Design, engineering and testing of an innovative adaptive automation assembly system

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Abstract

Purpose – Industry 4.0 emerged as the Fourth Industrial Revolution aiming at achieving higher levels of operational efficiency, productivity and automation. In this context, manual assembly systems are still characterized by high flexibility and low productivity, if compared to fully automated systems. Therefore, the purpose of this paper is to propose the design, engineering and testing of a prototypal adaptive automation assembly system, including greater levels of automation to complement the skills and capabilities of human workers.

Design/methodology/approach – A lab experimental field-test is presented comparing the assembly process of a full-scale industrial chiller with traditional and adaptive assembly system.

Findings – The analysis shows relevant benefits coming from the adoption of the adaptive automation assembly system. In particular, the main findings highlight improvements in the assembly cycle time and productivity, as well as reduction of the operator's body movements.

Practical implications – The prototype is applied in an Italian mid-size industrial company, confirming its impact in terms of upgrades of the assembly system flexibility and productivity. Thus, the research study proposed in this paper provides valuable knowledge to support companies and industrial practitioners in the shift from traditional to advanced assembly systems matching current industrial and market features.

Originality/value – This paper expands the lacking research on adaptive automation assembly systems design proposing an innovative prototype able to real-time reconfigure its structure according to the product to work, e.g. work cycle, and the operator features.

Keywords Assembly line design, Assembly, Flexible manufacturing, Flexible assembly systems, Industry 4.0, Engineering design, Industrial engineering, Manufacturing flexibility, Technology implementation, Self-adaptive assembly systems, Reconfigurability, Adaptive automation, Prototyping

Paper type Research paper

1. Introduction

Manufacturing is the backbone of the global economy. Currently, more than 27 million people are employed in 230,000 manufacturing companies, creating, in the European Union (EU) area, a total added value of about €1,300m (Westkämper, 2007). In this context, Industry 4.0 (I4.0) emerged as the Fourth Industrial Revolution, enhancing the manufacturing and assembly paradigms and driving them on the way to a knowledge-based and digital era (Ghobakhloo, 2018). The final challenge is to create the so-called Smart Factory, an intelligent industrial context in which all the elements are integrated together and communicate in real time (Nascimento *et al.*, 2018; Rachinger *et al.*, 2018). According to the Boston Consulting Group, I4.0 includes nine enabling technologies to support the paradigm implementation in industry (Rüßmann *et al.*, 2015). Table I lists and describes them.

Among these technologies, advanced manufacturing solutions, i.e. Id.1, have a direct impact on the modern manufacturing and assembly systems. This enabling technology refers to the set of flexible, smart and modularized manufacturing and assembly systems integrating sensors and standardized interfaces (Rüßmann *et al.*, 2015). In particular, reconfigurable, changeable, smart and self-adaptive manufacturing systems falling in this category are equipped with actuators, sensors and control architectures to achieving elasticity and agility and to enabling the integration of real time data sources into service-oriented architectures (Andersen *et al.*, 2018a; Andersen *et al.*, 2018b; Bortolini *et al.*, 2018; Bortolini *et al.*, 2019).

This study focuses on assembly systems, representing the last phase of production. In particular, manual assembly systems

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Table I I4.0 enabling technologies

Id.	Enabling technology	Description
1	Advanced manufacturing solutions	Autonomous, cooperating industrial robots Numerous integrated sensors and standardized interfaces
2	Additive manufacturing	3D printing, particularly for spare parts and prototypes Decentralized 3D facilities to reduce transport distances and inventory
3	Augmented reality	Augmented reality for maintenance, logistics Display of supporting information, e.g. through glasses
4	Simulation	Simulation of value networks Optimization based on real-time data from intelligent systems
5	Horizontal/vertical integration	Cross-company data integration based on data transfer standards Precondition for a fully automated value chain
6	Industrial internet	Network of machines and products Multidirectional communication between networked objects
7	Cloud	Management of huge data volumes in open systems Real-time communication for production systems
8	Cyber-security	Operation in networks and open systems High level of networking between intelligent machines, products and systems
9	Big data and analytics	Full evaluation of available data (e.g. from enterprise resource planning (ERP) and machine data) Real-time decision-making support and optimization

Source: Rüßmann *et al.* (2015)

bring to high flexibility and low productivity if compared to fully automated systems (Kamali *et al.*, 1982; Heilala and Voho, 1997; Heilala and Voho, 2001; Fletcher *et al.*, 2019). To increase productivity, maintaining flexibility, the future systems need to include greater levels of automation to complement the skills and capabilities of the human workers. Within the current literature, this stream emerged as adaptive automation assembly (Fletcher *et al.*, 2019). Adaptive automation assembly systems must be able to automatically modify themselves in response to the changes in their reference operating environment (Huebscher and McCann, 2008; Krupitzer *et al.*, 2015). These changes deal with adjustments of some of their hardware and software attributes. The increasing product variety asked by the market makes these systems of strong interest within mixed-model flexible manual assembly lines (Faccio, 2014; Faccio *et al.*, 2015; Galizia *et al.*, 2019). To successfully implement such systems with high adaptivity and interactivity between human workers and technology, a comprehensive understanding of the design requirements is needed. However, lacks in practical solutions exist and applied research needs to propose innovative and effective design of assembly systems able to manage different product models characterized by different attributes in terms of parts, dimensions, tasks and production volumes.

This paper presents the design, engineering and testing of a prototypal adaptive automation assembly system, called self-adaptive smart assembly system (SASAS) in the following, highlighting its features and its potential impact on industry. The prototype includes an easy-access fast-picking area for the fast-moving parts equipped with two motion axes to optimize its position, while a third motion axis allows the reconfiguration of the working area height. Its main element of innovation is the real-time reconfigurability according to the product features, the work phase and the operator features, allowing a reduction of the movements during the picking and assembly phases for both small and medium size products, i.e. gross volume up to 1.5 m^3. This is a relevant benefit because of the high number of operator movements both in the front and in the back positions, especially in the pick and place phases. A quantitative field test of the improvements coming from the prototype use are in the lab experiment and in the industrial scenario sections. An Italian company assembling industrial refrigerators and including the prototype in each station of its mixed-model assembly line is involved in the study.

According to the background and goals, the remainder of this paper is organized as follows. Section 2 revises the literature on the topic. Section 3 presents and describes the SASAS prototype. Its lab field-test is in Section 4, while Section 5 showcases the system use in the aforementioned relevant industrial scenario. Finally, Section 6 concludes this paper with final remarks and future research opportunities.

2. Literature review

2.1 Assembly system design and component management

Assembly represents the capstone process for product realization in which components and subassemblies are integrated together to get the final product (Hu *et al.*, 2011). In the I4.0 context, based on the shift from mass production to mass customization, assembly workplaces have to evolve to maintain acceptable productivity standards as well as top working conditions for the human operators (Bortolini *et al.*, 2017). Assembly activities, i.e. tasks, usually include several operations, e.g. component picking, walking, assembly task execution, etc. Previous research by Finnsgård *et al.* (2011), Finnsgård and Wänström (2013) and Wild (1975) finds that picking covers a relevant portion of the cycle time, frequently higher than the 50 per cent of the total time. The possibility to reduce this time, not immediately and directly adding value to the products, is of much interest, and it is linked to the reduction of the operator movements and to the distance of the components to pick. To get this goal, both the assembly station layout and the working conditions play a crucial role. Within the latter point, the choice of the part feeding policy is of major interest. The literature suggests three feeding modes, i.e. line stocking, kitting and sequencing (Sali *et al.*, 2015). Sali *et al.* (2015) define them and propose a model to assess the associated operating costs. Limère *et al.* (2015) link the part storage place and the feeding policy to the amount of stock and the operator walking distance during assembly. Globally, compared to the line stocking, in which parts are collected by reference in dedicated containers, the part kitting strategy increases the productivity and the assembly line availability because of the ready-to-use kits of the components to mount at the same time. By adopting such strategy, less time is spent for searching, and the training of the assemblers is easier (Limère *et al.*, 2012; Hanson *et al.*, 2015). Furthermore, in the case of large and heavy parts, kitting is mandatory to reduce the space utilization and the ergonomic impact of the assembly station activities (Battini *et al.*, 2011). In this field, Bortolini *et al.* (2017) propose a multi-objective optimization model for the assembly line balancing problem (ALBP), minimizing the assembly line takt time and the ergonomic risk caused by the task execution and the component picking activities. Further efforts are from Bautista-Valhondo and Alfaro-Pozo (2018) and Tiacci and Mimmi (2018) adopting the multi-objective perspectives, optimal and heuristic approaches. All the authors conclude about the strong connection between the assembly system layout and the component management policy, encouraging further research in the field through comparative analyses in industry.

2.2 The Industry 4.0 environment

I4.0 is changing the industrial environment, the manufacturing and assembly paradigms. The term "Industry 4.0" comes from a project on high-tech strategy promoted by the German government in 2011 to spread computerization in manufacturing (Lee *et al.*, 2015), and in the past years, it emerged as the Fourth Industrial Revolution (Cohen *et al.*, 2017). The concepts of Smart Factory (SF) and Smart Manufacturing (SM) drive this upcoming revolution, while augmented reality, internet of things (IoT), cyber-physical systems and cloud technology are among the major technologies adopted in SF and SM (Kang *et al.*, 2016; Yao and Lin, 2016). Radziwon *et al.* (2014) study the evolution of SFs analyzing the literature and define them as "manufacturing solutions that provide flexible and smart production processes to solve problems arising on a production plant rapidly changing boundary conditions in a world of increasing complexity." Similarly, SM is defined as "a set of various technologies able to promote a radical innovation of the existing manufacturing industry through the integration of humans, technology and real-time information" (Kang *et al.*, 2016). The National Institute of Standards and Technology (NIST) defines SMs as "fully-integrated and collaborative manufacturing systems that respond in real time to meet the changing demands and conditions in the factory, supply network, and customer needs" (National Institute of Standard and Technology, 2015). In this new industrial environment, information is real-time collected and distributed to support human operators in their work (Tzimas *et al.*, 2018). Fasth-Berglund and Stahre (2013) discuss the importance of considering both the physical and cognitive automation to handle the increased demand variability and to improve the social sustainability within the company. Chaplin *et al.* (2015) define an architecture for evolvable assembly systems to enhance the ability to react to changes in products, processes and market. Furthermore, Sand *et al.* (2016) present the so-called smARt.assembly – a projection-based augmented reality assembly assistance system for industrial applications to support human workers in picking activities eliminating the use of smart glasses. Tzimas *et al.* (2018) introduce a study on the use of augmented reality technologies to real-time give instructions to the operators supporting manufacturing tasks.

Finally, the recent literature states that industrial companies need to be educated and trained toward the adoption of the upcoming industrial paradigms. In this context, a strong collaboration between academia and industry is crucial to spread the culture of innovation. The so-called "learning factories" are promising environments for research, training and education. They reproduce small smart production and assembly systems and their use is proved to be beneficial to train industrial companies toward reconfigurable smart and self-adaptive systems (Abele *et al.*, 2017; ElMaraghy, 2019). From this perspective, the proposed SASAS can be of help to set up future learning factories for assembly, highlighting the potential upgrades in terms of flexibility and productivity toward the current widely diffused industrial scenarios.

3. Assembly prototype description

Figure 1 presents a computer-aided design (CAD) front and lateral view of the proposed prototype of SASAS, while Figure 2 shows the three-dimensional (3D) layout and a real picture of the prototype, with a detail of the four functional modules.

The workstation consists of three roller conveyors, one in the central position on which the operator performs the assembly tasks (4), and two lateral units allowing the product flow (3). Thanks to two screw-nut groups driven by two digital motors (2), the central roller conveyor can translate vertically. When the workpiece reaches this position, a set of spring-loaded devices locks the table on the main roller conveyor, and a rotating mechanism located below the roller conveyor allows the rotation of the workpiece table. The assembly components are stored in a fast-picking area (1) made of two modules containing the parts and components needed for the product assembly. Such two modules move along the two Cartesian axes, opening and closing symmetrically and moving toward

Figure 1 CAD model of the self-adaptive smart assembly system

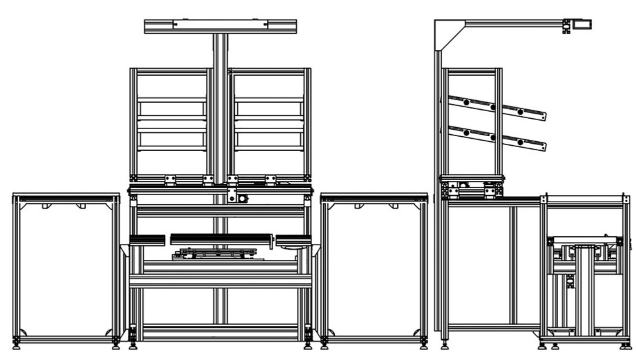

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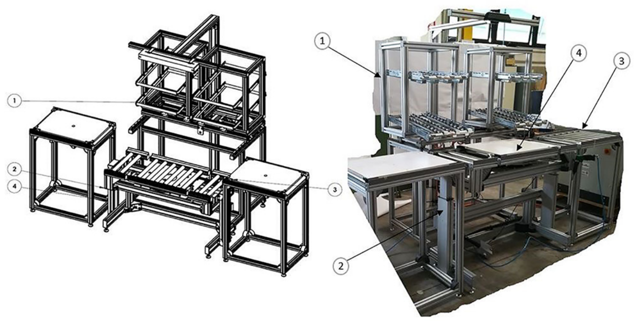
Figure 2 Components of the prototype



Notes: ① Modules for the storage of the assembly parts and components; ② Extendable supports of the main roller conveyor; ③ Lateral roller conveyor; ④ Main roller conveyor

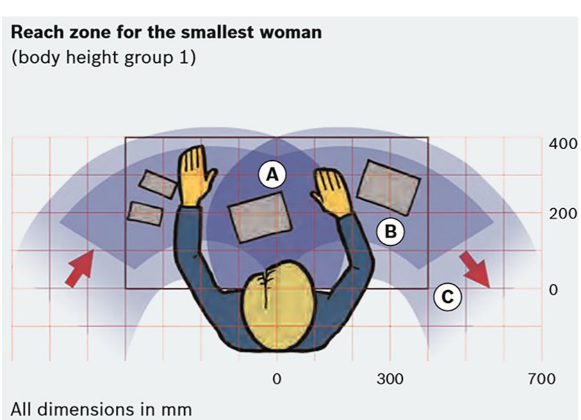
the operator to ease the component pick. This mechanism overcomes the industrial practice, in which the components to assemble are usually placed behind the operator, and allows the reduction of the operator movements and, consequently, of the picking time. This functional module is designed according to the Ergonomics Guidebook for Manual Production Systems edited by Rexroth – Bosch Group (Rexroth, 2012). According to these guidelines, all containers, equipment and operating elements must be easily accessible and arranged in the anatomic/physiological range of movement of the operator (Figure 3). Furthermore, torso rotations and shoulder movements, particularly when under exertion, are avoided.

In Figure 3, Area A is suitable for working with both hands, Area B is an area for tools and components that are often grabbed with one hand, while Area C is for occasional handling. The benefits coming from such a design are:

- the reduction of operator discomfort and fatigue;
- the reduction of operator movements; and
- the consequent reduction of the component picking time.

The prototype information and control are real time managed by the system logic controller. The adopted programmable logic controller (PLC) is a Bosch Rexroth XM model, accessed

Figure 3 Reach zones classification



Source: Derived by Bosch Ergonomics Guidebook (Rexroth – Bosch Group, 2018)

through Bosch IndraWorks Engineering software and connected to Matlab development environment. Appendix presents the pseudocode of the SASAS main control instructions together with the two functions called to act on the storage module position and the workplace height. After the variable declaration, the software acquires the product work cycle and operator features from an external file, saves them and initializes the SASAS motion axis. The initialization procedure checks the storage module position and the workplace height. The former has to be in the closing position; the latter initial height is at 90 cm, according to reference ergonomic metrics. After that, the controller cycles over the work phases and self-adapts the position of the workplace (module ④ in Figure 2) and of the easy-access storage modules (module ① in Figure 2) according to the operator features, e.g. physical body, and the assembly operation to perform. In this study, the human operator drives the self-adaptation identifying the product type to assemble, and he/she is responsible of managing the progress of steps according to the work cycle. Controls on the feasibility of the axis movements are done to avoid collisions among the SASAS, the product and the operator. In case of potential danger, the system returns to a safe base position autonomously and a feedback is given to the operator. Otherwise, the transition between a work phase and the next one is managed automatically as soon as the operator acknowledges the end of the mounting activities of the current work phase. Thanks to the connection to a dynamic product library containing the product work cycles and operator features the SASAS is fully flexible and autonomous for its reconfiguration and real-time adaptation to the current working activities.

Finally, the SASAS prototype and its managing system are suitable to the assembly of small- and medium-size products characterized by an overall volume up to 1.5 m^3 having a depth value close to 400 mm and a width value up to 640 mm. The following Section 4 field-tests the SASAS through a lab experimental campaign, while Section 5 proposes an industrial application of this technology.

4. Prototype experimental field-test

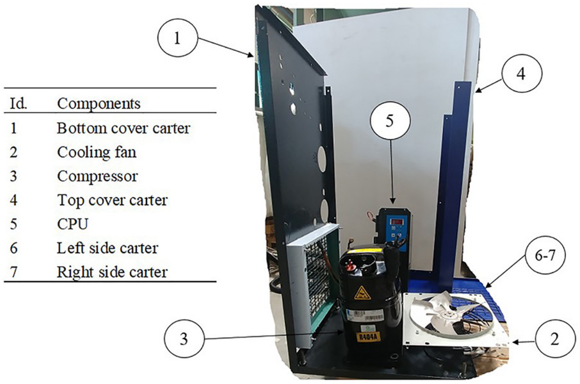
The preliminary lab field-test aims at testing the prototype working conditions within a realistic full-scale environment. The focus is on the assembly process of the industrial chiller in Figure 4, further including a simplified bill of materials. The product dimensions are of about 370 × 500 × 764 (h) mm, while the components to assemble are to place both on the bottom and on the top of the carter structure.

The developed analysis is multi-scenario and comparative among the three different assembly configurations listed in the following.

- *Configuration #1*: standard assembly + line stocking component feeding;
- *Configuration #2*: SASAS prototype use + line stocking component feeding; and
- *Configuration #3*: SASAS prototype use + kitting component feeding.

In *Configuration #1*, the prototype is used as a fix workstation, with no adaptation to the part and operator features. The main roller conveyor is set to a height of 0.95 m, and the two modules that characterize the fast-picking area are as in Figure 1. The

Figure 4 Industrial chiller used for the lab experimental field-test



components and the support tools, e.g. screws, screwdrivers, etc., are stored in a shelf unit located behind the assembly workstation, at a distance of 2 m. In *Configuration #2,* the SASAS reconfigurability features are used. In such a configuration, the system real time changes its hardware position following the working cycle of the product. In this scenario, the components are stored in the shelf unit located behind the workstation, while the support tools, e.g. screws, screwdrivers, etc., are stored in the fast-picking area of the assembly workstation. Finally, in *Configuration #3*, the prototype is as in *Configuration #2,* but the kitting feeding policy is adopted (Hua and Johnson, 2010). Components are fed in a kit located on the left lateral roller conveyor, while the support tools are located in the fast-picking area. Figure 5 shows the changes while switching from line stocking to the kitting feeding policy.

The multi-scenario analysis focuses on the assembly process monitoring the cycle time T_c, i.e. the duration of the assembly tasks, to get the system productivity $Q = \frac{1}{T_c}$. Assembly time values are collected through multiple lab field-tests. For each configuration, according to statistics, a lower bound to the number of tests, n, to get reliable data is by applying equation (1) (Kenny, 1986):

$$n = \left(\frac{z}{h} \cdot \frac{\sigma}{t}\right)^2 \qquad (1)$$

where:

N = minimum number of tests;
T = mean assembly time [s];
σ = standard deviation of the assembly time [s];
Z = confidence interval [per cent]; and
H = margin of error [per cent].

Equation (1) correlates the minimum number of tests to their duration, supposed to be normally distributed, i.e. $N(t, \sigma)$, the expected confidence interval and the accepted margin of error. During the experimental field-tests, an incremental approach is used comparing the number of tests to the current value of n until in all configurations, a good confidence level is reached. The results are collected in Table II after a sequence of ten tests per each configuration. Because of n is equal to 5.67 in *Configuration #1*, 8.50 in *Configuration #2* and 8.38 in *Configuration #3*, a statistic significance is guaranteed.

Starting from the obtained field-results, the system productivity for all configurations follows as in Table III.

The results show the impact of the SASAS adoption both itself and when combined to an advanced component feeding policy, i.e. kitting policy. Compared to *Configuration #1*, the cycle time decreases by 25.2 per cent in *Configuration #2* and by 40 per cent in *Configuration #3*, while the productivity increases

Table II Field-test results for the three configurations, cycle time [s/pc]

Test Id.	Cycle time in Configuration #1	Cycle time in Configuration #2	Cycle time in Configuration #3
1	124	100	74
2	117	96	75
3	119	91	67
4	130	95	70
5	126	85	71
6	112	83	80
7	119	88	75
8	115	92	71
9	121	81	73
10	115	85	62
Mean assembly time (*t*)	119.8	89.6	71.8
Standard deviation (σ)	5.27	5.9	4.67
Confidence interval at 99% (*z*)	2.58	2.58	2.58
Margin of error (*h*)	0.02	0.02	0.02
Minimum sample size (*n*)	5.67	8.5	8.38

Figure 5 Assembly system configuration with line stocking (left) and kitting (right)

Table III Average productivity for the three configurations [pcs/h]

Configuration Id.	Average productivity	Increment
Configuration #1	30.0	–
Configuration #2	40.2	34.0%
Configuration #3	51.1	70.3%

by 34.0 per cent in *Configuration #2* and by 70.3 per cent in *Configuration #3*.

Behind these performance improvements, a relevant element is because of the savings in the picking time and operator movements within the working environment. To quantify such savings, a space analysis is done using a motion capture (MOCAP) system collecting dynamic data on the operator positions during assembling. The results are post-processed getting *spaghetti charts* tracing the traveled distance during the task execution. Figure 6 exemplifies the charts for *Configurations #1* and *#2* while tracking the operator body.

The overall traveled distance during the assembly process is close to 30 m for *Configuration #1* and 20.5 m for *Configuration #2,* with a saving of about 31.7 per cent because of low accesses to the storage locations behind the operator. Figure 7 compares the right-hand movements between *Configurations #2* and *#3*.

The overall distance is equal to 27.6 m for *Configuration #2* and 15.6 m for *Configuration #3,* with a reduction of 43.3 per cent, highlighting the strong impact of the kitting feeding policy on the operator movements allowing the full cut off of the storage area in the back of the operator position.

Figure 6 Spaghetti chart of operator body movements for *Configuration #1* (left) and *Configuration #2* (right), top view

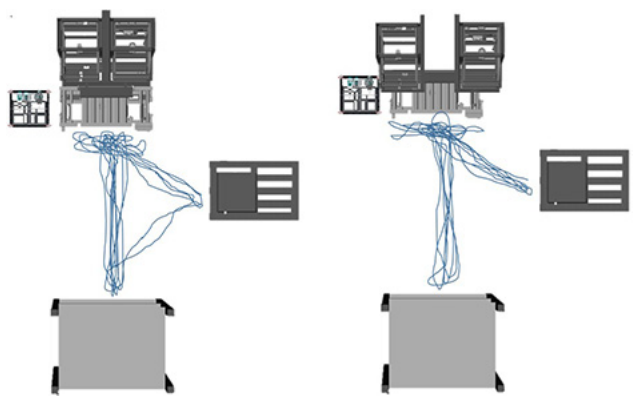
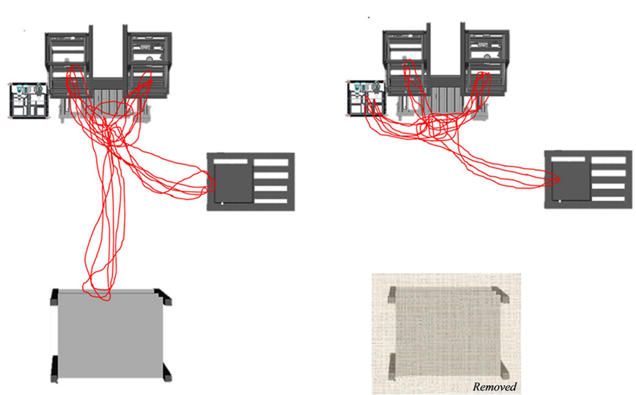


Figure 7 Spaghetti chart of operator right-hand movements for *Configuration #2* (left) and *Configuration #3* (right), top view



5. Industrial case study

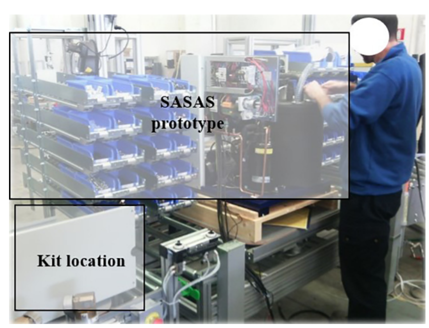
To validate and spread into industry the proposed SASAS prototype, a company is involved in this study. The company assembles industrial refrigerators. The market mix is wide so that manual assembly is still used. The assembly line is made of four stations equipped with components, tools and auxiliary materials to perform the assembly tasks. After the setup and training of the operators to make them confident with the new assembly system, the same multi-scenario analysis developed during the lab experimental field-test is done collecting results on the overall productivity increase. Figure 8 shows the initial conditions, i.e. *Configuration #1*, with no use of the new solution. In particular, all components and support tools are stored in a shelf unit behind the assembly workstation, i.e. line stocking strategy is implemented.

Figure 9 presents the new configuration, i.e. *Configuration #3*, after the SASAS adoption. Support tools are stored in the fast-picking area of the assembly workstation, while according to the kitting strategy, product components are fed in a kit located on the left lateral roller conveyor.

The comparative analysis is performed collecting data for operators with different skills and over a period of two weeks. The aggregate results show, on average, a reduction of the cycle time up to 38 per cent and a productivity increase close to 66 per cent, confirming the benefits of the SASAS introduction compared to the previous traditional assembly conditions adopted by the company. Positive feedbacks came, also, from

Figure 8 Industrial case study, *Configuration #1*, base scenario

Figure 9 Industrial case study, *Configuration #3* adopting the developed prototype



the line operators stating better working conditions and an increased quality of their daily activities. From the economic point of view, flexible automation implies always an initial investment effort to be able to reduce operative production costs over the system lifetime. The proposed SASAS needs three actuators to control the motion axis, safety sensors and the controller. In this paper, savings are quantified adopting technical metrics, i.e. cycle time and distance reductions, leading to a productivity increase. Cost and return on investment (ROI) depend on market demand and production policies and should be addressed after the full ramp up from the lab to the industrial scale.

6. Conclusions and next steps

This paper presents the design, engineering and testing of an innovative prototypal adaptive automation assembly system, called SASAS. The prototype includes a fast-picking area located in front of the operator working area, to store components, equipped with two motion axes to optimize its relative position. A third motion axis allows the reconfiguration of the working plane to ease the operator movements. The main element of innovation of the system is the ability to reconfigure itself according to the product working cycle and the operator features, allowing a potential reduction of the movements during the picking and assembly phases for both small- and medium-size products, with a volume up to $1.5\,m^3$. A multi-scenario lab field-test proves the benefits of the proposed prototype in terms of flexibility and productivity, assessing the full-scale assembly of an industrial chiller, further adopting traditional, i.e. line stocking, and advanced, i.e. kitting, component feeding policies. Compared to the base case, the SASAS prototype allows a significant reduction of the assembly cycle time and of the operator movements during the assembly process with a consequent improvement of the productivity (up to 70.3 per cent in the lab tests). Finally, an application to industry is presented to validate the system in a relevant industrial scenario. Evidences confirm the upgrades in terms of flexibility and productivity making the proposed system of potential interest and immediate applicability within industry. Future developments of this study include the ergonomic assessment of the prototype to match productivity enhancements to better working conditions for the human operators. In addition, a motion capture technology can be included to identify and follow the operator movements and to adjust the SASAS position automatically. Finally, other applications to relevant industrial sectors are of interest and welcomed.

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Appendix

High-level pseudocode of the main control instructions to real-time manage the workplace (WP in the code) and the storage modules (SM in the code) of the SASAS. Calls to IndraWorks standard functions are underlined.

```
main begin

# variable declaration
var WP_pointer, SM_pointer as axis_pointer;
var WP_position, WP_upper_limit, WP_lower_limit as real;
var SM_position as boolean;
var phase_index, num_phases as integer;
var workcycle[1..num_phases] as cluster of {WP_target,SM_target};

# workcycle data loading
read product input from external file: save data into {num_phases, workcycle};

# SASAS axis initialization
WP_pointer:=get_motion_axis("physical_path_to_workplace_driver");
WP_position:=95;
WP_upper_limit:=120;
WP_lower_limit:=75;
f_workplace(WP_pointer,f_position(WP_pointer),WP_position);
SM_pointer:=get_motion_axis("physical_path_to_storage_module_driver");
SM_position:=false;
f_storage_module(SM_pointer,f_position(SM_pointer),SM_position);

# SASAS real-time control and self-adaptation
phase_index:=1;
do
      if (workcycle[phase_index,WP_target]<WP_lower_limit) or
         (workcycle[phase_index,WP_target]>WP_lower_limit)
            then
                  begin
                        send warning to user;
                        wait rebuttal from user;
                        f_workplace(WP_pointer,f_position(WP_pointer),95);
                        WP_position:=95;
                        f_storage_module(SM_pointer,f_position(SM_pointer),false);
                        SM_position:=false;
                        terminate;
                  end
            else
                  begin
                        f_workplace(WP_pointer,f_position(WP_pointer),WP_target);
                        WP_position:=WP_target;
                        f_storage_module(SM_pointer,f_position(SM_pointer),SM_target);
                        SM_position:=SM_target;
                        wait until USER OK;
                        phase_index++;
                  end
while (phase_index <= num_phases);

f_workplace(WP_pointer,f_position(WP_pointer),0);
WP_position:=95;
f_storage_module(SM_pointer,f_position(SM_pointer),false);
SM_position:=false;

end
```

High-level pseudocode of the two functions called to change the workplace height (f_workplace) and the storage module position (f_storage_module). Calls to IndraWorks standard functions are underlined.

```
function f_workplace(Axis_pointer,Axis_origin,Axis_destination)
begin
if (Axis_origin != Axis_destination)
       then
        begin
              f_motionpower(Axis_pointer,"on");
              if (Axis_origin < Axis_destination)
              then   f_moveabsolute_up(Axis_pointer,Axis_destination - Axis_origin);
              else   f_moveabsolute_down(Axis_pointer,Axis_origin - Axis_destination);
              f_motionpower(Axis_pointer,"off");
        end
end

function f_storage_module(Axis_pointer,Axis_origin,Axis_destination)
begin
if (Axis_origin != Axis_destination)
       then
        begin
              f_motionpower(Axis_pointer,"on");
              if (Axis_destination == 1)
              then   f_moveabsolute_open(Axis_pointer);
              else   f_moveabsolute_close(Axis_pointer);
              f_motionpower(Axis_pointer,"off");
        end
end
```

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