THE DESIGN OF ELEMENTS OF AN ADAPTIVE ASSEMBLY SYSTEM

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The paper is an overview of the design of elements of an adaptive assembly system. Furthermore, this paper seeks to address with analysis and evaluation of the elements of the adaptive assembly system. The work presents a taxonomy in the field of adaptive assembly. The core of the work consists of the design of the architecture of individual systems. It is necessary to broaden knowledge about this topic because the designed elements can serve as an overview of this issue. Moreover, at the same time, they can use it in industrial practice. The proposal provides an overview of the elements for possible detailed processing of a specific design of an adaptive assembly system, either when changing an existing assembly system or when designing a new system. To ensure the long-term sustainability of the company's competitive ability, it is necessary to be able to respond flexibly to changes in production and assembly requirements. The issue (theme) is current and was defined based on the finding that there was a demand for the ability to offer multiple product variants and the introduction of new products in shorter and shorter time intervals.

KEYWORDS

Adaptability, Components, Cobot, Assembly worker

1 INTRODUCTION

There are several definitions for system adaptability in the literature [Sharma, Bhargava, 2014], [Ali, 2014]. We have combined these definitions, as with some previous definitions, into one. We can talk about an adaptive system if the system can continue to operate even if it faces changes (in this case, the definitions in the literature vary, whether the changes should be predictable or unpredictable, i.e. whether the system was designed for such changes or no), or malfunctions of its internal structure or external disturbances. Adaptability includes the search, selection, and allocation of new resources (or substitute resources) to fulfil new requirements (or circumstances – adapting to new circumstances, new tasks, etc.).

An adaptive assembly system is a set (complex) of elements that are connected by mutual relations (bonds), and which is a subsystem in the production system, the output of which is the connection of parts of the assembly subgroup (or semi-finished product) to the state of the next assembly group (or semi-finished product) / future product). The input can be parts of an assembly subgroup (or semi-finished product/future product), modules, through subjects (workers, automated machines), resources (equipment, tools), and services, connected according to the required instructions (instructions, technological procedure) and in the presence of energy.

Such an adaptive assembly system can adapt to assembly requirements:

- different variants or families of products, within a short time frame of the alignment of the assembly system,
- the absence of assembly workers,
- the search for replacement (alternative) materials, semi-finished products / semi-finished products/parts, tools, or assembly resources to reduce costs, shorten production and retyping times, increase productivity, and increase quality with an emphasis on special customer requirements.

Adaptive assembly can combine new, innovative processes, namely automation, robotics, intelligent assistance systems, etc., using changes in the properties (dimensions, shapes, tolerances, materials used, etc.) of the final assembled products, and also properties of production systems, to overcome existing process limitations. In adaptive assembly, robots can act as robotic human assistants (Cobot - in hybrid assembly) or fully robotic assembly workplaces (adaptive robotic assembly system) [Cuhna, 2008], [Dashchenko, 2006]. In the literature [Wang, 2011], [Hu, 2011], [Kruger, 2009], [Bi, 2007], we identified three types of assembly systems, according to which we proposed three types of adaptive assembly systems and subsequently their elements:

- Adaptive Manual Assembly (AMA),
- Adaptive Hybrid (partially automated) Assembly System (AHAS) a
- Adaptive Robotic Assembly System (ARAS).

The use of ergonomics to improve the performance of a manufacturing process and the positive effects of ergonomic design on productivity and human performance are drawing attention from researchers and practitioners in the field of industrial engineering, i.e., ergonomics can optimize human performance and overall work system performance. [Bortolini 2023]

2 ANALYSIS AND EVALUATION OF RELATIONSHIPS BETWEEN ELEMENTS OF THE ADAPTIVE ASSEMBLY SYSTEM

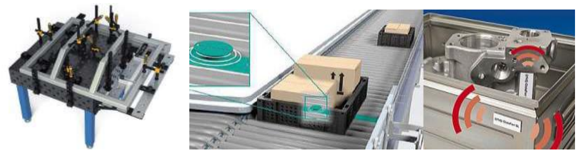
These systems will be characterized only after the design of the elements of the adaptive assembly system, but their identification is necessary, considering that some elements are characteristic only for the given type of assembly system.

We can provide the basic elements that enable the creation of an adaptive assembly system divided into the following groups and subgroups:

- **assembly operator** - an adaptive element in the assembly process, they can offer many advantages over robotic assembly sources. Assembly operators in ARM form the control, control and at the same time element that contains the knowledge base, intelligence, and skills in the system,
- **cobot** - they can cooperate and communicate with people in joint activities [Michalos, 2016], [Krajcovic 2019], [Krajcovic, 2011], [Grznar 2021],
- **assembly robot** - The conditions for the introduction of assembly robots include: sufficient serial production of products, suitability of the structure for automated assembly, availability of means for automated assembly [Haluska 2013], [Durica 2019],
- **control element** - Production systems require greater adaptability in product design, project planning, planning, and process management. This can also be achieved through integrated software and hardware architectures that generate real-time decisions based on information gathered from assembly systems and executing those decisions [Dagli, 2012].
- **intelligent sensory systems:**

- *automatic identification* - is a process that uses an identification element to identify, record, and track any objects [Buckova 2020], [Westkamper 2007].
  - *advanced vision systems* (ARM, AHMS, ARMS) - can also be used in the adaptive assembly system
  - for checking assembly operations, detecting the presence and number of material, and parts, finding surface defects, identifying colors, determining the position of products (guidance of Co-Bots and assembly robots), and checking the assembly procedure. This increases the space for the adaptability of the assembly.
- **visual-information elements** - it is possible to identify the mounted part, or a family of products, and subsequently visualize their assembly procedure together with the necessary components and tools needed to perform the given operation
- visual-informational elements [Hagele 2002],
- **intelligent assistance systems**,
- **adaptive preparations** – (Figure 1a) The preparation can be marked and tracked using AutoID, thanks to which it is possible to monitor the availability of free preparations, the number of preparations in the assembly, and the overall progress of the assembly,
- **intelligent assembly base** - it can not only contain information but can also make decisions about itself. It can be aware of the components from which it is made and can act as their proxy (in an adaptive assembly system). The intelligent mounting base enables the adaptability of the mounting system [Frei 2011], [Meyer 2009],
- **parts, subassemblies, assemblies –** the most frequently used representational methods for assembly is the bill of materials [Zeimpekis 2002],
- **assembly tools** - they are a necessary part of the assembly to connect the parts of the assembly subgroup to the state of the next assembly group and the final product,
- **orientation-input units** - they serve to supply non-oriented parts from arbitrary to a defined position, to maintain this position and orientation (so that they can be removed by a manipulator) or also to place parts in an assembled unit, various devices are used, which can be divided into groups
- **interoperation transport, and storage** - the most widespread are conveyors [McFerlane 2003].

By combining the elements defined above and their relationships, they will enable the creation of an adaptive assembly workplace that can adapt to different families and variants of assembled products, the absence of workers and the absence of assembly parts, tools,
workers or robots.



a) b)

Figure 1. The example of elements of the adaptive assembly system [McFerlane 2003]

The design of the system, in addition to the above-mentioned characteristics of the elements, must also be subject to the rules and principles when planning the assembly layout. The assembly method must be defined, the sequence of operations determined, and the selection of tools and equipment for assembly. The assembly must be optimized so that we can reduce costs and shorten time.

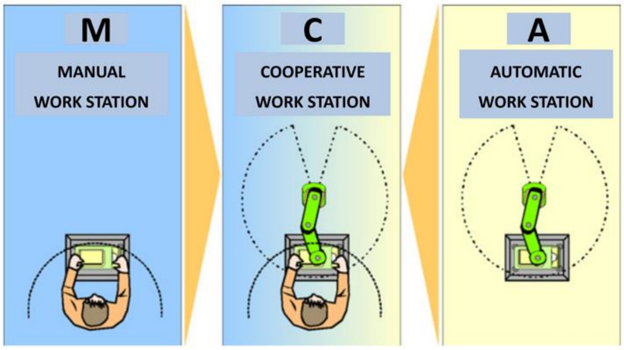


Figure 2. Method of online data collection from the production system [own collaboration by Frei 2011]

3 ARCHITECTURE OF ADAPTIVE MANUAL ASSEMBLY (AMA)

Adaptive manual assembly consists of elements that create an adaptive manual assembly workplace. With the help of the automatic identification element (AutoID), assembly workers, critical assembly tools, an intelligent assembly base, and can also be important parts, sub-assemblies, assemblies are recognizable and traceable in the system. Using automatic identification, it is possible to detect what types of smart product variants are included in the assembly process, which enables the subsequent adaptation of the assembly system to the given variant or family of products.

The assembly worker is marked with AutoID, thanks to which it is possible to track his presence at the workplace (correct position in the assembly system). Performs the assembly of parts, subassemblies, and assemblies on an intelligent assembly base (increases added value) with the help of assembly tools, intelligent assistance systems, orientation-input units, and assistance and control from advanced vision systems and visual-information elements. An essential part is interoperational transport, in which the assembly worker actively participates. In the following figure, 3 shows the architecture of adaptive manual assembly.

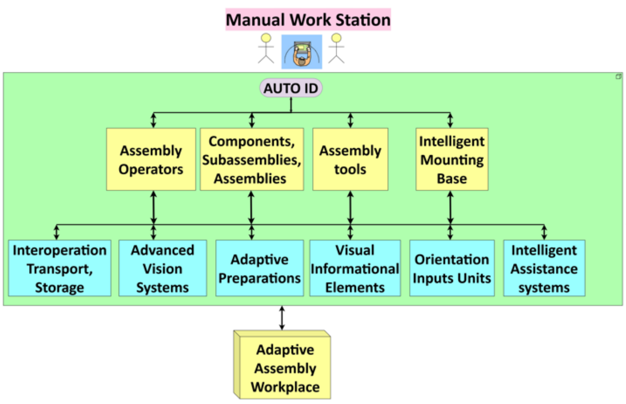


Figure 3. The architecture of the adaptive manual assembly [own collaboration 2023]

Assembly workers are considered a major tool of adaptability, as they can quickly adapt to changing products and market situations [Bernhardt 2008].

Components, sub-assemblies, and assemblies are assembled by assembly workers on an intelligent assembly base, with the help of assembly tools. Their correct assembly is checked by an advanced vision system and visualized through visual-informational elements. Important parts of components, subassemblies, and assemblies can be marked with the AutoID system. Parts, assemblies, and sub-assemblies are fed into the assembly process using orientation-feeding units.

Assembly tools help and make it easier for the worker to assemble parts, sub-assemblies, and assemblies on an intelligent assembly base. Critical tools can be marked with AutoID. They can be controlled through an advanced vision system. Multi-purpose assembly tools or tool magazines and their quick change contribute to the adaptability of the system.

The intelligent assembly base is marked with AutoID and clamped in an adaptive fixture in which it moves through the assembly process using interoperation transport. In the assembly process, the assembly worker assembles parts, sub-assemblies, and assemblies onto it using assembly tools. Its assembly process is controlled by an advanced vision system and displays a visual information element. The intelligent assembly base enables the adaptability of the assembly system as it can be identified with AutoID, can communicate with the environment, store data, and can participate or make decisions about itself as it can be identified. Adaptive fixtures speed up and facilitate the clamping of the intelligent mounting base. During assembly, the assembled intelligent assembly base moves in the fixture by interoperation transport and is manipulated by the assembly worker with the help of intelligent assistance systems.

Adaptive preparations increase the adaptability of assembly workers, robots, and cobots and thus the adaptability of the system thanks to their simple and unambiguous use and assistance in assembly and handling. Visual information elements help the assembly worker with visualization in his activities. Using feedback from the advanced vision system, they are involved in controlling its progress. They can alert him to errors in the assembly process, as well as help new or substitute workers to adapt, thus helping to increase the adaptability of the system.

Orientation-input units actively assist the assembly worker in the assembly of parts, sub-assemblies, and assemblies on an intelligent assembly base. By feeding and orienting parts, subassemblies, and assemblies, they significantly speed up the assembly process.

By adapting to different types of product families, orientation-input units increase the adaptability of the system.

Intelligent assistance systems assist the assembly worker in handling the intelligent assembly base clamped in the adaptive fixture during assembly and preparation for interoperation transport.

Intelligent assistance systems help with the handling of heavy objects, including when changing the product family, if a change of assembly worker (more physically fit) is necessary, or equipping the workplace with other types of handling aids.

By doing so, they help adapt the system. Advanced vision systems scan and control the assembly process of the final product of the assembly worker, identify parts, sub-assemblies, and assemblies and, by connecting to visual information elements, can warn of assembly errors in real-time.

Advanced vision systems thus prevent the output of defective pieces from the assembly even after the introduction of a new type of product. They can also recognize a new type of product and thus adapt the system to a given variant or family of products.

Interoperation transport and storage is an essential part of the assembly process. It ensures the smooth movement of the material flow (intelligent assembly base as well as the supply of parts, subassemblies, and assemblies to the assembly workplace) through the assembly process.

Interoperational transport contributes to adaptability by adapting individual parts of the transport to adapt to changes in the material flow, such as direction or shape. AGVs offer a great advantage in their reprogrammability.

4 ARCHITECTURE OF ADAPTIVE HYBRID ASSEMBLY SYSTEM

It is not always easy to separate tasks that can be performed automatically from tasks that require manual assembly along the assembly line. The approach was to explore the possibility of combining manual and robotic assembly in one workplace. Operator safety rules prohibit the use of workplaces where operators can reach the contact of the robot working in automatic mode. Methods to overcome this problem have been discussed and explored in several research projects.

The most promising approach seems to be the use of intelligent sensory systems (advanced vision systems) to prevent the robot from moving where it is human [Hu, 2011].

In a system where robots and humans share a workplace, performing manipulative tasks as well as assembly tasks in two different configurations: - either the robot performs the assembly task and a human worker a manipulation task, or a robot performs a manipulation task and a human worker performs the assembly task [Krüger, 2009].

The following Figure 4 shows the architecture of the adaptive hybrid assembly system.

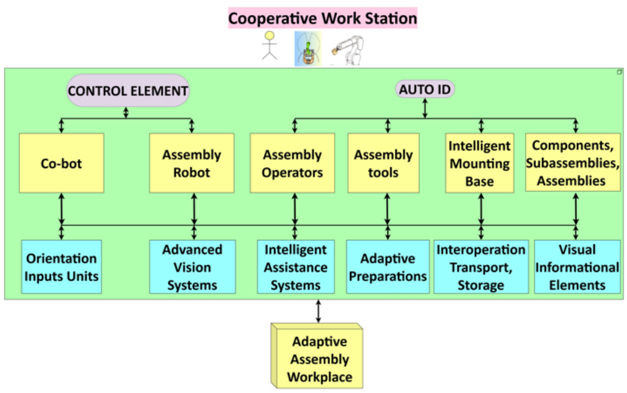


Figure 4. Adaptive hybrid assembly system architecture [own collaboration 2023]

An adaptive hybrid assembly consists of elements that create an adaptive hybrid assembly workplace. The control element directs and controls the work of robots and cobots in the hybrid system.

The control element is designed in such a way that it can use the adaptability of the designed elements to enable the adaptability of the system as a whole.

The co-bot actively cooperates with the assembly worker in the assembly of parts, sub-assemblies, and assemblies, which can be brought to them by orientation-feeding units on an intelligent assembly base using assembly tools, in this case, effectors and an advanced vision system such as control, identification, and guidance of the procedure.

It can actively participate in interoperation transport by relocating the intelligent assembly base in the adaptive fixture.

Cobot combines the advantages of industrial robots with passive handling devices. The goal is to combine flexibility, intelligence, and human working skills forces with advanced and sophisticated technical systems. Thanks to this, co-bots increase the adaptability of the system.

The robot actively cooperates with the assembly worker but is not in direct contact with him. Performs assembly tasks of parts, sub-assemblies, and assemblies that can be fed to them by orientation-feeding units on an intelligent assembly base

using assembly tools, in this case, effectors and an advanced vision system as control, identification, and guidance. It can actively participate in interoperation transport by relocating the intelligent assembly base in the adaptive fixture.

The mobile robot, thanks to the ability to move and a shorter time for reconfiguration and reduction of efforts to put a new robot into operation with an operational adaptation of robots when handling and assembling different parts, increases the adaptability of the system.

The assembly worker is marked with AutoID, thanks to which it is possible to track his movement (correct position in the assembly system). Performs the assembly of parts, subassemblies, and assemblies on an intelligent assembly base (increases added value) with the help of assembly tools, intelligent assistance systems, orientation-feed units, robots, co-bots, and with assistance and control from advanced vision and visual information systems elements. An essential part is interoperational transport, in which the assembly worker can also participate.

Assembly workers are considered a major tool of adaptability, as they can quickly adapt to changing products and market situations.

Assembly tools help and facilitate assembly for the assembly worker and, in the case of robots or co-bots (effectors), enable the assembly of parts, subassemblies, and assemblies on an intelligent assembly base. Critical assembly tools may be marked

using AutoID. They can be controlled by an advanced vision system, and in the case of robots and co-bots, they can be identified with the help of advanced vision systems.

Multi-purpose assembly tools or tool magazines (effectors) and their quick exchange contribute to the adaptability of the system.

The intelligent assembly base is marked with AutoID and clamped in an adaptive fixture in which it moves through the assembly process using interoperation transport. In the assembly process, an assembly worker, robot, or co-bot mounts parts, subassemblies, and assemblies onto them using assembly tools. Its assembly process is controlled by an advanced vision system and displays a visual information element.

The intelligent assembly base enables the adaptability of the assembly system as it can be identified using AutoID, can communicate with the environment, store data, and can participate or make decisions about itself as it can be identified.

Components, subassemblies, and assemblies are assembled by an assembly worker, robot, or co-bot on an intelligent assembly base, using assembly tools. Their assembly correctness is checked by an advanced vision system and visualized through visual-informational elements. Important parts can be marked with the AutoID system. Parts, assemblies, and sub-assemblies are fed into the assembly process using orientation-feeding units.

Advanced vision systems scan and check the assembly process and the final product of the assembly worker, identify parts, sub-assemblies, and assemblies, and with the help of a visual-information element, they can point out an error in the assembly in real-time, or help a new or substitute assembly worker to adapt.

In the case of equipping a robot, or co-bot with this system, it is a so-called robotic vision. This helps robots and co-bots to sense, control, recognize and thereby perform assembly tasks. In the case of co-bots, this system enables cooperation with the assembly worker.

Advanced vision systems thus prevent the output of defective pieces from the assembly even after the introduction of a new type of product. They can also recognize a new type of product and thus adapt the system to a given variant or family of products.

Intelligent assistance systems assist the assembly worker in handling the intelligent assembly base clamped in the adaptive fixture during assembly and preparation for interoperation transport.

Intelligent assistance systems help with the handling of heavy objects, including when changing the product family, if a change of assembly worker (more physically fit) is necessary, or equipping the workplace with other types of handling aids.

By doing so, they help adapt the system. Adaptive fixtures speed up and facilitate the clamping of the intelligent mounting base. During assembly, the assembled intelligent assembly base moves in the adaptive preparation using interoperation transport and is manipulated by the assembly worker with the help of intelligent assistance systems, or by a robot, or co-bot with the help of effectors.

Adaptive preparations increase the adaptability of assembly workers, robots, and co-bots and thus the adaptability of the system thanks to their simple and unambiguous use and assistance in assembly and handling.

Interoperation transport, and storage an essential parts of the assembly process. It ensures the smooth movement of the material flow (intelligent assembly base as well as the supply of parts, subassemblies, and assemblies to the assembly workplace) through the assembly process. Assembly workers, co-bots, and robots can be an active part of the movement of the assembled intelligent assembly base.

Interoperational transport contributes to adaptability by adapting individual parts of the transport to adapt to changes in the material flow, such as direction or shape. AGVs offer a great advantage in their reprogrammability. Visual information elements help the assembly worker with visualization in his activities. Using feedback from an advanced vision system, they participate in checking the assembly process. They can alert him to errors in the assembly process, as well as help new or substitute workers to adapt, thus helping to increase the adaptability of the system.

With the help of the automatic identification element (AutoID), assembly workers, critical assembly tools, intelligent assembly base, and important parts, sub-assemblies, assemblies are recognizable, traceable, and traceable in the system.

Using automatic identification, it is possible to detect what types of smart product variants are included in the assembly process, which enables the subsequent adaptation of the assembly system to the given variant or family of products.

Orientation-input units actively assist the assembly worker, robot, or cobot in the assembly of parts, subassemblies, and assemblies on an intelligent assembly base. By feeding and orienting parts, subassemblies, and assemblies, they significantly speed up the assembly process.

By adapting to different types of product families, orientation-input units increase the adaptability of the system.

5 ARCHITECTURE OF AN ADAPTIVE ROBOTIC ASSEMBLY SYSTEM

This is the most demanding assembly, as regards the financial aspect of putting it into practice and the perspective of development. The customer's request is transformed into an order for the robotic assembly system.

The automotive industry and its supply chains are currently the main users of robotic systems due to their ability to perform tasks (assembly, inspection, etc.) with higher quality and repeatability. Minimizing the transition time between models is the main goal of ARAS. The following Figure 5 shows the architecture of the adaptive robotic system.

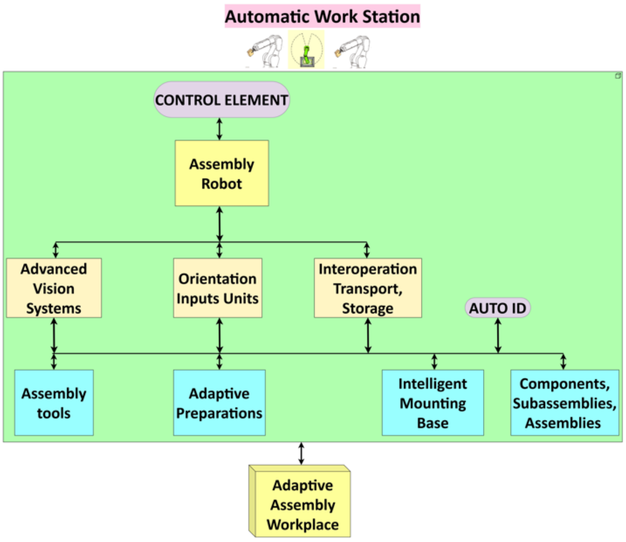


Figure 5. Architecture of an Adaptive Robotic System [own collaboration 2023]

An adaptive robotic assembly system consists of elements that create an adaptive assembly workplace.

The control element directs and controls the work of the robots in the robotic system.

The control element is designed to be able to use the adaptability of the designed elements to enable the adaptability of the system as a whole.

The robot is the main element of the robotic assembly system. Performs assembly tasks of parts, sub-assemblies, and assemblies, which can be brought to them by orientation feeding units to an intelligent assembly base using assembly tools, in this case, effectors and an advanced vision system such as inspection, identification of parts, assembly sub-assemblies and their location. It can actively participate in interoperation transport by relocating the intelligent assembly base in the adaptive fixture. Its behavior is controlled by the control element.

The mobile robot, thanks to the ability to move and a shorter time for reconfiguration and reduction of efforts to put a new robot into operation with an operational adaptation of robots when handling and assembling different parts, increases the adaptability of the system. Assembly tools in the case of effector robots enable interoperational transport and assembly of parts, subassemblies, and assemblies on an intelligent assembly base. Critical tools can be marked with AutoID for easy identification.

They can be controlled using an advanced vision system. Multi-purpose assembly tools or tool magazines (effectors) and their quick exchange contribute to the adaptability of the system.

Orientation-input units actively assist the robot during assembly on the intelligent assembly base. By feeding and orienting parts, subassemblies, and assemblies, they significantly speed up the assembly process.

By adapting to different types of product families, orientation-input units increase the adaptability of the system.

The intelligent assembly base is marked with AutoID and clamped in an adaptive fixture in which it moves through the assembly process using interoperation transport. In the assembly process, the robot mounts parts, sub-assemblies, and assemblies on it using assembly tools. Its assembly process is controlled by an advanced vision system.

The intelligent assembly base enables the adaptability of the assembly system as it can be identified using AutoID, can communicate with the environment, store data, and can participate or make decisions about itself as it can be identified.

Interoperation transport, and storage an essential parts of the assembly process. It ensures the smooth movement of the material flow (intelligent assembly base as well as the supply of parts, subassemblies, and assemblies to the assembly workplace) through the assembly process.

Interoperational transport contributes to adaptability by adapting individual parts of the transport to adapt to changes in the material flow, such as direction or shape. AGVs offer a great advantage in their reprogrammability.

With the help of the automatic identification element, the system can recognize trackable and traceable critical assembly tools, intelligent assembly bases and critical components, subassemblies, and assemblies.

Using automatic identification, it is possible to detect what types of smart product variants are included in the assembly process, which enables the subsequent adaptation of the assembly system to the given variant or family of products.

Adaptive fixtures speed up and facilitate the clamping of the intelligent mounting base. During the assembly of parts, sub-assemblies, and assemblies, the assembled intelligent assembly base moves in the adaptive fixture by inter-operation transport and is manipulated by the robot with the help of manipulative assembly tools of effectors.

Adaptive preparations increase the adaptability of assembly workers, robots, and cobots and thus the adaptability of the system thanks to their simple and unambiguous use and assistance in assembly and handling.

Parts, subassemblies, and assemblies are assembled by a robot on an intelligent assembly base, with the help of effectors. Their correct assembly is checked by an advanced vision system. Important parts can be marked with the AutoID system. Parts, assemblies, and sub-assemblies are fed into the assembly process using orientation-feeding units.

Advanced vision systems sense and control the progress of robot assembly using assembly tools on an intelligent assembly base, and identify parts, subassemblies, and assemblies. In the case of equipping the robot with an advanced vision system, it is a so-called robotic vision. This helps robots to sense, inspect, recognize and thereby perform assembly tasks.

Advanced vision systems thus prevent the output of defective pieces from the assembly even after the introduction of a new type of product. They can also recognize a new type of product and thus adapt the system to a given variant or family of products.

6 CONCLUSIONS

The paper deals with the design of elements of an adaptive assembly system, which are aimed at a comprehensive reduction of time in assembly processes.

In the first part, we created an overview of theoretical knowledge about the basic definitions of the system and system elements. Next, we defined the assembly system and its categories, which create the background for processing the topic of adaptive assembly systems.

One of the main proposals in the second part of the paper is the definition of system adaptability, adaptive assembly system, and adaptive assembly. In the second part, the main elements of the adaptive assembly system were also designed, which are the assembly operator, control element, intelligent sensor systems, visual information elements, intelligent assistance systems, adaptive fixtures, intelligent assembly base, parts, subassemblies, assemblies, assembly tools, orientation- infeed units, inter-operational transport and warehouse that create an adaptive assembly workplace.

In the third part, three types of adaptive assembly systems are identified, namely adaptive manual assembly, adaptive hybrid assembly system, and adaptive robotic assembly system. The architecture of the individual systems was designed, in which the elements designed by us are present for each system, or only for them characteristic system. In each system, the interaction of individual elements with each other and their role in a specific system are described, which as a whole form an adaptive assembly workplace of the given system.

In the future, it is possible to use the proposals as a nomenclature for a specific design or research of an adaptive assembly system in practice, as well as a possible basis for pedagogical purposes.

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