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Virtual reality based time and motion study with support for real walking
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Abstract

Manual operations in mass production are important cost drivers. Thus, tools like the MTM (Methods-time Measurement) – a time and motion study method – were introduced, which are nowadays established in industry for evaluation and improvement of production facilities. In this method, cardboard engineering is used to build simplified physical mock-ups of machines or production lines, in which the manual working process can be simulated. However, new strategies like e.g. decentralized production require the worker to walk, which is not well incorporated in the MTM and times are only estimated from the walking distance.

Since many workplaces, machines or production lines already exist as digital models, it is obvious to perform the MTM completely virtually. However, this comes at the cost of a complex handling and strongly reduced realism because a desktop-based MTM application does not allow natural navigation – like walking – within the full-sized models like the cardboard setups do.

This paper introduces a virtual reality-based MTM that also allows for real walking in virtual factories without using a treadmill or other walking devices. With a subtle redirection of the user during walking, these virtual factories can even be larger than the available physical space. Hence, a realistic measuring of walking times and distances can be done instead of an estimation. Since the MTM can be completely performed within a virtual environment, it gives a new realism to the method compared to the cardboard procedure. The paper closes with an outlook on future work and extensions of this novel virtual MTM.

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1. Introduction

Manual operations in production contribute to the overall costs of a product and should therefore be carefully measured and evaluated. This becomes increasingly challenging as products change more rapidly and workplaces are decentralized. Thus, an evaluation on the machine level only is not sufficient. Since recent, worker behavior is not static anymore, but also includes locomotion, mainly driven by new production strategies such as Chacu-Chacu or decentralized production. Thus, also cell level, shop floor level and even factory level should be taken into consideration when evaluating manual work efficiency.

Today, manual operations are evaluated on the machine level only at fixed workplaces using the MTM (Methods-Time Measurement). For such workplaces, cardboard full-scale mock-ups are typically used to evaluate manual operations. These manual operations are videotaped and manually transcribed. Besides inaccuracies of this method, the MTM lacks strategies to measure and analyze more recent working behavior including walking in cell-, shopfloor-, or factory level. Finally, the current MTM is time consuming due to the need for physical mock-ups and manual video transcription. In short, MTM is (i) inaccurate, (ii) not yet adjusted to higher manufacturing levels, and (iii) time consuming.

To address (i – iii), the paper will introduce a system that allows performance measurements of manual operations completely within a virtual environment. It will thus extend the existing MTM by novel capabilities such as walking and automatic transcription. Instead of physical mock-ups, virtual representations of workplaces and machines will be generated out of existing CAD data. As a significant extension of the existing MTM, real walking in such a virtual environment will allow perceiving sizes and distances, and thus to measure walking times of the worker in all levels. Instead of videotaping and later manual transcription of motions, all worker operations will be automatically captured and evaluated.
2. Related work

2.1. Time-motion studies and assembly evaluation

With growing mass production in an automated or semi-automated work environment, manual assembly tasks also gain importance. Since this mass production is increasingly characterized by customized products and thus the quantity “1”, changes in production have to be achieved in shorter time. Depending on a product’s configuration, manufacturing and assembly tasks can vary in time, and thus current research focuses on decentralized production [1].

However, decentralized production needs not only careful planning, but also thorough investigation of manual assembly tasks, including walking and human-robot interaction. While many supporting tools are available for production planning, such as e.g. Tecnomatix Plant Simulation for an event-based material flow investigation, or visTABLE for planning a production from a geometrical aspect. However, there is no such a support for planning manual work, and thus the Measured-Time Method (MTM) is still based on traditional cardboard engineering.

MTM is based on a long history [2] and is established in industry. The basic principle of MTM relies on subdividing a worker’s manual operations into basic motions such as “reach”, “grasp”, “move”, “position”, or “release”. Based on empirical studies, standard times needed for basic motions were established. Standard times could then be used to estimate mean costs of a manual operation. MTM can be used to analyze, describe, structure, predict, and design work processes [3,4].

MTM also aligns with the Toyota lean production philosophy described in the Toyota Production System (TPS) [5].

Since MTM is based on visual observation of a worker’s manual operations, it is required to have a physical workplace installed. While this is suitable for optimizing existing work procedures, MTM has its shortcomings when fully new products are to be manufactured and workplaces need to be completely redesigned. To deal with such problems, physical mock-ups are used, the so-called cardboard engineering [6] (see Fig. 1).

Building physical mock-ups with cardboards brings the benefit that not only real sizes are perceivable, but also distances can be experienced and measured. Thus, a reliable MTM procedure is possible even if the user has to walk from one position to another. However, this comes at the larger cost of jointly preparing for such setups, and to the low adaptability if new machines need to be involved. It becomes obvious that such a cardboard engineering (Fig. 1) cannot be used anymore if multiple variants and constellations of a production should be investigated, since any rearrangement would again cause large costs.

In summary, the current cardboard-based MTM cannot cover emerging fields in production such as variant-rich production lines, human-robot interaction or decentralized assembly. Since it is still based on physical mock-ups, it cannot benefit yet from the fact that other fields in production planning already rely on the digital representation of the employed components. Porting an MTM from the analog basis (cardboard engineering) to a digital one will allow more iteration loops for an optimized production planning. Using a Digital Mock-up (DMU) instead of a Physical Mock-up (PMU) saves the time for building physical objects. In return, this time can be used to perform more iteration steps to achieve an optimized plant layout. Such an approach is in particular important for a change management, in which different (concurring) solutions have to be tried out.

This paper thus introduces a freely programmable MTM system, which will allow workplace designers to rapidly prototype and validate any work environment regarding real walking for time and motion studies. Thereby, the existing and established MTM method will be extended with the capability of walking. Moreover, the virtual environment will also allow for a spatial impression of future workplaces, which is not yet possible with cardboard engineering. Compared to existing approaches in hard- and software, this new system comprises the following improvements:

- Analyse workplaces completely in VR: Lower cost, shorter cycles
- Redirected walking allows experiencing complete factories in a limited tracking space
- Fully automatic analysis of walking actions no video analysis required anymore
- Completely immersive using real walking (unlike mouse-based avatar control in [8])

2.2. Real walking in virtual environments

Natural walking is our most natural way of navigation in the real world. Often, it is an inherent part of assembly systems. Therefore, pure stationary VR systems or desktop based systems which use e.g. mouse and joystick for navigation lack the realism and immersion required for realistic time and motion studies. Real walking allows a natural navigation [9] together with better orientation [10] in virtual environments. In general, real walking was shown to be superior to other navigation metaphors such as mouse or other gestural walking (e.g. walking-in-place [11] or stepping-in-place) [12].

Typically, enabling a user to really walk inside arbitrary virtual environments – like virtual assembly lines – is realized by letting the user walk in a physical/real room. A tracking system can be used to track the user’s viewpoint in real time and render the virtual environment from that perspective. The scene is presented to the user on a head mounted display (HMD). However, this approach has the disadvantage that the size of the real room (or the tracked space) limits the size of the virtual environment that can be walked through. In order to avoid costly or unat-

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2 Plavis, http://www.vistable.de/
ural mechanical locomotion interfaces and still be able to walk freely in arbitrary virtual environments. Razzaque et al. [13] proposed Redirected Walking (RDW). RDW is a method that uses a set of techniques to guide a user on a different path in the real room than what he is walking in the virtual environment. This allows “compressing” a large virtual environment into a smaller physical room or tracking area.

Different techniques for redirection were proposed so far. For instance, one redirection technique called curvature gain makes users, who walk on a straight line in the virtual environment, walk on a curved path in the real room. For a taxonomy and summary of various redirection techniques see Suma et al. [14]. Redirection techniques themselves are not sufficient to allow for free walking in large virtual environments. A so-called steering algorithm or RDW controller, as e.g. [15,16], is needed, that decides which redirection technique has to be applied and with what strength. [17] lists the perceptual thresholds for different redirection techniques.

3. VR for time and motion study

3.1. VR system

The wearable VR system for really walking in virtual environments is shown in Fig. 2. The system is composed of an Oculus DK2 Head Mounted Display (HMD) with 960x1080 resolution per eye and a backpack to carry a notebook. In order to track the user’s viewpoint in the real room, an Intersense IS-1200 6 degrees-of-freedom tracking system [18] (180 Hz update rate, 6 ms latency) is attached to the HMD. The notebook is used to process the tracking data from the tracking device and render the scene. Furthermore, it powers all hardware components. Hence, the whole VR system is wireless allowing the user to walk freely in the real room. The size of the used tracking space is about 12 m by 6 m. Inaccurate tracking, low refresh/update rate, latency, jitter, etc. can quickly cause simulator sickness and render the VR system useless. Hence, it is crucial that all system components have a low latency, high update rate, and high precision (tracking system).

The software of the VR system processes the tracking data, runs an RDW controller, applies redirection (if required), and forwards this data to a rendering engine. For this paper the Unity3D game engine is used.

The above tracking system only tracks the user’s viewpoint. In order to add partial or full body tracking – e.g. to track a user’s hands – additional tracking hardware is required. For full body tracking an optical tracking system with additional markers could be used. Recent alternatives approaches try to integrate depth cameras into the HMD to track a user’s hands and fingers. As tracking is not the main focus of this paper, a simple wireless inertial sensor is used here, see [19] and Fig. 6 (right).

3.2. VR based time and motion studies

To conduct VR based time and motion studies, no complex physical mock-up and no time-consuming video analysis is required. In fact, instead of using physical mock-ups, a virtual scene with models of assembly stations, machines, or robots is used. Furthermore, instead of an elaborate post processing and video analysis of all the motions performed by the workforces, tracking hardware is used to track the user’s motions. Software then classifies these motions into the according actions (e.g. a “grasp” action or a “screw” action). This process is visualized in Fig. 3.

I.e. the whole time and motion study is done in real time and modifications of the setup can be tested immediately. The resulting statistical data can be generated on-the-fly. It is necessary that the tracking hardware delivers accurate position or movement data and accurate time measurements. This is generally the case for today’s tracking hardware which is used for VR purposes. Because real walking is possible, time and motion studies are not limited to a single workstation but can include a whole assembly line.

Below, the different components of this time and motion study system are discussed in greater details.

3.3. Virtual assembly lines or production facilities

For a virtual assembly line or production study, the production/assembly line has to be available as a digital model for visualization. As all machines, tools, workpieces, assembly stations, etc. are available in the form of computer-aided design (CAD) data anyway, this imposes no limitation on the usability of the VR system. Using a rendering engine allows designing a whole assembly line in little time and placing the models accordingly, see e.g. Fig. 5 for a scene generated with the Unity3D rendering engine. VR based time and motion studies have another advantage. Assembly robots can be easily integrated using the virtual models from the vendors. This even allows integrating human robot interaction at a very early stage without any risk for the workforces participating in the evaluation.

However, a disadvantage of a pure virtual mock-up is that it lacks real haptic feedback. E.g. if a workforce has to lift a heavy workpiece, its weight will influence his movements and performance. Similarly, touchable physical tools are different.

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3[https://www.oculus.com/]
4[http://unity3d.com/]
to handle than pure virtual interactions without haptic feedback. Therefore, the proposed system can easily be extended to include physical mock-ups. E.g. a user can work on a real workpiece which is tracked in the real environment and visualized in the virtual scene. Similarly, real tools can be used for interaction. However, in contrast to non-VR based approaches, much simpler physical mock-ups are required.

3.4. Classification of actions

Just having a stream of sensor/tracking data and timings from various sensors is not sufficient to determine how long it took a person to perform a task at a virtual assembly line. It also does not help in finding out what task or how the task (i.e. sequence of actions) was done. For this, the tracking data has to be interpreted and combined with the context information about the virtual scene.

Machine learning methods are best used to classify a stream of sensor data and determine which action they represent, see [20] for an overview. This does not only provide information about what action is performed but also when a specific action (e.g. a “grasp” action) started and ended.

Two types of classifications are performed. A primary classifier determines the user’s pose of his full body. I.e. if the user is walking, standing, or seated. To improve the classification it is combined with context information about the scene. For instance, if the user is positioned between two stations and there is no chair, he must be either walking or standing.

A second classifier determines the (manual) work actions using suitable machine learning approaches (see [20]). E.g. if the user is standing in front of an assembly station this classifier determines the type and sequence of manual actions. Hence, not only the timings per station or per workforce can be analyzed and compared, but also if there are differences in the sequence of actions. More information about these so-called assembly trees and VR based assembly design is given in [21].

Because both, walking and stationary activities are combined with this approach, it allows for a much more complete analysis. For instance, if a workforce has to walk from one station to another but there is an obstacle (e.g. a dynamic obstacle like a robot) on the direct path, the cost of the required detours can be analyzed.

4. Evaluation study

In order to test the capabilities and evaluation possibilities of the proposed immersive VR system, an evaluation study was conducted. As the system supports free and natural walking in a virtual production facility or shop floor of arbitrary size, any time and motion study can be made with the same system and evaluation software. I.e. the system is not limited to assembly design, production design or other simple shop tasks only.

The layout of the study is shown in Fig. 4. Four virtual stations were modeled which each user has to visit. The user starts in a seated position on a chair. At each station one or two manual tasks have to be performed. After finishing the tasks, the user walks to the next station. Finally, the user returns to the first station. Fig. 5 shows a screenshot of the scene. The semi-transparent green boxes in the virtual scene indicate where the user has to perform the tasks.

The following stations were used:

- Station 1, chair: simulate mounting above the user’s head while the user is seated (e.g. as found in automotive industry)
- Station 2, shelf: simulate picking up an assembly unit or workpiece
- Station 3, machine: simulate placing a workpiece in a machine (or pass it to a robot)
- Station 4, workbench: simulate various manual assembly tasks on a workbench

The chair is a special case because it is not only modeled in the virtual scene but also has a physical counterpart. I.e. the users can really sit down. For this, the chair has to be placed properly in the real room and must match its virtual counterpart. This demonstrates how to use physical objects for extending the virtual environment. The use of physical workpieces or real tools would easily be possible but was avoided for simplicity.

The following two tasks are performed:

- Push/pull: user has to move this hand forward and backwards (five times) – at station 1,3,4
- Screw: user has to rotate his hand five times as if he would tighten a screw – at station 2,3

With the help of the inertial sensor and the tracking system these different movements are classified automatically. This allows recording all timings and all required movements (including walking movements, hand movements, etc.) and split the actions for the evaluation using a classifier. For the two tasks, this is easily done using measurements from the gyroscope for the screw task and using accelerometer measurements for the...
push/pull task, see Fig. 6.

Of course, this study does not reflect a realistic production environment. Instead it aims at demonstrating the capabilities of the immersive VR system and automatic data evaluation. A user while performing the study is shown in Fig. 6 and 2.

Fig. 6. A user during the evaluation study. (left) Screw task, seated user. (right) Inertial sensor attached to the user’s hand.

5. Results

Four people participated in the evaluation and performed the task described above for a total of seven times.

In the following section, an analysis of the data gathered in the evaluation is presented. While this is by no means a complete analysis of a manufacturing process, it should serve as an example of what can be achieved even with the limited hardware used here.

For this task two main values are of interest, the time needed and the distance traveled. The time required can be further broken down to a workstation-by-workstation level as well as the time used for individual activities such as executing the push/pull action or the screwing action. Table 1 shows the average time the participants spent on each of the stations as well as the time relative to the respective station \( T/T_{\text{station}} \) as well as the overall time \( T/T_{\text{total}} \). All values were determined automatically from the recorded sensor data using a set of simple decision rules.

From the results it is easy to see that more time is required for stations 1 and 3. At station 3 two different tasks have to be executed, which requires more time. Station 1 on the other hand is visited twice and the same task is repeated also resulting in a higher time requirement.

Figure 8 shows all the paths walked by the participants. The mean distance traveled was 16.4 meters with a standard deviation of 0.79 meters. The speed was 0.8 meters per second with a standard deviation of 0.17 meters per second.

6. Conclusion and outlook

This paper has shown how time and motion studies can be done using immersive VR with support for real walking. This virtual MTM avoids building complex and costly physical mock-ups but still allows integrating physical components like real tools. With the help of a special technique (RDW), a user of the system can walk freely inside a virtual assembly facility of arbitrary size while really remaining in a much smaller physical space. By applying real walking in virtual environments to MTM, existing time and motion studies can be extended to include walking. Furthermore, a whole assembly line can be evaluated because the user can move freely between different stations while remaining immersed in the virtual scene.

Because the user’s movements are tracked with sensors, a fully automated analysis of actions and timings using machine learning approaches was proposed. An elaborate post processing and manual video analysis as used for classic MTM is not necessary anymore.

In future, an in-depth user study should be performed to validate the system in detail. Furthermore, the integration of assembly robots and human robot interaction for virtual MTM could greatly impact the importance of the proposed system. Finally, the VR system would also allow two or more workforces to interact with each other inside the virtual scene. Such a multi-user time and motion study could provide interesting insights for evaluating the interaction performance.

References


