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Rapid and highly detailed productivity analyses for assembly processes using motion capture systems

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Abstract

The major part of industrial assembly processes is carried out manually. Therefore, it is very important to design the workplace and the assembly processes ergonomically and productively in order to protect the workers and to ensure high labour productivity. However, many methods of analysing ergonomics and productivity require a high level of manual effort, as they are very complex and need a large amount of data to be captured. This article focuses on analysing productivity in assembly processes and presents a concept for capturing the data for productivity analyses with a motion capture system and evaluating the results with a digital assistance system. This allows the productivity of a work system to be analysed rapidly and with little effort so that workstation and process design can be improved.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

1.1. Motivation

According to a study by Hu et al., the percentage of manual labour in companies is 72%. Consequently, companies can still achieve a competitive advantage through high labour productivity [1]. To achieve this, companies should design workplaces ergonomically and economically and should adapt work to people. When designing a work system, aspects such as work and operating equipment, work task, work process, work environment and work place must be taken into account. Ergonomics and efficiency are with some exceptions mutually reinforcing [2]. Our goal is to analyse ergonomics and productivity simultaneously by feeding motion data into a digital assistance system which can perform standard ergonomics and productivity analyses. We have presented a concept for ergonomic analyses in [3] [3]. This paper is therefore focused on productivity. Productivity analyses are used, for example, to determine standard times or to identify waste and should be carried out again regularly to continuously improve processes [4, 5]. As even a single productivity analysis is very time-consuming (about 200 minutes are required to analyse a one-minute movement sequence in the basic MTM-1 method [6]), it is hardly possible to carry out these analyses frequently at an economically acceptable cost. In addition, subjective expert knowledge is usually required for each analysis. Consequently, the limited number of industrial engineers can usually carry out only a fraction of the analyses required, leaving a big proportion of the existing productivity potential unexploited.

A large number of productivity analyses have in common that, for example, movement elements (reaching, moving, etc.) or movement lengths must be recorded. Manual recording of this data involves a high level of effort. Motion capture systems (mocap systems) can be used to capture this data automatically. This article presents a concept that uses an electromechanical mocap system to capture data for productivity analyses, which can then be processed using a digital assistance system and enhanced with additional metadata so that productivity analyses can be carried out automatically. The system enables companies to carry out productivity analyses rapidly and to evaluate the results soon after, with minimal subjective expert knowledge required throughout the process.

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1.2. Structure of the paper

After the introduction, productivity analyses, mocap systems and digital assistance systems, the MTMmotion interface and the research gap are presented in the current state of research. Building on this, the concept and implementation of the process analysis is presented. The article concludes with a summary of the results and a description of current limitations and the outlook.

2. Current state of research

2.1. Productivity analyses

Productivity is the ratio of output to input. As the focus of this contribution is manual labour, we use labour productivity and relate the output in pieces to the labour input, which is measured in paid hours worked [7].

There are a number of work system related methods that can be used to analyse labour productivity in detail. These include established time management methods such as the MTM methods. The MTM process building block systems such as MTM-1 or MTM-UAS are used to determine the standard times for work processes. When using these methods, a work process is divided into basic movements (MTM-1) or basic tasks (UAS) with defined standard times [5].

Further analyses used in this article are the primary-secondary analysis and line balancing.

2.2. Digital assistance systems and motion capture sytems

Digital assistance systems support people in their activities by helping them to recognise and analyse information [8]. The Institute of Production Management and Technology has been developing digital assistance systems in areas such as maintenance, service, assembly and collaboration since 2012. In recent years, our Institute has developed a web-based software platform for implementing digital assistance systems that enables our applications to be used on various end devices (smartphones, tablets) regardless of the operating system. In this article, the platform is used to connect a mocap system using an SDK, which provides the data for various productivity analyses that are carried out at the logic tier and whose results can be accessed and visualised via the assistance systems. At the same time, data can be entered via the assistance systems, e.g. to create parts lists.

Mocap technologies capture and document movements and transfer them to a digital human model [9]. There are various methods of motion capture, such as optical, electromechanical, electromagnetic and acoustic systems [10]. This article uses a mocap system from Xsens, which is an electromechanical system. In this tracking suit, the worker is equipped with 17 motion sensors with inertial and magnetic measuring units that include 3D gyroscopes, 3D accelerometers and 3D magnetometers. The mocap system determines position and orientation data and sends it wirelessly to a receiving station at a maximum of 60 Hz [11]. This data provides the basis for carrying out productivity analyses in this article.

2.3. Previous work and research gap

There are several examples in the literature that try to automate productivity analyses with mocap systems. Benter develops a partially automated determination of standard times and the execution of an extended primary-secondary analysis using 3D cameras. The results show that camera occlusions restrict the capture of motion sequences, making the calculation of time-based information more difficult [12]. In [13], an approach is presented in which the movement data of an optical mocap system is used as a training data set for a deep learning algorithm in order to classify movements that can then be assigned to MTM-1 movements. In [14], several cameras are used to capture the movements of a person and to determine various productivity indicators, such as walking distances, the analysis of hand movements and the time share spent between the different working activities. A procedure for a fully automated execution of an MTM-2 analysis in a virtual reality environment is developed by [15]. Jonek et al. use the Xsens Awinda mocap system to capture body movements and data gloves from Manus to capture finger movements in order to automatically recognise a limited number of assembly operations with the help of the movement data and space partitioning [16].

Although existing solutions show approaches to automate certain productivity analyses with the help of mocap systems, these are associated with three major deficits:

1. Most analyses have only been partially automated. On the one hand, only some of the MTM movements have been recognised and, on the other hand, no standard times have been determined even for the recognised movements.
2. Often, only the assembly processes that occur during a specific use case are recorded and analysed. There is no generic concept that is directly applicable to different use cases.
3. In most studies, only one productivity analysis is carried out, which means that productivity potentials remain undiscovered. Furthermore, possible correlations between different analyses are not identified.
4. There is no link between the results and the application domain (parts lists, work plans, etc.). This makes it difficult to interpret the results and identify improvement actions for the specific use case.

Our article shows how an electromechanical mocap system can be used to capture data which can then be processed with a digital assistance system with low effort and enriched with additional metadata. Consequently, several productivity analyses can be carried out automatically and simultaneously. This provides companies with highly detailed information quickly in order to optimise workstations and processes.

2.4. MTMmotion

As the application of the MTM-1 analysis plays a central role in our article, the MTM Association's MTMmotion service will be presented in this section. MTMmotion was developed with the aim to ensure that technologies that generate or record human motion data such as human simulation, virtual reality or motion capture all have equal access to the MTM process building block systems and deliver valid, rule-compliant MTM analyses. The MTMmotion service consists of two major aspects. The first important aspect is an interface for the various technologies. The interface describes all the information related to human work that is necessary to deduce valid MTM analyses. Therefore, it consists of an object list and six motion channels that describe human work processes. The object list contains the objects and their properties such as weights and dimensions that are interacted with during the work process, and the channels represent the movements and postures of the worker during the execution of the tasks.

The second aspect of the service is the translation algorithm that transforms the interface data into correct MTM analyses. Using this translation, once the interface data is provided by the technology, a valid MTM analysis such as MTM-1, MTM-HWD or MTM-UAS can be created. The translation takes place in four steps: 1. validation of the input data, 2. completion of the input data, 3. translation into MTM process building block systems and 4. combination of different body parts [17, 18].

3. Concept and implementation of the process analysis

The process analysis for the preparation, execution and evaluation of different ergonomic and productivity analyses comprises five steps: 1. work system administration, 2. initialisation, 3. preparation of motion data, 4. carrying out ergonomic and productivity analyses and 5. design of the user interface. Steps 1 to 3 are carried out by an analyst using the digital assistance system. Steps 4 and 5 are carried out by the analyst and a worker. While the worker performs the workflow in step 4, the analyst records the data using the digital assistance system. In step 5, the analyst and the worker examine the analysis results together to identify possible improvements in workplace and process design.

3.1. Work system administration

The subject of the study is a work system in which a specific product is assembled. For this purpose, information about the employees involved, the equipment and the parts list of the product to be assembled must be stored in the digital assistance system. A modular parts list is used, where modules and components can be created, which can then be assigned to a product. In addition to information on the dimensions and weight of a component or module, information for MTMmotion, such as the ObjectId from an object catalogue, can also be assigned. A work plan is created dynamically from the parts list by generating an operation for each component or module to be assembled. The previously created operating resources and employees can be assigned to the operation. In addition, a description and the work place number can be assigned to each operation. The sequence of the operations can be adapted by the user, whereby the change options are restricted by the assembly precedence graph, which results from the product structure and the associated operation. On the one hand, the work plan provides the basis for carrying out the further steps of the process analysis; on the other hand, the results of the analysis can later be connected to the contents of the work plan (employees, operating resources, materials). This reference to the application domain allows targeted improvements to be made in the work station and process design. A simple work process will serve as an example in the further part of the article: An employee picks up a screw, turns it into a thread and tightens it with a wrench.

3.2. Initialisation

The purpose of initialisation is to detail the work processes using various elements such as materials or operating resources so that they can be linked to the recorded movements.

An early idea was to assign absolute positions to these elements in a work system, for example, in order to be able to track and analyse the employee's actions after data recording. Due to the drift in the data of the mocap system used, this procedure proved to be impractical. In the current solution, the user initialises the operation manually with various elements in the digital assistance system. Figure 1 shows the initialisation procedure for the work process described in section 3.1.

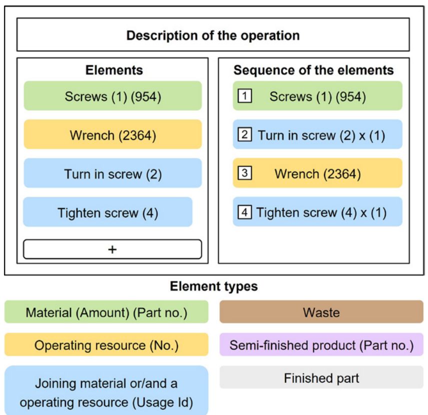

Fig. 1. Initialisation

The first step in initialisation is to create the elements that occur in an operation for each operation of the work process. The elements material (here screw, quantity: 1, part number: 954) and operating resource (here wrench, equipment number: 2364) are created automatically by the digital assistance system using the information from the work plan. Four further elements can be created manually using the plus button: Joining, waste, semi-finished product and finished part. When creating an element, the user can specify, for example, whether the joining is carried out with a material and/or an operating resource and which joining operation(s) (usageTypes) are involved. The usageTypes come from the MTMmotion object catalogue and are object-specific (here usageType 2 ‘turn in’ for the screw and usageType 4 ‘tighten’ for the wrench). A specific sequence of basic MTM movements is stored in MTMmotion for the various joining operations. In the second step, the elements can be arranged in a sequence using drag and drop. An element-specific information box appears after the drop. For example, for the materials, the user can specify how many materials are to be picked up and whether the material is to be picked up with one or both hands, and for the joining area, the user can specify how many joining operations are to be performed (the number is shown after the ‘x’, in this case one joining operation each with the screw and the wrench).

3.3. Preparation of motion data

The purpose of preparing the motion data is to check whether the system has correctly calculated hand movements, body movements and postures as well as joining times using the data from the motion capture system. These movements are then linked to the initialisation in order to display the work process in detail. Thereby the user is supported by a video or digital human model. Figure 2 shows the recorded arm movements for the example mentioned in section 3.1.

Digital human model or video | Arm motions | Body motions and postures | Joining times

No.	Start frame	End frame	Body half	Direction
①	100	120	Left	Leaving the joining area
②	130	150	Left	Entering the joining area
③	450	480	Right	Leaving the joining area
④	500	530	Right	Entering the joining area
⑤	650	678	Right	Leaving the joining area

Number of required arm motions: 5

Fig. 2. Preparation of the motion data

In order to minimise the subjective knowledge required for the analysis, the user only has to check whether the system has correctly detected the two directions of movement, i.e.: leaving the joining area and entering the joining area of the respective half of the body during the arm movements. Leaving the joining area means that the worker leaves the joining area, e.g. to reach towards a material (here a screw from frame 100 to 120 with the left hand). Entering the joining area means that the worker performs an arm movement in the direction of the joining area, e.g. to move a material into the joining area (here a screw from frame 130 to 150 with the left hand). The user has the option of deleting or changing incorrectly calculated movements and of manually adding any movements that have not been captured. From the previous initialisation, the required number of arm motions can be determined and is displayed to the user interface. In the example, five arm motions are necessary, which is displayed on the bottom left of Figure 2. The respective missing frames between the arm motions indicate basic MTM movements such as gripping (period between frames 120 and 130 for picking up the material) or joining (period between frames 450 and 150 for turn in the screw, this leads to a joining time of 300 frames or of 5 s). The data on body movements and postures as well as joining times can be processed in a similar way. The body movements (e.g. walking and turning) and postures (e.g. standing, sitting or kneeling) are automatically determined from the movement data. The system recognises joining processes by the fact that the last hand movement of both halves of the body is entering the joining area and a body posture such as sitting or standing is assumed by the worker. As with the arm movements, the number of joining operation can be derived from the initialisation and visualised for the user to check. In general, the user has the option of changing, deleting or adding body movements and postures as well as joining times.

3.4. Carrying out ergonomic and productivity analyses

The purpose of this section is to describe in detail how an MTM-1 analysis is carried out and to briefly list other analyses performed by the system. The initialisation and preparation of the movement data form the basis for carrying out MTM analyses with MTMmotion, as shown in Figure 3. The example is based on Figure 1 for the initialisation and Figure 2 for the preparation of the motion data.

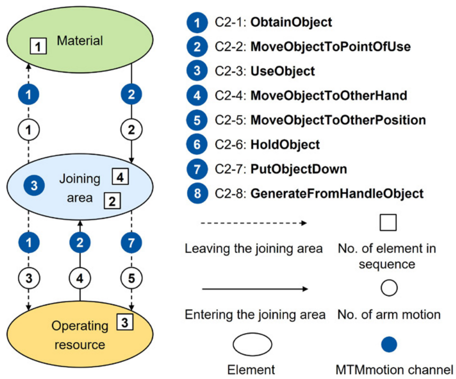

Fig. 3. Logic for linking initialisation and data preparation for MTMmotion

Information is generated for MTMmotion depending on the element and direction of the arm movement. An arm movement out of the joining area towards the material (here element [1], screw) or an operating resource (here element [3], wrench) can be described by the C2-1 ObtainObject channel (arm movement ① and ③). In the case of an operating resource, however, an arm movement out of the joining area can also mean that the joining operation (here element [4], tighten screw with wrench) is complete and that the operating resource (here element [3], wrench) is put down, as shown by the fifth arm movement. In this case, channel C2-7 PutObjectDown must be used. The sequence of the arm movements and the elements is therefore decisive for determining the correct MTMmotion channel. If a material (here element [1], screw) or an operating resource (here element [3], wrench) is brought into the joining area (arm movement ② and ④), channel C2-2 MoveObjectToPointOfUse must be used. The previously determined joining times (see section 3.3, 5 s for turn in the screw and 2 s for tighten the screw) and the joining operations from the initialisation (here element [2] and [4]) are linked to the channel C2-3 UseObject. Channels such as C2-4 MoveObjectToOtherHand cannot be captured directly by the mocap system, but are included in the analysis via assumptions resulting from the motion sequence. Note that only some of the influencing variables defined by MTM-1, such as the movement length, are transferred to the movement channels of the arm movements. Other influencing variables such as gripping case cannot be recorded automatically. As a manual specification would require too much manual effort, the default values from MTMmotion are used instead. This must be taken into account when checking the validity of the results. In addition to the arm movements, MTMmotion offers further movement channels. The system serves four out of six channels. The initialisation described above is only required for arm movements (channel 2). The data for body postures and movements (channels 1 and 5) can be generated automatically based on the processed data. The leg movements (channel 3) have not yet been implemented and the eye movements (channel 4) cannot be recorded with the Xsens mocap system. The arm postures (channel 6) can be recorded fully automatically by the mocap system. Depending on the input data, a specific sequence of basic MTM movements is stored in MTMmotion for all channels. E.g., MTMmotion translates the ObtainObject input in subchannel C2-1 into a reach and grab movement. This shows how an MTM analysis can be carried out by initialising and preparing the motion data for an entire work process. As a result, MTMmotion delivers various MTM process building block systems depending on the query. In this analysis the MTM-1 process is queried. Figure 4 shows a section of the MTM-1 table for the example used in this article, which MTMmotion provides through the input data for the arm motions (channel 2). Though a comprehensive evaluation of the validity of the results is still pending, the section of the MTM table shown in Figure 4 has been checked by MTM experts and found to be correct.

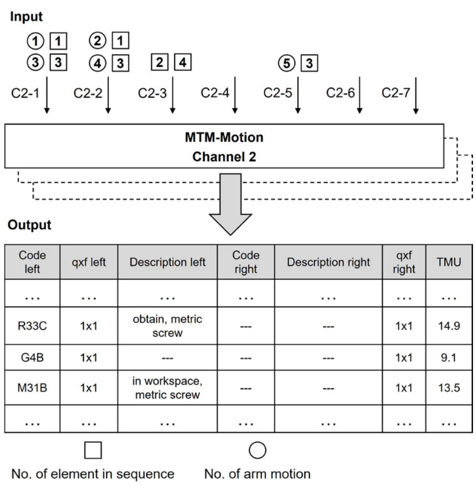

Fig. 4. Input and output information of MTMmotion

As described in Section 3.4, the input data is made up of the information on the arm movements and joining times as well as the elements from the initialisation. Figure 5 uses the input combination ① [1]) (obtain a screw, channel C2-1) to show how the data for MTMmotion is generated.

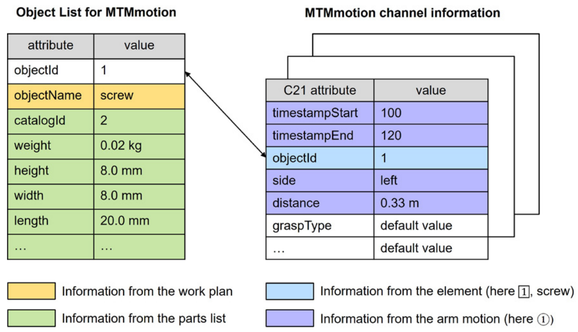

Fig. 5. Generating the data for MTMmotion

The object list for MTMmotion can be seen on the left-hand side of Figure 5. Using information from the work plan, an entry is created in the list for each object (material, operating resources, etc.) and provided with object-specific information (weight, dimensions, etc.) from the parts list. The figure on the right shows that the arm movement (here ①) and the element from the initialisation (here [1], srew) can be used to generate the data for a subchannel C2-1. Default values from MTMmotion are used for the data not specified. Of course, the other channels must also be provided with data according to the same principle.

As soon as the results of the MTM-1 analysis are available, various analyses can be carried out. Including MTM-1, five different analyses have yet been implemented: MTM-1, a primary and secondary analysis, line balancing, a comparison of standard and actual times and a measurement-based ergonomics analysis (see [3]).

3.5. Design of the user interface

The purpose of this section is to describe how the results of the productivity and ergonomics analyses carried out in section 3.4 can be evaluated by the user with the digital assistance system. Figure 6 shows which productivity and ergonomics indicators can be analysed at which of the four levels of detail.

The results are linked to the application domain at all levels of detail, which has the advantage that targeted improvements can be made in workstation and process design. The key figures are visualised in tables, bars or pie charts. The left-hand side of the illustration shows the 4 levels of detail through which the user can navigate: 1. work plan, 2. workstation, 3. operation and 4. motion element. The right-hand side of the illustration shows which analysis results can be evaluated at each level of detail.

4. Summary and outlook

This article presents a concept and its implementation for capturing data for productivity analyses with a mocap system and evaluating it with a web-based digital assistance system. The system allows very detailed and comprehensive productivity analyses to be performed with greatly reduced effort. As a

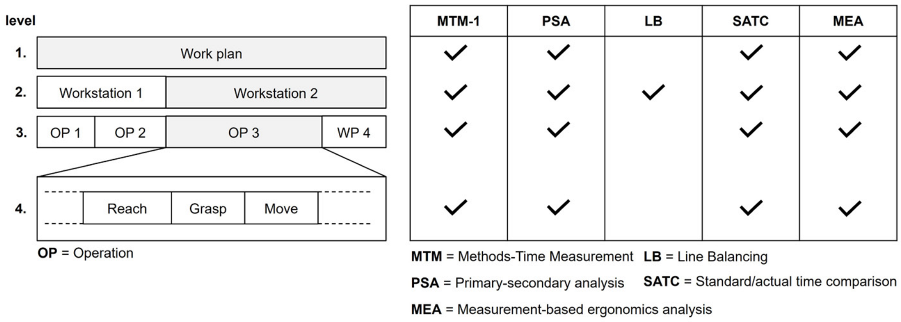

Fig. 6. Levels of detail and evaluation options for the analyses

result, the industry can apply these analyses to a larger number of processes and at a higher frequency, which makes a significant impact on increasing production productivity.

A limitation of our approach is that it must be validated whether the result corresponds to a correct MTM analysis. This is because the reasons for an incorrect analysis can be the missing influencing variables for MTMmotion for which assumptions are made (e.g. no specification for gripping case) or the assumptions made by MTMmotion to enable simplified use of the tool.

In addition to the validation of the various modules, the next step in this project will include a comprehensive evaluation in the model factory and in industry. Here, the validation of the MTM analyses for a broader range of applications will be carried out by MTM experts. In this context, the boundaries of the mocap system used should also be discussed in more detail. Besides the analysis itself, the evaluation should take a closer look at how specific changes can be made to the workplace and process design depending on the results of the analysis. A catalogue of actions can possibly be created for this purpose. Consequently, the result of the evaluation should show the effectiveness, restrictions, requirements and boundaries of the digital assistance system for analysing assembly processes.

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