International Journal of Computer Integrated Manufacturing

ISSN: 0951-192X (Print) 1362-3052 (Online) Journal homepage: https://www.tandfonline.com/loi/tcim20

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To cite this article: Panagiota Tsarouchi, Alexandros-Stereos Matthaiakis, Sotiris Makris & George Chryssolouris (2017) On a human-robot collaboration in an assembly cell, International Journal of Computer Integrated Manufacturing, 30:6, 580-589, DOI: 10.1080/0951192X.2016.1187297

To link to this article: https://doi.org/10.1080/0951192X.2016.1187297

International Journal of Computer Integrated Manufacturing, 2017
Vol. 30, No. 6, 580–589, http://dx.doi.org/10.1080/0951192X.2016.1187297

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On a human-robot collaboration in an assembly cell

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(*Received 10 October 2014; accepted 15 April 2016*)

This is a study of a Human-Robot Collaboration (HRC) framework for the execution of collaborative tasks in hybrid assembly cells. Robots and humans coexist in the same cell and share tasks according to their capabilities. An intelligent decision-making method that allows human-robot task allocation is proposed and is integrated within a Robot Operating System (ROS) framework. The proposed method enables the allocation of sequential tasks assigned to a robot and a human in separate workspaces. The focus is rather given to the human–robot coexistence for the execution of sequential tasks, in order for the automation level in manual or even hybrid assembly lines to be increased. Body gestures are the means of a human's interaction with a robot for commanding and guiding reasons. The proposed framework is implemented into a case coming from the manual assembly lines of an automotive industry. A preliminary design of a hybrid assembly cell is presented, focusing on the assembly of a hydraulic pump by robots and humans.

Keywords: assembly cell systems; human–computer interaction; resource planning; robot scheduling

1. Introduction

Hybrid assembly lines keep up with the industrial needs for advanced production solutions, enhanced product quality, production flexibility, cost reduction and ergonomics improvement (Krüger, Lien, and Verl 2009). There are multiple operations in the manual processes that require more flexibility and robustness (Hermawati et al. 2015; Makris et al. 2014; Tsarouchi et al. 2014). Despite the fact that industrial robots are used in a wide variety of production lines, there are not considered mature enough to be in close collaboration with the humans. This keeps up with the fact that the human capabilities cannot be fully replaced by those of the robots; however, it is possible for a solution to be achieved by combining the capabilities of both sides. Last but not least, the unconstrained conditions in production lines, including variable lighting conditions, the crossing workers and the autonomous mobile units, such as the automated guided vehicles, are some important reasons that provoke the collaboration in complex assembly cells.

In this research work, there is a Human-Robot Collaboration (HRC) framework proposed, allowing sequential human and robot tasks execution. It belongs to the shared tasks and workspace in terms of human–robot interaction (HRI), when the tasks of human and robot resources are sequential. The proposed method focuses on the task allocation between multiple human and robot resources that constitute a hybrid assembly cell. An intelligent decision-making algorithm is the basis for the tasks allocation, through the evaluation of multiple criteria such as mean flowtime. An analysis about the decision steps in task allocation includes the resources suitability, availability and processing time. The interaction between a human and a robot is achieved through a depth sensor and the gesture handler software tool. The software implements a task scheduling generation, the human–robot (HR) tasks execution and the interaction between them. The individual elements of the cell are the two robots, the depth sensor and the human. A number of ROS nodes have been developed aiming to implement the functionalities of every module and achieve their communication over a ROS-based architecture. The main contribution of this paper compared to existing research is summarised as follows.

- HR collaborative tasks are modelled in the form of an hierarchical analysis. The human and robot resources are classified into hierarchy also in the same model.
- An intelligent decision-making method for HR task allocation and planning is also proposed, upon the capabilities of both humans and robots.
- Further to similar previous work, a set of criteria with unique definition are applied for the alternative assignments evaluation. It is worth mentioning more natural ways of interaction are used than allow switching from human to robot tasks and vice versa, via a number of gestures.

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- The proposed method is integrated in a modular framework where the individual software modules are able to communicate with each other through the exchange of ROS messages. This modularity enables the extensibility of the modules' functionalities for the future.

The structure of the paper is organised as follows. A short literature research is presented in Section 2, while Section 3 presents the HR task allocation method and the criteria for the generation of alternative schedules between the resources. Section 4, describes the ROS-based communication architecture. Section 5, focuses on the HRC tasks execution, by commanding/guiding the robot to execute a task through body gestures. The automotive industry case study follows in Section 6. Section 7 focuses on the results and conclusions.

2. Related work

HRI for collaborative task execution and scheduling aims to improve the efficiency of manufacturing and assembly processes, in order for high levels of adaptability and robustness to be achieved in the cell (Wilcox and Shah 2012). In addition, a safe and flexible cooperation between a robot and a human, in a hybrid assembly cell, may lead to better productivity. The requirements of the hybrid assembly lines are related to guarantees for the synchronisation and timing of the tasks, therefore, a centralised controller should schedule all agents participating in a cell (Wilcox and Shah 2012).

HRI is classified into four main categories. The coexistence of a human and a robot composes the hybrid cells classified into the shared tasks and workspace, the common task and workspace and the common tasks and separate workspace (Mayer et al. 2014). In the case of 'shared tasks and workspace', the tasks and workspaces of the human and robot resources are sequential and are shared accordingly. There are numerous research studies concerning HRI for assembly and manufacturing cells.

Project Jahir (Joint-Action for Humans and Industrial Robots, 2015, URL:http://www6.in.tum.de/Main/ResearchJahir) aims at introducing HRI to the assembly of products with great complexity, focusing on the cognitive knowledge of tasks, thus rendering robots equal to human partners. The efficient cooperation concepts, studied in this project, rely on the common understanding of tasks and the perception among robots and humans that interact via soft and virtual buttons. A hybrid assembly cell, as described in Wallhoff et al. (2010) and in Wilcox and Shah (2012) comprises an industrial robot that can learn new tasks from a human and execute them in a shared workspace. Multiple sensors are used for the monitoring of the area and the detection of objects and humans, where multimodal channels are offered for communication purposes (speech, gaze, haptic).The reason for the use of multimodal devices was to help the operator understand and execute his tasks in the assembly line.

So far, there have been several research efforts on HR task planning. Task allocation issues between humans and robots are examined in Chen et al. (2011), where the evaluation and the alternatives generation were based on 'Dual GSPN model' (stochastic petri net). The proposed assembly strategy was based on the calculation of the time cost and payment before the allocation of a task. A decision-making algorithm, integrated into a planner to assist in the HR task allocation was described in Agostini, Torras, and Wörgötter (2011).

A human aware task planner (HATP) under the CHRIS EU project generates alternative plans for robots, even in the case where the interaction tasks are included (Montreuil 2007; Alili et al. 2009). Kwon and Il Hong (2014) present a study that is based on the prediction of behaviours for HR cooperative tasks in a probabilistic way. An approach based on semantic maps was described in Galindo et al. (2008) and has been evaluated in the case of HRI and robot task planning. This approach was focused on improving the use of generic knowledge and on making agents more autonomous. Additionally, Wallhoff et al. (2010) present a hybrid assembly cell, where a human worker is able to teach an industrial robot new tasks to be executed simultaneously, in a shared workspace. A decisional framework of the HRI task achievement is presented in Alami, Clodic, and Montreuil (2006), where the human is aware of the task execution (EU Project Cogniron: Cognitive Robot Companion, http://www.cogniron.org/). Finally, a method of human and robot task allocation in hybrid assembly cells was presented in Takata and Hirano (2011), using as criteria the minimal production changes in order for the production costs to be minimised.

The cognitive HRI is a keyword that describes the factory of the future (Zaeh et al. 2009), where human capabilities, such as perception, adaptability, ability to solve complex problems and the robots' advantages, namely repeatability and accuracy, are perfectly combined into a hybrid assembly cell. Additionally, the cooperation between human operators and robots, as well as the social interaction are new concepts, as the anthropomorphism of robots increases (Moniz 2013, Mayer et al. 2014). Furthermore, the human and robot communication is described in Gleeson et al. (2013) and is based on analysing the ways that operators behave and collaborate in assembly lines. This study focused on gestures as being a natural way of interaction. Additionally, gestures have also been considered in the case of a robot's programming, where abundant research have been done (Waldherr, Romero, and Thrun 2000; Chang et al. 2006; Neto and Pires 2009; Neto, Pires, and Moreira 2010; Bodiroža, Stern, and Edan 2012; Neto et al. 2013; Makris et al. 2014; Saphari project: http://www.saphari.eu/).

3. Human-robot task allocation method

HR task allocation and planning are achieved through a decision-making algorithm that is based on the evaluation of multiple criteria, as described in Chryssolouris and Subramaniam (2001), Chryssolouris (2006). An hierarchical model for representing the human and robot tasks, as well as the available human and robot resources is used, as described in Makris et al. (2014).The hierarchy of an assembly line is broken down into related workcentres, each one comprising a number of resources. In this structure, a workload consists of jobs and is undertaken by the assembly line. Each job consists of tasks related to the station. The tasks are assigned to the suitable resources. Additionally, there are earlier and later conditions defined to each task. A graphical example of the workload and the resources' structure is illustrated in Figure 1.

In this method, a HR task allocation is achieved through a set of decision and the evaluation of multiple criteria. A set of decision steps has been considered that allows for the determination of the efficiency of the specific task assigned to a resource. These decision steps are summarised as follows:

- **Resource suitability**. This metric is used in order to be ensured that a resource is suitable for the execution of a task. For example, it takes into account the payload capabilities of the resources before the decision on the tasks' assignment.
- **Resource availability**. This metric is used in order to be identified if a resource is available for the execution of a task.
- **Operation time**. This is the time that a resource needs to execute a task. In this direction, a task will be assigned to the resource with minimum operation time.

An example of task allocation in the case of human and robots tasks is visualised in Figure 2. In this example, a task that is finally assigned to a human has been considered. Upon the need for the generation of a set of task assignments via a message, the suspended human and robot resources are checked according to the above decision steps. The first step to be decided is the availability of the resources being in the station. Given the resources'

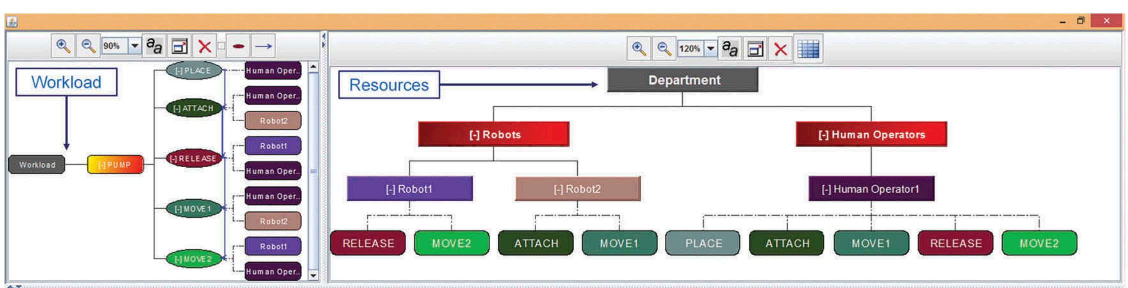

Figure 1. HR hierarchical model – Workflow and Resources classification.

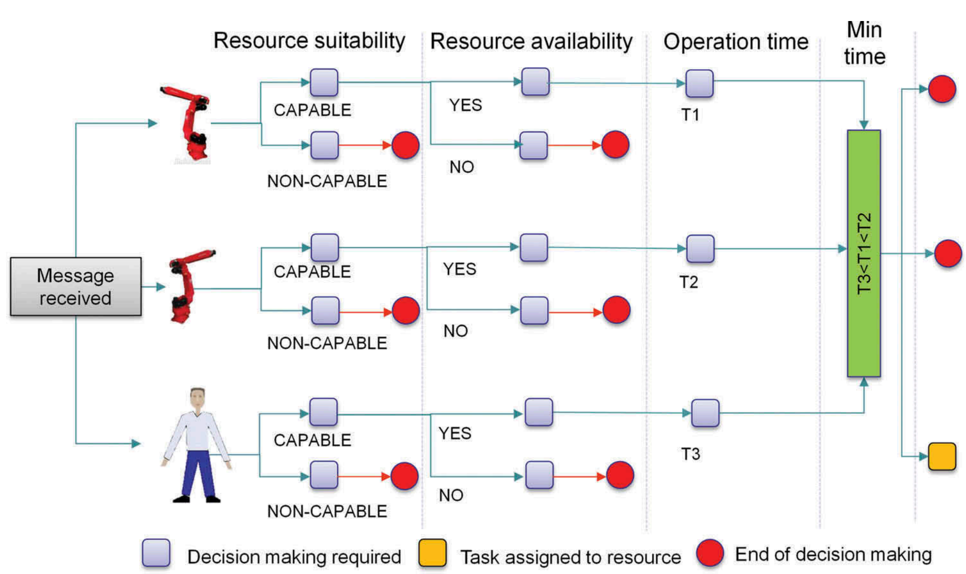

Figure 2. Visualisation of the human and robots consideration in the task allocation.

availability, the decision steps continue with the suitability of the resources in terms of their being capable of executing a task. The last step includes the consideration of the operation time. The human operator has the minimum operation time in this example and the task is assigned to a human, that is the suitable resource. In case that the two resources have the same minimum operation time, a task can be assigned to both of them. The scheduling of the tasks will be based on intelligent decision-making algorithm for the efficient exploration of the tree branches and the evaluation of multiple criteria.

An intelligent scheduling algorithm on the basis of the depth search concept follows the previous steps in order for a schedule between the allocated tasks, based on multiple criteria evaluation. This algorithm is described in Michalos et al. (2015), where the main control parameters used are the decision horizon (DH), the sampling rate (SR) and the maximum number of alternatives (MNA). Some performance measures used in scheduling problems are based on the completion times, such as mean flowtime and on utilisation costs (Chryssolouris 2006). The following criteria are used for the selection of a good quality alternative to be distinguished from another one of poor quality:

- **Average resource utilisation (ARU)**: The percentage of time (%) defined as the ratio of the resource's busy time, over the total time, required for the production of all orders in the system (Michalos et al. 2015). It is numerically calculated by the following equation:

$$ARU = \sum_{i=1}^{r} \frac{RU_i}{r}. \quad (1)$$

  where
  - RU_i is the resource utilisation
  - r is the total number of resources in the system
- **Mean flowtime** ($\overline{F}$): It is the average time that a number of jobs spend in a workcentre. Minimising $\overline{F}$ implies that a schedule's cost is directly related to the average time it takes for the production of a single job. The results remain the same provided that the mean completion time is minimised. The flowtime (F_i) is defined as the time spent by each job in a workcentre according to Chryssolouris (2006). It is estimated as follows:

$$F_i = t_i^{comp} - r_i = \sum_{k=1}^{m} \left(t_{ik}^{wait} + t_{ij(k)}^{proc} \right). \quad (2)$$

where:

- t_i^{comp} is the completion time of a job
- r_i is the arrival time of job i into the system
- t_{ik}^{wait} is the waiting time of job i after the end of (k–1)th operation and before the start of its k^{th} operation
- $t_{ij(k)}^{proc}$ is the processing time of the k^{th} task of job.

Given the above criteria, the next step is the selection of a good alternative via a matrix that constraints the different design alternatives, based on the values of these criteria. The ultimate decision requires a normalisation of these values that should be minimised or maximised. The selection of a resource combines the total score of the utility factor or each alternative, taking into account each criterion weighted factor. The steps overview of the proposed method and the respective functionalities are illustrated in Figure 3. The H52 task allocation tool is integrated into the communication architecture presented in the next section, as a *Scheduler Service*.

4. Framework architecture

The communication architecture implemented in this collaborative framework is based on the representation of each resource as a service and the exchange of messages between them. The proposed architecture is service oriented and allows interaction between the services that run independently but are roughly coupled. The utility of such an architecture schema in robotics increases reconfigurability, as well as enables the extensibility of the system. In this way, the same architecture can be used in different robot platforms, while new services can be easily added. The architecture overview is illustrated in Figure 4. These services are loosely coupled with each other and are namely R1...RN *Robot Services*, a *Human* and a *Scheduler service*.

The proposed architecture is based on the ROS platform and allowed the communication between different modules and services under the same infrastructure. Additionally, the integration of multiple services is easier through ROS, without the need for considerable changes, if a new module/service is added. In this study, the framework architecture supports the integration of the scheduling tool which allocates and schedules tasks for the existing resources that are represented through a service module, such as *R1 Service, RN Service* etc. The scheduling results are automatically stored into the database through the *Scheduler Service* and then each service can access the assigned task.

The implementation of each resource in the form of a service/ROS node enables the coexistence of multiple different services and the successful sequence of the tasks' execution. In more detail, each *Robot Service* undertakes the control of its own gripper. Each robot service interface is implemented into an external Linux PC as a ROS node, being responsible for the execution of all

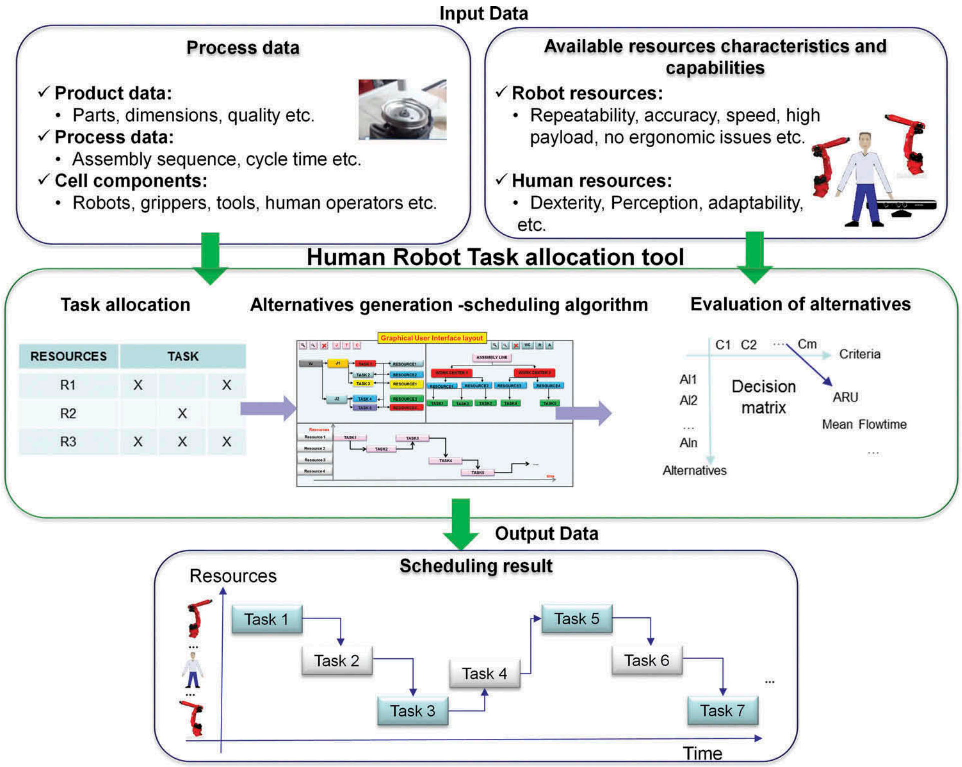

Figure 3. Human-robot task allocation method overview.

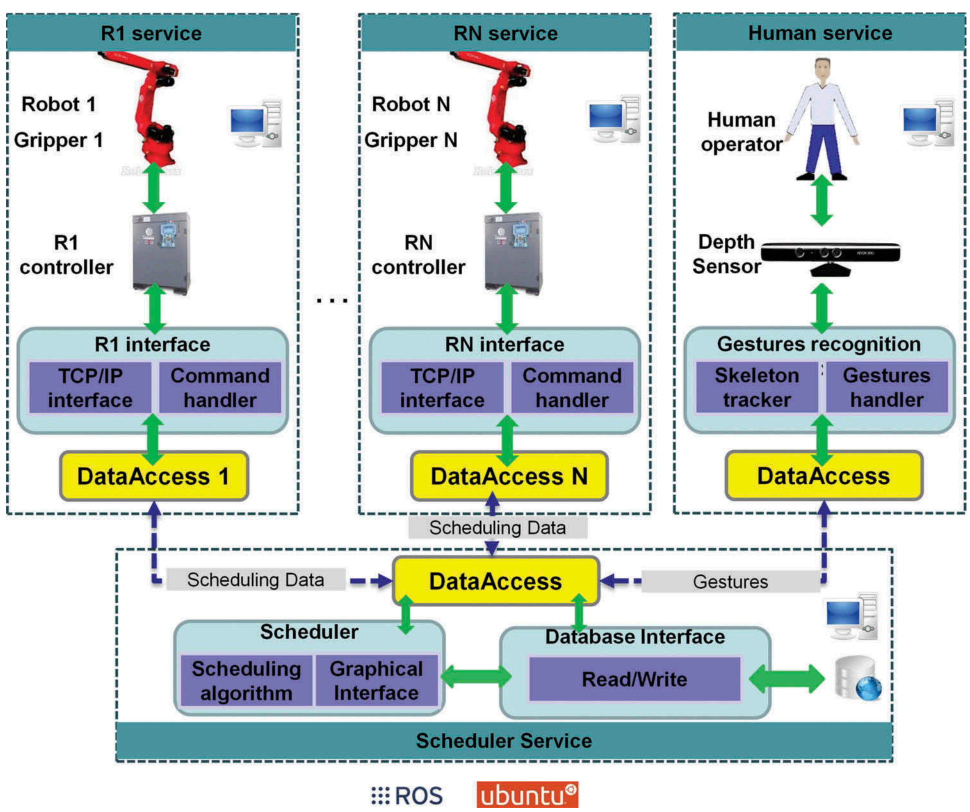

Figure 4. Overall framework architecture for HRC.

possible actions supported by the robot. A typical example is to decode the task received in commands in the form of the robot language, in order to be sent to the robot controller for execution, via TCP/IP connection. Each of the services has a 'communication channel', through which ROS messages are exchanged with the other services, as well as the task scheduling data and the robot motions/actions. In the aforementioned architecture, this 'communication channel' is called *DataAccess* and each service runs internally as a function that allows the communication between services.

In this architecture schema, the *Human Service* is connected to the commanding/guiding functionalities and implements the gestures recognition module. The latter takes data from a depth sensor, which is capable of recognising body gestures via a skeleton tracker application. Based on the definition of the recognised gestures semantics, the gestures are transferred through ROS messages to the other services. The role of the human service is to send ROS messages through the *Human Service DataAccess* to the *Robot Services* and the *Scheduler Service* concerning the task execution.

The *Scheduler Service* in this architecture enables the *Robot Services* to read and write data through a read/write interface, apart from running the scheduling algorithm. The communication between two or more services is executed through their *DataAccess*, based on the exchange of ROS messages. The *Robot Services* after the task allocation and scheduling can read the task, which is to be executed, via the *Scheduler Service DataAccess*. The ROS messages exchanged can be visible from all the services including the Start Task, the Finished Task and the Next Task message all of which ensure the sequential task execution.

5. Human-robot collaborative tasks execution

The HR collaborative task execution in terms of communication between humans and robots is managed through the interaction modules. Such modules include the body motion capturing and the gestures recognition that allows for a natural way of interaction and the commanding of a robot via low-cost depth sensors.

The design of the HRC concept takes into account the user-friendly character of gestures and the safety of both humans and robots by defining separate workspaces. The user friendly character is related to the selection of gestures that can be easily used by human operators, without special training and skills. The safety in the collaboration area is another important factor that is managed in this study only by using the START and STOP gestures. This way is not a certified approach, but the safety aspects are out of this paper scope. Among the selected gestures, there are two simple gestures that trigger two separate actions. The START gestures triggers the start of a human or a robot task and the STOP gesture trippers the stop of a robot task. These gestures correspond to three different functions in the gestures' dictionary.

The implementation of the 'STOP' function, being the most important among them, is implemented with raising the right hand. On the other hand, the 'START' function is defined by a relative unusual gesture. The function that implements 'START', checks when the two joints of the operator's arms are crossed. This will prevent any accidental gesture recognition or motion recognition by humans crossing the shop floor. In addition, when a human task starts, a START and a STOP signal are sequentially sent to the robot, in order to ensure that it remains with the motor drivers' off-line, while the human enters the robot's workspace. In any other case, even if the operators are recognised by the depth sensor, the robot remains with the motor drivers switched off. The proposed idea concerning safety during execution does not include any certified safety sensors and is mainly adopted in this framework for simplicity reasons.

In a similar way, a number of gestures for commanding/guiding the robot during a task execution have been implemented. These gestures enable the user to guide the robot according to the understanding of the human position. Thus, the user may guide the robot Left, Right, Up, Down, Back and Front according to his body pose. The *Human Service* implements a 'gestures' vocabulary that is available for interaction in the module illustrated in Figure 5. The visualisation of gestures was based on the skeleton tracker application. The system was implemented in Linux under ROS Groovy version, using OpenNI drivers.

6. Automotive industry case study

6.1. System implementation

The system layout is illustrated in Figure 6. Two SmartSix Comau Robots are included in the setup, while a depth sensor is placed on the right side of this area, being referred to as the HRC area. This sensor is used for body gestures recognition for the task execution, as explained in Section 4. The working table is placed in front of the two robots, in the middle of their bases, including the components that should be assembled. These components are namely the hydraulic pump, the pump carrier and the pump pulley. The decision-making algorithm has assigned the five tasks of the assembly sequence to the suitable human and robot resources, based on the three criteria that were selected.

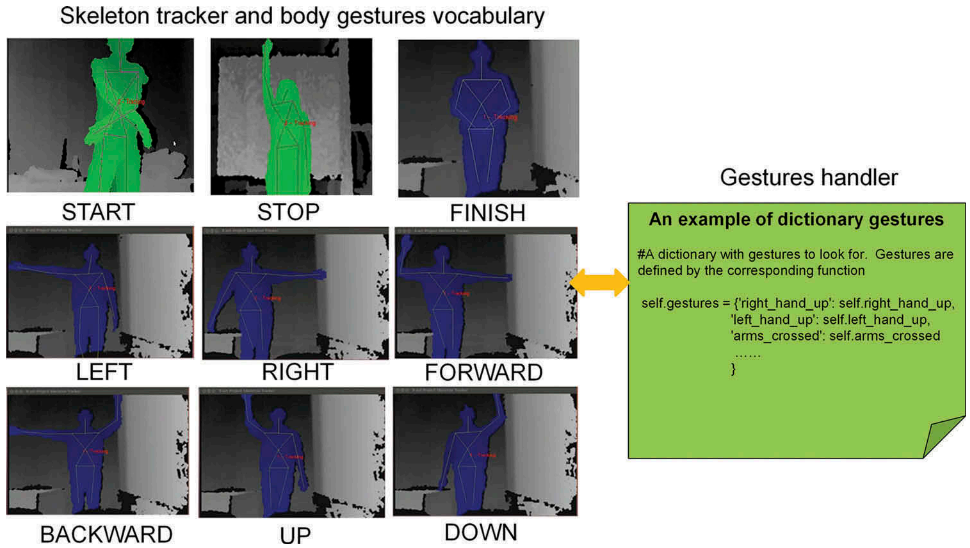

Figure 5. Gestures recognition using Kinect and skeleton tracker application (pi_tracker: http://www.ros.org/wiki/pi_tracker).

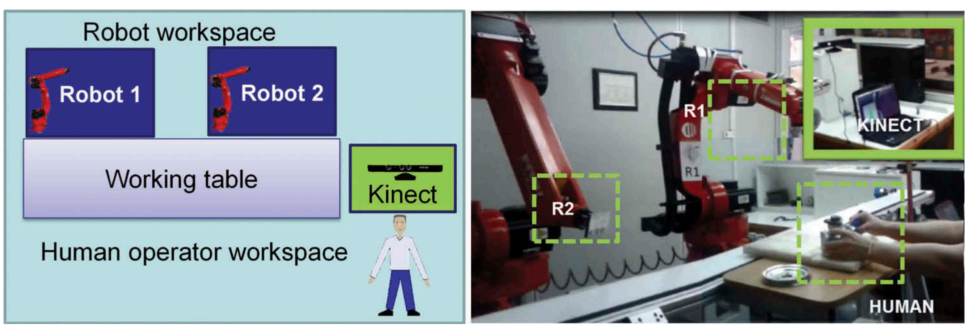

Figure 6. HRC cell layout.

6.2. *Case study description*

The first task in this sequence is assigned to a human and includes the placement of the hydraulic pump, as well as the pump carrier on top of it, after the time required by a human to reach the working table. The human starts the collaborative task execution sending a START command, which is decoded from the robot side into the start of the human task. Before entering the assembly cell, a second gesture is sent to the robot, in order to ensure that it will remain disabled, while the human is entering the assembly cell. When the human task has been completed, the human operator returns to the HRC area and signals the end of the task. In this case, the robot is allowed to continue with the pending tasks. Since a STOP gesture is sent to the robot, all robot motions are cancelled and a new gesture command is expected in order to deal with the next task.

During the next task, Robot 2 is assigned to place the pump pulley. In this task, the robot to robot cooperation is enabled. It includes the placement of a pump pulley using Robot 1, with the help of Robot 2. After the collaborative task of both robots end, they return to their home position. The visualisation of the above tasks is presented in Figure 7.

This case study has been implemented in the proposed framework architecture. The sequence of the five tasks selected was scheduled by the intelligent decision-making algorithm and the results have been stored into the database through the *Scheduler Service*. Both *Robot Services* have access to the scheduling data, through the *Scheduler Service*. When the data are retrieved, each robot controller receives a message. The messages are decoded into the standard PDL2 program that plays the role of the server and the robot moves or acts based on these results.

7. Results and conclusions

The proposed method for HRC in an assembly cell enables the introduction of a HR task model in a unified structure. The intelligent decision-making algorithm allows human to robot and robot to robot task allocation and cooperation in the same workspace. The alternative

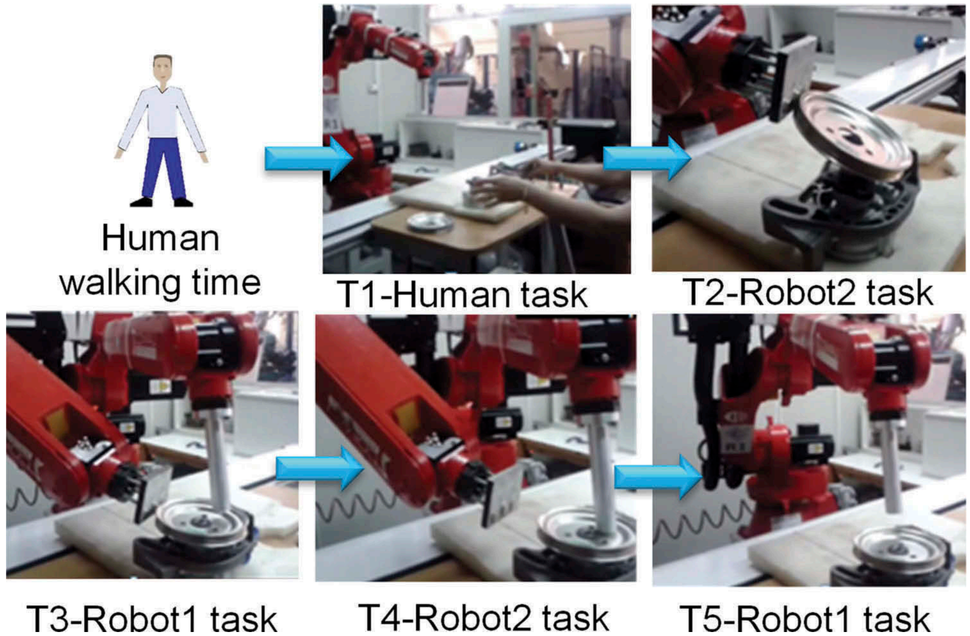

Figure 7. Assembly sequence of hydraulic pump.

schedules are automatically generated and evaluated using multiple criteria.

The proposed ROS-based architecture for HR task execution has also numerous advantages for the HR collaborative assembly cells. The service entities enable the easier implementation of different modules, which are being represented by a service structure. This structure provides the capability of supporting a number of actions apart from the communication with other services via ROS messages. In this way, it is easier to manage and extend systems that are based on this kind of architectures.

The human and robot tasks are accessed through the related resources and the use of *rosservice* calls (URL: http://www.ros.org/) in the *Scheduler Service*. The graphical representation of three alternative schedules is illustrated in Figure 8. The first alternative represents the final selection of the schedule, where the mean flowtime is estimated at 69.2 seconds. The second alternative has mean flowtime increased by 0.6 seconds. Finally, in the third alternative, four of the tasks are assigned to a human operator and the mean flowtime is estimated at 70.4 seconds.

The average resource utilisation per task for the selected alternative scheduling is illustrated in Figure 9. In comparison to the manual assembly case, the time required for a human to perform a task is reduced by 78%. In this way, the human operators could work in other processes or even in the nearby assembly cells. Task1, takes 22% of the total cycle time when it is assigned to a human, while T2–T5, which are assigned to R1 and R2, take 28%, 19%, 17% and 14%, respectively.

This study contributes to a fast and effective reconfiguration of the hybrid assembly cells by introducing a HR

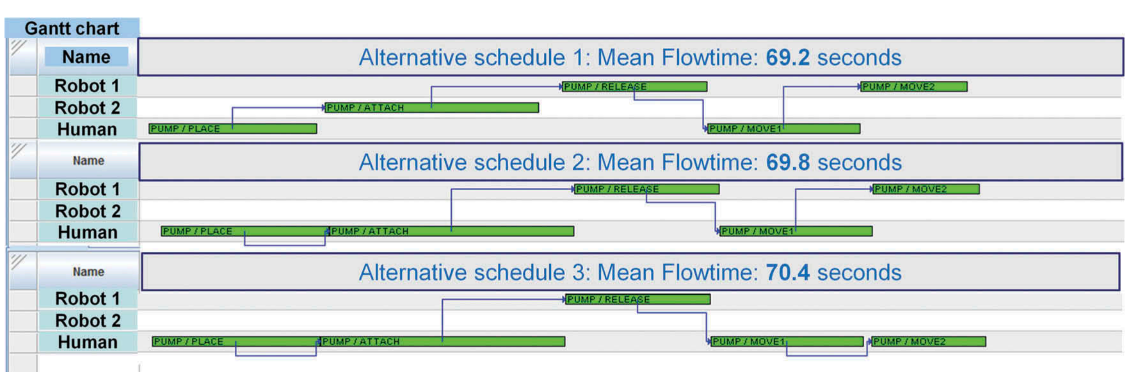

Figure 8. Human-robot task allocation and alternatives.

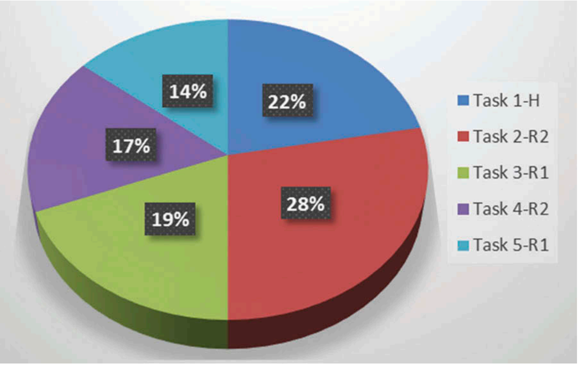

Figure 9. Average resource utilisation (%) per task in alternative scheduling 1.

task allocation and planning. The current status of a resource is considered in this algorithm and allows rescheduling of the tasks, if required. In case of a resource breakdown or its inability to perform a task, the *Scheduler Service* is triggered and generates a new task HR planning. Additionally, this intelligent tool enables a human to perform concurrent work at nearby stations or cells.

The HRC proposed method is oriented towards the human task allocation and execution, without taking into consideration the safety aspects according to the related safety norms. The development of gestures for robot commanding has helped with the control of the robot's performance, namely the start or stop a motion or action. The use of separate working spaces for the human operators and the robots has enabled the execution of the collaborative tasks without the use of fences. Additionally, the human operator used a relative unusual gesture for starting a human or a robot task, thus avoiding the possible recognition of such a gesture from any operator crossing the shop floor.

8. Future work

The presented framework is a further step in the direction of introducing human operators and robots to work together in separate workspaces, with the perspective of a dynamic HR task allocation. The framework architecture, which was tested in this case study, as well as the HR task allocation tool are at a premature level. In the nearby future, the scheduling tool is expected to make a dynamic allocation of tasks to a resource, if something changes unexpectedly in the assembly cell or line. Additionally, the gesture recognition application will be able to support the simultaneous execution of HR tasks, by enabling the online commanding of the robot based on the human gestures. Last but not least, the decision-making algorithm will be extended in order for the execution of parallel tasks to be supported.

Acknowledgement

This study was partially supported by the project X-act/FoF-ICT-314355 (http://www.xact-project.eu/), funded by the European Commission in the 7th Framework Programme.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This study was partially supported by the project X-act/FoF-ICT-314355 (http://www.xact-project.eu/), funded by the European Commission in the 7th Framework Programme.

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