in Chemnitz. This intelligent robotic roll forming (iRoRoFo) is being developed to automate straightening processes. These processes are characterised by inefficiency, but these cannot be avoided if more dimensionally accurate shapes are required. Straightening processes are mainly carried out manually by experienced skilled workers and cause a considerable amount of work. iRoRoFo is an incremental forming process in which the component geometry is automatically measured in the last increment and then straightened. During the straightening process, the robot moves autonomously along the calculated path. Based on the data input in the form of forces and moments, geometry prediction is calculated using AI and ML algorithms. The correction path is then calculated and transferred to the robot controller.

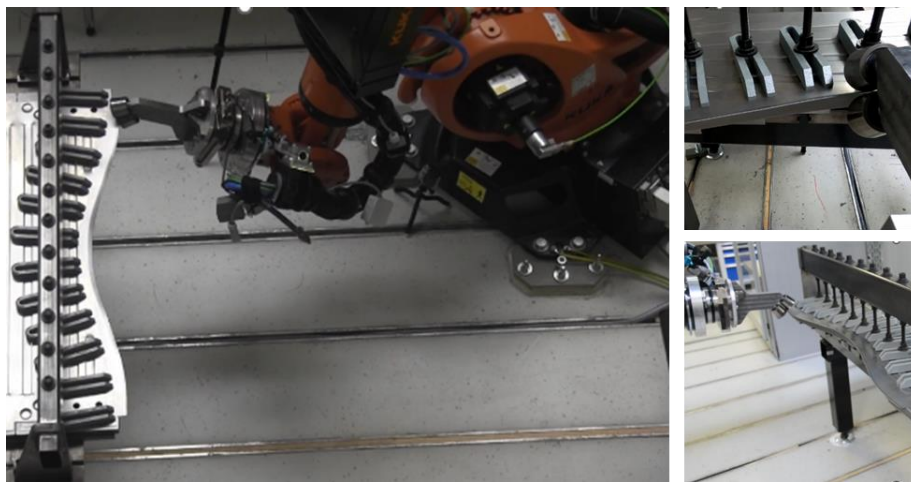


Fig. 7. Autonomous straightening process – iRoRoFo [15, 16]

8. CONCLUSION

In order to meet the challenges of the European product market (Fig. 1), autonomy in industrial production is of particular importance. Especially in the step-by-step implementation of future circular production, more precisely in the sub-areas of reuse and recycling, autonomous assembly and disassembly offers an immensely important approach. Autonomy in industrial production can be understood as a combination of elements from cognition and automation. Technical systems are thus able to cope with complex tasks and situations by means of »cognitive capabilities« as well as to plan actions independently, which are important abilities to survive in the application area of assembly and disassembly. The differentiation and delimitation of autonomy can take place in six different levels. With each increase of the level, the respective assembly or disassembly system is able to cope with increasingly complex tasks within the scope of its field of application and its requirements. Assembly and disassembly are characterized by the most varied and complex interrelationships. Starting from strongly varying product complexities up to the most complex processes, there are the most different requirements and boundary conditions for the respective assembly

and disassembly system. Each area of application therefore presents a multitude of challenges. For assembly and disassembly, state-of-the-art robotics and the use of AI and ML are extremely important elements that enable a significant increase in autonomy. Not every system is necessarily suitable for increasing the level of autonomy, i.e. when reaching a higher level, an »intelligent« system does not bring any further advantage. In the final level of autonomy, the vision of aiming for fully autonomous system Here, the individual system operates in an integrated manner as part of an overall system. The individual subsystems are able to communicate with each other and organize themselves adaptively and according to the situation as an overall system. The development and realization of autonomous assembly and disassembly systems is thus an important step towards realizing the vision of a smart factory.

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