ROBO-PARTNER: Seamless Human-Robot Cooperation for Intelligent, Flexible and Safe Operations in the Assembly Factories of the Future

George Michalos¹, Sotiris Makris¹, Jason Spiliotopoulos¹, Ioannis Misios¹, Panagiota Tsarouchia¹, George Chryssoulouris*²

¹University of Patras, Department of Mechanical Engineering and Aeronautics, Laboratory for Manufacturing Systems and Automation, 26500, Patras, Greece
* Corresponding author. Tel.: +30-2610-997-264; fax: +30-2610-997-744. E-mail address: xrisol@lms.mech.upatras.gr

Abstract

This paper presents the vision and architectures, proposed by the EU project ROBO-PARTNER. The project aspires to the integration of the latest industrial automation systems for assembly operations, in combination with human capabilities. Focus is given to combining robot strength, velocity, predictability, repeatability and precision with human intelligence and skills to get at a hybrid solution that would be involving the safe cooperation of operators with autonomous and adapting robotic systems. The main enablers are: the development of intuitive interfaces for safe human-robot cooperation (HRC), the use of safety strategies and equipment, allowing fenceless human robot assembly cells, the introduction of methods and tools for the efficient planning programming and execution of assembly operations, as well as the use of mobile robots, acting as assistants to human operators. The project also provides a more flexible integration and communication architecture by utilizing a distributed computing model along with ontology services. A pilot case from the automotive industry is used as the ground for developing and testing the aforementioned technologies.

1. Introduction

Today’s European industry faces the challenge of achieving flexibility and efficiency in order to improve its competitive position in the world market. There are numerous industrial applications, where the assembly process is mainly performed by human operators due to the fact that a) operations require a human like sensitivity, b) the materials handled vary and often show a compliant, unpredictable behavior (upholstery, rubber, fabric etc.) and c) often more than one operators are active in order to perform cooperative or parallel operations in each station [1],[2]. Nevertheless, the automation of operations in manual assembly stations and lines is highly demanded so that: quality levels are increased in terms of precision and repeatability, throughput time is reduced in assembly stations, traceability of the performed operations is enabled and also the ergonomic stress of the operators is reduced.

Industrial automation systems for assembly operations have to integrate the required human capabilities having the characteristics of robotic automation such as strength, velocity, predictability, repeatability and precision. Additionally, the introduction of robots to support assembly operators reduces the need for physical strength, especially in the cases of large part assembly such as in the capital goods industry. Therefore, it is possible for older people to continue working inside the production facility, having to undertake mostly the cognitive tasks (coordination, troubleshooting etc.).

The advantages of industrial robots within the European production plants, are not exploited in their full potential. Currently, there are about 2.3 million industrial manufacturing SMEs in the EU representing about 99% of all companies [3].
Surveys by the European Business Test Panel (EBTP), across 90 European companies, have identified the poor acceptance of robots within small and medium sized firms (60% of the companies employed less than 50 employees, 22% employed from 50 to 250 and only 18% had 500 or more employees). The vast majority of these companies (61%) use 1 to 10 robots, and only 32% uses between 11 to 50 robots [4].

The main reasons that companies do not use robots yet are estimated by the International Federation of Robotics (IFR) (www.ifr.org) and involve challenges of adopting new technologies. Moreover, especially in cases that the manufacturing/assembly process cannot be completely automated, the lack in advanced safety systems for the supervision of human robot workspace sharing and cooperation, has restricted the assignment of the task only to human resources.

The ROBO-PARTNER promotes a hybrid solution, involving the safe cooperation of human operators with autonomous and self-learning/adapting robotic systems, through a user-friendly interaction. The synergy effect of the robot’s precision, repeatability and strength with the human’s intelligence and flexibility will be much greater, especially in the case of small scale production, where re-configurability and adaptability are of great importance.

2. Assembly paradigm and motivation

This chapter is dedicated to presenting the main research areas that ROBO-PARTNER is investigating for the integration of humans and robots into a common working environment.

2.1. Human Robot Interaction and safety

The ROBO-PARTNER intends to enable the cooperation of humans and robots, during the execution of the assembly task, at different cooperation levels. Figure 1, shows three cooperation cases that are examined within the project. The first one involves the concurrent execution of different assembly tasks by the robot and the human, while sharing a common workspace. No fences or other physical safety devices need to be present since the robot is always aware of the human presence by utilizing a plethora of force/vision/presence sensors. This enables it to implement a safety-first behavior. In the second level, the cooperation is mainly carried out at the cognitive level since the mobile robot can provide the operator with the correct assembly parts, thus reducing the time to identify and retrieve them from areas far from the assembled product. The final level of cooperation is the execution of the same assembly task by the robot and the human being in direct physical interaction. This approach enables the combination of human skills, such as perception and dexterity with robot strength, accuracy and repeatability in order for the same task to be efficiently performed. The robot’s involvement also permits the automated quality check through the robot sensors.

In order for the direct human-robot cooperation concept to be realized, the focus is on implementing control algorithms and multi modal interfaces for the regulation of the part’s movement by both operator and robot [5]. For example, the operator is capable of moving the robot TCP (tool center point) bare-handedly, by exploiting the force sensors and standardized voice commands or gestures in order to perform any additional functionality (Figure 2). At the same time, the robot carries the part’s payload and through virtual windows ensures the collision free path. In order for Human-Robot Cooperation (HRC) to be achieved, advanced sensorial networks, capable of efficiently fusing the acquired data under the real time process control algorithms, are required. Following this direction, intelligent multimodal interfaces (different physical background) enhanced with new sensorial capabilities, need to be integrated with the use of tactile/
force sensors, microphones, cameras etc. designed for withstanding the hard industrial environment (e.g. dust, extra lighting, noise etc.).

2.2. Safety

Since industrial robots are normally large, move fast and carry heavy or blunt parts, their collision with a human being may cause severe injuries. Current manufacturing practices require complete physical separation between people and active industrial robots (typically achieved using fences or similar physical barriers) as a precaution to ensuring safety. Given the safety issues that arise from the coexistence of robots and humans, the means of detecting/monitoring the human presence and adjusting the robots’ behavior, need to be researched. Currently, several industrial solutions can be used to offer some sort of fenceless operation (e.g. the SafetyEye camera system [6]); however, a lot more are in an embryonic stage and not close to industrial application [7],[8].

New approaches for ensuring the safety of people, found in close proximity to robots, in an industrial workcell, involve the automatic adjustment of the robot speed to the detection of humans in there as well as ways of adjusting to the trajectory in real time. Novel approaches for generating alternative robot paths, by considering environmental constraints, such as the ones proposed by [10],[11] need to be introduced for supporting engineers in designing safe processes. The main challenge remains the conformance and certification against the EU legislation and standards (e.g. ISO, DIN etc.).

The trends nowadays are towards providing a fenceless intrinsic safety system, by considering the robots’ dynamic power, static force, speed etc., as well as the human’s reflex actions. Protective safety levels may be ensured through the use of redundant sensors including cameras, ultrasonic or laser range sensors, thermal imaging devices, capacitive or conductive robot skins etc. The most important aspects to be addressed involve:

- crash safety: by avoiding collisions among obstacles, robots, or humans in the fenceless system and in real time
- active safety: by using two levels of safety proximity sensors (consisting mainly of vision systems) and contact sensors (force/pressure/ contact detectors etc.)

2.3. Human robot cooperative tasks planner

Under this research area, the scientific focus is given to the derivation of robust methods for determining an efficient planning of assembly/disassembly operations, by utilizing, to the highest possible extent, the capabilities of both humans and robots.

Towards this direction, planning tools such as the one in Figure 3, need to encompass the following functionalities:

- Efficient consideration of the product structure and the assembly specifications for the extraction of assembly tasks and the related requirements (physical strength, accuracy, dexterity etc.).
- Planning of the assembly processes and the assignment of tasks to the most suitable human/robot entities.
- Exploitation of the human and robot simulation for evaluation of the ergonomics and feasibility of the assignments, in a structured and semi/fully automated way. The challenge is to automatically generate and evaluate the numerous possible combinations of human and robot collaboration scenarios.
- Evaluation of task assignments against user criteria (e.g. operator and resource utilization, matching of operators’ skills to task requirements etc.) by using proven decision making methods. This will ensure that the process be executed in an efficient time and that the skills of each entity be efficiently exploited.
- Further exploitation of the planning/simulation results in supporting the operators through the integration of the latest technologies, such as Augmented Reality. An example would involve the operator helping a robot to move a part, among obstacles, in the 3D space. The 3D models from the simulation can be used at this time to superimpose the final position of the part on the assembly so that the operator can visualize and confirm its correct
position, where he will guide the robot. Finally, the potential dangers and dangerous areas, due to the invisible robot paths, can be visualized by the human operator via the AR equipment, as shown in the Figure 3.

![Fig. 3. Augmented-Reality – assisted safety](image)

2.4. Innovative robot programming

In order for further adoption of the robotic technologies, by small companies to be achieved, significant efforts need to be undertaken in reducing the time and simplifying the robot’s programming. A promising direction is development of user friendly intuitive robot instruction libraries that would allow for fast and effortless alterations in the robot’s programs, during the assembly. These libraries need to include common robot programming instructions (pick, move, place, copy etc.). Intelligent algorithms can be used to combine these routines in order for the programming of the desired task to be achieved.

![Fig. 4. Intuitive robot instruction libraries and multimodal interfaces](image)

Furthermore, the improvement of programming by demonstrational (PhD) techniques involving: a) the use of voice to dictate commands the robot, b) the use of visual programming techniques such as vision based posture/motion recognition systems [8] and c) robot arm manipulation by the user via force/tactile sensors [9]. Up to now, defining the robot’s accurate poses or frames through advanced interfaces (such as using mobile phones or gestures), has not reached yet the appropriate maturity in industrial use. Furthermore, the human unpredictability as well as the behavior of several individuals needs to be considered in order for these programming methods to be made more robust.

Emphasis should be given to the area of providing on site, a user friendly software for the robot path planning and control in order for aspects such as programmability, autonomy and adaptability, reactivity and consistent behaviour to be satisfied for the guidance of the human reactions and robustness [12].

2.5. Mobile unit for smart logistics and operator support

Apart from the actual assembly process itself, the human operators need to be supported in reducing or efficiently undertaking non value adding activities. In this direction, the ROBO-PARTNER project aims at the introduction of mobile units and/or mobile manipulators that act as assistants to the operators during the assembly. The objective is to enable autonomous resources that can provide the operator with the correct parts/tools, at the right place (Figure 5).

![Fig. 5. Human operator assistance by mobile units](image)

The pursued benefits involve:
- Reduction of physical strain by providing the parts at a comfortable posture and
- Reduction of cognitive load by providing the correct parts thus, relieving the operator from the task of having to consult the product documentation, identify and retrieve the correct part from the storage area.

This type of support minimizes or even eliminates the human errors that are related to the variability and complexity of the parts, as well as the fatigue accumulation effects [13]. Moreover, the use of mobile units with onboard sensors will assist in implementing smart logistics processes by allowing the automated part tracking and inventory reporting and replenishing at the shop floor.

In this context, the mobile robots will need to exhibit a large set of functionalities for their behaving in an intelligent way. For instance, the robot will have to navigate in the shop floor, avoid obstacles/ humans and ensure human safety, by finding the path towards the station and the worker that needs to be served, while respecting the required production cycle time etc. In the context of the ROBO-PARTNER, these characteristics are researched in two robot categories. On the one hand, a typical mobile platform is customized in order to serve human operators in an assembly line and on the other hand, an overhead robot with high payload, aims is set out to follow a human in an intelligent and safe way, by avoiding obstacles, in order to fulfill a part handling task.
2.6. Integration and communication architecture

The successful implementation of the aforementioned technologies is strongly dependent on the development of a robust backbone system that will allow the easier integration, networking and control of the resources using agent based, web and ontology services. The expected result, in terms of communication, lays in the distribution of these acquired data to every relevant resource (e.g. robot, machine, human workforce via multi-modal interfaces etc.). The advantages concern the robustness, flexibility, autonomous behaviour and openness of this architecture in case of failure.

The ROBO-PARTNER’s intention is to avoid the “hard” program and conventional integration ways that are offered in an industrial environment, such as LANs oriented to specific industrial requirements (e.g. capable of supporting real time control) and applications based on PLC programming. These ways of integration and communication are stiff and require a lot of time and changes when alterations in the production process are required. Ontologies are regarded as the means of solving interoperability issues [14] within decentralized production systems, which are becoming more knowledge intensive. Under this scope, the main challenges are to:

- prove that the Service / Agent Oriented Architectures are now mature enough to be widely applied. Indicative examples are the works in [15] and [16], where such architectures have been investigated into so as to deal with operational assignments to mobile and stationary resources.
- develop an open architecture that supports the connectivity of technologies such as industrial PCs connected with widespread industrial networks (e.g. Industrial ETHERNET) that follow a number of criteria (e.g. support real time control, high data integrity, high reliability in harsh environments, high noise immunity etc.) in terms of service/agent orientation.
- Enable the performance of changes on the configuration of a production line, while enabling the automated setup of newly inserted resources via the use of software services.
- develop and exploit manufacturing ontologies that can handle processes such as knowledge capturing, analysis and classification and use them in order to guide the decision making at different levels.
- use open source operating systems, which enable the introduction of standard software modules connected via standard signal interfaces and programming [17]. Indicative examples are the ROS (Robot Operating System) (http://www.ros.org), and the Open Robot Control Software (OROCOS) (http://www.orocos.org/).

The expected benefits of using such architectures involve:

- minimization of the use of complex programming methods for integrating and networking purposes (e.g. PLCs)
- elimination of or drastic reduction in the existing centralized decision making with fixed control logic
- reduction in the time required for supporting the addition of resources to the networking, without calling for high efforts and workforce expertise
- reduction in the high configuration costs, by not requiring specific devices and accompanying software packages.

3. Case study

In this section, a preliminary evaluation of the technologies discussed, is attempted through a simulated case study, stemming from the automotive industry. The case involves the loading and assembly of the rear axle of a passenger vehicle with the rear wheel group. The latter consists of the drum/disk brakes and the pipes for its actuation. In the current production, the process is carried out manually. The operator uses a balancer to load and position the axle to a fixture (Figure 7) and then loads each wheel group that weighs more than 12kgs. He loads the required screws to a screwdriver and by holding the wheel group in one hand and the screwdriver in the other, he performs the assembly. Once the wheel group has been assembled, he proceeds to install the pipes and cables. The process is repeated for the second wheel group.

Considering the wheel groups weight and the frequency of operations (cycle time is less than two minutes) the ergonomic implications are very important. Moreover, there are four different axle variants in the same line that require similar but yet different operations and follow a random sequence. Therefore, the probability of quality problems being created is not negligible.
Next, the hybrid assembly paradigm that was described above has been applied to the redesign of the cell as shown in Figure 8. A high payload robot is used to support the human by performing the loading of the axles and the rear wheel groups. Axle loading is carried out solely by the robot, while the wheel group assembly requires the cooperation between the robot that handles the weight and the human, who uses his hands to directly adjust the position of the parts (Figure 8).

The heaviest part that the operator lifts in this scenario is that of the screwdriver (1.5kg). While the human performs delicate tasks (cable assembly), the robot continues to bring the second wheel group, by avoiding any collision with the human. At any time, the operator can guide the robot through gestures or audio commands.

The simulation experiments have revealed potential and significant savings in terms of operator efforts, cycle time and process quality. Table 1, summarizes the main key performance indicators that were used for the evaluation.

<table>
<thead>
<tr>
<th>Table 1. Comparison between current state and ROBO-PARTNER system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current state</td>
</tr>
<tr>
<td>No of Tasks allocated to human</td>
</tr>
<tr>
<td>No of Tasks allocated to Robot</td>
</tr>
<tr>
<td>Max weight handled by human (kg)</td>
</tr>
<tr>
<td>Human working time in cycle (sec)</td>
</tr>
<tr>
<td>Robot working time in cycle (sec)</td>
</tr>
<tr>
<td>Total Cycle time (sec)</td>
</tr>
</tbody>
</table>

4. Conclusions and future work

This paper has presented the envisaged hybrid production paradigm that is pursued by the EU project ROBO-PARTNER. The required software and hardware technologies have been outlined along with the potential benefits by their adoption. The preliminary evaluation has indicated significant savings in terms of productivity (17% cycle time reduction) and operator’s working conditions (25% less tasks, less physical demand).

Future work is aimed mainly at bringing the majority of the aforementioned technologies to a readiness level that would allow their introduction to normal production conditions. Enormous work is required for the accomplishment of safety certification for multi modal interfaces and mobile assistant robots. The development of the supporting architecture is another challenge due to previous approaches lacking in such a wide application range. The evaluation of the cost effectiveness in applying such technologies is also a pending task.

Acknowledgements

This research has been supported by the research project “ROBO-PARTNER – Seamless Human-Robot Cooperation for Intelligent, Flexible and Safe Operations in the Assembly Factories of the Future” (Grant Agreement: 608855) funded by the European Commission (www.robo-partner.eu).

References