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Robot Workmate: a trustworthy coworker for the continuous automotive assembly line and its implementation

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Abstract

The automotive industry is facing significant challenges due to shortened product lifecycles, increased product variances, and fluctuating markets. The current assembly systems are unable to handle the increased requirements for mass customisation, so they need to be optimised with new technologies. Human-robot cooperation has evolved as a solution to overcome these difficulties and create flexible and customizable automation processes. This paper delivers an approach for a methodology to implement HRC robotic systems into the continuous assembly line. This optimisation allows for cooperation between robots and the manual labour, which enhances the ergonomics, productivity, and quality level of the process station.

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Keywords: HRC robot system; cooperative robot; physical human-robot interaction; automotive assembly

1. INTRODUCTION

Many companies are under pressure to increase their productivity to remain globally successful in competition. Simply increasing the degree of automation is not very promising because of the complexity of the assembly operations and the high number of variants and fluctuating quantities [1]. An empirical study in the German industry gives evidence that automation has been implemented in many companies beyond economical value and often in an inappropriate manner. Approximately one third of all companies that invested in high automation recognized that these solutions are not flexible enough and reduced again their level of automation [2]. As a consequence, a significant number of tasks in the assembly and commissioning line – especially in car manufacturing – are performed by manual labour. Newly developed HRC robot systems in combination with the latest sensor and safety technology have created the opportunity to overcome these difficulties with a physical cooperation of humans and robots (HRC) in the same workspace. The automotive industry is especially interested in implementing these new systems. They are facing the problem that their assembly systems are unable to cope with increasing requirements of mass customisation and need to be enriched with new technologies for a higher flexibility potential [3]. In order to maintain their competitiveness the car manufacturers are searching for future oriented concepts to increase the performance of the assembly line and reduce costs at the same time [4]. Human-robot cooperation and the possibility for customized automation are identified as new key technologies to enhance the efficiency of assembly processes and the overall productivity of the factory.

This paper delivers an approach for a methodology to implement HRC robot systems into the continuous automotive assembly line. A modular means of production system is presented together with an integration and control concept. Using this procedure all suitable assembly operations can be reviewed and the robot can be integrated as a co-worker wherever it is capable to optimize the process.

2. State of the Art

2.1. Automotive assembly line

In the last decades the automotive industry changed from mass production to mass customization which was based on the need for more customized vehicles and providing many

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models, with the use of fewer resources and materials in the shortest time possible [1]. An increasing number of driver assistance, electronic comfort systems and alternative drives like hybrid or electric drives, leads to a higher complexity and a large number of variants. On top of that new product models and facelifts are frequently introduced into the market due to rapid technological advancement and varied customer preferences. The sales volumes wildly fluctuate caused by unforeseen changes in the market situation [5]. New production technologies are necessary to increase the productivity, achieve flexibility and transformation ability.

A high number of variants, mixed model assembly and the requirement of complex movements are the main obstacles for automation in the assembly line [1]. Conventional automation strategies are limited for these applications because a majority of the task execution requires a high level of perception, dexterity and reasoning which cannot be met technically in a cost-effective or robust way [6].

2.2. Hybrid assembly systems

Hybrid assembly systems or also called semi-automated systems are characterized by a synchronous cooperation of humans and machine, without taking the humans self-determination away [1]. In order to attain the full potential of the physical cooperation, an optimal division of labour on the process level should be aimed for. In terms of cost a customized automation process, whereby humans and robots can each be allocated a specific type and/or amount of work, seems to provide an optimal balance between the cost of manual labour and the capital investment [7]. In addition, a product-independent process station layout and the flexible nature of human workers should provide high conversion and transformation flexibility. Because of the shared workspace, the factory layout can be used very efficiently and enhance the capacity utilisation. The removal of safety fencing gives the worker the opportunity to enter the robot's workspace at any time without hazard. Malfunctions can be rectified easily without disruptions of the overall process and a continuous availability is ensured [8], [9]. The robot offers high reproducibility; hence a subjective influence on the tasks can be excluded. The process capability is increased and a permanent quality control is set in place.

2.3. Assembly planning methods for a cooperative assembly

Human centered and skill based approach based on task analysis

To allocate the assembly tasks to either human or robot Tan et al. adopted the task analysis method for the purpose of planning cooperative work stations [10]. The tasks analysis is a commonly used scientific methodology to model human tasks in various ergonomic and human factor studies. The task is defined as a goal and required activities to achieve this goal are broken down to form a hierarchical tree.

Different subtasks from the hierarchical tree are then allocated to human and robot by using a qualitative analysis. The possible allocation is done by the definition of the specific skills and key characteristics of human and robot to combine their strengths and reach an optimal efficiency [7][10]. These skill based analysis is shown in Figure 1.

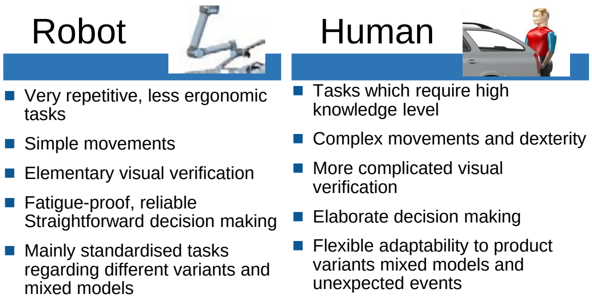

Figure 1. Specific skills and key characteristics of human and robot

In summary, the tasks which require a high level of knowledge, individual decision making and complex movements can only be performed efficiently by the human. The strengths of the robot are high repeatability and a fatigue-proof elaboration of the tasks, which ensures a reliable result and a high process capability [7] [8] [10] [11].

A quality based task planning method

Manual assembly processes lacking of reproducibility, process capability and reliable documentation due to the human factor. The increasing complexity from the high number of variances can overstrain the workers and results in quality problems. Quality relevant processes can be possibly taken over by a robot which ensures a high repeatability [12].

A transformation and flexibility based planning method

Due to frequent model changes and fluctuating production volumes the demands for flexibility to assembly stations are very high. Additional investments in automation might not be covered by the cost reduction effects. The processes likely to be adjusted are performed by humans while robots handle the sections that do not need a big effort to be adapted [13].

2.4. Technical set-up of an assembly station using modularisation and integration

Modularisation provides the opportunity to reduce the complexity of comprehensive systems. This is achieved by subdividing the system into manageable parts. A modularization in functional units is pursued by relating to the planning and technical implementation of hybrid assembly systems. This creates a comprehensive systematic understanding which can be used for an effective, efficient, and flexible configuration [14].

For the implementation the modules need to be integrated into a control concept. Integration describes the set-up of a functioning system built out of modules [15]. A configuration concept is necessary to fulfil the demand for increased efficiency as well as achieving flexibility and versatility. This concept must be able to find a suitable module feature based on the systematic description and combine those with a complete customized system [14].

3. Methodology for the Implementation of a cooperative process station into the continuous assembly line.

The development of the methodology is illustrated in a use case of an automotive end-off line process station. In this process station product properties are manually checked as a last quality control, before the fully assembled vehicle leaves the factory. This process is especially suitable for HRC because reproducible error detection can't be insured due to the human influence. The increasing complexity of vehicles as well as the ergonomically not favorable inspection processes can overstrain humans and cause quality problems. An automated system which takes over repetitive tasks is a significant improvement and relieves the workers.

3.1. Approach

As described in the section 1 and 2 the conventional assembly systems reaching their limits meeting the requirements of mass customization, quality and costs. The human-robot cooperation and the possibility for customized automation are identified as new key technologies.
The main questions are:

- How can the cooperative process be planned and the tasks allocated to human or robot?
- Which means of production are necessary how can they be determined efficiently and integrated in a safe control structure?
- How can this optimized system be implemented in the continuous assembly line and safely work parallel to workers?

In order to address these questions a methodology is presented which allows an integrated process from product analysis to technical implementation of a cooperative process station.

3.2. Methodology for an integrated planning, configuration and implementation process

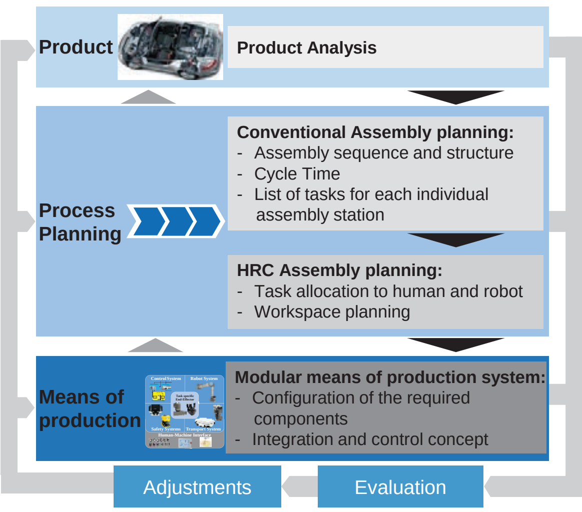

Figure 2. Procedure for the integrated planning and configuration process

Figure 2. shows an overview about the methodology. The starting point is a detailed analysis of the product and its components to define product-related requirements for the assembly process. The next step is the planning of the assembly process. This is started with the conventional assembly planning which results in an assembly sequence and structure, the cycle time and a list of tasks for each assembly station. This information is the base for the HRC assembly planning. The planning methods from section II are used to determine the most suitable task distribution. The result is a task allocation to human and robot and a workspace planning for the process station. To determine the necessary means of production a modular system is defined together with an integration and control concept.

This procedure can be used to review all suitable assembly operations and integrate the robot as a co-worker wherever it is capable to optimize the process.

The following chapters are focused on the planning of the cooperative production process based on the input of the conventional assembly planning and then the technical implementation of the workstation using the modular system and integration concept.

3.3. Design and planning of a cooperative process station

For the planning of the cooperative end-off line process station the required activities are summarized in an assembly task tree. The result is shown in Figure 3. To maintain an overview it was focused on the most important processes. The procedure and order varies between different manufacturers and factory layouts.

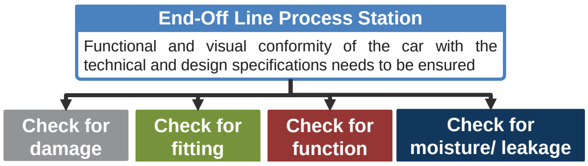

Figure 3. Assembly task tree for the end-off line process station

The main goal to check the functional and visual conformity of the vehicle can be subdivided into four main checks:

- Checks for damage and fitting are very well suited for qualified workers with a deep knowledge of the product. The complex movements necessary and the high level of product dependency make a cost effective automation very complicated.
- Checks for function have a more repetitive less specific workflow. An automated functionality check of the interior would be possible by using a robot system equipped with sensor technology. Nevertheless different variants and models can cause an extensive programming effort.
- The check for moisture in the interior could be automated by using a robot equipped with an image processing system. The inspection of the trunk areas is harder to automate because it is very product specific and several closures need to be opened to check the cavities.

For the further planning the check for moisture/ leakage of the interior is selected as a use case. This task is especially suitable for the robot because it needs to be carried out at all vehicles in the same way and is ergonomically unfriendly. Considering the quality aspect this process is also highly critical if performed manually. Reproducible error detections are often missed by manual workers and a clear documentation is not possible. The automated moisture detection is done by applying an image processing system to the robot. A thermographic camera takes pictures of the interior of the vehicle, and processes the images to detect wet spots. The inspection result is used for a go/no go decision where a defective vehicle is transported to a manual rework station [16].

The result of the process analysis and planning is the following task allocation and sequence:

Before the vehicle comes to the process station it has been watered in a rain tunnel. To ensure the accessibility of the interior for the robot the worker needs to open all doors. The robot performs the inspection of the vehicle's interior. The areas sensitive for leakage are checked with the thermographic camera. If any moisture is detected by the camera system a feedback to the operators is given and an error log can be automatically created and send to the rework station.

The worker takes over the checking task of the trunk area. Also the checks for damage, fitting and function are done by the workers. A possible distribution of tasks and the corresponding workspaces are shown in Figure 4.

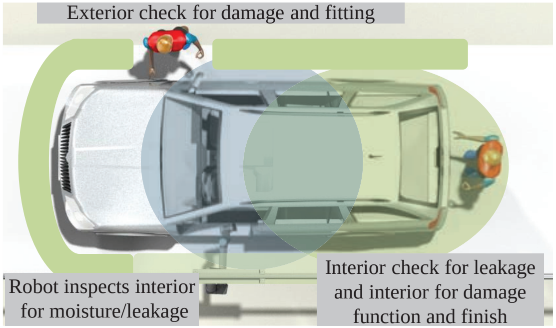

Figure 4. Task distribution and workspace

In summary the type of HRC in this application can be described as cooperation between robot and human worker by sharing the same workspace. The robot checks the vehicle interior independently and is included in the workstation as a co-worker to the human operators.

The next step after the planning of the process is the configuration of the necessary means of production.

3.4. Modular system and integration concept

Based on the tasks the robot got allocated (chapter 3.3) the components necessary for the technical implementation must be configured. At the moment safety issues are the biggest obstacle for a broad implementation of the human-robot cooperation. Due to the high safety standards of the HRC there is often extensive individual planning and configuration effort necessary for every single process station

Our approach is to reduce the complexity with a modular double stage process which is shown in Figure 5.

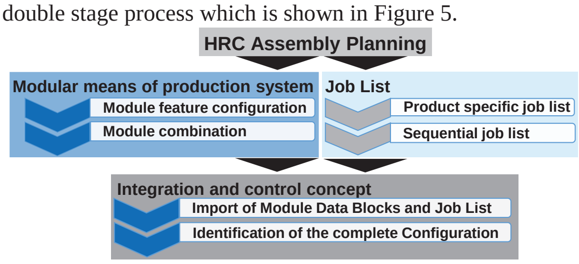

Figure 5. Double stage configuration process

The results of the HRC Assembly planning are the input for the first stage. It is separated in two parts:

- Modular means of production system which contains the necessary technical components clustered according to their tasks
- A job list which is a sequential list of the tasks that need to be executed by the robot

The second stage is the integration and control concept where selected modules are integrated into a standardized control structure. The tasks of each module are distributed by the control system based on the job list.

The detailed contend of the two stages is explained in the following chapters.

3.4.1. The modular means of production system and job list

For the application in the automotive assembly line the modular system is subdivided into 6 submodules shown in Figure 6. The module component can be selected using a configurator. The configurator determines the most suitable component out of a data base based on the task description from the HRC assembly planning. For each chosen component the configurator creates a data block which can be imported into the control concept.

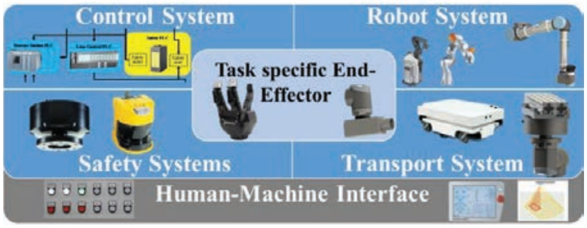

Figure 6. Submodules of the modular means of production system

Description of the submodules and their tasks:

Control System:

A control system is necessary, to control the complete system and merge all safety components. This can be configured according to the necessary connection bus systems and volume of the data flows. The control system also communicates with the higher-level control unit.

Robot system:

Based on the application numerous HRC robot systems are available on the market. An individual choice is made based on the required robot parameters like reach and load capacity.

Safety systems:

The foremost consideration for the development of shared workspace for humans and robots is safety. Under no circumstances should the robot cause harm to humans, directly or indirectly, either in regular operations or in failures. The amount of necessary safety systems and their application needs be defined by conducting a detailed safety assessment of the application and the evaluation of the possible risks. A wide range of safety systems to safeguard the cooperation of humans and robots are available. Important components for workspace monitoring are laser scanners, camera systems, and sensitive mats. Also important are systems for force limitation in the event of a collision, e.g. a pneumatic safety clutch.

Human machine interface

To allow the worker to communicate with his robot co-worker, a human-machine interface can be implemented into the assembly station. This includes easy devices like buttons or switches with indicating lights or more advanced technologies like smart devices (e.g. smart watch, touchscreens) and digital or laser projectors.

Transport system

A transportation system is necessary to synchronize the robot with the moving assembly object depending on the procedural organisation of the assembly. Transport systems that are adapted to the floor or ceiling based tracks, handling devices or automated guided vehicles are possible.

Task specific end effector

Based on the requirements of the robot's task the necessary actuators and sensors need to be applied. These tools need to be specially customized to the requirements of human machine cooperation (e.g. no sharp edges or other risks of injury [17]) and considered in the risk assessment.

Job list

The job list is created out of the tasks allocated to the robot in the process planning (chapter 3.3) and their sequence. The job list contains individual tasks which the robot needs to perform in a sequential order on the control level. It can be flexibly adjusted based on the different variants. The completed job list is then uploaded into the control system.

3.4.2. Integration and control concept

The core element of the control concept which allows the integration of the different modules is a standardized intelligent control structure implemented in the control system (PLC). The data blocks for each module are imported in the control structure. The control has the ability for self-identification and determines the complete configuration and its available capabilities. These capabilities are compared to the required tasks from the job list. If the tasks can be executed with the available modules they are executed in the sequential order of the job list with the required modules.

4. Validation of the process in a model factory

In the scope of this project and parallel running research, four stations of an automotive final assembly are installed at the ZeMA research facility as a model factory and demonstrator. This model factory consists of an overhead conveyor system and four equal process stations with a base area of 6x6 meters and a height of 4.5 meters. (Figure 8. left).

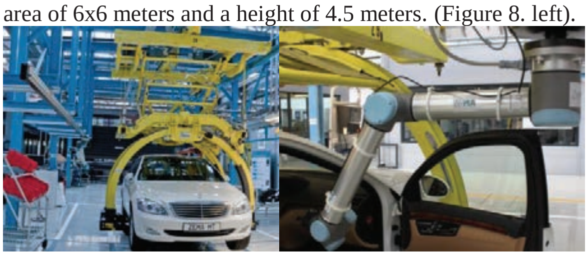

Figure 7. Model Factory and process for the interior inspection

The process station for end-off line inspection is shown in Figure 7. In contrast to practice in the factory, the vehicle is transported in an overhead conveyor system due to the requirements of the other process stations. Nevertheless, the process can be simulated exactly as in reality.

4.1.1. Implementation of the means of production system

In this chapter the means of production system is used to pick the right production equipment for the water leak test and its configuration and implementation into the model factory. An established control structure is used. This structure contains tested and safety approved components. The components and links are shown in Figure 8. A comprehensive risk and safety assessment of the complete system is nevertheless necessary. It is also simplified because of the common standard components.

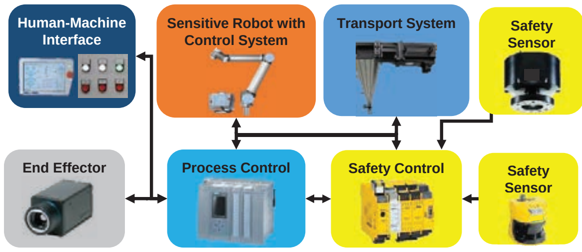

Figure 8. Control structure and integration of the components

Robot system:

The Universal Robot UR 10 was selected for this interior check. The robot has several features which makes it suitable. First, the high reach of 1300 mm is important for the reachability of the interior for inspections inside the vehicle. The robot is certified by the TÜV Nord a German technical inspection association and fulfils the standard EN ISO 13849:2008 PL d and EN ISO 10218-1:2011 which approves it for the physical human-robot cooperation [18]. This certificate is only valid for the robot itself, which means the safety of the complete system including the camera and transport system is in need of a careful risk assessment.

Control Technology:

For the control of the process station and the communication with the higher level process control a standard programmable logic controller (PLC) commonly used by the automotive industry is utilised.

Transport system

To be able to keep the additional investment for the upgrade of a manual process station low, standardized aluminium profiles and connectors are used for the linear track. For the engineering of the system detailed calculations of the forces applied to the system were done to configure the profiles. A travel carriage was designed to move the robot. It is driven by a standard servo motor with a gear belt.

Safety systems:

The safeguarding for the validation of the process is done in several levels. The lowest level safety function is the force limitation implemented in the robot. The process forces are measured by interpreting the motor current with two redundant controllers. If the applied forces are above a defined level the robot goes to an emergency stop [18]. The second level safety to protect the worker is a pneumatic safety clutch which is a standard component normally used to protect robot tools or actuators. In this application the clutch is mounted between the robot base and the carriage. The triggering force is proportional to the applied air pressure and can be flexibly adjusted. In an overload occurrence the clutch is released and the robot can freely rotate around the vertical axis and an emergency stop signal is triggered which is send to the safety PLC to stop the entire process. On top of protecting the human the clutch also prevents the vehicle to get damaged. If an error with the robot system or the synchronisation of the axis and the vehicle should occur the clutch is released and the robot can safely slide out of the vehicle without any damage to itself and the product. To prevent a possibly harmful contact between worker and robot at all, the implementation of a sensory workspace monitoring is currently developed in ongoing research.

Task specific end effector

For the inspection process a thermographic camera is applied to the robot. The taken images are processed with a patented image processing algorithm which has been developed in previous research activities [16] [19]. The camera has no sharp edges or corners and does therefore not present any additional hazard [17].

Job List

The different inspection areas are listed in their order in a job list. Specified to each type of vehicle (e.g. station wagon, limousine, coupe or convertible) an individual job list is created and implemented in the control system.

4.2. Practical implementation of the technology

Several original equipment manufacturers (OEMs) identified the automated leakage detection as a possible innovation for their manufacturing line. Feasibility studies are currently done to plan the practical implementation of the process. A model for a possible process station in the factory with a floor-based transport system is shown in Figure 9.

Figure 9. Implementation of the system in the factory environment

In summary, the technical feasibility is shown in the demonstrator case and currently developed further to a pilot production stage. The cost effectiveness of the process was proven as well [16].

5. Conclusion and outlook

The key challenge is how HRC processes can be implemented in the automotive final assembly in order to increase the process capability and efficiency but also create transformation ability and flexibility. To solve this problem a newly developed integrated planning and configuration method customized for the requirements of the automotive assembly was presented. A modular means of production system followed by an integration concept was developed to implement the planned process into the factory. This methodology allows for a skill oriented planning with pre-developed safety approved components. The planning and programming effort is significantly reduced. The self-identification method and independent task allocation creates the necessary flexibility. The methodology of the modular means of production system is currently developed further to create an easy to use configuration software combined with a sophisticated procedure for the integration and set-up of the control concept.

The planning process was validated using the example of an inspection system for moisture detection. It shows how the human-robot cooperation can be implemented to its fullest potential in practice. The utilisation of a cooperative robot in the continuous assembly line is the next development stage of the human-robot cooperation. The technology and planning method can be further extended to other assembly and inspection tasks in the assembly line. Assembly processes, such as screw-fastening or sealing operations are being analyzed and feasibility studies are under way. Due to the great interest of the automotive industry in the human-robot cooperation, a practical implementation is very likely.

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