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Analysis of manual work with 3D cameras

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Abstract. This paper presents a low-cost and low-effort approach to analyze labor productivity with 3D cameras. The developed methodology tracks the movement of employees in assembly operations. The collected data is then analyzed with a methodology that is based on the primary-secondary analysis.

Keywords: labor productivity, 3d cameras, primary-secondary analysis

1 Introduction

The production costs of manufacturing companies are an important factor when facing international competition. Labor costs make up a vital proportion of the production costs when the production is characterized by a high amount of manual processes and high wages. Labor productivity is the main objective for controlling labor costs. Its analysis allows finding areas of improvement and appropriate measures to increase productivity. Classical work analyses such as the MTM system or the REFA systematics require expert knowledge and induce relatively high costs for the execution of the analysis. Small and medium-sized companies often have neither the knowledge about the methodologies nor the capacity to analyze the labor productivity in depth.

This paper presents a low-cost and low-effort approach to analyze labor productivity with 3D cameras. The developed methodology tracks the movement of employees in assembly operations. The collected data is then analyzed with a methodology that is based on the primary-secondary analysis.

2 Productivity analysis

2.1 Analyzing labor productivity

Productivity is defined as the ratio between the output and the input of a system. In manufacturing areas, the output consists of the produced goods and is often measured in units. The input consists of the resources that were necessary to create the output. Resources are for example mechanical and human work. The ratio between the created output and the particular input is the respective partial productivity [1].

The labor productivity of a manufacturing area is thus the relation between the output of produced goods and the staff working time as input. As the output of a pro-

duction is determined by the market, usually the paid working time is analyzed to investigate labor productivity.

The assessment of actual working times can be performed by dividing the paid working time into work steps and measuring the times for these individual steps [2]. Instead of using measured actual times, some methods use predetermined times. Basic idea of these methods is to divide work processes in small work steps to which then times are assigned based on defined influencing factors [2]. Known representatives are MTM [3] or the work factor method [4].

2.2 Primary-secondary analysis

The primary-secondary analysis is a method developed by Lotter [5] to analyze the labor productivity of assembly processes. Basic principle is the distinction between primary processes (PP) and secondary processes (SP). This is similar to the Lean Management classification of value adding and non-value adding times [6]. According to Lotter, all efforts that add value are primary processes. For assembly operations, the most important examples are joining processes. Efforts that do not add value, such as the transportation of parts, are secondary processes.

Based on that, Lotter defines the efficiency (E) as the ratio between the duration of all the primary processes and the total duration. The efficiency equals one if the work task only consists of primary processes and is smaller than one if secondary processes occur. Fig. 1 shows a graphical representation of the efficiency.

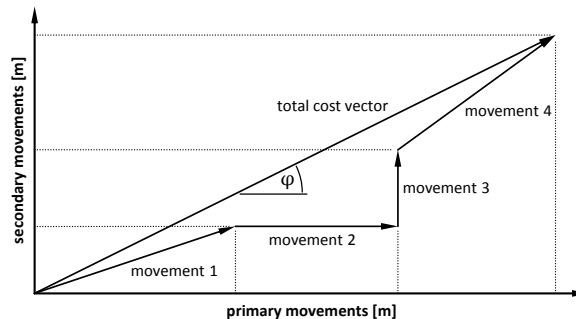


Fig. 1. Graphical representation of the economic efficiency

The abscissa shows the amount of primary processes and the ordinate the secondary processes. Movements that only consist of primary movements are drawn horizontally (movement 2) and movements that do not add value are drawn vertically (movement 3). The graphical addition of the processes results in the total cost vector of the analysis with the slope φ . The reduction of this angle corresponds to an increase in economic efficiency.

If the definition of primary and secondary processes is applied strictly, only joining movements are primary processes, while all other movements do not contribute directly to the customer satisfaction and are therefore secondary processes. However,

this definition would imply that the proportion of primary processes would be minimal and the economic efficiency would be of little relevance. Lotter therefore proposes to classify necessary movements up to a defined minimum length as primary processes even if they do not add value.

3 The Microsoft Kinect as a 3D camera

Motion capturing methods recognize, track and digitalize human movements for further processing [7]. The methods can be distinguished by the used type of sensors. Optical methods usually consist of a transmitter that emits infrared light, which is reflected by the analyzed object to the receiver. Depending on the mode of operation, markers are used as reflectors [7]. The tracking method of the Microsoft Kinect belongs to the non-marker-based systems [8], which means that the natural reflection of the body is used. This has the advantage that the user does not have to wear any devices, which might disturb him or her from the work.

Microsoft developed the Kinect for the gaming console Xbox as an inexpensive motion control. Microsoft also published a software development kit (SDK), a collection of tools and documentation, for non-commercial applications. The SDK includes the functionality to recognize human persons from the coordinates that the infrared camera collected. This way, the relevant joints of a person and their coordinates can be identified. The Kinect 1 detects 20 body joints while the updated Kinect 2, which was released in 2014 [8], detects 26 points. If joints and corresponding limbs are represented graphically, a skeleton image is created, that supports motion capture.

The Kinect is capable to identify the joints of the body and to record their coordinates. Velocity and acceleration of the joints are not measured but can be calculated from the coordinates. A deficit in applying the Kinect for productivity analyses is that it cannot identify stopping points between two movements. Furthermore, it is necessary to combine these stopping points to stopping areas to identify joining or material areas. Another difficulty in carrying out a primary-secondary analysis is the distinction between primary and secondary processes. Therefore, a productivity analysis, such as the primary-secondary analysis, is still very time consuming with the Microsoft Kinect and only executable by experts.

4 Data collection

This chapter describes how the recorded data is prepared for productivity analysis. Section 4.1 describes the experimental set-up. Section 4.2 shows which raw data is recorded and what data can be derived directly. Section 4.3 describes how the stopping points can be determined and Section 4.4 describes how stopping areas can be deduced.

4.1 Experimental set-up

To demonstrate the modified primary-secondary analysis with the Kinect, we recorded an exemplary assembly task. Fig. 2 shows the experimental set-up. In this task, the recorded worker assembled small plastic tractors for 20 minutes. Each tractor consists of four parts, which are located in four material boxes. The recorded joint was the right hand. The worker used this hand to pick up materials from the boxes one, two and three and the left hand for box four. The distance between Kinect and the worker was three meters.

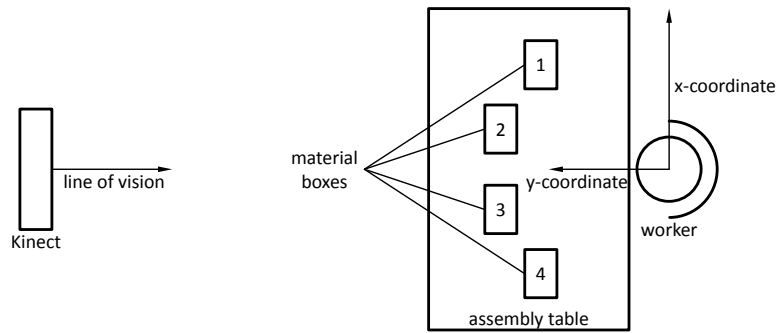


Fig. 2. Experimental set-up

4.2 Coordinate tracking

To carry out the analysis, firstly the joint coordinates are read out. This is done with a rate of 30 frames per second. Thus, the data collection corresponds to a work sampling with a very high number of recordings. The following data is read for each joint:

- x-, y- and z-coordinate
- the tracking status of the joints: the information if the joint was identified or not.

If the joint is identified correctly, the coordinates can be used for the further analysis. The coordinates of the right hand joint are displayed graphically in Fig. 3 Left. The velocity and the acceleration can be calculated using the following equations.

$$v_{x,n} = \frac{\Delta x}{\Delta t} = \frac{x_n - x_{n-1}}{t_n - t_{n-1}} \quad (1) \quad a_{x,n} = \frac{\Delta v}{\Delta t} = \frac{v_{x,n} - v_{x,n-1}}{t_n - t_{n-1}} \quad (2)$$

x_n : x-coordinate at recording n t_n : time of recording n
 $v_{x,n}$: velocity at recording n $a_{x,n}$: acceleration at recording n

Velocities and accelerations for the other directions can be determined in the same way.

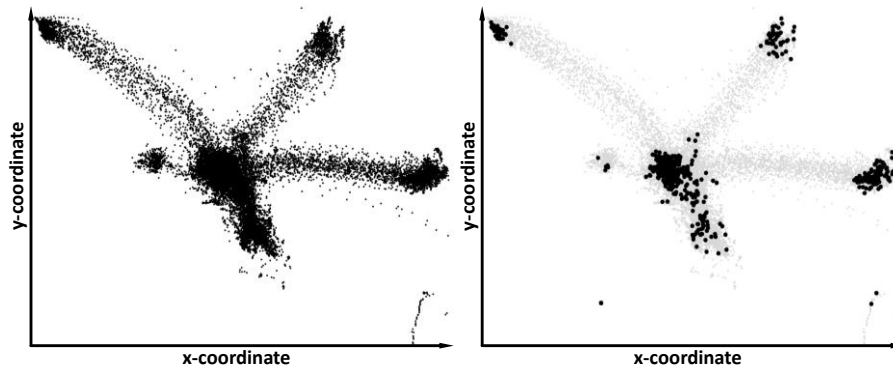


Fig. 3. Left: Right hand coordinates; Right: Right hand stopping points

4.3 Determination of stopping points

The coordinates, velocities and accelerations can be used to determine stopping points. They are defined as times, at which a joint stops between two movements. Since the Kinect does not deliver them automatically, algorithms were designed to determine these times:

1. *Velocity falls below a limit:* This algorithm checks whether the velocity of a joint falls below a predefined value for a certain period. This option is particularly suitable for processes in which longer stops dominate. This recognition algorithm fails when the performed movements are very fast.
2. *Sign change of acceleration:* This algorithm checks whether the sign of the acceleration changes from negative to positive over a certain period. This option is suitable for processes, where only short stops are performed, for example button pressing. There are problems with this algorithm if the movement gets slower and then accelerates again, but no stop occurs. Then, a false stop may be detected. This problem can be mitigated by combining this algorithm with the first one (adding a velocity limit).
3. *Change of movement direction:* This algorithm checks whether the motion vector of a joint changes by a defined angle over a certain period. This option is of great value when most movements are non-stop. This option is less suitable when stops are performed without changing the direction of the movement.

The combined use of the three algorithms leads to a good detection of stopping points as shown in Fig. 3 Right, in which the stopping points are marked black.

4.4 Cluster analysis to determine stopping areas

During manual activities such as assembly operations, many stopping points occur. The points have to be combined to stopping areas to allow meaningful interpretations. Thus, the next step is a cluster analysis to identify the stopping areas. In this approach, a hierarchical cluster analysis is performed which consists of three steps [9]:

1. *Determining the similarities:* A variety of distance measures exists to measure the similarity. For scale properties such as the x-, y- and z-coordinates of the stopping points, the Euclidean distance measure is commonly used [9].
2. *Selecting a fusion algorithm:* In this step, objects with small distances are merged. We used an agglomerative technique that starts with each object representing a single cluster and then merges these clusters gradually. This merging process can be performed with different fusion algorithms. In our case the single linkage method is used [10].
3. *Determining the number of clusters:* There are many different statistical concepts that determine the optimal number of clusters. For this approach, a maximum distance is defined when merging clusters [9].

The outcome of the cluster analysis are stopping areas as shown in Fig. 4 Left. One can see in the figure all the breakpoints of the right hand and their allocation to different clusters. Cluster G, F and A represent the boxes one, two and three from the experimental set-up.

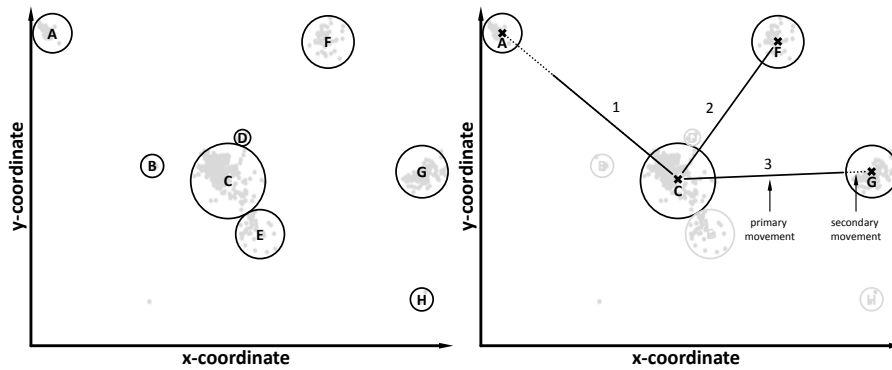


Fig. 4. Left: Determined stopping areas; Right: Movements

5 Primary-secondary analysis using 3D cameras

This chapter shows how the primary-secondary analysis can be performed by using the Microsoft Kinect. The analysis determines, which activities add value and which do not. The approach is divided into three steps. First, the joining point is determined from the stopping areas derived in Section 4.3. Subsequently, non-relevant movements are identified. The last step is the classification of the relevant movements in primary and secondary movements.

In the primary-secondary analysis by Lotter, the user determines the joining point and the primary range is set based on that point [5]. Alternatively, the joining point can be automatically identified. The Cluster analysis results in a number of stopping areas. In most cases, the stopping area with the most stopping points will also be the joining area. To make sure the right area is selected, the user still has the option to choose the joining area manually. In Fig. 4 Left stopping area C is the selected joining

point. The middle of this joining area then will be used as the joining point for the further investigations. This option has the advantage that in contrast to the first option, the determination is based on the recorded data. In addition, different joining points can be defined for both hands.

In the next step, an overview of movements that took place between the different stopping areas is created. The user now examines the movements. He decides whether the movements were relevant to the assembly task (relevant movement) or not (non-relevant movement). The latter movements are henceforward referred to as tertiary movements. The number and duration of these tertiary movements can be easily computed from the captured data and may be an important area for further improvements. In the experimental set-up only movements between the joining area (Cluster C) and the boxes (Cluster A, F, G) are classified as relevant movements.

In the primary-secondary analysis by Lotter the second important step for classification is to determine the nearest material box or stopping area to calculate the minimum level of movement. This minimum, which is necessary for the joining, has to be defined by the user [5]. Two additional options have been developed:

- **Nearest stopping area:** In this option, the nearest stopping area is determined (area F in fig. 4 Left). The distance from the center of this area to the joining point is used as minimum level of movement (movement 2 in Fig. 4 Right). Prerequisite for this option is that the non-relevant movements were identified correctly before.
- **Determination by using ergonomic aspects:** This option is based on ergonomic aspects, which means biological data like arm length is used to determine a movement distance which can be done quickly without harm for the body. An example is the distance that the hand can cover without moving the upper arm and without having harmful or uncomfortable angles for the elbow joint.

For our analysis, we chose the first option. Following the determination of the minimum level of movement, the relevant movements are divided into primary and secondary parts according to the primary-secondary analysis. To visualize the results of that analyzes the average length and duration are calculated for every pair of stopping areas that form a relevant movement. Fig. 4 Right shows the relevant movements and their primary and secondary parts. These movements now can be drawn into a vector diagram as introduced by Lotter (see chapter 2.2). Fig. 5 shows this result.

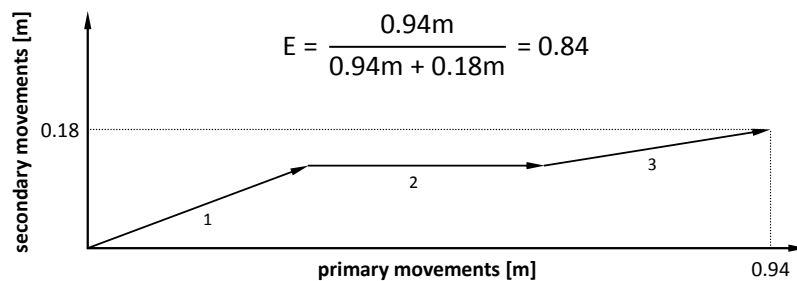


Fig. 5. Graphical representation of the vector

6 Summary

This article presents an approach to analyze labor productivity using 3D cameras. The methodology developed is based on the primary-secondary analysis by Lotter. It divides the movements of a worker into primary, secondary and tertiary movements and thus shows potential for productivity improvement. In comparison to the classic primary-secondary analysis the presented approach offers the following advantages:

- **Recording of actual data:** The presented method does not assess the ideal, but the actual process, thus showing tertiary wastes in addition to the secondary ones.
- **Semi-Automated:** By using the Microsoft Kinect, the effort of recording the processes is significantly reduced.
- **Higher Accuracy:** The determination of the joining point from the stopping areas is based on real data and can be determined separately for both hands.
- **Visualization:** The graphical representation of the stopping areas and movements can help to directly determine incorrectly positioned parts.

Several aspects can further enhance the method. For example, additional body joints can be examined. In addition, the method could be used to reveal ergonomic potential.

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