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Virtual evaluation of industrial human-robot cooperation: An automotive case study

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Abstract
The manufacturing industries in the developed countries face challenges in terms of increased competition that puts demands on productivity, and a demographic change leading to an older population. One way of managing these challenges is through closer cooperation between human operators and robots. The robots can perform heavy, repetitive and hazardous tasks in a workstation, while the human operator does the more complex and flexible operations.

Most industrial human-robot interaction research focuses on the safety aspects, often performed and presented in the form of physical demonstrators, while little research is made on virtual simulations. Several simulation and visualisation tools for robot evaluation exist, as well as tools for digital human modelling. However, few tools can be found that virtually combines human and robot.

The aim of this paper is to contribute to narrowing that gap by presenting a method for virtual evaluation and optimisation of industrial human-robot cooperation. The new software demonstrator developed for this is based on the DHM tool IMMA. The presented method was implemented in a truck industry case comparing three assembly scenarios; fully manual, fully robotised or human-robot cooperation assembly. The method considers three dimensions which are compared and optimised for the human and robot; reach, operation time and biomechanical load.

The software demonstrator presents a virtual simulation of industrial human-robot cooperation. The result from this simulation can be used to find the optimal ergonomic manufacturing system based on biomechanical loads as well as finding the system with shortest operation time. The specific industrial case verifies the statement that a human-robot collaborative assembly system gives a less physically demanding workstation compared to a manual system, and thus is better adapted to an elderly workforce. This is achieved at the same time as the operation time decreases and productivity increases, which is necessary to meet the global competition. There are though safety issues to be solved and safety standards to be changed before these benefits can be applied in practise in industry. However, the software can be used to analyse different kind of human-robot interactions that are less cooperative and can be implemented within current regulations.

Keywords: Digital Human Modelling, Virtual simulation, Production Design Optimisation, Human-robot interaction, Industrial Robots.

1. Introduction

Two of the major future obstacles for future growth of industries in the developed countries are increased global competition and demographic change. Increased global competition puts higher demand on productivity improvements to compete with the challenges from industries in the emerging markets. The demographic problem arises from two issues; the average life length increases at the same time as the fertility rate decreases, resulting in a negative population growth (UN 2013). This increasing average age of the available workforce has to be addressed by adapting workstations to meet the needs of the elderly. These obstacles can, among other things, be overcome through closer
cooperation between human operators and robots. This is accomplished by introducing robots to perform heavy, repetitive and hazardous operations. Remaining for the human are the more complex and flexible tasks at a workstation. In addition to the possible ergonomic benefits, the general main reason to introduce robots in industry workstations is to increase productivity (Krüger et al. 2009).

1.1. Human-robot interaction

To facilitate interaction between human and robots, barriers surrounding the traditional industry robot cells must be removed. One prerequisite for doing this is to solve the safety issues in order to guarantee personal safety for operators. Most industrial human-robot interaction research focuses on these safety aspects, often performed and presented in the form of physical demonstrators. Some examples of this are presented in Krüger et al. (2009), Morioka and Sakakibara (2010) and Zwicker and Reintart (2013).

Other researchers have also focused directly on the safety system issue, not on creating a physical demonstrator as in the previous examples. Some instances of this can be found in Pedrocchi et al. (2013), Fischer and Henrich (2009) and Schmidt and Wang (2012). The paper by Salmi et al. (2014) is worth a special mention since it presents the state of the art regarding safety in industrial human-robot cooperation. The authors describe the problem of utilising the delivered safety systems in the robots and present a redundant safety system that facilitates cooperation. It includes depth sensors (Kinect), SafetyEye solutions and the internal safety system in the robot. Use of virtual simulation and digital manufacturing tools results in a reduction of development time as well as cost and also facilitates cooperation between different departments in the company (Chryssoulouris et al. 2009). Such tools are in general already an integral part of all engineering activities that take place in a typical manufacturing organisation (Mourtzis et al. 2013). The only paper found on virtual simulation of industrial human-robot cooperation was written by Busch et al. (2013). It presents a welding cell where the human does the welding and the robot holds the objects that are to be united. A character animation system and the software FAMOS are used to create a virtual simulation of the system. The aim is to give a sufficient representation of the human worker to perform collision, visibility and reach analysis and to include biomechanical load analysis of the human in the simulation.

1.2. Digital human modelling tools

Digital human modelling (DHM) tools use computer manikins to simulate, visualise and optimise human product/workplace interaction. A typical full body manikin has more than 100 degrees of freedom and the task of simulating a human body performing a specific task in a specific environment in a natural manner requires many algorithms and extensive computer power due to this complex nature of the human body.

There are a number of commercial digital human modelling (DHM) tools on the market. Some of the most commonly used are AnyBody (Rasmussen, Vondrak et al. 2002), Jack (Webber et al. 1993), Ramsis (Seidl 1997), Safework/DelmiaV5 (Fortin et al. 1990) and Santos (Abdel-Malek et al. 2006). In the production design context all of the existing software is complex to use and demands expertise knowledge and/or a substantial amount of time to produce a representative simulation output (Busch et al. 2013; Fritzsche 2010).

1.3. Robot simulation tools

The main purpose of using robot simulation tools is to create off-line programs for industrial robots. However, the software is also used for optimisation of workspace layout and planning of robot tasks (Pan et al. 2012). The standard industrial robot has six degrees of freedom (DOF). Even in research initiatives the maximum complexity in these robots is 14 DOF; a two-armed robot with seven DOFs on each arm (ABB 2014; Rethink robotics 2014).

There are two types of commercial robotics software, specific ones developed by robot manufacturers and generic ones developed by large digital manufacturing software suppliers. Almost all robot manufacturers have their own specific robotic software; ABB’s software, for example, is named RobotStudio, KUKA’s is called KUKA.Sim (Vollmann 2002) and Motoman’s is named MotoSim. Some of the most commonly used generic software programs are Delmia (Brown 2000), Robcad (Dong et al. 2007) and RoboSim (Lee and ElMaraghy 1990). The general differences between the two types are that the generic ones have better data exchange possibilities than the specific ones. The robot-specific software usually has its own data format that cannot be used in any other system. The advantage of the generic ones comes with a higher cost for licenses (Pan et al. 2012).

One of the problems that users of industrial robots must overcome is the amount of time needed for programming. According to Pan et al (2012) is the programming time approximately 360 times the execution time of a large welding process, and this results in that small to medium sized companies (SMEs) can have problem in investing in a robotised welding cell.

1.4. Combining DHM tools with robotic simulation

In current research, virtual simulation of industrial human-robot cooperation is rarely presented. One possible reason for this is that the possibility for such cooperation has been faint due to safety
legislations (ISO 2011(a); ISO 2011(b)). That is changing as the safety systems controlling such cooperation are evolving. The amount of computer power required to make the needed calculation and present credible graphical representations has also been a limitation that is now being resolved as computer power is becoming increasingly accessible.

1.5. Purpose of this paper

There is an opportunity to introduce new virtual human-robot simulation tools in the present digital manufacturing environment. Research papers presented in the area have their limitations in the evaluation possibilities and the accuracy of the human model. The aim of this paper is to contribute to narrowing that gap by presenting a method for virtual evaluation and optimisation of industrial human-robot cooperation. This is done by combining a DHM and a robotic simulation tool into one software. This is then used in an industrial case where robot and human cooperate in handling heavy (up to 60 kg) components. The case is analysed for three production design parameters, reach possibilities of handling the product, operation time and biomechanical load on operator. The evaluation compares three assembly scenarios: a fully manual station, a fully automated station and a human-robot cooperative station.

2. Method

The method for virtual evaluation of human-robot cooperation was based on new software capable of analysing the human together with the robot. This software was then used in an industrial case where the optimisation possibilities were presented.

2.1. IPS and IMMA tool

The IPS (Industrial Path Solutions) software is a tool for virtually verifying that products can be assembled and subsequently disassembled. It contains methods and algorithms for automatically generate collision free assembly paths. The user can import a scene from almost any CAD system and thereafter set any object as a so called planning object, which IPS will create an efficient path for as long as one exist.

The IMMA software is an expansion to IPS. It is used for verifying that a human can do the assemblies that have been found in IPS. The manikin in IMMA consist of 81 segments connected by 74 joints to give 162 degrees of freedom (Hanson et. al. 2011). To describe operations and facilitate motion generation, the manikin is equipped with coordinate frames attached to end-effectors like hands and feet. The inverse kinematic problem is to find joint values such that the position and orientation of hands and feet matches predefined target frames during an assembly motion (e.g. grip positions). This inverse problem leads to an under-determined system of equations since the number of joints exceeds the end-effectors’ constraints. Due to this redundancy there exist a set of solutions, allowing for picking of a solution that maximizes a scalar valued comfort function.

The robot used is a IRB6620 from ABB and with its six degrees of freedom and a coordinate frame attached to its tool centre point there are eight solutions to each TCP position. This is called solution spaces and the solver should stay in one to fulfil continuity of motion. The software demonstrator presented in this paper uses the IMMA interface and is referred to as IMMA in the text.

2.2. Industrial case

A flywheel cover assembly station at engine assembly at the heavy vehicle manufacturer Scania in Södertälje, Sweden, was simulated and used as an industrial case. In this station the flywheel cover, with a weight of up to 60 kg, is assembled on the engine block. The current assembly is done by a human using a lifting tool.

The current layout was modelled in the IPS software as presented in Figure 1 with three positions of specific interest: Position 1, get flywheel cover from trolley with incoming material. Position 2, load and unload flywheel cover in an automated silicon-applying machine. Position 3, assemble product on an engine block with 12 to 15 screws using manually handled nut runners.

Collison-free paths for the assembly of the flywheel cover were also calculated in IPS.

The layout and paths were imported to IMMA and virtually evaluated in the following five steps: (1) Importing the robot model and optimising the layout in order for the robot to reach all positions, (2) creating robot paths following the collision-free product path, (3) importing the manikins and
implementing human-robot cooperation, (4) creating different assembly scenarios, (5) analysing production design parameters.

2.3. Assembly scenarios

The assembly task was developed into three different scenarios: to be done solely by a human, solely by a robot or as cooperation between human and robot. Solely by a human (H): This case represents the current situation. An operator uses a pneumatic lifting device to tilt the product and move it up and down in the z-direction. The x and y translation is performed through an overhead rail system and is controlled by force from the operator. Solely by a robot (R): This scenario represents a system where a robot reaches all the needed positions and does all the assembly work without human cooperation (except for the tightening of screws at position 3).

Human-robot cooperation (H-R): The cooperation solution aims to combine the best parts of human and robotic performance. The robot does the simple handling tasks which in this case cover positions 1 and 2. In the assembly situation (position 3) the robot movements are controlled by the operator but the robot still carries the load. This is done through force sensors in the robotic joints.

2.4. Production design parameters

Three production design parameters, reach, operation time and biomechanical load were evaluated through every assembly scenario. Reach and access to all assembly positions are vital for designing any workstation. Operation time is often the crucial parameter when choosing one layout before another. The total operation time equals the cycle time of the assembly and comprises human and/or robotic time.

Human time was measured through the work analysis method SAM. It is based on the MTM-1 (method time measurement) method, but groups several MTM-1 movements into one SAM movement. This gives a more simplified analysis method resulting in shorter time to learn and use the system without any significant loss of precision in the output (Laring et al. 2002). The SAM codes on the manikin were extracted from the software, representing the human’s operation time. The robotic time is not included in the software demonstrated. In the case this time was obtained through calculations. The movements of the robot axes were extracted from the software; maximum speeds of the robot axes presented by the specification from the supplier of the ABB IRB 6620 robot. With these two parameters, distance and speed, the time for robot handling was calculated. To consider the acceleration and retardation of axels in the robot, the speed used in the calculation was reduced to 80 % of the maximum speeds from the data sheet. In the case of human-robot cooperation (H-R) the operation time was extracted from the SAM method since the human total control the movement and the fact that the human time is larger than the robotic. Biomechanical load on the operator is an important input in selecting the most appropriate solution. In the presented research the ergonomic evaluation method RULA (Rapid Upper Limb Assessment) is used (McAtamney and Corlett 1993). The result from a RULA analysis is a score that represents a risk level from one to seven, where the higher number indicate a higher risk of injury due to biomechanical loads on the human. From the manikin in the industrial case the joint angles were extracted and analysed with regard to the RULA assessment analysis.

3. Results

3.1. Virtual simulation of human robot cooperation

Human-robot cooperation was modelled in the software demonstrator IMMA, as shown in the screenshot in Figure 2.

Figure 2: Human-robot cooperation created in the software demonstrator IMMA.

The next section describe the results obtain from this software demonstrator.

3.2. Optimisation of production design parameters

The results from the production design parameters reach, operation time and biomechanical load were presented and evaluated through three assembly scenarios: a fully manual station, a fully automated station and a human-robot cooperative station.

3.2.1 Reach

The current layout was first optimised in order to fit the available robot, the ABB robot IRB 6620. The result of this manual optimisation is presented in Figure 3. This layout was then used in the further simulations.
This layout was optimised for the robot, thus making all positions available for the robot to reach. In the fully manual station a lifting device was used that was designed to perform all the operations. This ensures that all positions are possible to reach in all three assembly scenarios.

3.2.2 Operation time
The operation times extracted from SAM and robot data are presented in Table 1. In all these time analyses, the times independent of the assembly scenario are not included (e.g. operation time of the silicon applying machine).

<table>
<thead>
<tr>
<th>Operation</th>
<th>Pos.</th>
<th>R</th>
<th>H</th>
<th>H-R</th>
</tr>
</thead>
<tbody>
<tr>
<td>Get product</td>
<td>1</td>
<td>1.6</td>
<td>10.3</td>
<td>1.6</td>
</tr>
<tr>
<td>Product to silicon</td>
<td>1–2</td>
<td>2.6</td>
<td>11.8</td>
<td>2.6</td>
</tr>
<tr>
<td>Product from silicon</td>
<td>2–3</td>
<td>2.4</td>
<td>8.6</td>
<td>2.4</td>
</tr>
<tr>
<td>Assembly product</td>
<td>3</td>
<td>0.7</td>
<td>7.0</td>
<td>9.5</td>
</tr>
<tr>
<td>Empty robot from assy</td>
<td>3</td>
<td>1.4</td>
<td>N.A.</td>
<td>7.2</td>
</tr>
<tr>
<td>Empty robot home</td>
<td>3–1</td>
<td>0.8</td>
<td>N.A.</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Σ</strong></td>
<td>9.5</td>
<td>37.7</td>
<td>24.1</td>
<td></td>
</tr>
</tbody>
</table>

3.2.3 Biomechanical load
Biomechanical load analysis based on RULA method of the two assembly cases that include humans are presented in Table 2 and Table 3. In Table 2 the human work alone and in Table 3 the human work together with a robot. In the average score in the tables have also the time spent in the operations from Table 1 been considered, and therefore are the averages not possible to calculate directly from Table 2 and 3.

Table 2: Biomechanical load analysis for human assembly, based on RULA. The numbers in the table represent the amount of time spent in each ergonomic zone in percentages.

<table>
<thead>
<tr>
<th>Operation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Get product</td>
<td>0</td>
<td>1</td>
<td>27</td>
<td>72</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product to silicon</td>
<td>0</td>
<td>0</td>
<td>39</td>
<td>10</td>
<td>51</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Product from silicon</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>64</td>
<td>26</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Assembly product</td>
<td>0</td>
<td>0</td>
<td>13</td>
<td>30</td>
<td>14</td>
<td>43</td>
<td>0</td>
</tr>
<tr>
<td>Empty robot from assy</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Empty robot home</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td><strong>Average score</strong></td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>46</td>
<td>13</td>
<td>34</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 3: Biomechanical load analysis for human-robot cooperative assembly, based on RULA. The numbers in the table represent the amount of time spent in each ergonomic zone in percentages. R represents operation performed solely by robot.

<table>
<thead>
<tr>
<th>Operation</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Get product</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Product to silicon</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Product from silicon</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td>Assembly product</td>
<td>0</td>
<td>1</td>
<td>18</td>
<td>41</td>
<td>40</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Empty robot from assy</td>
<td>0</td>
<td>0</td>
<td>38</td>
<td>38</td>
<td>23</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Empty robot home</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
<td>R</td>
</tr>
<tr>
<td><strong>Average score</strong></td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>39</td>
<td>41</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

4. Discussion
4.1. Software demonstrator
The software demonstrator presented in this paper simulates human-robot cooperation virtually. Different types of human-robot interaction in a work system are possible to simulate. These can include systems where human and robots do not share workspaces (even in the absence of physical barriers), systems with a shared workspace and completely collaborative systems as presented in the industrial case in this paper. In all these applications there is a need to optimise the system regarding production design parameters. The software demonstrator is easy to use and don’t demand any expert knowledge. Realistic movements of humans and robots are performed with relatively little effort in the software.

4.2. Optimisation of industrial case
The results from the industrial case validate the assumed benefits of human-robot cooperation, both the ergonomic situation of the operator is better and the productivity of the station is increased from human-robot cooperation compared to worker working without support from robot.
4.2.1 Productivity
Productivity is measured through operation time of the assembly station in this paper. Table 1 clearly shows that the total operation time of the station is lowest in the sole robot assembly situation. This result can be considered common knowledge, that speed of robot movements is higher than of human movements. A possible advantage of using humans in the operations is to use the flexibility and intelligent decision making that is more difficult for a robot to deliver.

In the case presented in this paper is a fully robotised station not a realistic alternative of two reasons. Firstly, the loading position for the engine block is not fixed. It can vary up to 10 mm. Secondly and more important, at least two operators are doing other assembly tasks on the engine block and it is difficult to find a safe assembly sequence if the robot moves without human interaction.

It is very difficult to assess suitable velocity to use in calculation of robot speed. In this paper 80 % of the presented maximum speed of the robot axis was chosen based on discussions with experienced robot programmers. It demands a lot of calculations on acceleration and retardation to get a more precise number. However the breakpoint when H-R cooperation and manual assembly have the same operation time is when the robot speed is as low as 40 % of the maximum. Actual speed of the robot axis used in industry is rarely in that low ranges.

One other productivity improvement is that it releases the human assembly operator to recover or perform other task. For each assembly sequence is the time spent by the operator reduced by half, from 38 to 17 seconds.

The case presented shows that the productivity improvement of utilising robots in industry stated by Krüger et al. (2009) also is valid in human-robot cooperation.

4.2.2 Biomechanical load
The RULA analysis performed shows that the biomechanical loads on the operators give the average score of 4,7 on the manual assembly station compared to 4,2 on the human-robot cooperative. Comparing table 2 and 3 shows that one major reason to this differences is the assembly operation where the manikin in the human assembly get a RULA score of 6 in 43 percentages of the assembly time, compared to the cooperative system, where the maximum score is 5 (in 40%). The major part of this difference come from the actual assembly position where the manual lifting device demands high positions of arms compared to the cooperative case, which is presented in figure 4.

This difference shows that the collaborative assembly system contains fewer risk factors to future biomechanical load injuries on the operator. This lower score compared to a manual station are also interpreted to that the station include less physical demanding operations, and thus is better adapted to an elderly workforce. Even if the result is improving with human-robot cooperation, these scores also indicate that further investigations may be needed. These further optimisations of the biomechanical loads are not included in this paper.

4.2.3 Safety
It is important to emphasise that the human-robot cooperation presented cannot be realised in industry with current safety regulations. In the case presented has 80 % of the maximum speed of robot been used in the area marked by the red box in Figure 5, that is when it do not cooperate with the manikin.

![Different assembly positions between manual assembly (right picture) and human-robot cooperative assembly (left picture).](image)

The close distance between this area and the human working area indicate the need of advanced safety systems that can deliver a safe work environment for the operator. But as the safety regulations are stated today physical barriers are the only possible way to design this kind of close workspaces between an industrial robot handling 60 kg and a manual operator.  

![The red box presents the area where the robot works without human cooperation and moves without speed limitations.](image)
4.2.4 DHM and robotic simulation
This industrial case illustrates the potentials of a virtual human-robot simulation with optimisation possibilities. It is possible to make early production design evaluations of complex workstations including human and robot and optimise the design of the parameters that is of interest to the user. The simulation can also be used to discuss and evaluate safety solutions and perform risk assessments.

4.3. Future research
In addition to the parameters presented in this paper (reach, operation time and biomechanical load), also robot selection, robot placement, factory surface utilisation and total operation cost can be included. All of these factors are of importance and possible to calculate, evaluate and optimise from a virtual simulation of human-robot cooperation. These possibilities will be further examined and developed in our future research.

5. Conclusion
The software demonstrator presented shows a method to simulate industrial human-robot cooperation virtually. This tool is used in order to optimise the workstation regarding reach, biomechanical load and operation time. The personal safety problem has to be resolved before the benefits of human-robot cooperation can be fully reaped; much research is undertaken and efforts are made by the robot suppliers to solve this issue. When this has been done, the possible benefits will be huge and the need of software to simulate cooperation will be strong. The future development of the tool aims to improve the output from the software in order to facilitate the optimisation as well as to introduce more optimisation parameters.

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