Consistent Virtual Planning Process of Human-Robot-Cooperation Using Software Tools and Virtual Reality

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Abstract— **Human-Robot-Cooperation (HRC) is seen as a new form of robotic applications, which enables a direct interaction between human and robot at any time. To avoid injury of human during the interaction, special safety and technology demands are required. Through the cooperation, human can be relieved and supported e.g. at the workplace; on the other hand, the handling with robots will become easier without fence. To implement and integrate faultless HRC applications in the production as early as possible to gain the maximal benefit, the planning phase plays a decisive part. Through the software supports nowadays, the production- and process-planning is getting more precise, effective and efficient. In many fields, planning without using software tools is because of time and cost reasons even not possible. The approach of this paper is to virtualize or digitalize the planning of HRC so that the effort and expense can be reduced. The purpose is to virtually execute the whole planning phase, i.e. rough and fine planning, risk assessment, acceptance test, virtual commissioning and training, before the implementation with hardware. This paper gives an introduction into the possibilities of a virtual planning process of HRC. A planning strategy using the combination of desktop software and virtual reality will be verified with a use case in the assembly.**

Index Terms— **Human-robot interaction; Production planning; Process planning; Virtualization; Virtual reality**

I. INTRODUCTION

An increasing number of Human-Robot-Cooperation (HRC) applications have been implemented in various industries; the cost effectiveness of these applications and an improvement of ergonomic at the workplace are proven [1]. For a successful implementation of HRC, a comprehensive and holistic planning is the fundamental precondition. Also a standardized planning method and procedure, which can be widely used for any number of HRC applications, is crucial; especially for companies with large production scope e.g. in the automotive industry. However, the planning of HRC applications is nowadays still complex, costly and individual. Experiments must be carried out with equipment e.g. robots, measuring device, causing high expenditure of time and danger of staffs as well. In case of wrong planning, the workplace muss be adjusted again, that is normally associated with high expense. Such events can delay the implementation, so that the improvements to be achieved cannot be realized in time. Dependent on every single HRC application, the planning of them distinguishes from each other. The results and experiences can be hardly further- and re-used.

Aiming at effective and efficient planning, the advanced planning software tools, which enable visualization, simulation and evaluation of workplaces and -processes before the implementation with hardware, have been widespread utilized [2] [3]. At the moment, such software tools are hardly used for the planning of HRC. Therefore, the approach of this work is to apply software supports for the planning of HRC. Based on a planning strategy, a continuous and virtual planning process of a HRC use case at Volkswagen Group using desktop simulation software and a virtual reality headset (HTC Vive) will be presented.

The sections are structured as follows. First of all, an overview of current research of HRC planning and applications as well as the usage of advanced planning software tools will be given in section II. In section III, an approach of planning strategy for HRC will be explained in detail. The realization of this planning strategy will be demonstrated through a prototype upon a use case in the assembly line afterwards in section IV. In section V, the achieved results will be evaluated and discussed; the available supports and the lacking features will be shown. Finally, a conclusion and an outlook in future work will be given.

II. STATE OF THE ART

In this paper, two research fields will be covered. On the one hand, the simulation software and virtual reality are provided as software planning tools. On the other hand, the HRC is seen as the application field, for which the software planning tools can be utilized. In order to maximize the advantages of the tools, specific requirements and aspects of HRC must be considered.

A. *Software planning tools*

The expense, time pressure and complexity of planning tasks is ongoing rising because of the increased variety of product models and decreased product life cycle. Thanks to the rapid development of IT technology, lots of planning tasks can be done or supported with software systems. Typical examples are the tools of digital factory, which are primarily deployed in the field of production planning [4]. The reduction of planning expenditure (time and cost) and increase of planning quality through using these tools have been proven in many industries [5]. Another big advantage is the frontloading of single up to the entire planning phases, so that simultaneous engineering between the development and

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planning as well as within the planning processes is possible [6]. In industrial scope, the planning software are utilized for various purposes e.g. planning of plant layout, simulation of assembly line or planning of robot cell included robot programming [5]. Despite the widespread utilize, the potential of such planning tools are not completely exhausted. Many tools are used only for visualization, although they provide a large range of functionalities for e.g. analyzing and evaluating processes. The issue at this point is that there is still a deficit between simulation/ virtuality and reality. This deviation is becoming smaller but a complete replacement of physical equipment is still not possible in many planning field in the near future. In recent years, the planning tools have been developed rapidly and some new technologies like virtual reality (VR) has been widely used for planning tasks. The VR enables immersion and presence of human in a virtual environment, in which user can interact with virtual components instead of physical and test random situations or variants [7]. A live exchange with other people who are not on site is possible as well [8]. These are crucial advantages of VR compared with desktop software and on site physical experimental setup. There are basically three embodiments of VR: CAVE, Powerwall and HMD (Head Mounted Display), each of which has their own special features e.g. convenient for cooperation or low space requirement and are appropriate for different use cases.

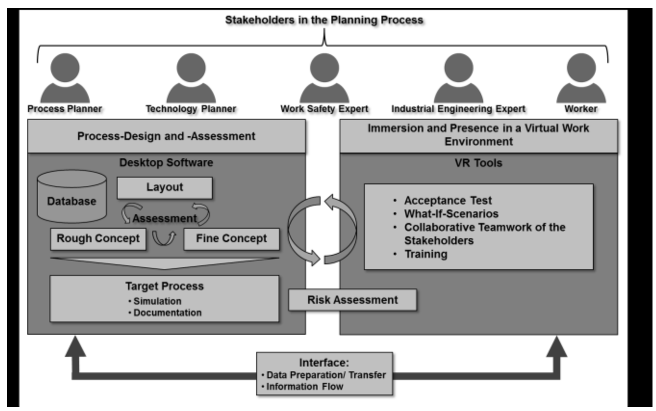
B. *Human-Robot-Cooperation*

In recent years, the technology of smart robotics has been widely researched and developed. Thanks to the rapid advancement of sensor system and IT technology, the spectrum of industry robot is expanded by so called collaborative robots (cobots) [9]. They are characterized by their light construction and high flexibility compared to traditional industry robots, and are especially designed for direct interaction with human in a shared workspace. This doesn't mean that only such cobots are applicable for HRC; with additionally appropriate safety equipment, traditional robots can also be applied for HRC [10]. The idea of HRC is that the human and robots can complement themselves mutually during work, i.e. their strength can be exploited and their weakness compensated [11]. Furthermore, human can focus on value-adding tasks and do their jobs without high physical strain. In the industry, HRC is often used to improve economic efficiency, productivity, quality and ergonomics [1]. Current developments and issues of HRC are comprehensive described and cited in [12]. A survey about the so far implemented HRC applications in Germany was executed through the Fraunhofer IAO [1]. The results show that most of the applications (60%) are among coexistence i.e. human and robot work in a separate or shortly overlapping area, and their tasks are independent from each other. It seems that a close cooperation is not requested or too complex to be implemented efficiently. The most complex and difficult part to plan the interaction is to ensure the safety of human because of the elimination of safety fence, so that the human can interact with the robot at any possible time. A risk assessment must be executed in order to identify potential dangers and derive appropriate measures. In ISO 10218 the requirements of construction, safety components as well as risk assessment for industry robots-(applications) are described in particular. Not only the robot but the whole application must be evaluated within the scope of risk assessment in order to get the approval for the planed HRC application. In ISO TS 15066 four safety concepts (Hand guiding; Safety-rated monitored stop; Speed and separation monitoring; Power and force limiting) of HRC are described including the requirements for collaborative robots using these concepts. The permissible biomechanical loads of human body by using the concept "power and force limiting" are also defined. For the planning of the concept "Speed and separation monitoring", ISO 13855 muss be used to determine the minimum distance between human and robot.

III. Approach to a Strategy for a Consistent Virtual Planning of HRC

Compared with other production processes, the planning of HRC is hardly supported through software at the moment. It's because on the one hand, the existing software tools cannot fulfill the requirements of the HRC planning. On the other hand, there is no strategy which describes the utilization of software systems aiming at planning HRC process virtually. In this section, an approach to the planning strategy for HRC using digital planning tools will be described [13], which is illustrated in the following figure.

Figure 1. Strategy for a continuous virtual planning of HRC



Similar to the planning of other production processes, a rough concept of the HRC workplace or process to be planned should be worked out at the beginning [14]. In this planning phase, a planner will draft several variants of concepts which differ from each other in e.g. utilized robots, safety concepts or task distribution. Through a comparison between these variants, the most suitable one can be chosen. It means the digital planning tools have to provide possibilities on the one hand to load product, process and resource data in order to build various concepts in the form of virtual scenarios, and on the other hand to compare these concepts qualitatively and quantitatively with each other. In this way, the advantages and disadvantages of each concept as well as the improvements against manual process can be represented visibly. After the decision of one concept which has to be refined later, a target process can be ultimately presented in the form of simulation. This planning process described above can be supported through the advanced desktop software mentioned in section II A, which can simulate realistic motion of robot and human. A successful utilization of such software for planning tasks in various production processes has been already proven and defined as standard [15].

The special characteristic of HRC is the interaction between human and robot. Not only the cases during the cooperation work as planned but also the cases that human principally has access to interact with robots (not foreseeable action of human) have to be considered. In order to take the latter situation (so called what-if scenarios) into account, where the worker could act differently than planned, and to verify the consequence and their acceptance, virtual reality (VR) tools can be used to support and complete the planning. Using VR-tools, different stakeholders e.g. planner, worker, work safety experts can execute the planned HRC process in a virtual environment and try out especially critical situations that should be verified. The operating robot reacts by every situation depending on predefined safety concepts automatically to the action of the human. This can also be used for qualification of staffs who will work at the planned workplace.

With this planning strategy, a consistent virtual planning process of HRC including risk assessment can be realized, i.e. the whole process and potential dangerous positions can be visualized or self-tested. An iterative process between simulation with desktop software and VR-tools ensures faultless and complete planning results, based on which a virtual commissioning can be made. An interface between the both tool worlds must be developed, in order to transfer the data to be used consistently and completely.

IV. Demonstration

In this section, the planning strategy described previously will be evaluated with a use case in an assembly process in the Volkswagen Group. The planning of this use case will be carried out through using desktop software and VR-tool as a representative example.

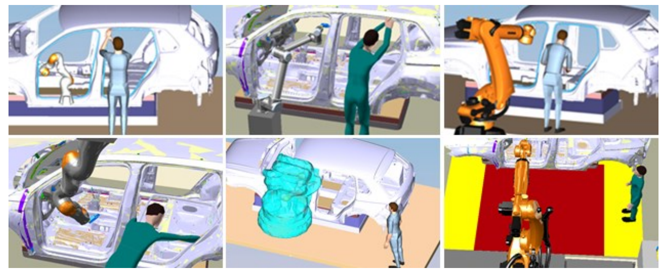
A. *Description of the use case*

During this assembly process, two door seals should be assembled. The first step is to attach the seals onto the doorframe and the second step is to fix them with a fixating device in place. The ergonomics and process time of this process is not optimal, wherefore the goal is to automate this manual process with HRC. Because handling and assembling non-rigid materials is difficult with current technology, the attachment of seals will not be suitable for robots to execute. The high costs for implementation and long duration of the process therewith would not be acceptable. In contrast to the attachment process, the fixing process is simple for a robot to execute. Hence, the task distribution between human and robot is defined (the human attaches the seal whereas the robot fixes it in place.).

B. *Simulation with desktop software*

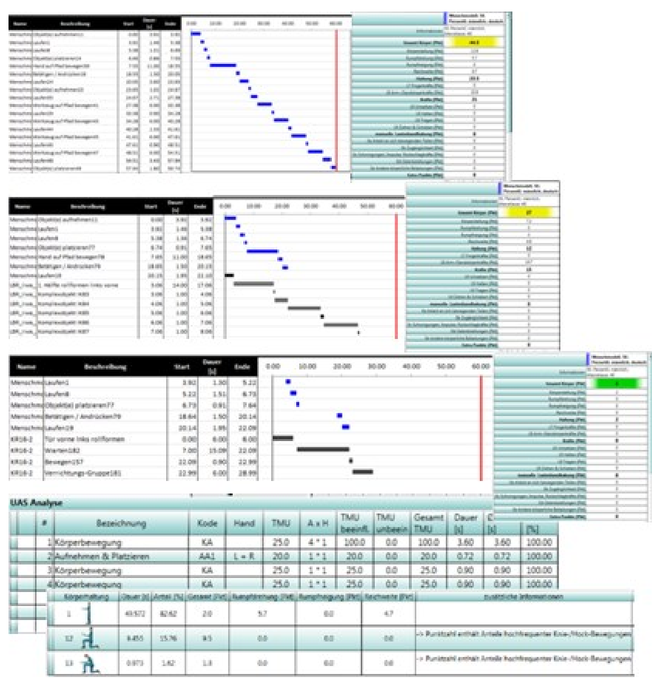
In this paper, two representative and market-leading software are chosen to carry out the investigation [16] [17]. They complement each other with their strength each in human and robot simulation. To create a simulation, all data needed must be provided or imported in the software at first. In this use case, such data are above all the car body, skid, seals, robots, human model and fixating device. Using these data the layout structure will be build. Based on the task distribution, the motion of human and robot will be defined and simulated. The operations of human and robot should be simulated separately at first. After that, possible problems during the work or cooperation e.g. mutual obstacle can be identified. Dependent on the flexibility and feasibility, human or robot must adjust themselves to each other in order to realize a plausible process and cooperation. In this use case, the safety concept "Speed and separation monitoring" using industry robots; and the concept "Power and force limiting" using cobots will be applied. To fulfill the safety requirements of the both concepts, additional equipment e.g. sensor must be used. The following figure shows several examples of simulation.

Figure 2. Simulation of various concepts



As the figure 2 shows, various concepts can be tried out and visualized in the software. The operations of human and robot in real time can be simulated. These concepts will be in the next step assessed by e.g. time, ergonomic, occupancy rate in order to compare them with each other and to verify the enhancements through HRC. Possible risks could be considered through the visualization as well. The following figure shows the assessment results in the software.

Figure 3. Assessment results of the concepts



These are above all the assessments of ergonomics and time. During the planning process, the concepts which are created will be assessed and ongoing improved. Based on these results, the best variant will be chosen. Thus, a target process can be simulative represented.

These simulations on desktop cover the plannable assembly process from an outside viewpoint. To additionally

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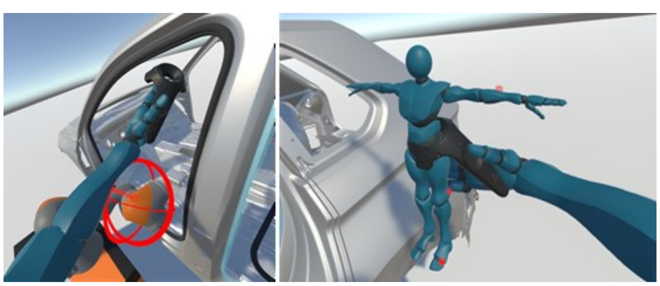
cover the not predictable interactions between robot and human and to get a first person experience or acceptance of the planned workplace, experiencing the planned workspace in VR is the next step in the virtual planning process.

C. *VR prototype*

For this work a VR prototype is developed for the given use case. A consumer grade HMD is chosen as the targeted hardware because these are easier to access by potential stakeholders in the planning process than more sophisticated VR systems like a CAVE. Nevertheless, for a higher visual fidelity it could be exported to work in a CAVE as well. For fast VR prototyping the Unity 3D game engine [18] is used. In the prototype the user can assemble the door seal virtually with natural body motions using 6 DoF (degrees of freedom) hand controllers. Based on the 6 DoF poses of the HMD and the two hand controllers, a virtual human body model estimates the user's posture. On the one hand this virtual body representation can enhance the user's sense of presence as indicated in [19]. On the other hand it is necessary to create collision volumes so that collisions between the user and the virtual robot or safety zones can be detected.

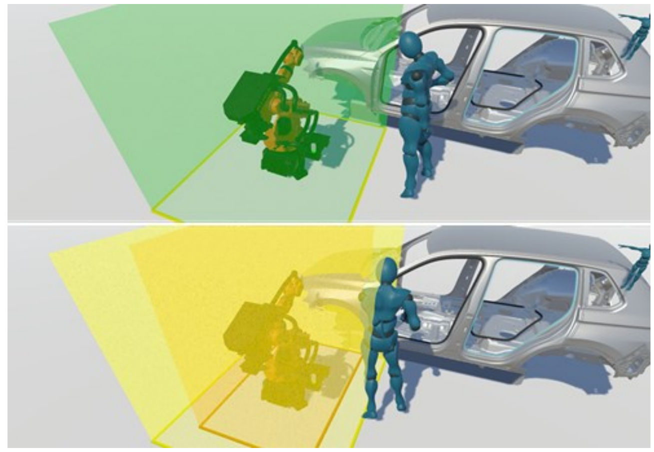
At first, the two assembly layouts built in the desktop software were transferred to VR. One using a cobot with "power and force limitation" and another one using a standard industrial robot with "speed and separation monitoring". With the former concept, the robot stops instantly when a collision occurs and resumes its motion automatically when the contact is released. The collisions are visualized in two forms in the VR prototype (see figure 4). For one thing, shrinking orthogonal circles give the user a direct feedback that a collision with the robot occurred and guide his attention towards the collision point. For another thing, all collision points on the human body that occurred during the assembly process are gathered as red points on a puppet-like miniature model of the body. This shows the critical body regions that the robot hit in the assembly process, which can support the risk assessment.

Figure 4. Detection and virtualization of collisions between human and robot



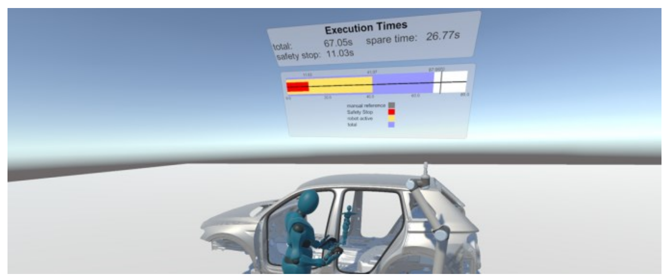
In this VR prototype the safety concept "speed and separation monitoring" relies also on collision detection (see figure 5). Two 3D safety zones were defined, a big outer and a small inner one. The zone boundaries are visualized by transparent surfaces with a slight noisy texture for a better depth perception, and with an additional border marking on the floor. By entering the outer zone the robot will slow down and by entering the inner zone the robot will stop. These effects will be reset when the user leaves the respective zone. Entering and leaving the safety zones is visually indicated by changing the color and visibility of the zones.

Figure 5. Interaction with 2D- and 3D-Safety zones



To show how far the interruptions of the robot work affect the overall process time, a graph is shown above the virtual car body after the assembly process is completed (see figure 6). It displays the total process time, the actual working time of the robot, the time lost due to safety-stops and the time the robot was idling during the process.

Figure 6. Illustration of execution times in the VR scene



D. *Data transfer*

To integrate validation in VR into the HRC planning process, the setup of the VR scene must be done first. Compared to traditional CAD solutions, VR has some different data requirements. First of all, for efficient real-time rendering, the geometry data need to be transformed from a precise geometric (in CAD) into an approximating polygonal format. Furthermore, the necessary or allowed user interactions in the assembly process must be defined (e.g. which objects can be picked up? What actions are required in the assembly process and what parameters do they have?) in a 3D environment. Current databases from desktop software often do not contain such information on the interactions, which makes a direct data transfer difficult. Eventually the robot behavior (motions and interactions with human) must be known for a real time simulation.

For the VR prototype in this work the geometry of car body, skid, seal and fixating device were obtained from a PDM system in *.jt format. Autodesk VRED [20] was used to convert the geometry data from *.jt to *.fbx which can be directly used in Unity. The polygonal 3D models of the robots in *.dae format and the positions of the equipment relative to the car body was directly taken over form the simulations in the desktop software. The robot motions as a key frame animation in *.csv format could also be transferred from desktop simulation to the VR environment. With a state machine controlling (when to play and to pause which animations), the virtual robot can react to the human as defined in the safety concepts. Hence, all data needed are loaded in the VR environment.

V. Evaluation

Using the chosen desktop software as example, planners can in general try out their concepts virtually and flexibly without hardware. Such software supports in the planning process of HRC above all visualization and assessment, which can be used for qualitative and quantitative comparison between different concepts and identifying possible risks. The simulation results like off-line program of robots can be partially directly used or if required manually adjusted [21]. Through the visualization, the dangerous points or areas can be presumed through the experiences of work safety experts; hence the safety monitoring area and the measure points for force and pressure can be derived. Apart from the advantages and benefits above, there are in such software hardly functions available for the calculation of parameters e.g. minimum distance, collision force, allowed velocity; and for the automatic identifying of potential dangerous points. These can be provided to planer as necessary information for decision making. In a nut shell, the desktop software with the current development state can be advisably used for a virtual verification before implementation with hardware, but the parallel use of external calculation tool and human experience is still essential.

The evaluation of the VR prototype focused on two main points: the user-experience and the (potential) use cases for the use of VR for planning HRC applications. For this in total 16 experts in the fields of process and technological planning, industrial engineering and work safety experienced the VR prototype and were interviewed. The experts appreciate the visualization in VR especially the virtual body for a better sense of presence but demand a more realistic replicating of their posture for collision detection. They also noted the unused potential of multisensory feedback e.g. haptic and audio, especially in the event of collisions; as some experts rated the current visualization is too distractive, similar to the transparent surfaces visualizing the safety-zones. A visually less obstructive method like a grid structure or a local fading was suggested. It was also noted that they feel uncomfortable with the unpredictable robot motions which indicates that VR can invoke human emotions against real robots, and hence lends itself for judging the acceptance of a HRC system by its future operators. The stakeholders see the most potential for VR in supplementing desktop software based simulations by interdisciplinary discussions; it provides a more intuitive understanding of the collaborative assembly process thus lowers communication barriers. They believe VR is especially useful to include experts and future operators in the planning process because the life-like experience facilitates more in-depth feedback by those. As the VR experience familiarizes operators with their future working process, the use of VR can also extend to training [22]. The assessment and earned feedback can be used for the preparation of decision making.

Because of the different data usage in desktop software and VR, a consistent data transfer is currently only possible to a limited extent. This can hinder a continuous planning process and cause more expenditure in the planning.

VI. Conclusion and Outlook

This paper shows a consistent virtual planning process of HRC in a practical use case using the combination of desktop software and VR tools. Their supports und mutual supplementing for the process-planning, -assessment and -understanding, acceptance judgement, risk assessment and decision making in the HRC planning process are verified. The limits or the improvement potentials of these software were shown as well. In order to realize a continuous planning, data transfer between desktop software and VR must be constructed as simple as possible and ideally without any data loss.

In the future the planning of HRC should be step by step completely supported through software application. To achieve this, the software have to be further developed, especially their functions for the simulation of interaction between human and robot, which is the special characteristic of HRC. The risk assessment should be digitalized because of its high expenditure as well, i.e. software should provide hints which indicate the danger points that have to be investigated. Through using artificial intelligence, the experiences of the work safety experts could be implemented in the software, so that an automatic risk assessment could be realized. To sum up, the software hast to be able to “calculate” and “suggest” by themselves. In addition, the deviation between the virtual reproductions of hardware components e.g. controlling, robots behavior and the real hardware must be minimized, so that the most parts of up to the whole planning results can be directly transmitted into the hardware and the real application. A structured database can be built to save the results have been made from the implemented projects for further- and re-use. In this way, the previous know-how of the HRC planning can be established.

Instead of only experiencing and validating, the VR prototype can also be extended to support manipulation of the HRC system to provide a more direct feedback loop. This would additionally require an export of the changes made in VR back to the CAD-database for consistency.

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