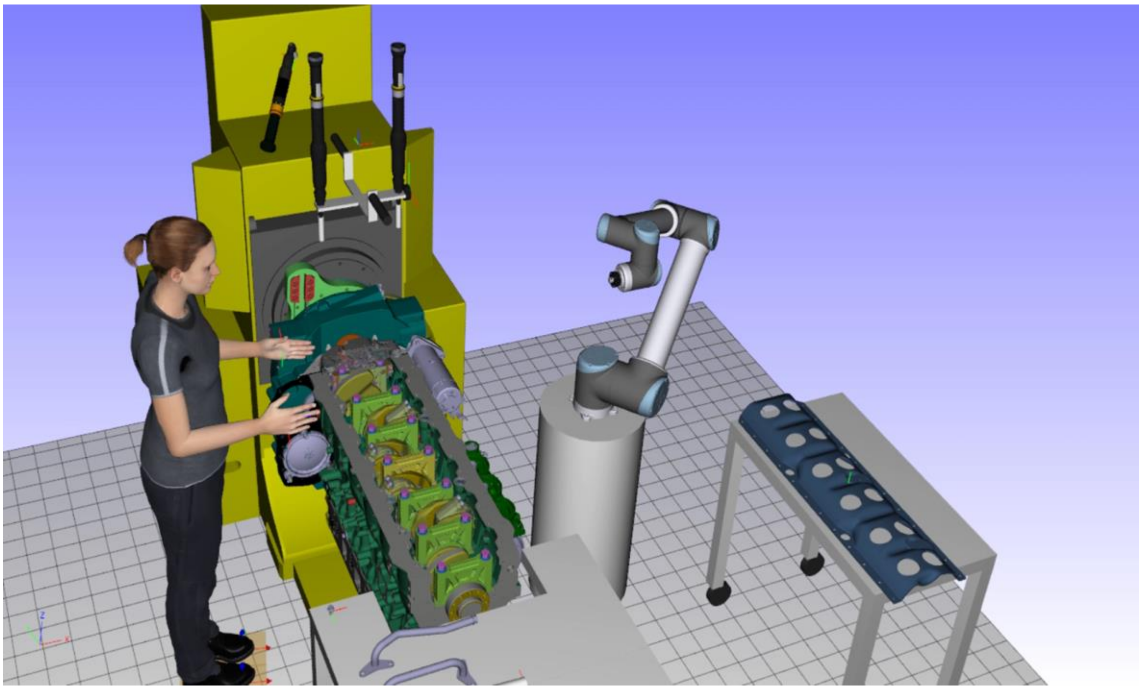
Virtual Verification of Human Robot Collaboration



Date: 20190502

Project within Sustainable Production

Innehållsförteckning

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För närvarande finns fem delprogram; Energi & Miljö, Trafiksäkerhet och automatiserade fordon, Elektronik, mjukvara och kommunikation, Hållbar produktion och Effektiva och uppkopplade transportsystem. Läs mer på www.vinnova.se/ffi.

1 Summary in Swedish

Europeiska och svenska forskningsagendor beskriver ett tydligt och omfattande behov av nya modellerings-, simulerings- och prognosmetoder och -verktyg. Forskningsagendorna beskriver även kommande demografiska utmaningar, där trenden är ökad livslängd. Ett lovande sätt att möta de demografiska utmaningarna visades i Vinnova FFI-projektet *TOMM - Collaborative Team of Man and Machine*. I projektet skapades arbetsstationer där människor samarbetar med robotar, där roboten avlastar människans fysiska och/eller mentala belastning. Idag finns det separata programvaror för robotsimulering och för simulering av människan och dess interaktion med sin omvärld (ergonomi). Vid projektstart fanns ingen simuleringsprogramvara som enkelt, effektivt och samtidigt kan hantera både människor och robotar för att verifiera samarbete mellan människor och robotar. Målet med projektet var att utföra forsknings- och utvecklingsåtgärder för att skapa en simuleringsprogramvara som möjliggör att på ett enkelt och effektivt sätt simulera samarbete mellan människor och robotar.

Projektet resulterade i en automatiserad mjukvarudemonstrator som kan användas i digitala produktionsförberedelser för optimering av arbetsstationer där människor och robotar samarbetar. Fyra användningsfall (use cases), baserade på industripartnernas önskemål, användes för att driva utvecklingen. Scanias användningsfall fokuserade på en monteringsstation för motorkåpa och på layoutoptimering. Funktionen som utvecklades gör det möjligt att på ett automatiserat sätt optimera en människa-robot-arbetsstation med en fast robotposition, varierande antropometri hos operatörerna, och varierande arbetsuppgifter, och utifrån dessa variabler finna den lösning som är bäst för både produktivitet och hälsa (ergonomi). Volvo Personvagnars användningsfall fokuserade på värmeplåtsmontering på fordonets undersida, på en kontinuerligt driven monteringslina. Denna montering är idag manuell men för att förbättra ergonomi planerar företaget att den ska utföras med assistans av en industrirobot. Mjukvarudemonstratorn utvecklades för att på ett enkelt sätt klara av att simulera samtidiga rörelser på monteringslinan, roboten samt varierande operatörer och uppgifter. Säkerhetszoner visualiserades också. Till skillnad från Scania och Volvo Personvagnar, som inkluderade större industrirobotar på arbetsstationerna, fokuserade Volvo Lastvagnars användningsfall istället på en mindre kollaborativ robot (cobot). Funktionalitet för att hantera denna typ av robotar lades till i mjukvaran så att arbetsstationen kunde utformas och utvärderas i termer av säkerhet, ergonomi och produktivitet. Fordonsindustrins tre användningsfall fokuserade på simulering och visualisering av montering. Utifrån GKN:s användningsfall utvecklades mjukvarudemonstratorn för att användas vid utformning och utvärdering av en kvalitetsinspektionsstation för flygplansartiklar.

Projektet bidar till det övergripande FFI-programmålet att minska tillverkningsprocessernas påverkan på miljön genom att göra det möjligt att simulera, visualisera och optimera arbetsstationer bestående av människa-robot-samarbete. Simuleringstekniken innebär minskat behov av fysiska prototyper och ombyggnationer, och detta resulterar i sin tur i minskad material- och energiförbrukning. Simuleringsprogramvaran bidrar även till att förkorta ledtider, öka kvalitet och öka konkurrenskraft (tre områden prioriterade av FFI - Hållbar produktion) genom att möjliggöra för företag att finna goda lösningar på människa-robot-arbetsstationer. Detta genom att dessa arbetsstationer kan designas, testas och optimeras i en virtuell värld. Demonstratorversionen av simulerings- och visualiseringsmjukvaran är en av de första där det är möjligt att designa, verifiera, simulera och optimera människa-robot-samarbete. Forskning för att vidareutveckla demonstratorn genomförs i projektet *VIVA - the Virtual Vehicle Assembler* (Dnr. 2018-05026).

2 Summary in English

European research agendas (e.g. FoF.NMP.2013-7) and Swedish research agendas (e.g. FFI HP Strategy Document and Produktion2030) describe a clear and extensive need of new modelling, simulation and forecasting methods and tools and also highlight coming demographic challenges, where one trend is increasing life expectancy. One promising way to meet the demographic challenges, shown in the Vinnova FFI project *TOMM – Collaborative Team of Man and Machine*, is to create workstations where humans collaborate closely with robots, where the robot assists the human in performing the work, both related to physical and cognitive work demands. At project start there existed simulation tools for robot simulation or digital human modelling separately. No simulation software existed that can handle both humans and robots to verify human-robot collaboration. The objective of the project was to perform research and development actions needed for the creation of a simulation tool that facilitates efficient and valid simulation of human-robot collaboration workstations.

The project resulted in a highly automated software demonstrator that can be used in digital production preparation for the optimisation of human-robot collaboration workstations. Four demonstrator use cases, based on industry partner's desires, were used to direct and push the development. The Scania use case focused on a fly wheel assembly station and layout optimisation. The use case shows that the demonstrator developed in the project provides the possibility to, in an automated way, optimise a human-robot collaboration workstation. The workstation use case consisted of: a static robot position, operators of varying anthropometry, and varying work tasks. The software demonstrator was able to find an optimal solutions for both productivity and worker health (ergonomics). The Volvo Cars use case focused on heat sheet cover assembly on the underside of the vehicle, on a continuously driven assembly line. This assembly is currently manual, but, to improve ergonomics, the company plans to redesign the workstation so that the operator will be assisted by a robot. The use case shows that the demonstrator provides the functionality to both simulate motions of the driven assembly line, the robot, and of human operators performing varying tasks. Safety zones were also visualized in the use case. In contrast to Scania's and Volvo Cars' use cases, who used larger industrial robots in the collaborative workstations, the Volvo Trucks use case included a smaller collaborative robot (cobot). Functionality was added to the demonstrator so that a truck engine assembly workstation was able to be designed and evaluated. The three automotive use cases all focused on assembly. In the GKN use case the software demonstrator was developed and used for designing a quality inspection workstation for checking aircraft components.

The project contributes to the overall FFI program target to reduce manufacturing processes' influence on the environment by making it possible to simulate, visualize and optimise human-robot collaboration workstations, and by that reduced material and energy consumption since fewer physical prototypes and rebuilds are needed. The software demonstrator also contributes to shorten lead times, better quality and higher competiveness (three areas identified in the FFI Sustainable Production road map) by enabling design, testing and optimisation of human-robot workstations in a virtual world. The demonstrator is one of the first software available for human-robot collaboration design and verification. The research and development of the software demonstrator will continue in the project *VIVA - the Virtual Vehicle Assembler* (Dnr. 2018-05026).

3 Background

European research agendas (e.g. FoF.NMP.2013-7) and Swedish research agendas (e.g. FFI HP Strategy Document and Produktion2030) describe a clear and extensive need of new modelling, simulation and forecasting methods and tools. These needs have been addressed by the research organisations after compiling results from discussions with industry and academia. The tools are needed for design, modelling, simulation, evaluation, optimisation and forecasting of production processes, resources, systems and factories during their entire life-cycles. There are opportunities for large cost, quality and time benefits from creating and optimising virtual factory models before the real factory is implemented, e.g. in terms of exploring different design options, evaluate their performance and virtually commission automation system and verify the manual systems. Hence, the virtual approach, when fully developed and integrated, reduces the critical time-to-production and supports superior production performance.

The European research agendas (e.g. FoF.NMP.2013-3) and Swedish research agendas (Produktion2030) also highlight coming demographic challenges, where one trend is increasing life expectancy. A related change is the increasing proportion of elderly people in the society. Due to this, governments in Europe discuss raising retirement ages gradually to ensure that their national pension systems are both affordable and adequate. Hence, a logic assumption is that the amount of elderly people in organizations' workforces will increase. Thus it becomes vital that manufacturing workplaces are created according to robust and inclusive design principles where environment, tools and tasks are designed to cater for a wide variation range within the workforce, e.g. related to age or experience, considering both physical and cognitive capabilities of workers. One promising way to enable that, shown in the Vinnova FFI project *TOMM – Collaborative Team of Man and Machine*, is to create workstations where humans collaborate closely with robots, where the robot assists the human in performing the work, both related to physical and cognitive work demands. This built on the foundation that humans are superior on performing certain kinds of tasks, whereas robots are superior on performing other kinds of tasks. There are several objectives of such an approach, where, from a production management perspective, inclusive and robot assisted workplaces would support flexibility, performance and robustness of the manufacturing facilities. Future workplaces should indeed enable high performance and quality output, but should also be appropriate and attractive in the eye of the operators to support that current staff both want to, and are able to, continue to stay healthy and contribute in high performance production, as well as for boosting new recruitments of high skilled employees. This is important to enable that production and associated employments can be kept within Europe.

These arguments highlight the need for simulation tools that enable the design and development of future workplaces that will suit a variety of operators and tasks, and where dynamic human-robot collaborations can be simulated and optimised already in the virtual world. Such tool is currently not available. Today there exist tools for robot simulation or digital human modelling separately. No tool can handle both humans and robots to verify human-robot collaboration. The development of such simulation tool goes in line with two of five central themes in the Produktion2030 description, i.e. *Virtual production development and simulation* as well as *Human-centred production systems*, as well as four of the six areas in the FFI program Sustainable Production: *competitiveness*, *environment*, *quality* and *lead time*.

4 Aim, research questions and method

The objective of the project was to perform research and development actions needed for the creation of a simulation tool that facilitates efficient and valid simulation of human-robot collaboration. In particular, the digital human modelling (DHM) tool IMMA (Intelligently Moving Manikins) and the robot simulation tool IPS (Industrial Path Solutions), both developed by Fraunhofer-Chalmers Centre (FCC) in collaboration with Swedish industrial and academic partners, were to be merged to enable performing simultaneous simulations of the human and the collaborating robot. This is to facilitate simulation and virtual verification of crucial aspects of the human-robot collaboration. In addition, the tool should be able to consider human variation, e.g. related to body size, joint mobility, strength, age or preferences, as well as robot variation, e.g. size, power and precision of the robot. The tool should also assist in balancing tasks between the human operator and the robot, based on their respective unique abilities, the present conditions, and the results from the ergonomics assessment methods in the tool.

A participative and use case driven software research and development process was used. The industry partners specified their goals, which were in line with the project objectives. These goals were communicated in the form of use case descriptions. These were divided into sub-tasks and sub-deliveries along the project period, as input for the actions of the core research and development team. The industry partners tested and assessed the deliveries, and based on the findings set new desires. This was done in a collaborative and repeated manner along the project period. This participate and iterative research and development process was used to end up with a software demonstrator that is relevant and useful for the industry partners, while meeting other project objectives, e.g. scientific publications.

5 Objectives

The project was divided into a number of work packages that led the project towards the overall objective. From each work package, knowledge and new functionality were iteratively developed and implemented, which resulted in a final demonstrator version of the human-robot simulation tool.

WP1. Project coordination and demonstrator development
Within this work package, a detailed project plan including scheduled tasks and milestones were delivered and continuously followed up and updated. Several internal and additional external meetings and workshops were arranged. Furthermore, progress and project reports were produced. The work package was also responsible for managing demonstrator development and the production of scientific papers.

WP2. Development of functionality to simultaneously simulate human and robot
This work package addressed collaborative operations in which a human and a robot work together to accomplish different tasks to perform the work. The goal was to develop methods and algorithms for the creation of simultaneous motions for the digital manikin and the robot that are efficient and ergonomic. The first step was to develop a generic programming way – a language – to describe tasks to be performed by the collaborating human and robot, which parts are involved, how they are grasped, need to be positioned etc. The language should be flexible enough to describe relevant operations in industrial environments. Once the tasks are properly specified, the description serves as input to algorithms for generating one or more solution alternatives for each task. Also, automatic path planning for generating motions from

the end of one task to the beginning of next task were developed, both for continuously driven lines with moving robot lines and for workstations with fixed robots.

WP3. Study and development of algorithms for simulating human variation and ergonomics assessment methods
All humans are unique and therefore a single digital manikin (human model) cannot represent all humans. In the current version of IMMA, state of the art techniques for the consideration of anthropometric diversity is implemented. Anthropometric variation is one parameter among others that differentiate humans between each other. The purpose of the work package was to investigate which other relevant parameters that are affecting human assembly work and how they can be considered in a simulation, e.g. related to range-of-motion and speed of working. Several ergonomics evaluation methods are available in industry and in research literature. In many DHM tools, observation based ergonomics evaluation methods are implemented, typically originating from manual observation-based evaluation methods developed for the assessment of few static instances. The strategy within this work package was to focus on the implementation of methods that include the consideration of time-related parameters, and to be inspired by direct measurement based evaluation methods. This because time-related aspects, such as speed, acceleration, duration and frequency, are easily provided from the digital human model. This as a way to end up with more precise and valid evaluations of ergonomics in simulations, especially for the simulation of dynamic work such as when collaborating with a robot.

WP4. Development of human-robot station balancing algorithms
This work package included the development of methods and algorithms for balancing work between robots and humans based on the IPS/IMMA current technology for load balancing, sequencing and path planning of multi robot stations and motion planning for digital manikins. In the first step (i), collision-free and ergonomic alternatives and motions to perform each task/assembly are calculated. In the second step (ii), tasks are balanced, sequenced between the resources of robots and humans, and collision-free and ergonomic motions between the tasks are calculated. In the last step (iii), coordination and safety aspects are handled, e.g. by minimizing overlapping motions between humans and robots. Furthermore, it is important that the off-line calculated solutions are robust so that on-line deviation by humans easily can be adopted by the safety supervisor system with minimal loss of productivity.

WP5. Development of functionality to simultaneously simulate human-human collaboration
Human-human collaboration is one possible definite solution from the balancing algorithms. This work package addressed collaborative operations in which two humans work together to accomplish work tasks. The goal was to develop methods and algorithms for the creation of simultaneous and coordinated motions for two digital manikins that are efficient and ergonomic. The work package led to important development since in the current version of IMMA only one digital manikin can perform work tasks. Challenges are development of the descriptive language and algorithms for collaborative work. The other definite solution, robot-robot collaboration, will not be considered within the project.

WP6. Cooperation with other human-robot collaboration projects
A number of human-robot collaboration research projects were running in parallel in Sweden, e.g. the EU project SYMBIO-TIC (project leader Prof. Wang, KTH Royal Institute of Technology), the Vinnova FFI project TOMM (project leader Dr. Johansen, Linköping

University), the SIO2030 project DYNAMTE (project leader Dr. Fast-Berglund, Chalmers University of Technology), and TOMM 2 (project leader Dr. Johansen, Linköping University). These projects mainly focus on physical test implementations and the safety related challenges rather than the proactive design and simulation based approach embraced within this research project. The purpose of this work package was to collaborate with ongoing projects in the area of human-robot collaboration, and to test the demonstrator version of the human-robot simulation tool developed in this project, to simulate and optimise industry cases identified in the other projects. After virtual verification of the human-robot collaboration in the demonstrator tool, these workstations could be further designed, produced and evaluated in laboratories facilitated in the parallel projects. Feedback from evaluations in laboratories provided possibilities to validate simulations and further refine the demonstrator tool.

6 Results

For each work packages, a number of deliverables were specified in the project proposal and followed up during the project. The deliverables are listed and commented in Table 1. The results from the more technical work packages 2, 3 and 4 are described in more details.

6.1 Overview results

Table 1. Deliverables per work package. Colour indicates degree of fulfilment (green = fulfilled, yellow = partly fulfilled, red = not fulfilled to the expected degree)

WP	Fulfilment	Deliverables	Comments
1		Meetings	A number of meetings were arranged, including kick-off, follow-up, technical and final presentation. Larger meetings were arranged every sixth month. Shorter more technical meetings were arranged with different intervals. During intensive periods every third week, otherwise less frequently.
1		Demonstrator releases and training activities	A demonstrator version was released approximately every sixth month. A training session or workshop with industry partners were arranged close to release date. About 10-15 persons were trained during the project.
2		Simulating human and fixed robot	The demonstrator software has this functionality. It is demonstrated in the Volvo Trucks use case where a collaborative UR (Universal Robots) robot assists a human in a screw tightening task at an engine assembly workstation. It is also demonstrated in a Scania use case where an industrial ABB robot collaborates with a human in a flywheel assembly task on the engine.
2		Simulating human and sliding robot	The demonstrator software has this functionality. It is demonstrated in the Volvo Cars use case, where a robot fixates a plate under the vehicle while the human is mounting it. The vehicle is on a continuously driven assembly line.
2		Instruction language for human and robot	The demonstrator software has this functionality. During the project an operations sequence editor for

			controlling actors (e.g. humans and robots) was developed.
3		Method for range and speed of motion of human operators	The demonstrator software has this functionality. The demonstrator provides the functionality to create personas (digital human model representatives) that can have different characteristics. In the final presentation an academic use case demonstrated personas with different flexibility (joint range-of-motion).
3		Motion strategy generation	The demonstrator software has this functionality. It is possible to shift motion strategy for the manikins, for example from a knee-bending lifting technique to a back-bending lifting technique.
5		Human-human collaboration	The demonstrator software has this functionality and it is demonstrated in the GKN use case.
6		Collaborate with TOMM2	This goal has been fulfilled. The Scania flywheel use case and Volvo Cars heat cover use case were also the focus in the TOMM2 project. During a period the use cases were available virtually in the software demonstrator developed in this project and physically in a lab at Linköping University (TOMM2).
6		Human-human industry case	This goal has been fulfilled. The GKN use case was a human-human collaboration task.
6		Industry cases human-robot collaboration	This goal has been fulfilled. The project was use case driven and all partners provided uses cases. All use cases were demonstrated at the final presentation. GKN specified a tool change case. Scania specified two use cases: a flywheel assembly case and engine inspection case. Volvo Trucks contributed with a screw tightening task with a smaller collaborative robot, and Volvo Cars with a heat cover assembly task.
3		Method for age consideration	This goal was partly fulfilled. In the demonstrator software, age is not a specific parameter that the tool user can adjust to get different human characteristics. The age effect can to some extent be retrieved by manually adjusting body size measures and degrees of joint range-of-motion (ROM). The more automated consideration of age related human characteristics turned out to be harder to facilitate than expected at project initiation, due to the lack of anthropometric investigations where data of both age, size, ROM and strength are reported, and the few studies that exists show low correlations between age, size, flexibility and strength.
4		Automatic balancing	This goal was partly fulfilled. The software demonstrator provides the functionality to do LUA coding and run multiple simulations. Simulation results that later can be used for optimising work

			station layout design and production balancing. The functionality was demonstrated in a master thesis.
3		Safety methods	This goal was partly fulfilled. The software demonstrator provide the functionality to for instance visualise safety zones.
3		EAWS implemented	The time-dependent ergonomics assessment method EAWS (Ergonomics Assessment Work-Sheet) consists of four parts. One part of EAWS, the one that was possible to be automatized in the demonstrator, was implemented. The implementation of the other parts would have required a lot of manual input from the tool user, which the project wanted to avoid.
3		Human strength and variation implemented	This goal was not fulfilled. Functionality for adjusting manikin strength was not implemented since that turned out to require larger changes of the biomechanics modelling and motion prediction functionality of the digital human model than was appreciated at project initiation. The muscle model available in the software demonstrator at projects start was judged by the project team not to be mature enough to build more advanced functionality upon. More research on muscle modelling is needed before variation in human strength can added. Muscle modelling is included in the follow-up project *VIVA - the Virtual Vehicle Assembler*. A project approved by Vinnova.
1		Dr disputation	This goal is not achieved. The PhD defence was delayed due to several reasons, one was high workload at the company. The PhD defence of the PhD student associated with this project is now planned to be in the fall of 2019.
1		Lic seminar	This goal was not reached. The PhD student recruited in the project left the position.
6		Collaborate with SYMBIO-TIC	The project was not able to start any efficient collaboration with KTH within the EU-project SYMBIO-TIC. This goal was not fulfilled. However, the project collaborated with KTH and Chalmers within the project DYNAMITE (Vinnova). The Scania engine inspection use case was built up at the KTH lab.

6.2 Detailed result descriptions per development work package (WP1 to WP5)

WP1. Demonstrator development

During the project, a software demonstrator was developed to solve the use cases specified by the industry partners. All knowledge gained during the project was integrated in the demonstrator. The software demonstrator was in the end of the project able to simulate use cases of both GKN, Scania, Volvo Cars and Volvo Trucks.

Within the project, Scania focused on a flywheel assembly workstation (Figure 1). In the end of the project, knowledge was integrated in the software demonstrator making it possible to generate decision material of how to design the workstation based on both productivity and worker health (ergonomics). To make this possible, LUA script was used and multiple of simulations with different groups of digital human models, layouts, and hand over positions, were simulated. The results were plotted in a graphs an optimal solutions along the pareto front could be identified.

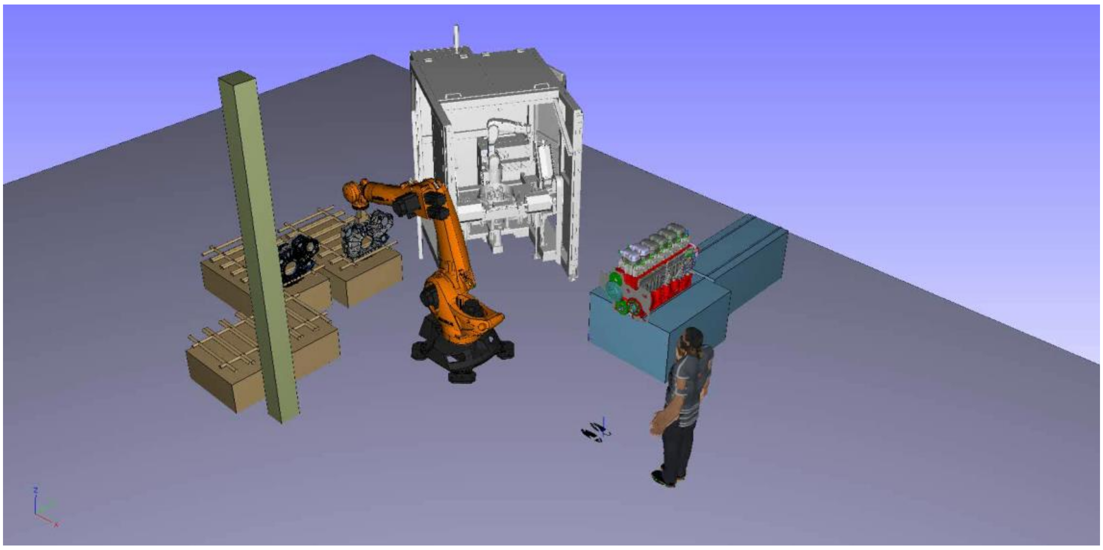

Figure 1. Scania flywheel assembly workstation.

The Volvo Cars use case represented a heat sheet cover assembly, where the operator is assisted by an industrial robot on a continuously driven assembly line (Figure 2). The challenge to simulate industrial robot and human collaboration on a continuously driven line was solved during the project. The use case also illustrated how safety zones can be visualized.

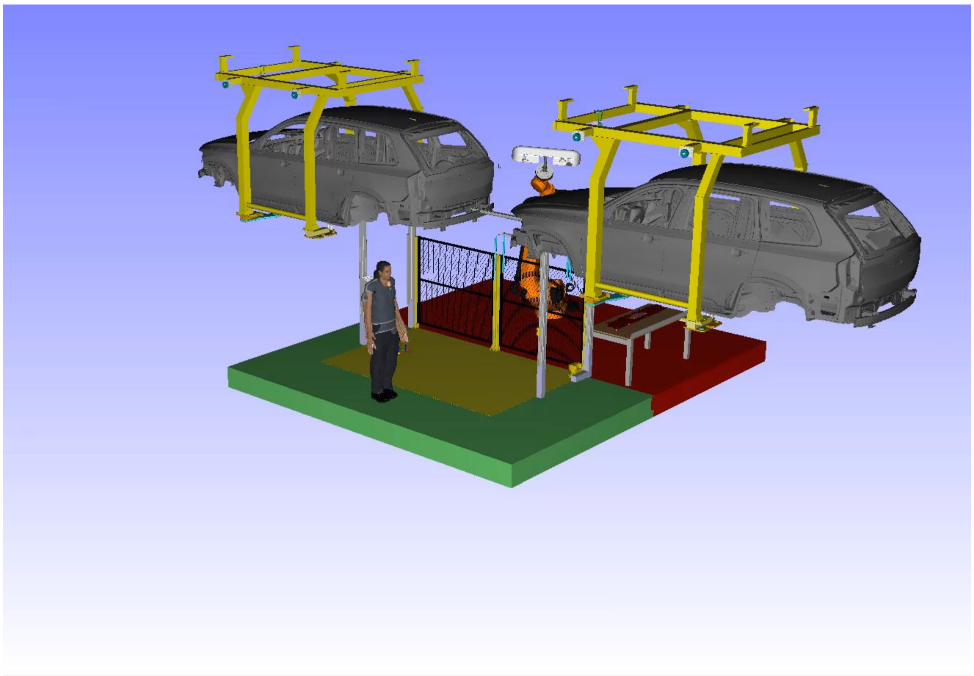

Figure 2. Volvo Cars simulation of heat sheet cover assembly.

The Volvo Trucks use case focused on simulating human-robot collaboration with a smaller collaborative robot (cobot). In the end of the project the software demonstrator was used for designing and evaluating an engine assembly workstation.

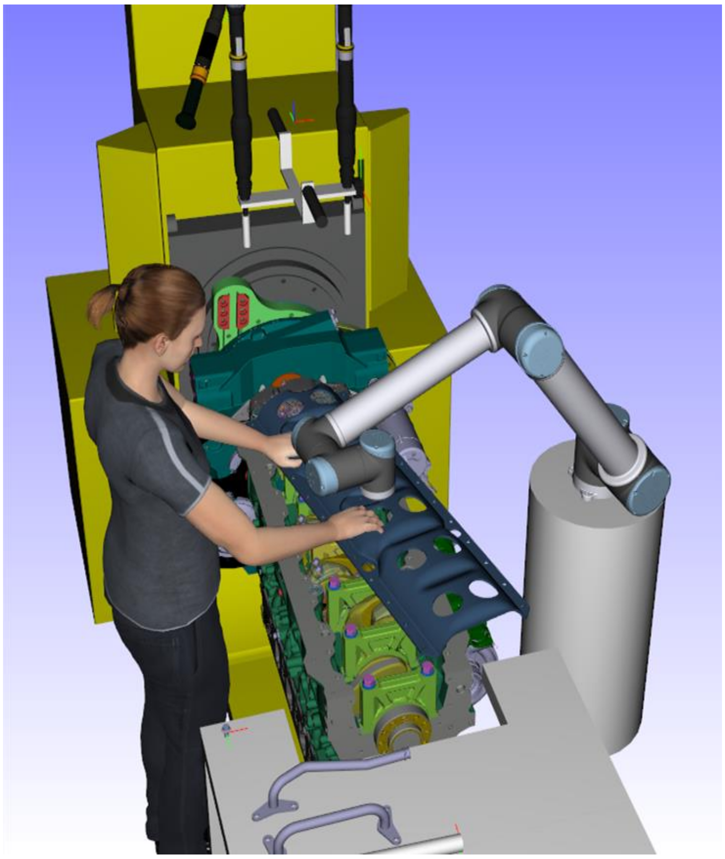

Figure 3. Volvo Trucks use case where a cobot and human collaborate.

The three automotive use cases focused on assembly. The collaborative robot can also be used in other areas. The GKN use case focused on simulating and evaluating a quality inspection workstation, for checking aircraft components (Figure 4).

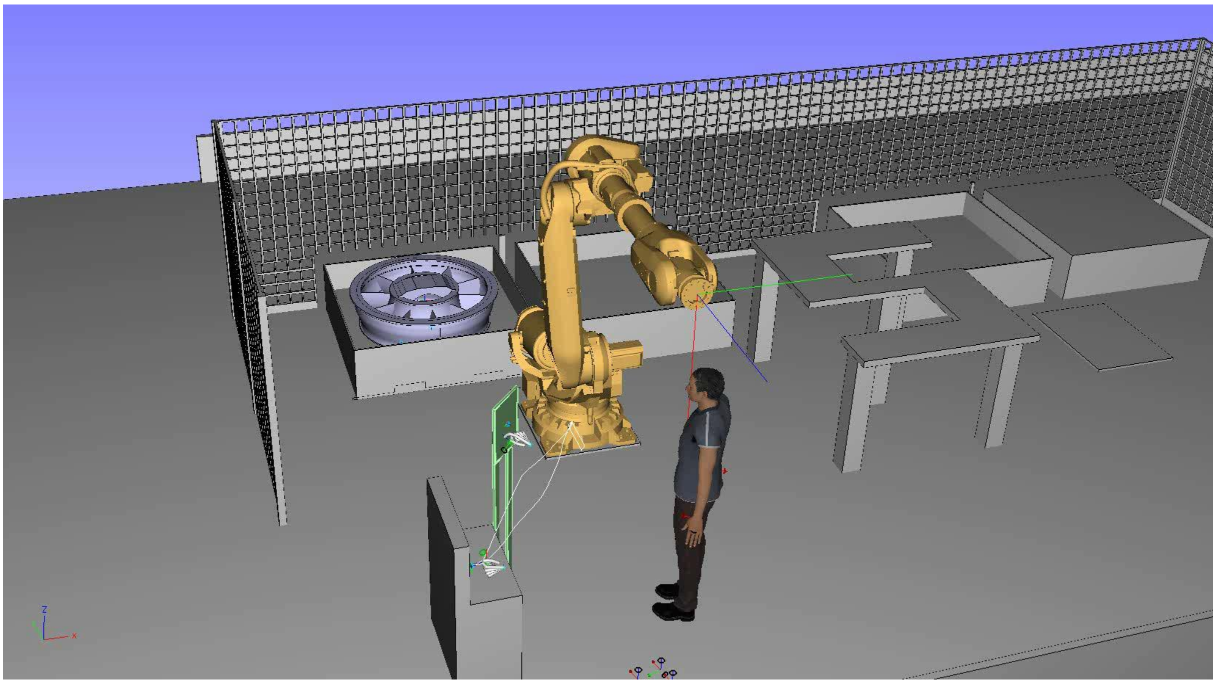

Figure 4. Human-robot collaboration in quality inspection at GKN

WP2. Development of functionality to simultaneously simulate human and robot
The main development has focused on building and extending the existing software platform to support simulation and optimisation of simultaneous collaboration between human and robot. One of the major activities has been the development of an 'attachment' concept with its respective functionalities. This implementation was necessary and allowed the simulation of robot picking and placing objects (e.g. cobots moving screws to an operator), robots carrying objects on pre-specified paths (e.g. robots holding workpieces to be manually assembled by an operator on a moving car body), assembly and disassembly in a time varying environments several objects (e.g. pillars assembled on body in white). The development allowed also the simulation of humans interacting with the robots through the 'attachment' objects. Based on this infrastructure, a simulation engine has been extended to simultaneously handle several actors: humans, robots, and other different objects. The simulation engine works by executing a sequence of operations for each actor, where each operation is defined by a high-level actor specific language. More in detail, the robot has operations like moving, picking, placing, pause, etc., whereas a human will perform grasp, release, walk, look, and other operations. A fundamental development has been the possibility for the user to create custom coded operation by means of a generic programming language (LUA). Another activity has been providing the user, on the top of the software, with an API to perform simulations in a repetitive way and to do process optimisation. Therefore, the user can use the optimisation routines for robot task planning, path planning, and scheduling embedded in the software and combine them with custom routines to handle company specific process information or confidential process designs.

WP3. Study and development of algorithms for simulating human variation and ergonomics assessment methods
All humans are unique and therefore a single digital human model cannot represent all humans. This calls for functionality to easily define representative digital human models, and

to easily incorporate these human models in the subsequent simulations. Work have been done to be able to generate manikins with variation in joint range-of-motion in addition to anthropometric variation. Such functionality has been implemented in a research version of the simulation tool, where it is possible to adjust a manikin or groups of manikins to have low, medium or high joint range-of-motion.
To enable ergonomics assessment through time-dependent, direct measurement influenced, evaluation methods, functionality have been developed through which it is possible to study and visualise torque and angular values in specific joints of the manikin for a complete simulation. A new external software module have been initialised to enable easier and more visually advanced ergonomics assessments in future work, including the possibility to assess work using a number of different ergonomics evaluation methods, depending of company standards, method preferences or type of work.

WP5. Development of functionality to simultaneously simulate human-human collaboration

Task based simulations for the IMMA manikin are generated using the Operation Sequence Editor in IPS. At project start this functionality was restricted to only one manikin at a time. In this project/work package the simulation framework has been expanded to also include multiple manikins, in the same sequence (Figure 5). To be able to compute these simulations, a new simulation engine has been integrated and tested in the simulation framework.
With this engine, it is possible to:

- simulate parallel dependencies between the actors (manikins, robots, rigid bodies, etc.).
- simulate coordinated motions of the manikins.
- simulate interaction between moving actors and moving objects.
- adaptively let actors react to changes in the environment during the simulation.
- customize own subroutines and tasks to be performed within the simulation.

It has been shown that these features greatly improve the simulation capabilities of the operations sequence simulation framework. However, there is still a need for future improvements of the simulation framework. For instance:

- there is a need to update the interaction between the actors, such as:
    - heuristics and strategies for which actors that should react to others and what they should do to cooperate in the workspace when they perform assembly tasks.
    - the automatic collision detection system needs to support multiple manikins collaborating in the same assembly station.
    - develop an interface for sharing e.g. physical data between the different actors, in order to, for instance, allow a manikin to react to the torque of a flexible cable during an assembly.
- the new simulation engine continuously computes all movements and times as the simulation is generated and this is currently not handled by the existing time computation system, which may result in manikin motions that are too fast.
- expand the script support with more commands as well as support for storing creating libraries of customized tasks and subroutines.
- another possible future step could be to implement support for “physical” actors in the simulation framework to allow support for digital twins of robots and humans.
- finally, there exist a need, but also a great potential, to improve the computation speed of the simulations.

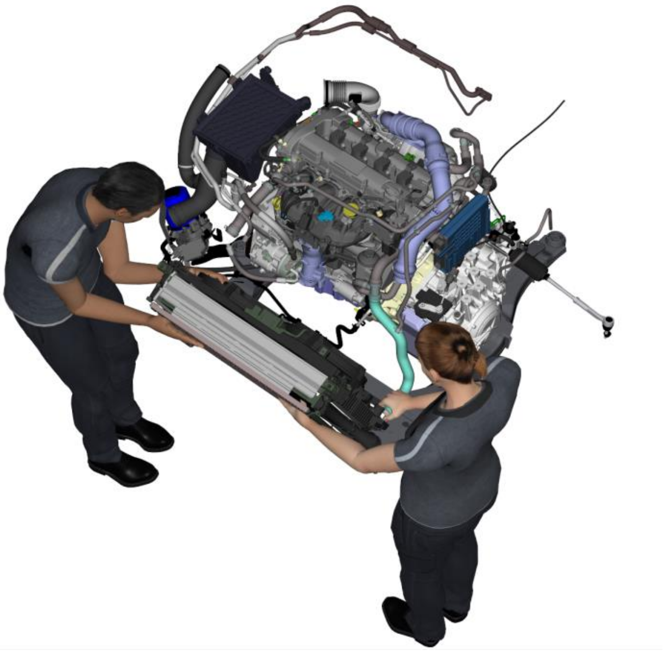

Figure 5. An assembly task where two humans cooperate.

6.3 Result in relation to program goals

The proposed project resulted in a highly automated software demonstrator that can be used in digital production preparation for the optimisation of efficient and human-centred production systems that allow industry partners to:

- predict, visualise and optimise human-robot collaboration. The product and workstation design can be verified by industry to ensure that the design and its production are efficient and are adapted to existing and future worker demographics related challenges.
- increase the efficiency of the product and production preparation process and advance the flexibility to make changes. This by using human-robot collaboration tools for simulation and visualisation early in the design process; using a tool that has the functionality to consider production efficiency in parallel with musculoskeletal load on workers assembling parts on vehicles, or performing similar work tasks.
- increase the efficiency of production. Combining robot strength and endurance with human precision and mind is argued to lead to more efficient and ergonomic production systems. It is well documented that ergonomic designed products and workplaces result in healthy and motivated users and workers, experiencing better comfort and causing fewer work-related musculoskeletal disorders. Additionally, operators working in ergonomic designed workplaces are producing more products (higher productivity) and products with fewer errors (higher quality). Hence, good ergonomics is good economics.
- decrease the environmental impact of the production preparation process and of the production and improve the product and production development process. Using a humanrobot collaboration simulation and visualisation tool in the design process enables a reduction of number of physical prototypes, less production down-time for programming, and also that less workstation redesigns and rebuilds are required. Having robots and workers producing products of high quality being right-first-time leads to less waste and reduced number of rejects, hence less extra parts and energy used in production.

- The proposed project will further strengthen Swedish research through building competence and global exposure, supporting the involved academic partners' position as one of the leading actors in the area of applied robotics as well as applied digital human modelling

The project contributed to the overall FFI program target to reduce manufacturing processes' influence on the environment by making it possible to simulate, visualise and optimise the human-robot collaboration assembly process and by that reduce material and energy consumption. The software demonstrator will also contribute to shorten lead times, better quality and higher competiveness; three areas identified in the FFI Sustainable Production road map. The demonstrator is one of the first software available for human-robot collaboration design and verification. The software demonstrator give the ability to, at an early stage in the product and production development process, prior to any prototype and physical vehicles and workplace are produced, simulate and balance workers' tasks when assembling parts on vehicles. Producing prototypes and physical vehicles for testing requires material and energy, which are not needed when simulation, visualization and optimisation tools are used. Furthermore, simulation and verification in early design phases reduces the development costs as well as costs for unforeseen problems at start of the production of new products in new or existing workstations. Focusing on simulation and visualization as well as virtual factories and workplaces gives access to virtual test arenas for testing and preparing for new installations or for continuous improvements. Having access to such virtual test arenas is crucial since access is rarely available in the real factories as they are aimed to be running on full time all days a week "24/7".

Furthermore, the adaption of products and workplaces to the workers' conditions and the reduction of manufacturing processes' environmental impact will strengthen the competitiveness of the vehicle industry and in the long run secure jobs in Sweden. Finally, providing possibilities to simulate and visualize with computer manikins representing also an elderly population will provide the possibility for industry to analyse how future jobs and workplaces should be designed to meet coming changes in workforce demographics Human-robot collaboration is a rare and unique knowledge area, still with large potentials to improve virtual development processes, and that knowledge area was developed and strengthened by this project. The importance of focus on the human aspect is highlighted in the FFI sustainable production road map. And, in order to improve quality, it is stated in the same document, there is a need to focus research on an effective, safe and seamless cooperation between humans and automatic systems in assembly. The proposed project was in line with these requests and was one of the first project focus on simulation and visualization of human-robot collaboration.
Furthermore it is stated in the FFI document, to stay competitive there is a need for competent, motivated and healthy workers. Using the software demonstration in the design process will contribute to make future human-robot collaboration workstations more attractive and more ergonomic, not causing negative health effects on workers, but rather the opposite.

7 Dissemination

7.1 Dissemination of knowledge and results

How will project finding be used and disseminated?	(mark with X)	Comments
Enhance knowledge within the area	X	Results from the project are included in lectures given to students and in presentations given to industry. Academic findings are presented at conferences, and published in books and peer-reviewed conference proceeding and journals.
Disseminated to other advanced technological development projects	X	The human-robot collaboration software demonstrator will be further developed in the Vinnova FFI project: VIVA - the Virtual Vehicle Assembler (Dnr. 2018-05026).
Disseminated to product development projects	X	The IPS human-robot collaboration software demonstrator is used by the partners. Findings from the project are valuable input for the general development of the commercial IPS software suite.
Introduced on the market	X	The IPS software suite is already available on the market, but is continuously developed and updated versions are released, typically twice per year. The mature parts of the human-robot collaboration software demonstrator will be included in these normal IPS release cycles.
Used in investigations / regulations / permit cases / political decisions		

7.2 Publications

Journal, conference publications and book chapters

- Hanson, L., Högberg, D., Carlson, J.S., Delfs, N., Brolin, E., Mårdberg, P., Spensieri, D., Björkenstam, S., Nyström, J., Ore, F. (2019). Industrial Path Solutions - Intelligently Moving Manikins. In: DHM and Posturography. Scataglini, S. and Paul, G. (Eds.). Elsevier Academic Press. pp. 115-124, ISBN 978-0-12-816713-7.
- Ruiz Castro, P., Högberg, D., Ramsen, H., Bjursten, J., Hanson, L. (2018). Virtual simulation of human-robot collaboration workstations. Proceedings of the 20th Congress of the International Ergonomics Association (IEA 2018), Volume V: Human Simulation and Virtual Environments, Bagnara, S., Tartaglia, R., Albolino. S., Alexander, T., Fujita, Y. (Eds.), pp. 250-261, ISBN 978-3-319-96076-0 (print), 978-3-319-96077-7 (online), DOI https://doi.org/10.1007/978-3-319-96077-7.

- Högberg, D., Brolin, E., Hanson, L. (2018). Concept of Formalized Test Procedure for Proactive Assessment of Ergonomic Value by Digital Human Modelling Tools in Lean Product Development. Advances in Human Factors in Simulation and Modeling. Cassenti, D.N. (Ed.). AHFE Conference, pp. 425-436, ISBN 978-3-319-60590-6.
- Ore, F., Hanson, L., Wiktorsson, M. (2017). Method for design of human-industrial robot collaboration workstations. Procedia Manufacturing, Vol. 11, pp. 4-12.
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- Ore, F., Hanson, L., Wiktorsson, M., Eriksson, Y. (2016). Automation constraints in human–industrial robot collaborative workstation design. Paper presented at the 7th International Swedish Production Symposium, Lund, Sweden.
- Ore, F., Hadialhejazi, G., Hanson, L. (2016). Verification of quantitative human–industrial robot collaborative simulation results. Paper presented at the 7th International Swedish Production Symposium, Lund, Sweden.
- Ore, F., Vemula, B.R., Hanson, L., Wiktorsson, M. (2016). Human - Industrial Robot Collaboration: Application of Simulation Software for Workstation Optimisation. *Procedia CIRP*, Vol. 44. pp. 181-186.

Master theses

- Jimenez Sanchez, J.L. (2019). LUA programming in HRC workstation design. Master Thesis. KTH Royal Institute of Technology.
- Ruiz Castro, P. and Gonzalez, V. (2018). Evaluation of a human-robot collaboration in an industrial workstation. Master Thesis. Halmstad University.
- Asplund, J. and Brile, J. (2017). Application of Human-Industrial Robot Collaboration - Prerequisites and benefits of HIRC. Master Thesis. Chalmers University of Technology.
- Hadialhejazi, G. (2016). Ergonomic Verification of Human-Robot Collaboration - A work environment assessment: employing motion capture and RULA. Master Thesis. KTH Royal Institute of Technology

8 Conclusion and continued research

The research project successfully achieved the main goal; a unique highly automated software demonstrator was developed able to simulate and visualise human-robot collaboration as well as human-human collaboration. The software demonstrator provides the functionality to verify and optimise collaborative workstations considering both ergonomics, safety and productivity in parallel. The industry use case driven approach was successful and gave the researchers challenging tasks and kept the industry partners engaged. The research and development of the software demonstrator will continue in the Vinnova FFI project *VIVA - the Virtual Vehicle Assembler* (Dnr. 2018-05026).

9 Project partners and contact persons

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