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Identifying the Potential of Human-Robot Collaboration in Automotive Assembly Lines using a Standardised Work Description

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***Abstract*—The increased availability of sensitive and compliant lightweight robots for use in assembly lines collaborating with the human promises significant improvements of different socio-technical aspects of work. Workplaces can be reorganized to assign monotonous or unergonomic tasks to the robot. Also unproductive jobs currently done by the human can be minimized by an improved work distribution. Since there is only little experience with the new generation of collaborating robots, the implementation of workplaces shared by human and robot is often influenced by subjective perspectives. In this paper, an approach to assess the collaboration potential of workplaces is presented. Based on existing standardised work descriptions, the suitability for human-robot collaboration can be derived and therefore a more objective evaluation and comparison of the whole assembly can be achieved.**

***Index Terms*—Human Robot Interaction, Future Work, Mass Production, Mass Customization, Automation Potential, Assembly, Methods Time Measurement (MTM)**

I. Introduction

Producing an increasing number of variants of cars with the product cycles becoming shorter at the same time is a major challenge for the automotive industry. Manufacturing needs to become smarter and more flexible in order to face the increasing complexity of processes. A recent development is the implementation of hybrid teams of human workers and robots in workplaces of the final assembly [19]. Humans and robots are no longer separated through fences but work together in an intelligent way sharing the same workspace. By individually adapting each process step of human robot interaction an optimal degree of automated assistance can be achieved. The potential of combining the strengths of humans (i.e. fast adaptation to new situations and independent problem solving) and robots (i.e. endurance, speed, precision) is obvious [3]. Processes become more efficient at higher quality while ergonomics are improved and the flexibility of the whole production system is increased. However, there are a number of challenges in order to implement collaboration teams of humans and robots in manufacturing plants. Not all processes are suited equally for humans and robots working in close collaboration. Therefore, strategies for assigning the assistance system to the right workplace are needed in order to assess the benefits promised by human-robot collaboration (HRC).

In this work, an approach to identify assembly steps with potential amelioration by HRC is presented. Taking existing standardised work descriptions as a basis, the automation potential for HRC is calculated for each workplace. The work description is encoded with the Methods Time Measurement (MTM) method. MTM is a tool to predetermine the time for human work, which is commonly used in automotive industry. The analysed data are taken from a final assembly line of a production plant within the Volkswagen Group. For promising workplaces benefits like improvements in ergonomics are analysed and the overall potential for the whole production is estimated.

The sections are structured as follows. In the following chapter, an overview on current issues in physical human-robot interaction in industry is given. Further the latest robots suitable for collaboration and applications thereof are reviewed. In the methodology part, the approach to find a score for workplaces, indicating the suitability for the implementation of HRC, is explained in detail. Then the results from the analysis are presented and discussed. Finally, an interpretation of the achieved results and an outlook on future work are given.

II. State of the Art

In physical human-robot interaction, safety of the worker is the main concern and must be considered when evaluating the HRC potential of workplaces. There are several possibilities to guarantee the safety for humans working together with robots in assembly lines. A good overview is given by Alami et al. [2] and also by Elkmann [6]. A common approach is to observe the workspace shared by human and robot in order to prevent collisions. Schmidt et al. [20, 21] presented an approach of active collision avoidance based on information from depth cameras. Kaldestad et al. [11] developed a collision avoidance strategy with potential fields that are based on parallel processing of 3D-point cloud data. Vogel et al. [23] implemented safe physical human-robot collaboration through a projection-based safety system. Another, more complex approach is to minimize the damage potential of a robot interacting with a human.

This is usually achieved through robots operating in an impedance mode, where joints are controlled in such a way that they show a compliant behaviour. In this context, Krüger et al. [13] presented a robust control of force-coupled human-robot interaction in assembly processes and Duchaine et al. [5] worked on safe, stable and intuitive control for physical

TABLE I
SPECIFICATIONS OF COLLABORATIVE ROBOTS USED IN AUTOMOTIVE ASSEMBLY LINES

Manufacturer	KUKA [14]	Universal Robots [18]	Gomtec [8] (ABB)	Fanuc [7]	Bosch [4]
Model	iiwa	UR5 / UR10	Roberta	CR35 iA	APAS assistant
Axes	7	6	6	6	6
Payload [kg]	7 / 14	5 / 10	8 / 12	35	2
Reach [mm]	911 / 931	850 / 1300	800 / 1200	1813	911
Technology	Torque sensors in all joints	Motor current monitoring	Torque sensors in all joints	6 DOF load cell in soket	Capacitive sensor skin

human-robot interaction. Furthermore the interaction of humans with robots requires techniques to detect collisions and react safely as presented by Luca et al. [15] and Haddadin et al. [9]. The advantage of robots performing movements with reduced damping and low stiffness is the possibility to interact with humans without posing any danger. The difficulty is that the robot has to know what potential damage it can cause to its human partner as stated by Haddadin et al. [10]. This includes the assessment of tools and parts used during the production process, as well as the environment in which the interaction takes place. It is clear that the insights have to be considered when analysing the potential of workplaces for automation with HRC.

Although the physical human-robot interaction is still a field of research, applications in assembly lines can already be found in the literature. Krger et al. [12] provide a good overview of possible applications of human- robot cooperation in assembly lines. Michalos et al. [16] aim at the integration of the latest automation technology in assembly lines. Within the project ROBO-PARTNER, the strengths from humans and robots are combined in a hybrid solution that would allow the safe implementation of human-robot cooperation in future factories. Müller et al. [17] present an application in a final assembly line, where a cooperative robot is assisting the water leakage test. From the Volkswagen Group, Audi [1] presented an assistance robot that picks components from a transport box and passes it to the worker, so that the worker is relieved from bending down for each part.

In order to evaluate workplaces of the assembly line, the characteristics of the latest robots for physical human robot interaction have to be known. In Tab. I, an overview of the most popular systems and their properties are given. The results from this product research are used later to define the capabilities of a universal assembly assistant.

III. METHODOLOGY

In order to determine the automation potential for the use of HRC, the approach is divided in three steps. First, an automation potential for each single movement within the whole assembly is estimated. Then, a score is calculated for each movement depending on the frequency of occurrence in a realistic product mix. Finally the scores of the movements are summarized in order to get scores for all workplaces within the assembly line.

A. Description of the data basis

The data analysed in this work originate from the work descriptions for logistic and assembly processes at the Volkswagen Group. The database for industrial engineering, containing the tasks of all human workplaces, can be used for two main applications:

- Describe human work using the Methods Time Measurement Universal Analysis System (MTM-UAS) Method in the time domain
- Provide links to other resources related to the workplaces (e.g. workpieces, tools, ergonomic load data)

The analysed data are structured hierarchically and ranges from the level of a whole assembly line down to single movements a specific worker has to do at a particular workplace at some point in time. In this work, the focus lies on the quantitative description of the human work in the time domain. The work to be conducted by one worker at a workplace in one cycle is split into descriptions related to different product variants of cars. For each variant, multiple work processes are grouped and weighted according to their frequency of occurrence during a complete shift (e.g. assembly occurs in every cycle, renewing tools only every 100 cycles). On the lowest level, movements are described using the MTM-UAS categories and characterized with the respective amount of time for execution.

B. Methods Time Measurement

The Methods Time Measurement (MTM) is a base tool to predetermine the time, a human workers needs to execute a task in industrial work [22]. Simple core tasks, which can be used to synthesize all complex work steps, are defined with their measured and fixed time needed to perform. A variant of MTM, which is often used in industrial production, is MTM-UAS [24]. It groups the original core tasks to a new set of task-groups which occur in the respective field of production. Based on the intensity and the duration of a task, a time value is assigned respectively. The time value is described as a multitude of the Time Measurement Unit (TMU, $1\text{TMU} = 0.036s$), which is the smallest time span identified in MTM. By combining movements of different categories, tasks performed by humans can accurately be described and the time needed can be calculated in a standardized way, e.g. to calculate expected labour costs for an manual assembly process.

C. Estimation of automation potential for movements

As described, the processes within one workplace consist of one or more movements. The movements are described by MTM-codes that belong to different categories. An automation potential is proposed for each code and therefore for each type of movement in order to estimate to which extent the movement can be assisted or performed by a sensitive robot. It is assumed that a universal collaborative robot is implemented with specifications comparable to recent systems shown in Tab. I.

Furthermore, aspects of specific implementations such as safety, reachability of work pieces, equipment of gripper and vision systems are not in the scope of this estimation.

TABLE II
ASSIGNED COLOUR OF ALL MTM-UAS CATEGORIES AND THE DEFINED HUMAN-ROBOT COLLABORATION POTENTIAL OF THE DIFFERENT TYPES OF MOVEMENT IN EACH CATEGORY

Category (Color)	**Movement Description**	**Potential [%]**
Pick	Up to 1kg / Easy-to-pick form	100
	Up to 1kg / Hard-to-pick form	25
	Up to 1kg / Hand-full	0
	Up to 8kg / Average form	75
	Up to 22kg / Average form	50
Place	Approximate	100
	Loose	75
	Tight	25
Sequence	Special Movement	25
	Adjust / Align	0
	Replace	0
	Attach / Release	100
Move	Walk	25
	Bend / Raise	50
	Sit / Stand up	75
Handle	Approximate	75
	Loose	75
	Tight	25
Trigger	Easy	0
	Combined	0
Check	Visual	50
Process	Wait	50

1) Pick: The picking task is probably the most crucial movement in order to evaluate the suitability of a workplace for robotic assistance. Each process contains one or more parts or tools that the robot has to pick and handle. Therefore the differentiation within the picking category is very detailed and takes two parameters of the object into account, namely the form and the weight of the work piece (compare Tab. II). Its form has the highest impact on the potential since it is assumed that the object has to be picked by a universal gripper. Also the weight has an impact on the potential, because the payload of the robot must not be exceeded. For small objects that are less than one kilogram, the weight is not enough information to characterize the gripping potential. It has to be described how the object can be picked. For heavier parts it is acceptable to assume a medium suitability since they have a certain volume, which automatically makes the parts easier to handle. The potential for picking a lightweight object with an easy shape is defined to be at 100%. This can for example be a small tool or car component that fits in one hand. Limp parts, for example cables or tubes are considered difficult to pick and therefore are assigned a very low potential of 25%. Picking a hand full of small parts, for example a number of clips is usually not possible for a robot and has therefore no potential. Medium weight parts can easily be picked, so their potential is high at 75%. For heavy parts, the robot payload has to be sufficient, so their potential is estimated at 50%.

2) Place: After an object has been picked, it usually has to be placed somewhere again. The potential for this category is divided in three types of movement to describe different accuracies for placing an object (compare Tab. II). The potential of approximate placing of an object (e.g. place a screwdriver on a table) is estimated at 100% because it is an easy task to perform for any robot. Placing an object in a loose position means that the object fits in a predefined form with high tolerances. This task is slightly more difficult for a robot, but still at a potential of 75%. Placing an object into a tight form can be very difficult since blockage and, depending on the robustness of the part, breaking of the part can occur. The potential therefore is estimated at only 25%.

3) Move: Movements of the whole body of the worker are summarized in the category *move*. The codes are used to describe changes in position and pose of the worker (compare Tab. II). The potential of assisting a worker in walking is estimated low because in a human-robot shared environment the robot has legally a maximum speed that is not very efficient compared to a human. Changes in pose of the worker like bending or sitting are assumed easy for a robot but burdening for a human. The potentials are therefore set to 25% for walking, 50% for bending, and 75% for sitting.

4) Sequence: The category *sequence* combines a number of specific movements that do not fit into any other category. The codes for special movements are used for tasks that are accomplished in one movement but cannot be described by any other basic movement or a combination of basic movements (compare Tab. II). An example for this code of movement is to open a screw cap or to feed a cable through a hole. The special movements can be very difficult for a robot to perform, but also include simpler sequences and are therefore rated at 25%. Adjusting or replacing are correcting tasks and referred to the human worker. On the other hand the attaching or releasing of an object, for example push in a clip, requires only a simple movement and its potential is 100%.

5) Handle: In the handling category the movements to handle equipment are combined. Like the category *place*, the handling category is divided into three different codes of movement (compare Tab. II). The codes for approximate and loose handling describe almost the same type of movement and are therefore both rated at 75% potential. In most cases a screwdriver has to be handled that either lies on a surface or is stored in a holder. Handling equipment within tight tolerances is still possible for a robot but more difficult and therefore given a potential of 25%.

6) Trigger: Although trigger a button or activate a process via system control is an easy task for any robot, these tasks should be performed by the worker. This assures that the final clearance is done by the human, which has the highest understanding of the process. The assistance potential within the trigger category is therefore set to zero (compare Tab. II).

7) Check: There is only one code for visual inspection in the check category, which accounts for a large number of different situations (compare Tab. II). Sometimes it is very easy to replace a visual inspection by a camera and image processing algorithm, but a general statement is difficult to make. Therefore the mean potential is assumed at 50%.

8) Process: Process time, e.g. the filling of a tank with fuel, cannot be influenced by a worker or robot. When the worker has to wait for a process to finish he is not able to perform another task in parallel. In this case, the automation potential depends on the previous task and is therefore set to the mean value of 50% (compare Tab. II).

D. Score calculation

After defining the potential for each type of movement, a score is calculated for each movement in the whole assembly line. The score of of a movement (S_m) is defined as product of the potential (p_m), the duration (t_m), and the relative frequency of occurrence per cycle (f_m):

$$S_m = p_m \cdot t_m \cdot f_m \tag{1}$$

Then the scores can be summarized over a multitude of movements to evaluate the score of a whole process, a workplace, or even multiple workplaces in order to compare the HRC potential of different workplaces within an assembly line:

$$S_W = \frac{1}{T \cdot n_w \cdot n_c} \cdot \sum S_m \tag{2}$$

The score of a workplace (S_W) is calculated by the sum of the scores of the movements performed during one cycle in the workplace (compare Eq. 1), normalized by the cycle time (T), the number of workers that work in one workplace (n_w), and by the number of cycles the workplace is designed for (n_c).

IV. Evaluation

A. Analysis of suitability of workplaces

After calculating the scores for all movements, the suitability of workplaces and their processes for HRC can be evaluated. In Fig. 1, the potential for robot assistance of two workplaces from an assembly line at the Volkswagen Group is visualized. Diagram (a) on the left represents a workplace where multiple easy sized parts are assembled and fixed with clips. The cycle starts by the worker walking to the next car (segment 1, category *move*). Then, the workpiece is picked up (segment 2, category *pick*) and placed at the assembly position

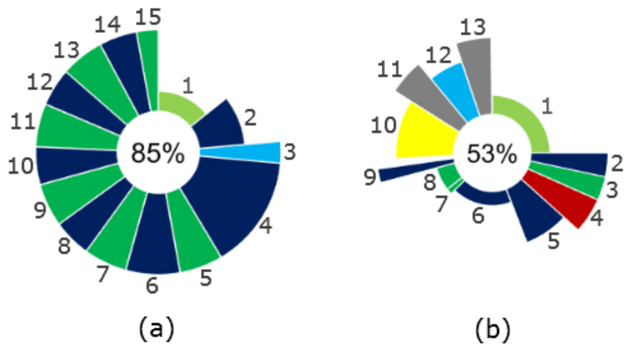

Fig. 1. Diagrams of two workplaces with different potentials for human-robot collaboration. The angular axis represents the duration of the movements within a production cycle with their corresponding potential on the radial axis. The numbered segments represent different movements in order to accomplish a task and are explained in section IV-A. The colour shows the category of each movement as presented in Tab. II. In the centre of the diagram, the score is shown relative to the maximum reachable value within one production cycle (compare Eq. 2).

on the car (segment 3, category *place*). Finally, the workpiece is fixed with six clips that have to be picked up (segment 4/6/..., category *pick*) and attached to the workpiece (segment 5/7/..., category *sequence*). The pick operation of the first clip is assigned a longer process time since the distance from the assembly point of the workpiece to the first clip is longer than the distance between the single clips. These steps can easily be assisted by a robot, as it can be seen from the visualization. Therefore, the workstation reaches a high potential of 85% for the implementation of HRC.

In diagram (b), a difficult to assist workplace is shown. The walking distance to the next car is again the first process in the cycle (segment 1, category *move*). Then, a fixation of a tube has to be attached and checked (segments 2-4, categories *pick/sequence/check*). Afterwards, a limb cable tree has to be picked up (segments 5-6, category *pick*) and is mounted in a difficult movement in the car (segments 7-8, category *sequence*). Finally another workpiece has to be picked up (segment 9, category *pick*) and transported to the other side of the car (segment 10, category *handle*) with a short waiting time (segment 11/13, category *process*) before and after mounting it on the car (segment 12, category *place*). As it can be seen from Fig. 1, the combination of complex and flexible parts in this workplace lead to a low relative potential of only 53%.

In Fig. 2, results form the analysis of a complete assembly line are shown. It can be seen from Diagram (a) that more than half of the workplaces in the assembly line have a potential that is higher than 50%, which means that more than half of the movements in these workplaces are suitable for automated assistance by a robot. This means that more than half of the workplaces in the analysed assembly line are suitable for HRC. Diagram (b) shows that the highest assistance potential is for the category *process*, but also *pick*, *place*, and *sequence* movements have a high potential. The mean potential of the whole assembly line is found to be 34%.

B. Impacts on ergonomics and quality of work

Not only cost and time, but also ergonomics and the quality of work can be positively affected by implementing assistant robots in assembly lines. All human work that is described in industrial assembly lines can be classified as either a value creating task (e.g. assembly) or a supporting task (e.g. preparation, walkways). The quality of work for a workplace is higher the more value creating, primary tasks are to be conducted.

When looking at the whole assembly line the total time spent, to build one car (excluding work in paint-shop and body-shop), is divided into 60% primary and 40% secondary tasks respectively. The score (see Eq. 1) gives an estimation of how many of the tasks can be automated to a certain extend. If both task types (primary, secondary) have equal automation potential the portion of the score contributed by secondary tasks should be the same as the portion of time spent for secondary tasks. On the given data, this is not the case: 31% of the cumulated score is attributed to secondary tasks while they take 40% of the time. In order to optimize the support and improve the quality of work for the human worker, the robot should best be applied to this secondary tasks. Taking the time and score values of primary and secondary tasks into account it can be concluded, that primary tasks are more promising for automation. They have a slightly higher rate of automation potential for HRC per TMU than secondary tasks. This can be explained by looking at the original data: Secondary tasks are walking, triggering and waiting tasks (see section III-C6), which are assigned a low potential for automation. Nonetheless there are still secondary tasks, where a HRC application will be beneficial, e.g. logistic processes in the vicinity of the assembly location (handling, picking). These tasks are also classified as a non-value creating and can be implemented by a robotic system.

A simple comparison of the ergonomic points and the potential of the movements shows that over the whole production, ergonomics can be lowered by 36% on average. By assigning the tasks with high value creation to the human in the team, satisfaction and motivation can be increased while achieving a higher effectivity of the personnel.

V. Discussion & Outlook

In this work, an approach to assess human work for robotic assistance is presented. The use of categories from existing work descriptions allows the estimation of an overall HRC potential of a production line. It is shown that there is a big potential for robotic assistance in today's assembly that promises substantial improvements in ergonomics, quality of work, cost, and time. The approach can also be used, to get insights into categories of work, which are most promising for automation using a HRC application. This aids the cost efficient and productive implementation of future workplaces.

A. Add more data sources

The analysis of the work description is dealing only with the MTM-description of manual work. In order to form a more complete view on the specific workplace other data sources have to be integrated and correlated with the given time information. For example the physical layout and dimensions of the given workspace have a big influence on the feasibility of the implementation.

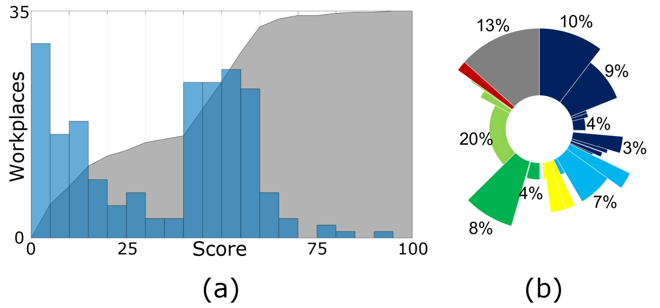

Fig. 2. Results of the analysis of a complete assembly line at a Volkswagen plant. The modified pareto diagram on the left shows a histogram (blue) of the absolute number of Workplaces ordered by score and the share of workplaces that are below this score (grey). On the right diagram, the distribution of the categories for all movements in one production line is visualized.

B. Combine multiple workplaces

In present automotive assembly lines tasks in a workplace are optimized to fill the cycle time of the worker. Since HRC is a new concept in production, the job contents of one workplace are not automatically suitable for a hybrid team which explains the high number of workplaces with a very low potential. For this reason, a rearrangement of tasks is necessary. Also there is no financial benefit of implementing an assistive robot in a single workplace while keeping the work content at the same level. It is therefore not appropriate to evaluate the integration of HRC only on a workplace level, but combinations of multiple workplaces should be considered.

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