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Toward a Real-Time Reconfiguration of Self-Adaptive Smart Assembly Systems

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Abstract

In the current industrial context, signed by the advent of Industry 4.0, traditional manufacturing systems are evolving towards the new class of Next Generation Manufacturing Systems (NGMSs), characterized by the main attributes of changeability, reconfigurability and self-adaptability. Such advanced systems are able to cope with the new industrial and market challenges as the dynamic market demand, short products life cycles and the need for flexibility. This paper presents the design and control of an innovative prototype of Self-adaptive Smart Assembly System (SASAS) able to real-time reconfigure its structure according to both product and operator features. An easy-to-use graphic user interface (GUI), developed in Matlab environment, supports the human operators in the real-time system reconfiguration and self-adaptability by storing information about the work cycles of the products manufactured by the case company and associating each operation of the product work cycle to a specific movement of the system. Finally, the proposed GUI allows the operators to quickly add new products work cycles in response to the customers' request for new product variants, matching the Industry 4.0 principles.

Keywords: Smart assembly, Industry 4.0, Reconfigurability, Next-generation manufacturing systems.

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1. Introduction and literature review

In the last few years, Industry 4.0 is emerging as the fourth industrial revolution significantly changing manufacturing and assembly paradigms. These systems need to incorporate higher levels of flexibility and intelligence, evolving toward the new class of Next Generation Manufacturing Systems (NGMSs) [1]. The final goal is to create the so-called Smart Factory in which all the elements are integrated together and communicate in real-time. According to the recent literature [2, 3], Industry 4.0 is characterized by nine key enabling technologies supporting its implementation in Industry, as in Fig. 1.

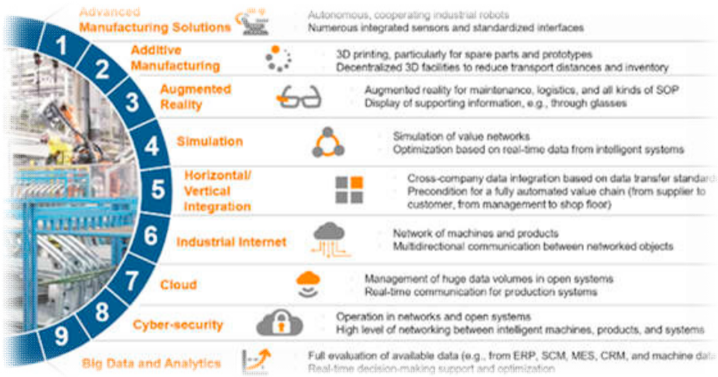

Fig. 1. Industry 4.0 enabling technologies. Source: Rubmann et al. [3].

The advanced manufacturing solutions, i.e. Id. 1, refer to the set of flexible, smart and modularized manufacturing and assembly systems integrating sensors and standardized interfaces and, in the last few years, they rise as the answer to the current industrial and market trends, e.g. dynamic market demand, increasing customization, flexible batches and short product life cycles. Changeable, smart and self-adaptive manufacturing systems fall in this category: they are equipped with actuators, sensors and control architectures to achieve elasticity and agility and to enable the integration of real time data sources into service-oriented architectures [4-6]. In this field, Chaplin et al. [7] present an architecture for evolvable assembly systems to enhance the manufacturing environment ability to rapidly react to changes in product, process and market. Liu et al. [8] propose a smart assembly system integrating elements of the Internet of Things (IoT) paradigm for mechanical products. These innovative assembly systems are composed of smart machines, storage systems and production facilities able to autonomously exchanging information and to promoting the design optimization of the assembly process and the intelligent operation of the assembly system. Sanderson et al. [9] and Sanderson et al. [10] tackle the design and reconfiguration of adaptive production systems by using functional modelling to capture the function, behaviour and structure of these systems. ElMaraghy and ElMaraghy [11] mark the need for modern assembly systems to adapt themselves to products, market, technologies and regulatory requirements and highlight the emerging trends of modularity and reconfigurability attributes using modular and reconfigurable assembly systems. Thramboulidis [12] and Thramboulidis et al. [13] present a framework for evolvable assembly systems to exploit the benefits of IoT technologies by using, at the same time, the huge investment based on traditional technologies in this domain. Anandan et al. [14] develop an optimization model to provide a logical layout for reconfigurable assembly systems from a library of available equipment modules. The objective of the proposed model is to minimize the overall equipment cost without violating their physical connectivity constraints and the precedence constraints of the assembly process. Chen et al. [15] propose a hierarchical architecture of the smart factory and analyse the key technologies from the aspects of the physical resource layer, the network layer and the data application layer. In the field of self-adaptive systems, Rohr et al. [16] highlight some key directions to reach self-adaptation, i.e. origin, activation, system layer, controller, distribution, and operation. Salehie and Tahvildari [17] introduce an overview of the landscape of self-adaptive software, including their own taxonomy for self-adaptation.

The focus of this study is on self-adaptive systems applied to assembly, which typically represents the last phase of production. These systems must be able to automatically modify themselves in response to changes in their operating environment [18, 19]. In particular, the design and control of a prototypal Self-adaptive Smart Assembly System (SASAS) is presented in this paper. The main element of innovation is its real-time reconfigurability and self-adaptability according to both product and operator features for the assembly of both small and medium size products. A graphic user interface (GUI) is developed to ease the human operators in the real-time SASAS control and reconfiguration according to both existing and new products work cycles. According to these goals, the reminder of this paper is organized as follows. Section 2 introduces a conceptual schematic to achieve real-time reconfigurations in smart manufacturing systems and describes the SASAS prototype while the GUI description is in Section 3. Finally, Section 4 concludes the paper with final remarks and future research opportunities.

2. Real-time reconfigurability in smart manufacturing systems

Next Fig. 2 introduces a conceptual schematic helping to achieving real-time reconfigurations in smart manufacturing systems. Afterwards the focus is on the description of the main components characterizing the proposed prototype of Self-adaptive Smart Assembly System (SASAS).

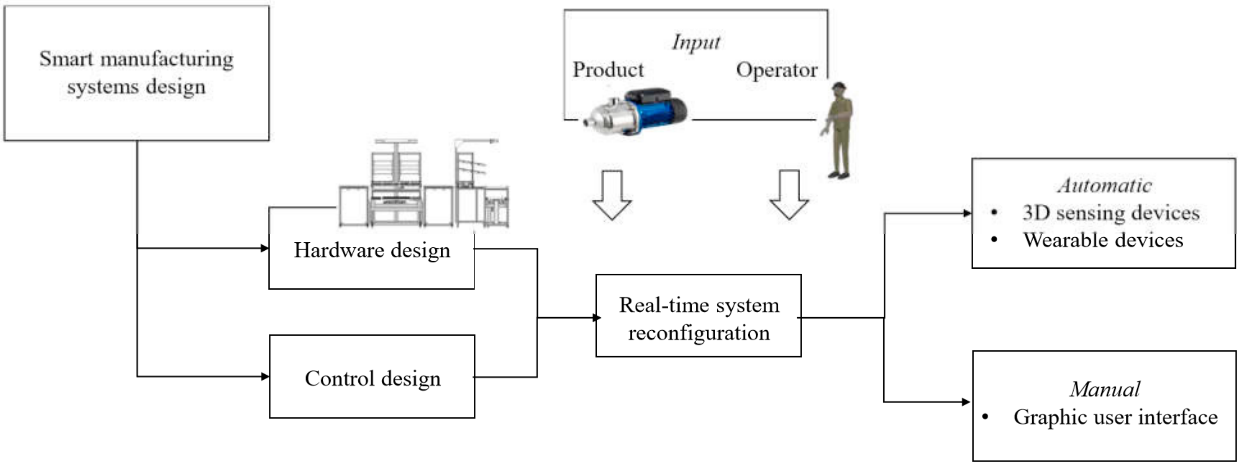

Fig. 2. Conceptual schematic to achieve real-time reconfiguration in smart manufacturing systems.

As in the above figure, once concluded the phases of hardware design and control design, in terms of Programmable Logic Controller (PLC) programming, it is possible to include reconfigurability issues in the smart manufacturing system. In particular, the main goal is to make the manufacturing system able to real-time reconfigure its hardware structure according to input data coming from the product, i.e. size, dimensions, work cycle, and from the human operator, i.e. anthropometric measurements. The real-time system reconfiguration can be automatically performed by using 3D sensing devices, i.e. depth cameras, wearable devices, or manually performed by using flexible GUIs. This paper provides a real case example of real-time systems reconfiguration through the development of an easy-to-use GUI.

2.1 SASAS prototype description

The main innovative aspect of the smart assembly system presented in this paper, named Self-adaptive Smart Assembly System, is its real-time hardware reconfiguration as effect of different input data from products and human operators. As highlighted in the CAD front view of the assembly prototype in Fig. 3, the components needed for final products assembly are stored in a fast-picking area located in front of the operator working area and composed by two modules. These modules move along the Cartesian axes, opening and closing symmetrically and moving toward the operator to ease the component picking. This mechanism reduces the operator movements during the overall assembly process, i.e. picking, assembly and walking activities, and consequently the assembly time. The central roller conveyor on which the assembly process takes place is able to move along the vertical direction thanks to two screw-nut groups driven by two digital motors. This feature provides significant ergonomic benefits because allows to adjust the height of the central roller conveyor when needed according to the height of the human operator and to the assembly operation to perform. A Bosch Rexroth XM model is used as SASAS PLC, programmed by using Bosch IndraWorks Engineering software and connected to Matlab development environment through the Motion Logic Programming Interface (MLPI). The PLC allows to synchronize the SASAS motion axes to the optimized work positions caught from external databases and listed, task by task, according to the operator features, e.g. physical body, skills, etc., the product dimensions and the product work cycle.

Fig. 3 shows the main steps followed to achieve the real-time reconfiguration of the SASAS prototype. Such a framework runs through the phases of self-adaptive system design, i.e. hardware structure, PLC programming integrating Bosch IndraWorks Engineering to Matlab software, and GUI development phase to achieve a real-time system reconfiguration according to both product and operator features.

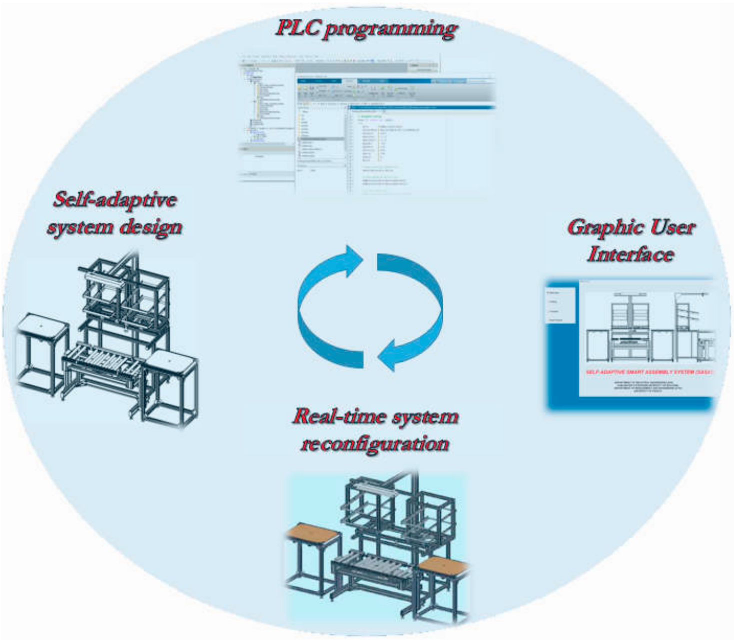

Fig. 3. Schematic framework for SASAS real-time reconfiguration.

3. A graphic user interface (GUI) to aid real-time system reconfiguration

After the phase of PLC programming, an easy-to-use GUI is developed to allow the human operators to real-time reconfigure the systems according to their anthropometric measurements, to the product features and products work cycles. The proposed GUI is developed in Matlab by using the Graphic User Interface Design Environment (GUIDE) tool and is composed by four main sections:

- Boot interface
- Setting
- Products
- New product

The main goal of the proposed GUI is to support the human operators in the real-time system reconfiguration and self-adaptability by storing information about the work cycles of products manufactured by the case company and associating each operation of the product work cycle to a specific movement/reconfiguration of the system components. The description of the GUI sections is in the following.

3.1 Boot Interface window

This section is the first screen of the developed GUI, as in Fig. 4. In this window, the CAD front and lateral view of the SASAS is shown together with the Academic institutions involved in the project.

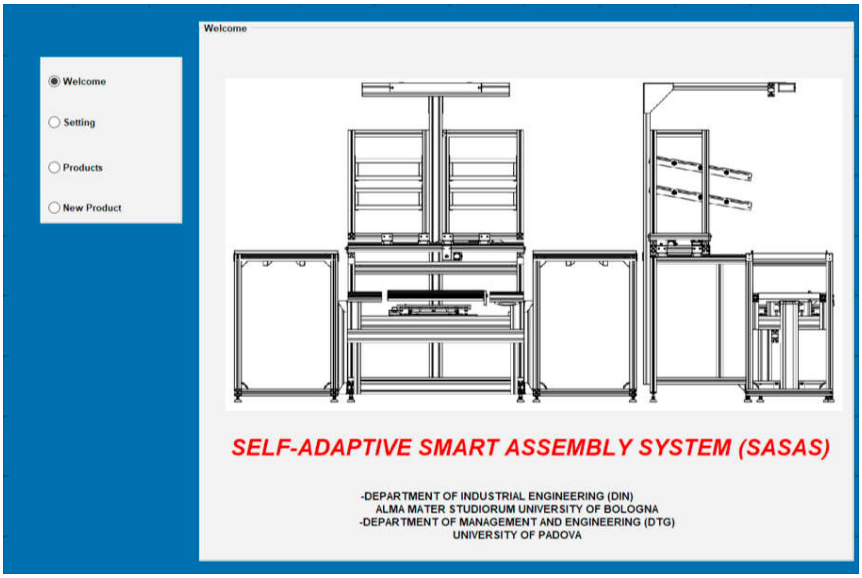

Fig. 4. Welcome section of the developed GUI.

3.2 Setting window

This section allows the manual setting of the SASAS motion axes, i.e. opening/closing of the fast-picking area and vertical moving of the central roller conveyor (Fig. 5). When the human operator starts to perform the different operations required by the product work cycle, the fast-picking area has to be in the closing position and the central roller conveyor set to a height of 0.95 m according to the ergonomic rules. The *Initial set-up* sub-section allows performing these tasks, requiring the current height of the central conveyor and the status of the fast-picking area. As an example, if the fast-picking area is opened and the height of the conveyor is 1.1 m, inserting these parameters and clicking the SET button, the software architecture automatically reconfigures the system, closing the picking area and lowering the conveyor to a height of 0.95 m. At this moment, a green square appears in the *Control* sub-section to indicate a correct initial setting. This sub-section allows also to manually setting the height of the central roller conveyor by inserting the gap between the current position and the desired position (Δh) or the exact value of the desired height (h).

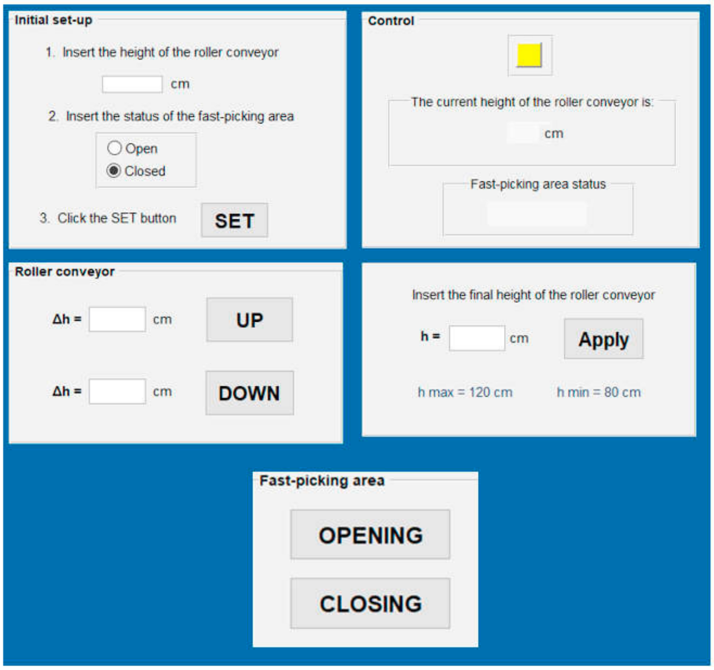

Fig. 5. Setting section of the developed GUI.

3.3 Products and New product windows

The *Products* and *New Product* sections are the most relevant ones characterizing the proposed GUI. In particular, the former (Fig. 6, left) allows the execution of a list of SASAS movements corresponding to the assembly of a specific product realized by the industrial company, according to its work cycle. As example, if the operator needs to assemble the product “Chiller”, clicking on *Push to execute product tasks* button at the end of the execution of each assembly operation, the SASAS automatically reconfigures itself in terms of opening/closing of the fast-picking area and vertical moving of the central roller conveyor according to the need of the next assembly operation.

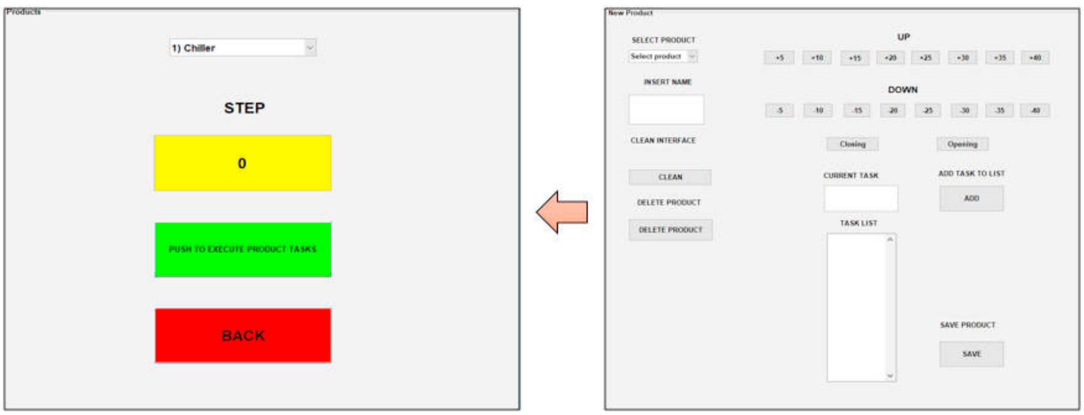

Fig. 6. Products and New product sections of the developed GUI.

The New product section (Fig. 6, right) confers higher levels of flexibility to the use of the self-adaptive system. This window allows in any moment to insert new products work cycles, store them, and make them available in the pop-up menu of the *Products* section. This feature is relevant because in the emerging context of Industry 4.0, which represents a way from mass customization to mass personalization production, customers ask for an increasing number of customized products which differ in shape, colour and size. In this scenario, industrial companies have to cope with the increased product variety rapidly and efficiently [20]. The *New product* section efficiently supports the human operators in product variety management allowing them to quickly insert new products work cycles selecting the appropriate SASAS movements from an available library.

4. Conclusions

In the last few years, an increasing number of factors such as the dynamic market demand, high flexibility, short product life cycles and huge products customization determines several challenges for industrial companies. In this context, they have to rapidly react to these challenges producing a wide range of products that fit to different customer needs. To achieve these goals, traditional manufacturing systems need to incorporate higher levels of flexibility and intelligence evolving toward the new class of Next Generation Manufacturing Systems (NGMS), matching the emerging Industry 4.0 principles. Smart, changeable and self-adaptive systems fall in this category allowing a rapid system reconfiguration to achieve elasticity and agility. This paper presents the design of a prototypal Self-adaptive Smart Assembly System (SASAS). The main element of innovation of the system is the ability to real-time reconfigure its hardware structure according to the product work cycle and the operator features, i.e. anthropometric measurements, allowing a reduction of the movements during the picking and assembly phases for both small and medium size products. An easy-to-use graphic user interface (GUI) is developed through Matlab GUIDE tool to support the human operators in the real-time system reconfiguration and allows to efficiently add new products work cycles in response to the customers' request for new product variants.

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