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New planning methods for systems with human-robot collaboration

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Human-robot collaboration (HRC) remains a topic that everyone is talking about. There are successful applications. The major breakthrough has not yet occurred, however. One main reason for this is that in the introductory phase, HRC was only integrated into existing systems that were not prepared for HRC, nor suitable for it [1]. The full advantages of HRC can only be exploited in new systems, and, even then, only if new system planning methods are used. This article highlights what changes are necessary and presents an extended planning methodology and planning principles for HRC.

Introduction

When new technologies are introduced, they generally have to demonstrate their characteristics and benefits in existing systems. From the perspective of the user, this minimizes risks and enables initial experiences to be made with the technology. This also applied to human-robot collaboration. Since the presentation of the first robots with corresponding safety functions for collaborative operation in 2014, HRC solutions have been integrated into existing systems, but the resulting solutions have only rarely been technically and economically convincing. Why is this?

HRC in existing systems

Existing systems (brownfield) were never planned and prepared for human-robot collaboration. On the contrary. Work was consistently divided between either manual workstations or fully-automated robotic stations behind a safety fence, light curtain or scanner. The manual workstations were synchronized in such a way that workers are optimally employed in terms of their abilities and the time required. Two very important aspects:

Human abilities and degree of utilization

If one were to attempt the technical replication of a human, it would consist roughly of the components illustrated in Fig. 1.

A 7-axis robot would be just one of many optimally coordinated components. This shows just how unfair the competition between humans and robots actually is. Does a single robot really stand a chance? Yes, whenever the abilities of humans are not fully utilized. One good example of this is screw fastening, where the human tightens multiple screws using a hand-held screwdriver. This is carried out using one arm. This means that only 50 percent of their capacity is utilized. Furthermore, while the screw is being fastened, the human can only wait. The capabilities of the individual fingers are not required at all. Moreover, if humans were able to remember positions in space better, they would easily be able to perform the task blind. As a rough estimate, the degree of utilization of the human worker's capabilities here is around 20 percent.

The situation is very different, however, in the case of more complex joining tasks, such as inserting a non-rigid seal into a groove. Even the removal of the seal from a small load carrier and the visual inspection of the seal require all the capabilities of the human, including the use of both arms. It continues with inserting the seal into the groove and smoothing it using the haptic abilities of the fingers. Tasks involving a very high degree of utilization of human capabilities should thus be left to humans.

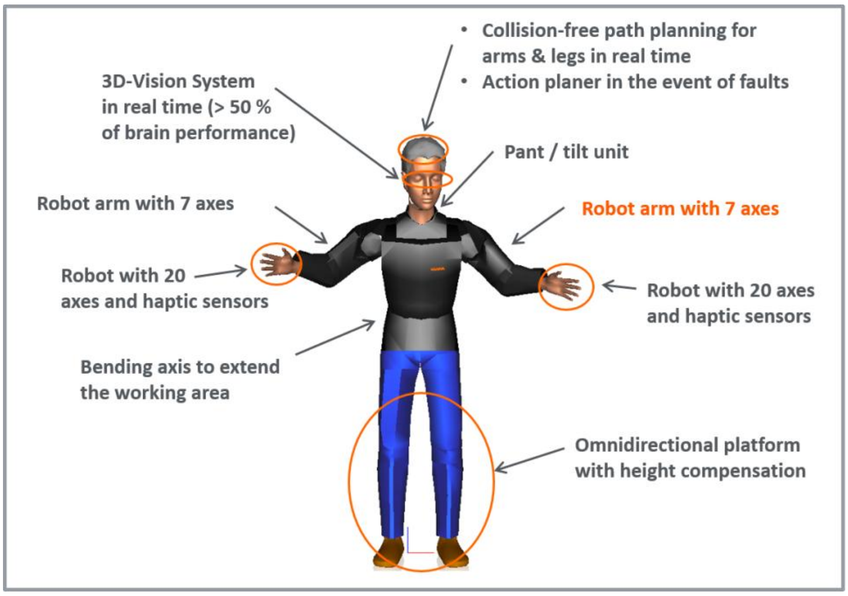


Fig. 1: Principal components of a technically replicated human

Utilization of time

In linked assembly workstations, the work is generally designed in such a way that each worker can perform his specific tasks well within the cycle time and without longer pauses occurring. If an existing system is well planned in this respect, it becomes apparent why the advantages of HRC are not fully effective there. Integration of an HRC robot generally only partly relieves the load on the worker. It is rarely possible to make sensible use of the worker's saved working time, however, as the cycle times of the upstream and downstream workstations are optimized. The workers do not require assistance. Other tasks are often located too far away, which would lead to unproductive walking distances.

There are rare exceptions. Tasks added subsequently (e.g. adhesive bonding for reasons of strength) can result in worker utilization of more than 100 percent. HRC relieves the human worker to such an extent that he can once again perform the remaining tasks well within the cycle time.

Another example is a workstation with a very low degree of utilization of human capabilities. Here, in individual cases, it may be possible for an HRC robot to take over the task completely, with minimal support from the workers of the upstream and/or downstream workstations. Both cases are so rare, however, that they were insufficient for a breakthrough of HRC.

However, if one considers not only a single workstation, but is also prepared to redesign several workstations, this opens up a whole new range of possibilities, as the work can now be divided according to new criteria. This is not generally profitable, however, in the case of existing systems that have already been invested in. In such cases, subsequent investments have to pay for themselves within a year to eighteen months, depending on the end user, making cost-intensive conversions unfeasible.

Fig. 2: System for screw fastening of the pendulum support (image: © Volkswagen AG)

HRC in new systems

In the case of HRC in new systems, a whole new set of parameters apply. All planning aspects of HRC can be taken into consideration from the outset. Work can be divided optimally between humans and robots. This means that the full potential of HRC can be exploited. Furthermore, considerably higher investment resources are available than for the conversion of existing plants.

Before we go into greater detail about planning a system with HRC, let us first briefly recap the advantages of HRC:

- *Lower space requirements*
  Humans and robots can work together in confined spaces. Work activities can be concentrated in a small area (see Figs. 2 and 3).
- *Improved process quality*
  The robot can take over processes in which quality is critical. It works with a high level of repeatability and without fluctuations in the process.
- *Improved ergonomics at the workstation*
  The robot is not troubled by ergonomically unfavorable positions, such as overhead work or stooped posture. It can also

Fig. 3: Worker and robot jointly mount a rear-axle transmission [2], image: © KUKA Systems GmbH

easily perform strenuous processes such as the fitting of clips, where a high pressure has to be applied to a small area.

- *Inline process monitoring*
  The robot can perform quality monitoring measures in the running process. With the LBR iiwa, for example, it is possible to check whether parts have engaged completely and correctly by having the robot pull on the component in the opposite direction following joining. If the robot does not move, the process has been performed correctly.
- *Robot is "data gatherer" for Industrie 4.0 concepts*
  This advantage applies particularly to production lines that, until now, have been hardly automated or not automated at all. In such cases, there is often very little data available. Nor does one want to burden employees with entering data. This task can now be performed by the robot by connecting it to an edge gateway or directly to the cloud.
- *Versatility*
  If the robotic solution is implemented on a movable vehicle (see Fig. 4), it can be relocated quickly from one place of use to another. In this way, existing production lines can be adapted to changing requirements without great effort. This is the versatility that has long been demanded.
- *Fast troubleshooting*
  If a fault occurs during a process sequence in a conventional robotic cell with a safety fence, e.g. the robot freezes while setting down or joining a workpiece, the robot has to be stopped, moved free and set to a safe stop state. The maintenance technician can then open the safety gate, rectify the fault and, after leaving the cell, restart the robot. This takes time. In the case of a safely designed and implemented HRC system with a sensitive robot the operator can solve the problem quickly and easily by gently pushing the robot during ongoing operation without specialist knowledge.

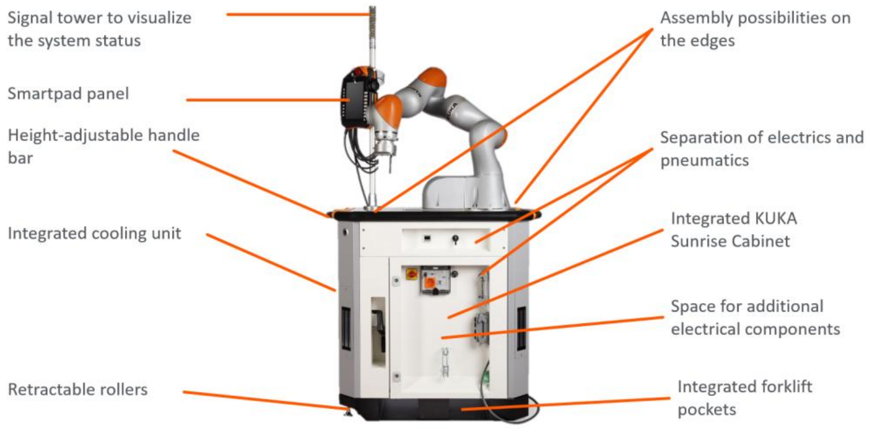
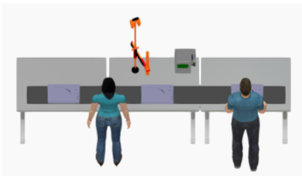


Fig. 4: A movable system (KUKA flexFELOW)

- *Lower costs for back-up solutions*
  With automated systems, it is always necessary to consider the scenario of an automation component failing. In such a case, a back-up solution is needed quickly in order to minimize production downtime. The versatile solution in Figure 4 also has its advantages in this case. Should a fault occur, the entire unit can be quickly removed from the production line. Since there are no further installed components, a stand-in worker can bridge the time required for the repair by performing the work manually in the same place. In the next break, the automated subsystems can be brought back into the production line.
- *Proportional saving of workers*
  The robot can also be used for a proportional saving of workers. This is particularly useful with a view to demographic development and the associated shortage of workers, as it means that production can be kept in industrial economies. This point is normally mentioned first, as it is the easiest to number in return-on-investment (RoI) calculations. In the future, however, it will be increasingly important to assign a monetary value to the aforementioned advantages in the RoI calculation, as they will otherwise not be realized.

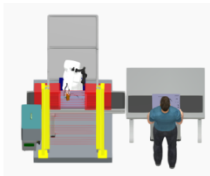
To ensure that these advantages can be exploited to



a) Manual Workplace
- Manually pre-plugging the screws
- Manually screwing with a position monitored handheld screwdriver
- Manuel assembly activity in a second workplace

b) HRC-workplace
- Manually pre-plugging the screws
- Automatic screwing by robot
- manual assembly activity in parallel

New
Needs new approach in the planning phase



c) Automatic Screwing
- Screws are fed automatically to the spindle
- Automatic screwing by robot
- Manuel assembly activity in a second workplace

Fig. 5: Example of an expansion of the planning concepts for a simple assembly

the full, the existing system planning methods must be the full, the existing system planning methods must be expanded and adapted to the new possibilities. Let us illustrate this with a simple example. A system is to be planned in which several assembly steps that are not easily automated are to be performed, together with a number of screw-fastening operations. Until now, the planner has distinguished between manual and automated assembly. This would result in the two variants a) and c) in Fig. 5. In variant c), the entire screw-fastening process, including the separation and feeding of the screws, is automated. Since a conventional industrial robot is used, it is safeguarded by means of a safety fence and a light curtain. This type of planning has been mastered for many years.

What is new is variant b), which represents an intermediate form in terms of the degree of automation. Here, the operator performs the preliminary insertion of the screws. Due to the skill of his hands, the human operator can carry out this process very quickly. While the human now performs the tasks that are difficult to automate, such as the insertion of non-rigid rubber seals, the robot takes over the screw-fastening operation. Due to the use of an HRC-capable robot both can perform their tasks simultaneously. This reduces the area required. Additional space, energy and maintenance costs are saved due to elimination of the screw separation system. A further advantage of variant b) is its versatility. If a product change results in a different screw head and/or length, all that is required is a change of bit and/or a program modification in the robot controller.

New planning methods for HRC

This was a simple example. In the case of more complex systems with a wide variety of different work sequences, the solution will ultimately be a combination of all three variants (manual, HRC, full automation). The existing planning methodology must be extended.

Fig. 6: Plug insertion in vehicle assembly with the sensitive LBR iiwa lightweight robot

The changes are dealt with in greater detail below. In the case of a new system, all assembly steps must first be classified. Two questions must always be answered here. Firstly, is the process step also suitable for automation under cost-effective conditions? Not everything that is technically feasible is also cost-effective. Tasks with a low degree of utilization of human capabilities, such as screw fastening, can generally be automated well and cost-effectively. Secondly, can a process step that can be automated also be implemented in combination with HRC? A welding process, for example, would not be suitable for HRC.

Taking the assembly graphs into consideration, it is now possible to form clusters of identical or similar automation tasks. This is helpful, as it is particularly cost-effective when a robot carries out as few processes as possible, preferably a single process. This eliminates unproductive times for changing end effectors, and the end effectors themselves are simpler, as the complexity of multi-purpose tools is avoided. The tasks must now be divided between the human and the robot in such a way that all resources are well utilized. This rough division is now implemented in a system concept with layout and resource allocation. This can result in an imbalance at the cell level. In case of doubt, the human takes over tasks from the robot, even though they would be well suited to automation, in order to avoid longer wait times for the human. Alternatively, contents can be distributed to other stations. This planning step is an iterative procedure.

Once the concept has received a positive appraisal, detailed system planning begins.

The following aspects should be taken into consideration when designing the system concept:

- *Avoiding imitation of the tasks of the human worker*
  Particularly in environments that have had been little automated in the past, it is noticeable that attempts are made in the planning to imitate the human activity with a robot. This rarely leads to the best solution, however. The manual workstation is tailored to humans with all their strengths and limitations. To the robot, on the other hand, many of these human limitations are unknown. It does not need to take ergonomic factors or exhaustion, etc., into account. This opens up entirely different design options. The robot can perform a screw-fastening operation, for instance, by moving the workpiece under a stationary scredriver That is something you would never consider asking a human worker to do.
- *Revolution rather than evolution*
  Until now, system planning has always been evolutionary. When designing a subsequent system, the planner has gone back to the concept of the previous system and eliminated all known weaknesses in the new concept. This procedure was successful in the past and led to highly sophisticated systems. In the case of HRC, however, it gives rise to a “mental brownfield” and, as with the integration of HRC into existing systems, not to the desired

effects. That is why a revolution is now required. Previous concepts must be set aside, and processes and work contents need to be rethought.

- *Utilization of robot capacity*
  Automation will be made more difficult if robots, like humans today, are expected to perform many different tasks in a cycle. Due to the flexibility of hands, the possession of two arms and the fact that all tasks can be performed in a closed control loop with the use of eyes, this is no great problem for the human. When assigning work to the robots in a system, it should therefore be ensured that each robot only carries out a single process where possible. This can lead to underutilization of the robot, however, if it only works in one station. By means of a clever arrangement of the individual workstations in the layout, the system can be designed in such a way that the robot takes over tasks in two or more stations and thus utilizes its full capacity once again. A meandering layout is useful here, for example.
- *Task-centered decision for fixed-cycle or continuous-flow operation*
  In very large systems, such as final assembly in an automotive plant, it remains to be decided in which areas the system is to run in fixed-cycle or continuous-flow operation. While both exist today, continuous-flow operation offers advantages given the still high proportion of manual work and thus remains prevalent. Depending on the equipment variant of the vehicle and the associated assembly tasks, continuous-flow operation enables workers to walk temporarily into the next workstation with the vehicle. Since robots cannot move with the product so easily, continuous-flow operation increases the complexity and the technical effort required. Fixed-cycle operation is considerably easier to master in this case. Continuous-flow operation is only advantageous for automation if the reach of the robot is limited. Here, as in the case of plug insertion (Fig. 6), the product moves to the robot and not vice versa. This means that despite the limited reach of the HRC-capable robot, all the plugs can be inserted along the longitudinal member of a vehicle, for example.

In this context, the sequence of the assembly of specific components should also be reconsidered. If the priority graph allows, assembly tasks can be shifted to preferred zones with fixed-cycle or continuous-flow operation.

These new aspects of HRC-oriented planning initially pose a certain challenge for the planner. The reward for this effort is a highly productive, cost-effective system with ergonomically optimized workstations. Furthermore, it is now also possible to automate processes that previously fell at the hurdle of excessively high costs for automation-friendly in and outfeed of workpieces. This is enabling automation to advance into areas that were previously closed to it.

The learning curve for the planning of systems can be supported very successfully by experts with HRC experience, particularly if these experts have already implemented systems themselves and developed solutions to meet a wide range of different challenges.

Literature

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About the authors

Dr.-Ing. Johannes Kurth studied Mechanical Engineering at RWTH Aachen University and at Dartmouth College, USA, and received his doctorate in 1994 at the Institute of Automatic Control, RWTH Aachen University. He has held various management positions within KUKA Group since 1995. He has been involved with human-robot collaboration (HRC) for more than 13 years, first as Head of Research & Pre-Development at KUKA Robotics. Since 2014, he has been in charge of the engineering department in the business unit Advanced Technology Solutions at KUKA Systems and has established new engineering and consulting services in the field of HRC there.

Dr.-Ing. Marcel Wagner studied Electrical Engineering, Robotics and Automation Engineering at the TU Chemnitz and received his doctorate in 2016 at the Fraunhofer IWU and the Institute for Machine Tools and Management Sciences (iwb) at the TU Munich in production planning and control. Since 2017 he worked as a planner for HRC systems at KUKA Systems and developed together with Dr. Johannes Kurth the HRC-Consulting division in the business unit Advanced Technology Solutions. Since 2020 he has been in charge of the engineering department in the business unit AGV Solutions, where he is also responsible for the mobile robotic solutions in HRC.

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