VERSATILE ASSEMBLY SYSTEMS - REQUIREMENTS, DESIGN PRINCIPLES AND EXAMPLES

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Abstract
The requirements of assembly systems are changing, due to trends such as shorter innovation and product lifecycles as well as an increase in the number of product variants and product customization. Certain markets are characterized by demand volatility and short delivery schedules. As a result of shortened product and innovation lifecycles and demand volatility, the assembly system design should be versatile. The aim of this paper is to demonstrate a versatile assembly system which was jointly developed by the Fraunhofer IOSB-INA and the Ostwestfalen-Lippe University of Applied Sciences.

Keywords:
Assembly System, Versatility, Modularity

1 VERSATILITY - CHARACTERISTICS, COSTS AND BENEFITS

1.1 Characteristics of Versatile Systems

Trends, such as shorter innovation and product lifecycles, an increase in product variants, combined with decreasing lot sizes and the demand volatility of certain markets, lead to changing manufacturing and assembly system requirements. Shorter product lifecycles result in an increase in new design or reconfiguration of such systems; due to global production strategies this applies not only to local plants, but also overseas. The trend towards a variety of products and product variants make it necessary to plan for machines to be able to produce a wide product spectrum, or to be quickly adapted to a new product or product variant. In short, many sectors require versatile manufacturing and assembly systems. Versatility or reconfiguration means structural modification of a system in a prearranged way to adapt the system functions to changed or new requirements.

Versatility is thereby to be distinguished from flexibility [1]: Whilst versatility is used in connection with structural changes to a system, flexibility means the reversible ability of a system to adapt to changed requirements without reconfiguration or dismantling. Both characteristics are applied not only to technical, but also to sociotechnical systems [2].

Versatility of technical systems means changes within a product lifecycle, particularly where the level of automation can be adapted to the production quantities as simply as possible and, in this way, a highly economic system configuration can be achieved. Versatility also means that at least parts of the system can be reused at the end of the product lifecycle in order to achieve a high return on investment (ROI).

Versatility gains in importance when referring to the supply of spare parts after a product has been discontinued. Important consideration is to be given to the fact that the spare part production timescale is usually much longer than the product lifecycle, but that the volume of components or units is generally much smaller after discontinuation and that the same, or similar quality measurements apply [3]. In order to guarantee economic efficiency, the versatility of manufacturing and assembly systems must be considered at the planning stage.

The modular design of assembly systems - in conjunction with the compatibility of single subsystems, units or components amongst one another - are an essential element of versatile structures. Thereby, a module is a subsystem of an assembly system, characterized by largely independent functionality, with standardized interfaces and can be comprised of sub modules [4]. Compatibility means that the modules can easily be mechanically and electrically connected to one another, using standardized interfaces, including the sharing of information and power supply.

According to Wiendahl et al. [1], aside from modularity and compatibility, universality, mobility and scalability also count as versatility enablers of a factory. Universality takes increased product variants and customization into account as, without adaptation, various products or variations up to customized products, as far as possible in "one piece flow", can be produced by one system. According to the above definition, universality is synonymous with flexibility. Mobility refers to the maneuverability of individual modules, for example the modules can be stored on wheels. Technical scalability is used to describe flexibility, adapting the capacity offered to customer demand by making system changes, taking the trend towards volatile markets into account. Ergonomics is a further versatility enabler, as the changeover process efficiency is highly dependent upon the configuration of the human machine interface [5]. Efficiency can be guaranteed by, for instance, the use of quick-change systems, where the machine operator can simply connect or disconnect modules with each other, where possible whilst standing. Ergonomic operating concepts also help to reduce the employee training effort required during new system configuration.

If sociotechnical systems are considered, system scalability can thus also be achieved by using flexible working time systems; adjusting the deployment of staff according to the size of current orders as much as possible. Universality can be used to mean that employees are in the

position to perform different functions within a department, for example programming, setting up, assembly of multiple product types.
“Plug and produce” functionality can be considered to be a particular characteristic of the compatibility of a manufacturing system; this means that, similar to “plug and play” functions of computer and its peripheral devices, the modules can be recognized by the system and configured automatically. Whilst the phrase compatibility can be applied to various levels of the entire system (subsystems, modules or components), “plug and produce” is primarily used to refer to mechatronic or IT (sub) systems and can, therefore be seen as a particular form of compatibility.

1.2 Cost and Benefit

The degree of system adaptability should be integrated into the system development phase. The economic benefit of adaptable manufacturing and assembly systems is that it is possible to re-use the individual modules after the end of the product lifecycle. As a result of this, the useful life of assets is lengthened, which leads to an increased investment efficiency. Furthermore, within the product life cycle a versatile system enables to change the automation level according to the current demand volume of customers. In the consequence highly economic system configurations can be realized during the product life cycle. Investment in individual modules, for example assembly robots, is made only when demand has reached a certain level, which will achieve the required return on investment (ROI). If the demand forecast does not materialize, or is lower than expected, then the investment, for example in an assembly robot, would not be made and the operation in question would continue to be executed manually. Further, versatile systems are, with low effort, adaptable to changed customer needs and thus contribute substantially to customer satisfaction.
The economic benefit of versatility can be summarized as follows:

- The useful lifetime of assets is lengthened and thus investment cost effectiveness can be improved.
- Uneconomic investment can be avoided and efficient system configurations can be implemented.
- Customer satisfaction can be improved.

However, use of versatile systems is accompanied by extra costs, which are reflected in an increase in investment volume. Above all, modularization of systems leads to extra interfaces, extra units (for example, drive units in a modular workpiece transfer system) and extra controls. As a consequence, versatility can lead to much higher personnel and material costs at the planning and implementation stage. However, these extra costs can be reduced by standardization of hardware and software on a company internal and external level (for example using a “plug and produce” feature).
The effects of versatility on investment decisions will be shown below, using the net present value method (NPV) as a dynamic investment calculation method. With the help of this method, the advantages of an investment to the sum of I_0 can be determined by calculating the NPV C_0. The NPV takes

the preference for fast ROI into account, using interest rate i, as part of a multi period observation. NPV is the difference between an investment made in period 0 and the sum of the discounted cash flow (DCF) over n periods:

$$C_0 = -I_0 + \sum_{t=1}^{n} (E_t - A_t) \cdot \frac{1}{(1+i)^t}$$

E_t means incoming payment of the period t, and A_t means outpayment. If there is a decision to be made between various investments, the investment with the highest NPV should be chosen [6]. The costs of versatility are shown in a higher investment volume, I_0. The benefits of versatility are shown in that an investment object can be used over additional periods, so “n” increases, thus cash flow is generated in additional periods. Furthermore, versatile structures create the conditions for continually efficient system configuration, through which single periods can also achieve greater cash flow.
The challenge with versatile systems economic assessment in the system planning stage is that the single effects are difficult to predict.

2 ASSEMBLY SYSTEM

The assembly system developed by the Fraunhofer IOSB-INA and the Ostwestfalen-Lippe University of Applied Sciences consists of a mobile terminal for order entry, a manufacturing execution system (MES), a robot cell, a manual assembly station (including an “augmented reality” system), a laser engraving cell and a workpiece transfer system including an RFID read / write module (c.f. Figure 1).
The first step is for the customer to decide between different products, consisting of lego bricks, and to enter their personalized text by using a mobile device. In the second step, the order data is transmitted to the MES for order planning and management. The third step the customer order data (a product with personalized text) are transferred to a workpiece carrier, using an RFID read/write module and RFID chip of the carrier (digital memory). Fourthly, the workpiece carrier is transported to the robot cell by the transfer module. There the RFID chip is read and the order data is transmitted to the robot system. After the robot has performed the assembly operations, the sixth step is to inform the workpiece carrier, using the RFID chip, which operations the robot has completed. The robot also places the workpiece back onto the workpiece carrier.

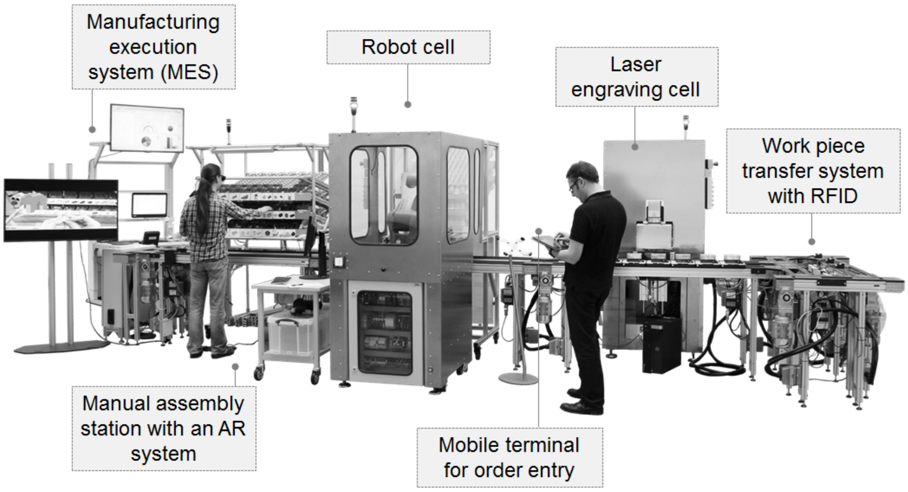

Figure 1: Structure of the developed Assembly System

The workpiece transfer module then, in a seventh step, moves the workpiece to the second processing station, the manual assembly station. There, the RFID chip is read again and the data transmitted to an augmented reality (AR) system, this is step eight and only the processes that the robot did not complete are shown in AR. After an employee completes the operations shown by the AR system, the current order status is saved again on the RFID chip. Figure 2 shows the AR operations from the employee viewpoint. The tenth step is the transfer module moving the workpiece to the laser cell, the third processing station. As in the two previous steps, the order data is read, the personalized text is engraved onto the workpiece using the laser, and the order data on the RFID chip is updated. Finally, the assembled and inscribed lego brick is transported to the goods collection area, where it can be collected by the customer.

Figure 2: Employee view using AR

3 ASSEMBLY SYSTEM VERSATILITY

3.1 Overview of versatility enablers

The versatility of the assembly system is accomplished primarily through use of a modular system construction, with largely autonomous and mobile operations cells, as well as decentralized motor-controlled transfer modules. Compatibility of the modules with each other is achieved in that all of the modules are equipped with uniform hybrid industrial connectors (compressed-air, power, Ethernet) and are connected to one another using bus topology. Furthermore, the mechanics of the assembly system is designed in such a way as to allow the modules to be disconnected within minutes, without requiring a reengineering of the system. Figure 3 shows an overview of versatile system characteristics, these are assigned to the six versatility enablers listed earlier.

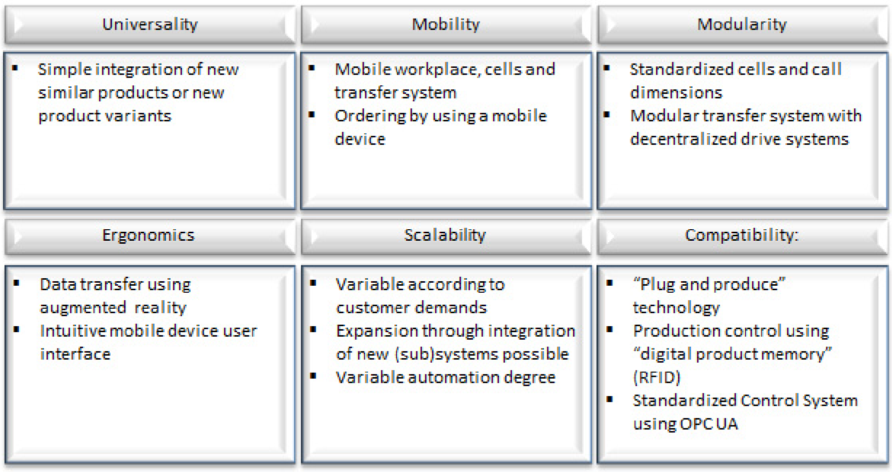

Figure 3: Assembly System Versatility Enablers

3.2 Universality

The universality of an assembly system is primarily expressed in that using the system, different products are assembled in a one-piece flow and can be individualized by text (laser engraving). In addition, structurally similar products can be integrated into the system with low effort. However, in order to do this, adaptations to workpiece carriers and workpiece receivers in the robot cell are necessary. Integration of further product changes into the control program is also required.

3.3 Mobility

In order to guarantee fast assembly system reconfiguration, cells and material supply systems are stored on rollers. The laser and robot cell rollers are retractable, so that the cells then stand on height adjustable feet. In this way the positioning accuracy and vibration resistance requirements can be complied with.

3.4 Modularity

Assembly system modularity is basically achieved by the three processing modules (robot cell, assembly workplace with AR and laser cell) and the modular workpiece transfer system. The processing cells are equipped with independent control systems and software, as well as RFID read / write equipment to enable communication with the digital memory of the workpiece carrier (RFID). The dimensions of the robot and laser cells are 90 cm x 140 cm x 200 cm (width x length x height).

The workpiece transfer system, a belt conveyor system, is comprised of 12 individual modules. Each belt conveyor module is equipped with an individual drive system with a frequency inverter that is connected to a power distribution system, a Ethernet network and a programmable logic controller. The decentralized system construction means that each processing module and belt conveyor module is capable of functioning autonomously.

3.5 Ergonomics

The worker is provided with information through an AR system, which comprises of a head mounted display that projects virtual information directly into the worker's field of vision. Information provision using AR particularly benefits customized products, or products with a high number of variations because the need for lengthy examination of a screen or order cards is eliminated. This form of information provision also facilitates shorter training times for new employees [7].

A further example of the implementation of ergonomic aspects in assembly systems is the mobile device multi-touch user interface. The products are shown as pictograms. The menu navigation conforms to user expectations and is self-descriptive, allowing intuitive operations.

3.6 Scalability

Modular assembly system construction particularly that of the belt conveyor system, enables the reconfiguration of widely varying layouts. The only restriction is that the transfer system must be a closed loop.

Due to decentralized drive technology, frequency convertors can be individually controlled, meaning that the belt conveyor module speed can be independently managed. If necessary, extra equipment can be integrated into the assembly system, for example to increase the automation or output levels according to customer demands.

3.7 Compatibility

The belt conveyor system and all other operation modules are equipped with industrial connectors, which supply the individual modules with power, compressed air and Ethernet connectivity. Standardized connectors ensure that each element can easily be connected to the others.
Each operation is recorded using digital object memory, which is integrated into each workpiece carrier by means of a RFID chip. The object memory includes all necessary assembly operation information, which is created initially by the MES at order entry and written directly to the chip. Assembly tasks are read at each processing module and each finished operation is confirmed on the RFID chip.
Communication between the MES, the operating cells and enterprise resource planning system (ERP) uses OPC-UA standard as well as PROFINET Real-time Ethernet standard.

4. OUTLOOK

The aim of further inter-disciplinary research is to develop mechanical, electrical, information and power standards for assembly system design. This will enable customers to configure their assembly systems according to their needs, put them into operation swiftly and easily adapt to requirements within a product lifecycle, using various differing base modules. The issue of how assembly systems universality can be optimized will also be examined; the vision is to enable the assembly system to assemble all parts of a similar size, but varying dimensions and shapes automatically according to a given working plan.

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