Mobile Assembly Units as Enabler for Changeable Assembly Lines

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1. Introduction

The ability to react on unforeseen environmental conditions e.g. demand fluctuations is inevitable for original equipment manufacturers (OEM) in order to succeed in a competitive setting. On the production level of an assembly line or of an underlying assembly station changeable production units and in particular reconfigurable assembly systems (RAS) are the keywords in this context [1]. Above all fixed and inflexible partly-automated and automated production units within the final assembly of cars make this task difficult. In order to reach the goal of an RAS the primary changeability enablers “automatibility”, “convertibility”, “scalability”, “mobility” and “modularity” have to be considered during the design process [1]. This paper is focused on proposing a solution to include these enablers in assembly units within the final assembly lines of an OEM by using a modularized, standardized and mobile platform.

Several RAS have been developed. As an example Onori et al. proposed a solution, where manual assembly stations can be extended gradually by automated and standardized assembly modules in the hyper flexible automatic assembly project (HFAA) [2, 3]. Furthermore, in [4] a moveable carrier for lightweight robots has been recently presented. However, with the named solutions it is hardly possible to face all challenges of a final assembly of a car manufacturer. One reason is for example that the systems are designed as static systems. Threewith it is difficult or even impossible to apply them to continuous flow production areas which are very common within automotive sector.
This paper presents a novel approach for an RAS considering the specific requirements resulting from different modes of production and degrees of automation of final car assembly. The central idea consists of creating different assembly units by combining mobile and standardized modules with fixed dimensions (see Fig. 1). For this purpose a cost-efficient mobile platform has been developed that can be built-up in a variety of geometrical configurations and can be extended by different modules (e.g. drive module, load module, etc.) for each application. The major advantage is the easy reconfiguration of the assembly units with these modules involving little effort and short time.

The main contribution of the presented paper is the proposal of an all new RAS. With the benefits of the system presented in the use case it is shown, that it is possible to react on various foreseen and unforeseen changes concerning the assembly line.

2. Previous Work and Research Gap

To make clear which research gap is envisaged to be closed by the proposed system an outline on RAS is given. Furthermore, current technological advances, which enable changeability for final assembly of cars, are presented.

2.1. RAS in Context of Changeable Production Systems

Meanwhile there is a very extensive literature on changeability. According to [1, 5, 6] changeability is an umbrella term for different classes of changeability which can be found on different hierarchical levels of production ranging from station level, where single part elements are machined, to production network level affecting the whole product portfolio. In this context an assembly line of a car manufacturer corresponds to the so called “system level” where flexibility and reconfigurability are the corresponding changeability classes. Flexibility describes logical changes like re-programming, re-routing and re-scheduling. In contrast to this, reconfigurability means physical changes of the structure of manufacturing processes like adding, removing or modifying machine modules [1].

There are two production paradigms addressing this definition of changeability, called reconfigurable manufacturing systems (RMS) and flexible manufacturing systems (FMS). The main difference between these two is the degree of flexibility. Contrarily to an RMS with a customized and limited flexibility, a FMS shows a general flexibility [7]. This high degree of flexibility is on the one hand an advantage and on the other hand also a major disadvantage of FMS due to the high costs caused by much built-in functionality [8, 9]. A reconfigurable assembly system can be characterized analogous to an RMS with its focus on assembly.

Together with RMS and a transformable factory (TRF) RAS build the physical level of a changeable manufacturing (see Fig. 2). In order to design a changeable assembly several change enablers have to be considered. These are modularity, scalability, convertibility, mobility and automatibility. A special focus is on mobility to allow the reconfiguration and relocation of modules or the whole system. Furthermore automatibility is important in order to react to different factors like production rate or wage level [1, 6]. Bi et al. give in [10] an extensive overview of RAS and design guidelines.

Different RAS solutions are described in literature [11, 12, 13, 14]. These contributions address solutions for the assembly of workpieces of relative small dimensions and scope which can be handled by small transfer systems. Major research takes place in the field of modularization methods of changeable production systems [15, 16, 17, 18, 19]. This also emphasizes the importance of modularity to reconfigurable systems. All these proposals are either not applicable in final car assembly because of the small dimensions of the workpiece or are very generic approaches that cannot be easily adapted.

2.2. Technological Advances for Final Assembly of Cars

There are several technological advances which are beneficial for final assembly of cars. One major point is human-robot-collaboration with small sensitive robots like the lightweight robot published in [20]. Their ability of cooperating with workers allows the application without any safety fences. Based on this and because of their low weight and small dimensions robots like these are predestinated for the application in an RAS. A theoretical approach called “robot farming” is published in [21] where several robots are operated, maintained and relocated by one single worker. This idea is supported by systems like a mobile vehicle, where the robot, its controller and some periphery are mounted [4]. This vehicle can easily be relocated by simply moving it manually. A more sophisticated approach is presented with an automated guided vehicle named “rob@work”, which can semi-autonomously relocate the robot [22]. The number of applications of sensitive (and mobile) robots increases steadily.
2.3. Research Gap

Above mentioned RAS solutions allow adding, removing, modifying and relocating machine modules. However, these functionalities are not sufficient for final car assembly, as they are mainly designed for machining small parts. For example, even within one assembly line there might be areas of cyclical as well as continuous flow production. So, relocating a machine module from an area of cyclical to an area of continuous flow production can make it necessary to move the whole assembly unit synchronously alongside the moving product. None of the above mentioned solutions are designed for this purpose.

Developments in the field of human-robot-collaboration with sensitive robots ease the application of reconfigurable systems. First steps towards mobile and reconfigurable systems are done. However these solutions only take the robot itself into account. For a successful application also solutions for peripheral systems (e.g. seal-plug feeder) have to be considered in a holistic approach.

This allows the formulation of the research questions as follows:

1. What requirements have to be met by an RAS within final car assembly?
2. How can reconfigurability be considered in final car assembly?
3. How can the mentioned recent technological advances (e.g. human-robot-collaboration, robot farming) be used to the best advantage?

3. Mobile and Modular Assembly Units

One answer to these research questions is the introduction of a system consisting of mobile and modular assembly units. For this purpose, all possible location-dependent varieties within final car assembly and changes as far as practicable have to be considered. Starting from this, several key design parameters of the final design solution can be derived. Finally, these design parameters lead to the final design of the specific modules.

3.1. Requirements on Mobile and Modular Assembly Units

Designing a changeable and reconfigurable assembly unit, respectively makes it essential to consider all possible varieties and especially the location-dependent varieties. For example there is different conveyor technology in modern assembly halls reaching from electric monorails over automated guided vehicles to slat conveyors. While first mentioned conveyors are mounted on the ceiling, the latter ones are mounted on the ground. This and varying planned logistics and assembly areas result in different usable areas for the planned assembly unit. Thus, changeable assembly units have to be variable according to their geometrical dimensions.

If changes like adding, removing, relocating and modifying modules are considered, further abilities of the system are required. Adding and removing modules requires an easily detachable connection of the modules. Adding, removing and relocating are also supported by a mobile design of each single module. The relocation of a whole assembly unit can also require major changes. E.g. it might be possible, that an assembly unit is moved from an area of cyclical flow production to an area of continuous flow production. Due to the limited working range of the processing units (e.g. robot) it might be helpful to move them during the assembly operation alongside the car to be produced. Consequently, this results in a transformation of a static into a dynamic assembly unit, which is able to move synchronously to the conveyor and to move back to the starting point of the process.

Furthermore modern assembly units have to ensure the possibility of the collaboration of humans and robots. So, it has to be ensured, that mobile assembly units can be basis for manual, partly-automated and automated assembly operations at the same time. It must be possible to support workers for example by transporting their tools and materials on some sort of platform. On a next step of assistance, it must be possible to add a sensitive robot to directly support the worker. Besides these ergonomic reasons it might be rational to increase the degree of automation in order to handle for example a decreasing cycle time caused by an increased number of pieces.

![Fig. 3. Basic requirements on mobile and modular assembly units.](image)

The described varieties and changes make it necessary to consider five basic requirements, as shown in Fig. 3. With these basic requirements it is possible to react on both foreseen and unforeseen changes. Additional to these functional requirements there is a permanent demand for cost reduction. Consequently and in accordance with literature, the implementation of mobile and modular assembly units has to be cost-neutral until the specific change arises. This means no extra costs come up a priori.

3.2. Key Design Parameters of the Design Solution

The identified basic requirements lead to several key design parameters, which have to be part of the RAS. The idea is to split assembly units into several small modules, where every single module has to be mobile by itself.

Mobility is achieved by each module being movable. It is necessary to equip each module with an own drive.
Mobility is one of the most important basic requirements in order to implement a changeable assembly line, because it reduces effort and time for adding, removing and relocating the assembly unit. So, mobile design of each module is the first key design parameter.

Additionally, the connection technique of these modules has a crucial role for the success of the whole concept and therefore the following characteristics have to be regarded:

- robustness
- ease of use
- maximum of possible combinations of modules
- low costs

Third key design parameter is about the requirement of realizing different sizes of the assembly unit. This accompanies with the connection technique and is of comparable importance. The overall dimensions of one module should not be oversized because difficulty of handling increases and at the same time mobility decreases. It is particularly advantageous to choose a rectangular but not quadratic geometry and it is especially helpful to choose a length ratio of three to two (short to long side). The reason is, with the free choice to connect the modules (short to short, short to long, long to long side) a finer scaling of different widths of the assembly unit is possible (see Fig 4). This is very favorable to fulfill the requirement of enabling different sizes of the assembly unit and helps to implement the systems in existing assembly lines.

![Fig. 4. Finer scaling of width by using rectangular geometry.](image)

3.3. Standard Modules and Periphery

Detailing the key design parameters and considering the demanded basic functional requirements results in the design of several standardized modules, which act as a basis for a set of modules of an RAS.

The most commonly module is a load module. It represents the basic module for every application ranging from transporting workers in continuous flow production to enabling mobility to robots and peripheral systems. It consists of a welded frame made of steel on swivel casters with attachment parts. Latter ones are centering pins and eccentric hook fasteners for connecting two or more modules. The fasteners can be operated with common hex keys. This makes it possible to join or split modules in a minimum of time. To ease ascending and descending the modules when using it as worker platform, the overall height is minimized. Moreover, for the case of manually assembling electric components, all parts of the module are designed to allow electrostatic discharge. Additionally, there are several prepared mounting surfaces on the steel frame to have the possibility to add peripheral mechanical and electric components.

The load module can be modified for special purposes, e.g. mounting a lightweight robot on it. In a frequent case. If the robot is directly assembling parts of the car, a special construction between load module and robot is needed in order to orientate the robot to the car. This construction is needed whether the robot is operated in cyclical or in continuous flow production. However, the description of this construction goes beyond the scope of this paper. For the case of applying a robot in continuous flow production a mechanical linking between load module and the conveyor or car can be beneficial. This linking can be mounted on the standardized mounting surfaces of the modules.

Besides, there are other components which can be mounted on the load module. Examples are racks for material supply and peripheral components for automatization (e.g. feeders, etc.).

In order to enable the application of the whole system in continuous flow production a drive module is needed to move the system along the conveyor and to return it to its starting point. The drive module can be connected to the other modules with the above described identical connection technology. The drive module consists of an electric friction wheel drive and a power supply. This power supply can be either mobile (batteries or capacitors) or fixed. The guidance of the modules is realized by two wheel-flange roles which are also mounted on the prepared mounting surfaces and which roll on a guidance rail mounted on the ground. If only manual assembly steps are carried out on the load modules, there is no need for a customized mechanical coupling to the conveyor or to the car to be produced. In this case the synchronization with the conveyor can be done by a visual tracking approach. So, there is no need of modifying mechanical parts in the case of relocating the system. Flexibility is guaranteed by only re-teaching the geometry, which is tracked by the camera.

The described standard modules, i.e. the load module and the drive module, ensure maximum reconfigurability not only to all partly-automated and automated assembly units where small robots like lightweight robots are used. It also offers a reconfigurable system to all manual assembly units.

4. Use Case: Seal-Plug Assembly

Seal-plug assembly is commonly a manually executed assembly operation during continuous flow production, where the worker has to walk along the conveyor and has to move back to collect new material. Within body in white (BIW)
production several holes are needed in order to allow the paint to empty off during cathodic dip painting or to guarantee accessibility for further processing steps (e.g. cavity preservation). In order to protect the BIW for example against corrosion, these holes have to be sealed with elastic seal-plugs. These are supplied as bulk material and have to be assembled manually in ergonomic inconvenient positions by workers. With the aim to improve ergonomics but also promoted by technological progress, three major changes are imaginable for this use case. All these changes are realized by reconfiguration of mobile assembly modules. Affected modules are the drive module with tracking technology, load modules to transport workers, load modules with racks for material supply and load modules for robots.

4.1. Change 1: Ergonomically Improved Seal-Plug Assembly

The first change concerns improving ergonomics for the workers during the manual assembly. For this, a mobile platform is built, consisting of three load modules and one drive module. The idea has been to provide a mobile platform to transport the worker and his tools and materials synchronously with the car to be produced. When all seal-plugs are assembled, the platform returns to the starting point powered by the drive module and the process starts all over again. Synchronization of the platform and the conveyor is done by a visual tracking as described in the previous section. The result of the change is improved ergonomics achieved by reduced walking distances and the possibility of transporting materials and tools on the platform.

4.2. Change 2: Automation in Cyclical Production

The next change affects the degree of automation as well as the mode of production. Technological advances make it possible to assemble seal-plugs with lightweight robots. In terms of reconfiguration the drive module is removed and load modules are modified or replaced. The new configuration consists of one load module with a top mounted robot and one load module with a feeder to supply the robot with seal-plugs. The seal-plugs are supplied as bulk material and are separated and stored within a magazine by the feeder. Both load modules are locked to the ground by a centering device in order to define the position between car, feeder and robot. With this configuration, seal-plugs can be supplied and assembled fully automated.

4.3. Change 3: Automation in Flow Production

The third change also affects the mode of production. It was decided to relocate the assembly unit. Therefore, it is necessary to switch from cyclical to continuous flow production. Because of the limited working space of the robot and in order to reach all holes, it is necessary to move the robot and the feeder synchronously to the car in production. After assembly it must be possible to return the whole assembly unit to the starting point. This can be done by again adding the drive module and modifying the robot module (see Fig. 5).

4.4. Overview of Changes

The performed changes are clustered in Fig. 6 according to the mode of production and the degree of automation. It starts with the provision of a mobile platform for manual assembly by connecting three load modules and one drive module.

Following, the degree of automation and the mode of production are altered at the same time. A lightweight robot is used for automated assembly in cyclical production. The assembly unit consists of two load modules (modified as robot module and feeder module), which are fixed to the ground.

Finally, the mode of operation is changed again to continuous flow production. For this purpose a drive module is added and a mechanical linking between the whole assembly unit and the car to be produced is realized.

The sequence of these changes is just exemplary. Basically every order of the described changes is feasible with the proposed approach. Using the proposed system helps to take advantage of the characteristics of small robots like lightweight robots. Even approaches like “robot farming” can be realized according to the mechanical perspective. Moreover, because of the possibility of moving workers and robots at the same time synchronously to the car, it enables human-robot-collaboration in continuous flow production.
5. Discussion

A critical assessment on the proposed system can be done from the electrical point of view. The proposed system is a mainly mechanical based approach. For example, the load modules do not contain any electrical parts. Only when used as basic component for example as a robot module, it is equipped with cabling and other electrical components. However, this potential disadvantage on the one side is a major advantage on the other side, as it ensures simplicity and cost efficiency of the overall system. The presented mobile and modular assembly units reflect all five named enablers of change of an RAS. Mobility and modularity is achieved by the system’s design of small mobile modules itself. Convertibility is ensured by the general possibility of modifying single modules. Furthermore spatial scalability can be attained by augmenting an assembly unit with additional modules. Technical scalability can be obtained by adjusting the degree of automation what accompanies with automatibility. Precisely, this involves substituting manual processes with automated assembly modules like robots or adding a drive module. The proposed system satisfies all typical demanded functions of an RAS like adding, removing and modifying single elements.

6. Conclusion and Outlook

This paper presents a novel approach to introduce changeability within final assembly lines of an automobile manufacturer. It shows that mobile and modular assembly units can be the basis for the implementation of a reconfigurable assembly system in final assembly. It is a solution to consider all relevant enablers of change. The mobile and modular assembly units are applied within a use-case about seal-plug assembly. Due to the easily detachable connection and the mobile design of the single modules, it can be proven that it is possible to perform several major changes of the assembly unit within short time. The degree of automation as well as the mode of operation can easily be altered. So it was verified, that it is possible to attach assembly units that perform high-precision tasks even in continuous flow production. Furthermore no big effort is needed to switch from cyclical to continuous flow production. The clear benefit of this approach is that reconfigurability and therewith changeability is achieved without causing high cost in advance of the change. Future work involves the augmentation of the set of standardized modules and applying the approach to other use cases.

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