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Performance assessment of production systems with mobile robots

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Abstract

This paper investigates the effect of introducing multi-purpose mobile robot manipulators to an assembly system. These units are easily relocated in the shop floor and are able to perform a plethora of production processes. This approach increases the system's responsiveness either in the case of planned system reconfigurations or in the resources breakdown. Both the conventional and the new paradigms are analyzed and compared in a case study from the automotive industry. Discrete event simulation techniques are used. The results of the investigation show that a significant increase in the production volume and resource utilization can be achieved.

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Keywords: Assembly; Robot; Flexibility; Reconfiguration

1. Introduction

The transition from mass production to mass customization requires the design and operation of systems that can handle the increasing product variety [1]. Mixed-model assembly systems are among the main examples of handling variety. In the automotive industry for instance, such system has led to a reduction in the investment cost, thanks to the accommodation of multiple products in the same line [2] [3]. However, it has also led to a reduced performance, in terms of quality and productivity, especially when introducing new products [4]. The long time required for changes to be performed in the line, results in losses whilst the part dedicated equipment, hinders the rapid recover from any breakdowns.

Due to this need for flexibility and reconfiguration capabilities [5], robots have been regarded as a main enabler in the implementation of automated assembly lines. Robots are now capable of handling very complicated tasks that require having their own processing power, memory, sensors and motors. Thanks to their high payload, accuracy and motion flexibility they are able to handle a plethora of parts and carry out virtually any type of joining or assembly process [6]. Their inherent flexibility, has provided to a certain extent all the required functionalities that enable the production system to respond to changes in the demand profile [7]. Through the execution of different programs and use of different end effectors the same line can implement several Bills of Processes.

No matter how flexible the robots may be, their use as stationary units constrains the ability of system level configuration. The time required for the installation, setup and integration of the robot with the station level control systems is significantly higher than that of other machines due to the multiple aspects that have to be configured (sensing, Programmable Logic Controller integration etc.). For this reason, the number of stations and consequently the length of the line are usually fixed [8]. As a result and in order for the Return of Investment to be minimized, the line needs to produce parts continuously at the maximum rate. This contradicts with the need for fluctuation of batch sizes and the total production volume [1]. In an ideal system the production volume should be allowed to vary the line length. Smaller volume signifies larger cycle time and therefore more tasks can be assigned to the robots, before their operation is saturated. This kind of operation surpasses the current system's capabilities, since the production needs to stop for a long period until new tasks/stations are added. This study examines the use of mobile robots to overcome such issues.

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1.1. Mobile robots in assembly

As mentioned above, stationary robots have a crucial disadvantage which is their lack of mobility [9]. Over the last two decades significant progress has been made in the field of mobile robots that can operate either individually or in groups and having a high level of autonomy [10]. Thanks to their ability of relocating themselves and the embedded interfaces for connecting and interfacing the plant control systems, the mobile units require a shorter period time to reconfigure and reduce the efforts required for a new robot's commissioning. An example has been presented in [11] where the robot control is able to generate feasible reconfiguration plans and replace malfunctioning robotic units without any human intervention. Another approach to controlling autonomous and mobile robotic production units, which can change tasks and position themselves in the shop floor to enable random production flow was made in [12]. Similarly, a dynamic layout that considers mobile robots capable of executing different production tasks under a two-level decentralized Multi-Agent System framework has been proposed in [13].

In terms of hardware development, the attempt to commission industrial mobile manipulators has yielded promising results. The latest examples comprise the introduction of a mobile manipulator for assembly applications [14], the creation of an autonomous multi-purpose industrial robot [15] as well as the development of a high payload mobile manipulator for Body in White (BiW) applications [16]. The Karlsruhe Autonomous Mobile Robot KAMRO is an example of a mobile two-arm robot, which has the ability to perform assembly tasks without human intervention [17]. OmniRob is also designed by KUKA for handling tasks and is an attempt for the validation of new technologies in terms of their robustness and suitability [18].

There are still some limitations of the mobile robots [19] concerning their ability to navigate and locate autonomously their destination and the ability to ensure a conflict free path among them and any human/obstacle [20]. This paper aims at investigating the impact of such equipment on the production system's level, by assuming their existing availability.

2. Problem definition

At present, serial assembly lines are mainly used for large scale production since they can provide short cycle times and high production rates. Nevertheless and in order for these benefits to be achieved, these production systems make use of (Figure 1):

- rigid flow line structures employing model-dedicated handling/ transportation
- fixed control logic and
- signal - based tasks sequencing that requires high manual effort for changes.

These systems make the line cumbersome in adding / modifying a product and this comes into conflict with the diversification sought after by production firms. Introducing or varying a product in the production line means that the process plan of the specific product can be accommodated by the line setup. Four main directions can be followed for the successful adaptation of the new production requirements:

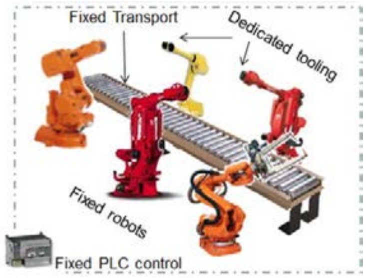

Figure 1. Conventional serial production line with robots

- **Ability of using the existing production processes, in a different order, by randomly routing parts in the system** (Routing Flexibility)**.** Random production flows signifies the ability of higher product diversification since it enables the realization of multiple production plans, in the same production system. However such functionality cannot be achieved today due to a) the use of **rigid transfer equipment** (e.g. conveyors) and b) the **lack in real time control of part routing**
- **Ability of using the existing processes, in a different order, by changing the system's structure** (Structural Flexibility). Currently, changes in the system's structure are realized over medium or long term periods since they require considerable time and resources for the performance of the physical rearrangement and setup of the equipment. This is attributed to a) the use of **large and immobile resources** that require careful planning before any intervention with their installation and b) the **lack in networking infrastructure** for "plug & produce" approach
- **Ability of adding new processes with the modification of already installed resources** (Resource Flexibility). The fact that the latest production resources are designed for performing multiple processes (e.g. a robot can be used for handling, spot welding or arc welding) is an advantage that has not been fully utilized so far. This flexibility characteristic is undermined by the fact that robots are planned, installed and not allowed to change their roles until the next shop floor reconfiguration, which may take place after several months or even years.
- **Ability of adding new processes with the addition of resources** (Expansion Flexibility). Should a system require the adaptation of new production processes not having been implemented before, it will have to introduce new resources. Although simple it may sound, there are many complications to be handled and are related to a) ensuring the **required installation space**, b) **minimizing the installation time,** c) handling the **complexity of the integration** with the existing control systems and d) maintaining **cost efficiency**. All these signify a wide time frame that is not satisfactory. The mobility of resource is a limiting factor for the production line flexibility.

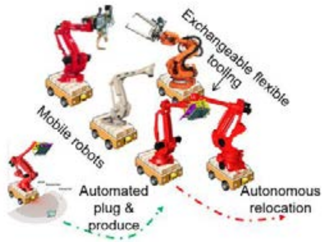

Figure 2. Assembly line concept with mobile robots

2.1. Mobile robotic units

Mobile robotic units that can be easily transferred around the shop floor and automatically take up tasks, is the main enabler of the approach discussed (Figure 2). This kind of units can communicate and cooperate among themselves and enable the production system to recover from failures in any robot/tool by switching position/job. Currently the breakdown of a robot or tool signifies a long period even up to a complete shift (8 hours) for repairs, provided that spare parts/tools are available. In the case of replacing it with a different robot, the tasks become far more complicated due to the need for the generation of new robot programs, new signals on the PLC etc. The integration of mobile units with line level intelligent control algorithms, enables them to undertake any task along the line, provided that they meet the task requirements in terms of hardware [11]. The robotic units should also exhibit cooperative behavior, i.e. robots communicating with each other for carrying out common tasks [21]. The cooperating robots' applications comprise characteristics such as [22], [23]: Workspace sharing, Motion synchronization, Program synchronization and Linked motion. These capabilities are crucial for the implementation of the reconfiguration activities stated earlier (e.g. gripper exchange, coordination between mobile and stationary units etc.). Such production systems were investigated by [24] and the conclusion derived was that the reduced reconfiguration time, required in cases of assembly lines using mobile units, results in higher flexibility and significant increase in the system's productivity.

2.2. Supporting technologies

The construction of mobile manipulators needs to be supplemented with several technologies required for achieving process flexibility and "plug & play" behavior, on top of the mobility offered. This section deals with two of the key technologies.

2.2.1. Reconfigurable and exchangeable tools

In order for part variability to be further accommodated, the mobile robots should be equipped with flexible and active end-effectors that will be incorporating novel actuation and control mechanisms; the latter enable the online reconfiguration of the end effector when required. This allows the handling large and different products since the same tool can be used at multiple stations to perform different tasks.

Figure 3. Exchange of parts and gripper between two robots

As an extension to the reconfigurable tools the concept of exchangeability provides a further flexibility aspect [11], [15]. The exchange of the part and the end-effectors between robots can be implemented by using multiple connection points on a single tool. This permits the secure transfer of the subassemblies and their components without the need for fixtures, while at the same time, maintaining the assembly tolerances throughout the process. This functionality is particularly useful when the robots experience malfunctions and can hand over their gripper and the part to another robot to randomly route the part between adjacent robots (Figure 3).

2.2.2. Intelligent control logic

In terms of achieving a Plug and Produce process that enables the mobile robots operation, an underlying architecture is required that will allow the mobile robots to:

- connect to the station/cell network,
- setup up their operating parameters and signals exchange
- download the description of tasks to be carried out (including motion plans, low level operations etc.)
- communicate with the higher level coordination mechanisms for cooperation with the rest of the resources.

The scope of the integration architecture is to allow easier integration and networking of the control systems through the utilization of agent-based, web-services and ontology technologies. The major challenge for robotics research and the developers, is the software that should be robust, open and assure autonomous behavior in case of failure. Moreover, it has to be flexible without being exclusively used by a particular robot or for a task [14]. In [11] a semantic web-based technology was used for the development of a tool that would enable the scheduling of the production plan, the assignment of tasks to resources, the modification of the tasks with respect to unforeseen changes, as well as the exchange of tools to resources. Besides, in [15] an open architecture with the use of ontology and service technonogies was developed and applied to a case study enabling the creation of an online production plan. This kind of aprroaches, using service oriented architectures result in the creation of reconfigurable systems [11], [15]. In order for compatibility with the existing systems, to be ensured, the open source initiatives can be used to develop architectures [14] namely the Robot Operating System – ROS (www.ros.org) and the Open Robot Control Software – OROCOS (www.orocos.org).

2.3. Motivation

Figure 4, depicts a qualitative comparison between a conventional line and a line with mobile resources.

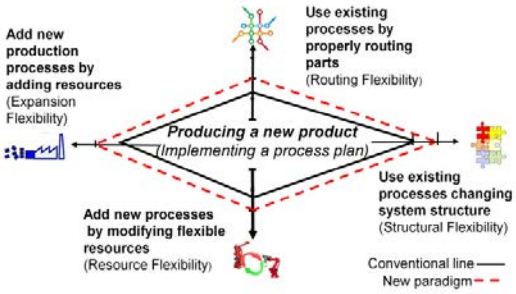

Figure 4. Main directions for adding a new product on a production line

The visualization in this figure is mainly based on the following advantages that a mobile robot based line can offer:

- **Reduction in reconfiguration time** – The system's structure can be changed with the relocation of the mobile units, thus obtaining the structure that better suits the production at each period. The same resources are used in different areas to perform a range of processes. The reconfiguration should take place in minutes rather than days or weeks.
- **Enhanced system reliability and reduction in breakdown times.** Considering the fact that in serial assembly lines such as those in the automotive industry, there are very small or no buffers at all between the stations, any resource breakdown can result in a stoppage. Since the time required for the repair is based on the type of malfunction, the mobile robots can promptly replace the problematic resources.
- **Reduction in commissioning time**. The advantage of mobile manipulators is that they include standardized mechanical and electrical interfaces allowing them to plug into the system, setup their parameters and start operating. The installation of fixed robots requires a line stoppage.
- **Reduction in the cycle time through the minimization of picking/placing operations**. The use of flexible and reusable tooling can eliminate the existing stationary tooling. In this sense the products will be continuously handled by the robots thus reducing any extra handling operations
- **Enabling higher product variability through robot to robot handling**. The aforementioned ability for parts to be transferred between the robots, overcomes the limitation of fixed, on-ground, tooling with respect to product routing. This can be translated into higher plant and product variability.
- **Reducing planning and control efforts by automated task allocation and resource integration**. This means that the system will have to decide on the reaction steps to be followed by evaluating its state and capabilities. The autonomous resources will be able to decide about the kind of task to be undertaken and then automatically navigate them to the specific area, plug into the system and carry out the task.

However, not in all scenarios this multi directional enhancement can be implemented. In the example case study of this paper a serial assembly line is considered. In this case, the possibilities for modifications in the part routing are limited due to the need for the process plan and cycle time to be respected. In other types of systems such as job shops, the routing flexibility dimension can be further enhanced. The mobile robots can also be used to transport parts at the shop floor thus further enhancing the random routing capabilities.

Real life constraints need to be considered in order for the concept to become feasible in production. The main constraints comprise the standardization of hardware (electrical/ mechanical) and software interfaces for achieving a seamless 'Plug & Produce' behavior of the resources.

3. Case study

The mobile unit based paradigm has been applied to an assembly line inspired from a real automotive assembly line. The final product is the floor of a passenger vehicle. The study considers a fourteen year period and five products which are either updated by a facelift model or replaced by a new one (current typical lifecycle [2]).

In the first four years, the line set-up allows the production of products A, B, C at random mix, using eight stations, which are serially connected with a conveyor (Figure 5). Following, the products A and B become outdated and a facelift is performed in order for the reduced market share to be regained. The facelift requires additional processes to be performed and the modification on the assembly line requires a period of one month. The main changes include the modification of the processes within stations 4 and 7, the addition of station 10 and a re-arrangement of the processes to the stations (Figure 5). The assembly of product C remains the same. At the end of the seventh year, the products D and E are introduced to the line whilst the products A, B phase out. Since the new products have significant differences from the older ones, a longer time is required (three months). Lastly, in the last four years a facelift of products C and D is performed.

The introduction of mobile units, available to replace any of the resources allows for the reduction in the downtime for changes (facelifts) and for any recovering from breakdowns. Based on the findings of recent projects such as the FP7 EU AUTORECON (www.autorecon.eu) [24] it has been estimated that the mobile robots can reduce the respective time as in Table 1. The effect is expected to be the same for any changes in the scenario since the introduction of mobile resources directly affects the availability of equipment and allows the maintenance of the productivity throughout the operation period.

3.1. Simulation models

In order for the conventional system and the new one to be compared, experiments were carried out via the simulation package Witness 2007. Both simulation models use as input the demand profile of Figure 6. Figure 7 shows the simulation model of the conventional system and the respective model with the mobile robots. In both systems the cycle time of stationary and mobile resources follows a normal distribution of 0.5 minutes with a standard deviation of 0.05 minutes, which is a typical cycle for the automotive lines.

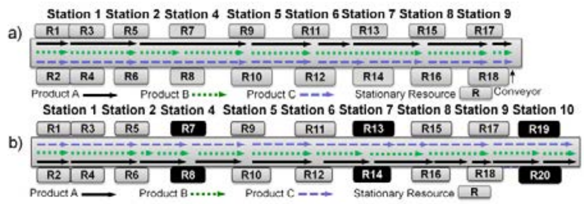

Figure 5. The structure of the line during: a) Year 1 and b) Year 4.

Table 1. Simulation model periods

	Conventional system	New paradigm
First Facelift period	1 month	2 weeks
Introduction of new products	3 months	1 month
Second Facelift period	1 month	2 weeks

3.1.1. Reliability of resources

Although modern industrial robots provide high availability, in the automotive welding lines, there are frequent and short failures occurring [25]. This is represented by the breakdown profile of the first line of Table 3. These failures represent the random ones of every individual robot, resulting in an availability of 99% for each robot and 90.45% for the entire system. Nevertheless, for a system comprising twenty different robots a regular period for maintenance should be established to prevent the need for massive changes (e.g. replacement of a stationary resource) [26]. This maintenance is represented by another breakdown profile (line 2 of Table 2 including a stoppage every 300.000 minutes (Mean Time Between Failure) and takes 1 day Mean Time To Repair (MTTR). Finally, a third breakdown profile was used to represent the need for service of more permanent failures (profile 3) [27].

Table 2. Breakdown profiles

Profile	MTBF (min)	MTTR (min)	Characteristics
1	NORMAL (400,10)	NORMAL (2,0.05)	Frequent and short failures
2	NORMAL (300000,5000)	NORMAL (1440,40)	Maintenance
3	NORMAL (2500000,300000)	NORMAL (25,5)	More permanent failures

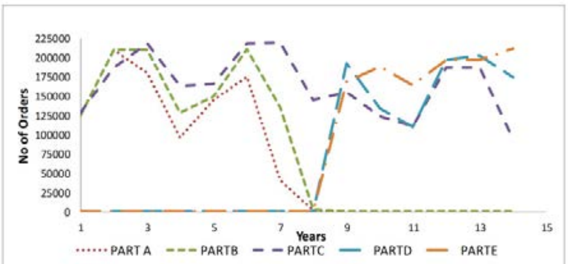

Figure 6. Demand – production profile over the lifecycle of the line

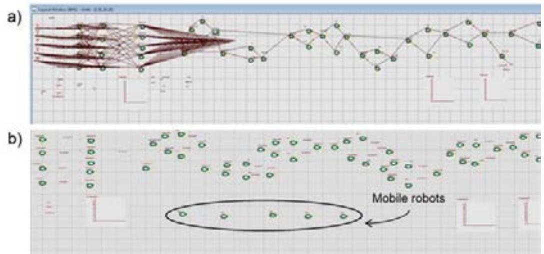

Figure 7. Simulation models for (a) conventional and (b) new paradigm.

4. Results and discussion

After the two models were run for the full period, the criteria of Table 3 were obtained and used for comparison:

Table 3. Comparison of the two systems

Metric	Conventional Line	New paradigm	Increase (%)
Volume (parts)	5.636.925	6.339.134	10,7
Utilization (%)	68,76	76,518	7,758
Availability (%)	90,59	96,328	5,738

As it can be observed, the production volume and the utilization as well as the system's availability have been increased with the mobile robots' introduction. In Figure 8, there is a presentation of the daily production of the conventional and the new paradigm. It should be mentioned that the demand profile is given for a failure – free system. The production capacity of both systems exceeds the maximum volume of the demand profile. This is a common practice used to accommodating fluctuations in the demand. The everyday failures of the resources result in parts being gathered into the buffers thus, increasing the future daily demand. As a result, the systems use their extra capacity to absorb this extra demand. The fact that the traditional paradigm presents more frequent breakdowns results in a lower availability and production volume. Thanks to the mobile robots, the new system can approximately produce more than a hundred parts per day.

The enclosed area in Figure 8 highlights the daily production of both systems during the facelift period. The area is enlarged in Figure 9. The production of the new paradigm exhibits a faster recovery. This more efficient performance is attributed to the introduction of the mobile robots that reduce the time required for modifications.

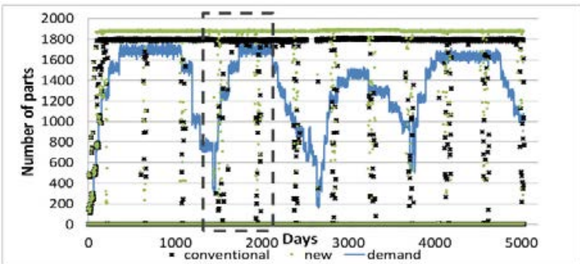

Figure 8. Daily production of (a) the conventional and (b) the new paradigm

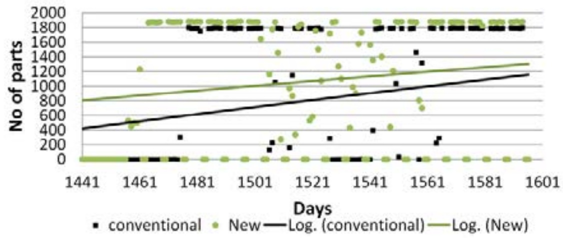

Figure 9. The daily production of the two systems for the facelift period

5. Conclusions

This paper discussed the mobile robots' introduction to an assembly line as a means of enhancing the system's flexibility and responsiveness. The respective hardware and software requirements for creating such systems have also been presented. The main advantages of assembly lines based on mobile robots are: higher reconfigurability, reduced duration of breakdowns, lower commissioning time, higher reliability and flexibility, minimum need for human intervention due to their autonomous behavior and higher production variability.

The findings of a simulated case study from the automotive indicate that the addition of mobile robots increases the production volume of the line due to its higher response to breakdowns and the shorter period of time required for its reconfiguration. The mobility also results in the system's higher utilization and availability, thus rendering the line even more efficient. Future research could enhance this analysis, by investigating the performance of the approach in systems of a different structure and lifecycle. The standardization of hardware/software interfaces in order for 'Plug & Produce' behaviour to be achieved is also essential. Finally, an open, service oriented architecture should be developed to ensure efficient communication between resources.

Acknowledgements

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