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Development of a Context-Aware Assistive System for Manual Repair Processes - A Combination of Probabilistic and Deterministic Approaches

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Abstract

Looking at the trend of mass customization of products, companies are confronted with an increasing number of different products and product variants. Especially for humans working in assembly and rework domain it is increasingly difficult to maintain an overview of all assembly paths and work steps. To tackle this problem, context aware assistance systems are introduced to the field. Although there is a lot of research in the area of context aware assistive systems, most work focuses on fixed work plans or purely probability-based activity recognition. As a result, these systems either restrict the worker's personal way of working or the modelling of the work plans is complex and time-consuming. The goal of our approach is a context sensitive support for all performable steps at a given time. That system requires an intuitive modelling of work processes including an activity recognition. Therefore, we present a process model consisting of the combination of a petri net and aspects of Hidden Markov Models (HMM). Based on the modelled work process, the system determines performable work steps at the given time, while the activity recognition selects the most likely work step on the subset of feasible work steps. In this paper we describe the structure of the process model and how petri nets and approaches from the area of HMM are combined in this model. The outlook shows an implementation approach for the model.

Keywords: Assistive Systems; Information Modelling; Flexible Automation; Ergonomic and Health

1. Introduction

Context-aware assistance systems are increasingly becoming an integral part of our daily life. These systems help us to make decisions or to process a wide range of tasks. Examples can be found in electronic shopping assistants [1], city tour guides [2] or driver support systems [3]. Besides private environments the development of assistance systems also reaching industrial domains such as manual assembly [4], quality control [5] and rework [6], for example.

While assistance systems for manual assembly are already well developed and optimized for efficient processing of assembly orders, there is a lack of suitable systems for the area of rework and repair. The main reasons for the discrepancy between these two areas can be found, among other things, in the fundamentally different working methods [6]. Assembly orders contain unmodifiable end results enabling the definition of activities, materials and tools before the start of the assembly. Applying optimization methods to that knowledge, the optimum processing sequence and method of processing can be determined for each assembly order. The main task of support systems in that area is consequently the guidance of workers through the optimized assembly process. Additionally, assistance is provided in case of problems. These systems face two main challenges. Firstly, providing knowledge and information about orders such that workers are neither over- nor underchallenged. Secondly, working contexts need to be captured to provide the correct information at the right time. Such systems are so called “Taylors Agents”, that tightly control procedures. They react immediately in case of failures

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and set working speed and method but offer less flexibility and space to work self-determined [7]. This clearly defined behaviour and predeterminable machining sequence by the work order allows the use of deterministic models or process descriptions such as state machines or Petri nets.

Repair orders, on the other hand, are characterized by many unknown variables that can only be identified during the process. Often operators only have access to fault descriptions or indications of the cause of the fault. It is therefore not possible to determine the optimum processing route for each order in advance. Instead of a straightforward processing of the order, the working method is characterized by intuition- and experience-based decisions to find the actual cause of the problem and to carry out a repair [8,9]. Moreover, the structure of rework workplaces is more open and flexible compared to assembly workstations to cover a wide range of repair tasks. Thus, assistance systems in repair field must master additional challenges to enable appropriate worker support. This includes the evaluation of the current work situation and the determination of all possible processing steps that can be carried out based on this situation [10]. For this purpose, the system must be able to recognize the current work situation, despite the variable and open structure of the repair workstations. Assistance systems that follow this design principle usually aim to enhance the work process with situation-related and relevant information and relieve self-determined decision-making situations [7]. For the implementation of such systems, often probabilistic approaches are used, which allow a probability-based determination of the current work situation and recommendations for action (cf. [11,12]). However, one of the main challenges in the development of such systems is the simple and low-cost creation of process models for work orders. While, for example, work steps and assembly sequences for the construction of a product can be extracted from existing design data and used directly by the deterministic models (cf. [13–15]), this is not easily possible with probabilistic models. One reason for this is that deterministic relationships, such as dependencies between work steps, cannot be directly represented with probabilistic models. However, to achieve an efficient support of the worker such dependencies need to be considered.

The research related to this paper is therefore mainly concerned with the question of achieving a simple creation of process models for the flexible performing of work orders. The aim is to advance the development of suitable assistance systems in the field of repair and rework on the one hand and to offer new approaches for assistive systems in other areas on the other hand. This includes the creation of a technical basis for a more self-determined way of working, for instance in manual assembly. A study with assembly line worker showed an effect of a more self-determined work on job satisfaction [16]. While an increase in job satisfaction alone is a worthwhile goal in supporting people, it also leads to a higher performance [17].

In this paper an approach is presented that tackles the above-mentioned challenges by merging aspects of deterministic and probabilistic models. The combined approach unites the simplicity of deterministic process models with the flexibility of probabilistic models. Based on this approach a system is created that provides the worker enough space to work self-determined but at the same time support the worker with information about performable work steps.

In section 2 of the paper a case of application in the repair field will be presented. This use case serves as a framework and provides the requirements that the combined model must meet. Based on this, it is discussed how petri nets can be used to cover the requirements regarding deterministic dependencies of a repair scenario. Furthermore, it is shown how the challenges of context sensitive support for a self-determined way of working can be met with the help of activity detection based on approaches used in the probabilistic Hidden Markov Models (HMM). At the end of this section the combination of the activity recognition and the modelling of the work processes is described. In section 3 the usage of the combined model is presented as practical application at the manual working station of *SmartFactory*$^{\mathrm{KL}}$.

2. Case of Application

For the chosen case of application, we use an actuating drive and simulate its repair based on the exchange of a faulty control board. The actuating drive consists of four parts that need to be disassembled in order to replace the faulty control board with a new one. Figure 1 shows these parts including the board. To achieve context-sensitive support the repair process is monitored by an assistive system that determines feasible work steps and provides support for the current work step. To do so the work process needs to be modelled in a way that all feasible assembly and disassembly paths as well as the progress of the process can be identified. In section 2.1 the modelling of work processes is shown, using the petri net model.

Furthermore, to achieve context-sensitive support the assistive system needs to recognize the activity and work step performed at a given time. In order to maintain the flexibility of repair processes or a self-determined working method, which is associated with changing products and undefined processing paths, the activity recognition needs to be flexible itself as well as adaptable to the progress of the process. This means the systems

1. must not rely on fixed sensors or detection systems and
2. should identify work steps that are feasible at the current time.

The implementation and modelling of an activity recognition according to these principles is described in section 2.2.

2.1. Modelling of Work Processes

Looking at the characteristics of the described application case there are two main aspects associated with modelling the work process. First, the work process needs to be modelled in an open and flexible way to ensure that not only one, but all feasible ways of processing can be represented and derived from the model. Secondly, the model needs to represent the progress of the working process. On the one hand, to enable the

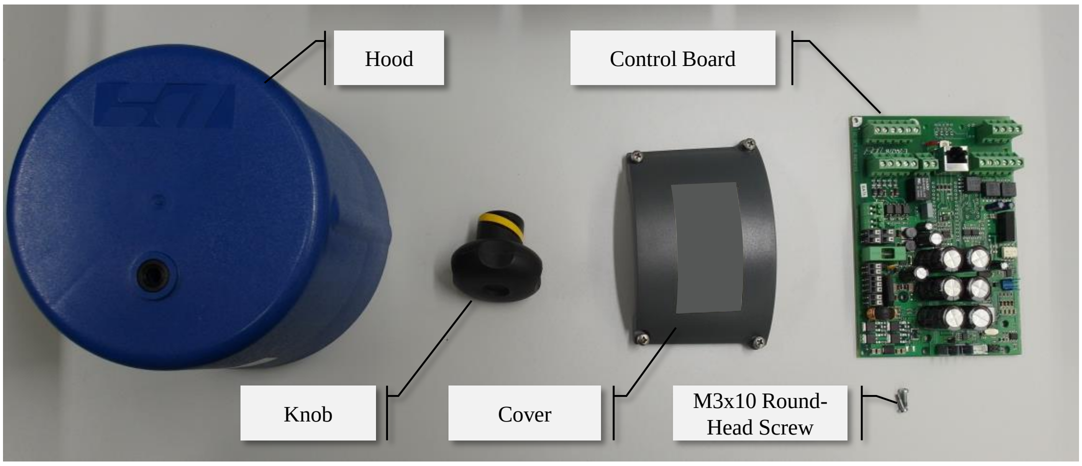


Figure 1: Actuator drive consisting of six parts (actuator body not shown)

system to recognize the current work step, and on the other hand, to simplify the derivation of further processing paths.

A commonly known model that can represent such concurrent and flexible processes is a petri net. The advantages of petri nets compared to other modelling languages are its simple representability as well as its mathematical definition that allows an automated analysis of the petri net characteristics and the transition behaviour. The structure of petri nets consists of two types of nodes, places (s) and transitions (t), as well as connecting edges, that link the two types of nodes. While the places of a petri net represent different states of a system or a process, transitions represent actions or events which lead from on state to another. The behaviour of the model is described by the linkage of places and transitions via edges and markings which indicate active places and thereby the state of the progress. For a deeper insight into petri nets we recommend the works of [18–21].

The construction of the petri net associated with the working process of the case of application follows four definitions. Figure 2 shows a section of the petri net corresponding to these definitions. The section is reaching from the completely assembled actuator (start of the repair process) to the removal of the control board and consists of nine working steps (see definition 1). In the shown state of the petri net the initial places s_0 and s_1 contain marks and lead into concurrent processing paths. While concurrent paths or places represent working steps that do not depend on each other (see definition 3), dependencies between work steps are represented as sequence of places (see definition 2). The markings in state s_0 and s_1 indicate the working steps that can be performed at the current point of time. The successful processing of a working step is represented by firing the transition subsequent to the corresponding place (compare place s_3 in Figure 3a and Figure 3b).

Definition 4 ensures a correct interpretation and handling in case of merging process paths (compare place s_6 in Figure 3a and Figure 3b). In contrast to work steps with one or no previous node (like s_0), work steps following a merge can only be performed if all previous work steps are finished. The increase of the edge weight corresponding to definition 4 ensures that a subsequent transition can only fire if all previous places have been passed. Additionally, the ability of a transition to fire indicates that the work step associated to the preceding place is performable (compare place s_6 in Figure 3b).

Definition 1: All work steps of the working process are represented by individual places.

Definition 2: Causally connected work steps are linked to each other via transitions, whereby the connecting edges point from the preceding to the following work step.

Definition 3 Independent work steps or sequences of steps are modelled by parallel paths. Parallel paths begin either without an incoming edge (see state $\boldsymbol{s_0}$) or by splitting (see transition $\boldsymbol{t_4}$). According to definition 2 these paths are merged via transitions as soon as a causal relationship exists (see state $\boldsymbol{s_6}$).

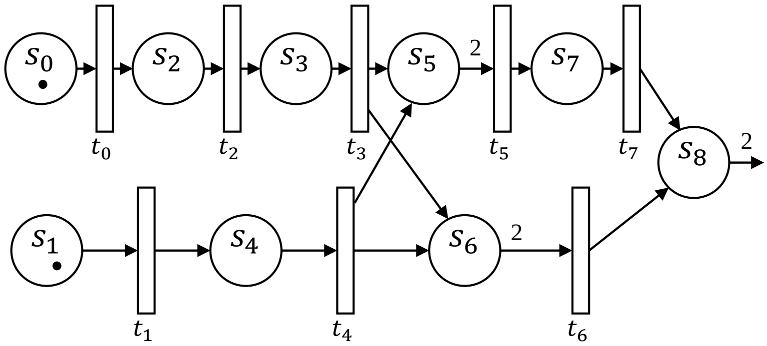


Figure 2: Petri net-based model for a section of the working process

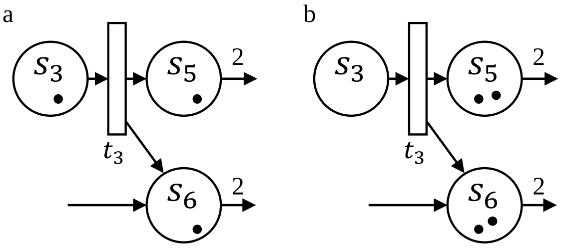


Figure 3: Switching behaviour of the model

Definition 4: Each state has exactly one outgoing edge with an edge weight equal to the number of incoming edges.

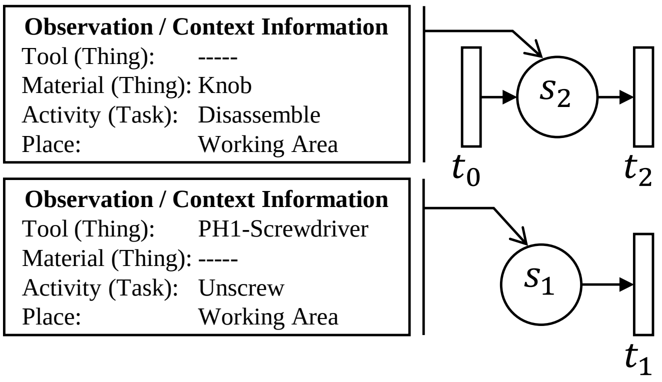
2.2. Modelling of the Activity Recognition

While the work process, consisting of all work steps, can be represented as a deterministic model, this is not possible for the modelling of context-sensitive worker support. Every worker is shaped by his own experiences and preferences, resulting in individually executed repair processes. However, this individual processing is a priori unknown. Therefore, the system needs an activity recognition based on a detection of performed work steps as well as a probabilistic modelling of work steps that can be carried out at any given time. Since it is not possible to recognize the work step directly, different aspects of the working situation will be detected in order to determine the work step being performed in a context-sensitive way. For this reason, we use principles and aspects of HMMs.

A special feature of HMM is the indirect determination of hidden states by recording observations. Based on the observations, the HMM calculates the probability of chosen states. Extensive information on HMM and their practical application can be found in the works of [22–25].

In our case the work steps being performed represent hidden states, that cannot be detected directly. Different conditions of the working situation represent observations to determine the work steps. For our scenario the definition of the observations is based on the context information models of [26,27]. They divided the context of a situation and defined it through information regarding the *work task*, the *place*, the *person* and *things* that are necessary to perform a work step. Based on this subdivision, we derived the four observation types *tool* (thing), *material* (thing), *activity* (task) and *place* of an activity. In order to use these types as observations for the probabilistic model, each work step is linked to a specific expression of these types (compare Figure 4). Looking at the work step "Remove the knob from the product" of our case of application, the specific observation types are:

- *Tool*: -
- *Material*: Knob
- *Activity*: Disassemble
- *Place*: Working area



Observation / Context Information
Tool (Thing): -----
Material (Thing): Knob
Activity (Task): Disassemble
Place: Working Area

Observation / Context Information
Tool (Thing): PH1-Screwdriver
Material (Thing): -----
Activity (Task): Unscrew
Place: Working Area

Figure 4: Linkage of observation information to work steps

This connection of observation types and work steps represents the context-sensitive description of the work process and is the basis for the activity recognition. The system compares the current work situation with the observation types of the work steps and determines the match for all work steps with the given situation. If the work situation corresponds completely with the modelling of a work step, it is valued as a 100% match. If these do not match completely, the match value is reduced linearly (compare Table 1). The step with the highest match value is selected for the provision of assistance through the system.

Table 1: Degree of agreement between the recorded work situation and the modelled work steps

Scenario	Observation	Conformity with s_1	Conformity with s_2
1	---- Cover Disassemble Working Area	2 of 4 ≙ **50%**	2 of 4 ≙ **50%**
2	PH1-Screwdriver Cover Disassemble Working Area	2 of 4 ≙ **50%**	3 of 4 ≙ **75%**
3	PH1-Screwdriver ---- Unscrew Tool Area	4 of 4 ≙ **100%**	2 of 4 ≙ **50%**

2.3. Combined Model for the Work Process and Activity Recognition

In order to achieve a context-sensitive and adaptable assistance that can both determine the processable work steps and detect which work step is in progress, the modelling of the work process and the activity recognition is combined. Due to the petri net-based modelling of the working process, the system can determine at any time which working steps are feasible. Based on this, the activity recognition takes place, which only determines a match with the work situation for the feasible work steps. Thus, the system does not provide assistance for work steps that cannot be carried out, which might confuse the worker or lead to attention tunnelling. Furthermore, the quality of the activity recognition increases, since similar work steps at different locations within the work process are not considered simultaneously.

Figure 5 visualizes the combined model based on the principles of petri nets, extended by the semantic modelling of the context and the selection of the assisted work step. The semantic annotation follows the description in section 2.2, while the definition 5 and 6 describe the principles of active and selected states. For practical application, active states represent the feasible work steps that are considered by the activity recognition. The selected state, on the other hand, shows the work step that was determined by the activity recognition as currently performed. Looking at the example in Figure 5, working step s_6 has already been processed whereas step s_7 must still be completed. Step s_8 can therefore not be processed at this time. In the combined model this is represented by the selected state and the inactive transition t_8.

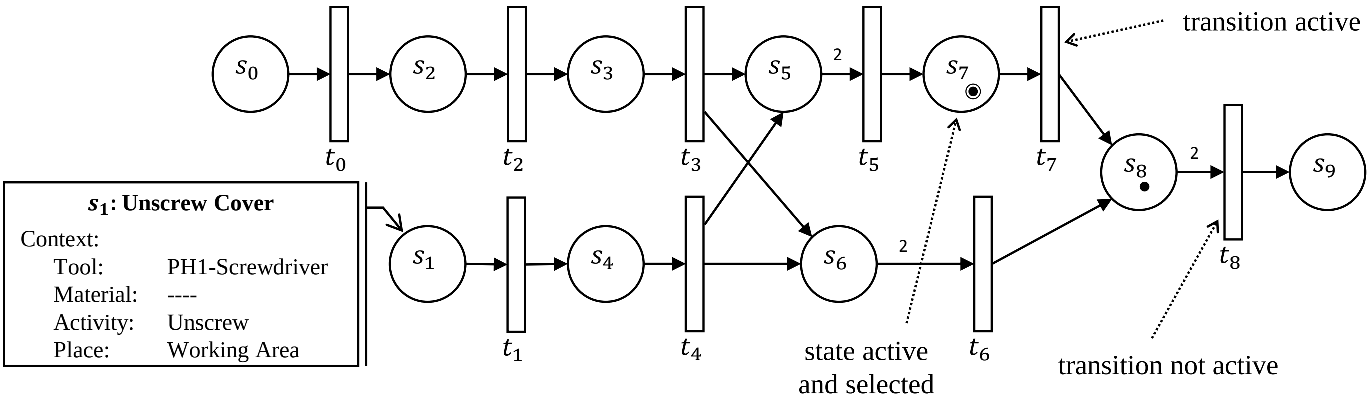


Figure 5: Section of the combined model for work process and activity recognition

As soon as step s_7 has been processed, transition t_7 switches and step s_8 becomes active and selected.

Definition 5: If a transition $\boldsymbol{t}$ is considered active according to petri net principles, the immediately preceding states (called input places) are also considered active.

Definition 6: From the set of active states (see definition 5), the state that has the greatest correspondence with the work situation represents the selected state.

3. Practical Application and Results

The practical application of the combined model from section 2.3 is done using the assistance system at the manual workstation of *SmartFactory*$^{\text{KL}}$. The system follows a modular structure consisting of independent sensor systems for data acquisition regarding the work situation and independent output systems for supporting the worker [28]. Central element of the system is a processing unit that collects all information provided by the input systems and that prepares the assistance by controlling the output systems [29]. The sensor systems include an intelligent material supply system that records the working materials used [30] as well as a depth-image camera to realize a hand, tool and object recognition [31,32]. Necessary information about the work situation in relation to the observation types *place*, *tool*, *material* is therefore already provided by the system. Information regarding the observation type *activity* cannot be detected automatically, so it is collected by a human observer and transmitted to the system via a graphical user interface (GUI). The manual working station described is shown in Figure 6.

The implementation of the combined model takes place in the central processing unit, by means of two software parts (*Work Step Detection* und *Workflow Manager*) dealing with the two aforementioned tasks of activity recognition and work process management. The *Workflow Manager* thus controls the petri net-based model and switches the appropriate transition. This provides information regarding the currently feasible work steps for the *Work Step Detection*. In addition, it controls the connected output systems, so that they provide support for the currently executed work step. Information about which work step currently is executed is provided by the *Work Step Detection*. The *Work Step Detection* collects all recorded information from the input systems regarding the observation types *activity*, *tool*, *material*, *place* and stores it into an observation history. The most recent information is processed corresponding to the aforementioned comparison with the information linked to the work steps (see section 2.2).

Tests with the system show that the core principles of a context sensitive and adaptable assistance could be achieved with the combined model. If the working situation changes, e.g. because the worker decides to use a different tool, the system recognizes the change and provides support accordingly. However, since there are only four observation types used to recognize the work step being processed, several work steps are equally likely. In these situations, the system cannot decide which work step is performed by the worker. Another situation that proves to be a challenge for the system is the recognition of when a work step has been completed. An obvious approach to detect the completion is to use a 100% match between the recorded work situation and the observation types linked to the current work step. However, this strategy has its limits. If there

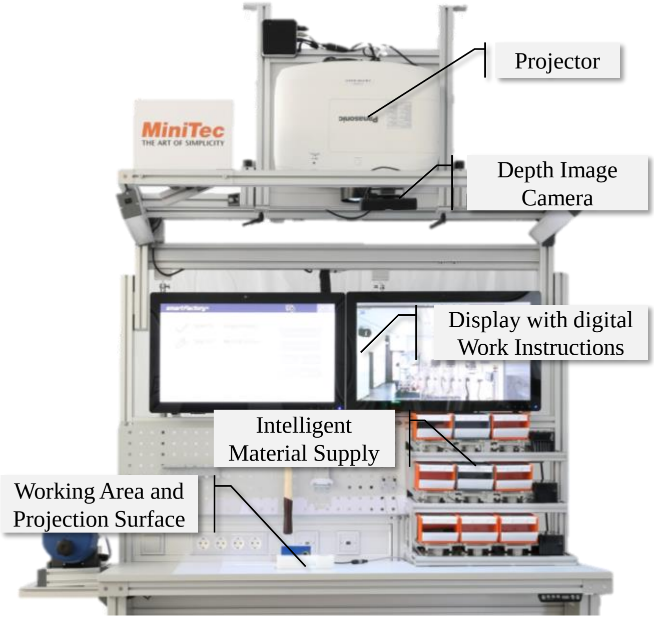


Figure 6: Manual working station with assistance system

are problems with data collection, important information may be missing, making a full match unreachable. Additionally, even if there is an accurate data acquisition and recognition of the work situation it is hard us a 100% match. To do so a proper modelling of the work step detection is a necessity in order to ensure the 100% match only occurs at the right point in time. If there is no proper modelling or there are differences in the working method of users, the system might detect a completion early. In both situations an accurate and context sensitive support is not achieved. Realizing this proper modelling might lead back to a time-consuming and complex preparation of work plans, which the presented approach is intended to avoid.

Furthermore, the test has shown that there is a need for a better provision of information. While conventional systems only provide support for one work step at a given time, the presented system switches between work steps to provide the right information according the current work situation. However, it is difficult for the worker to distinguish why the system switches back and forth between different work steps. The reason for the change can be initiated by the successful processing of a work step or because the activity detection has determined that another work step is being processed. In case there is a frequent switching between the work steps and the provided support, the system might overwhelm the user with too much information. If this happens constantly it would lead to a lack of acceptance by the workers and thus to a useless system.

4. Conclusion and Outlook

In this paper we introduced a context-aware assistance system based on a combined model consisting of a deterministic and a probabilistic part.

Once the structure and functionality of both parts were explained, the implementation of model at the manual working station of *SmartFactory*^{KL} was presented. Initial tests with the system show that a context-aware and adaptive behavior to the working method of the user could be realized. However, in order to realize an operational and economical system further improvements must be achieved. This includes the area of work step recognition as well as the provision of information to assist the worker. Approaches to achieve this goal are the continuous further development of the developed model, for example by integrating further aspects of HMM or by extending the observation types.

A useful aspect of HMM could be the probability-based switching between states. While in the current model any new step is selected after the successful completion of a step, a probability-based change offers the possibility to define preferences for the subsequent selection. For example, assume a component is unscrewed in the current step. It is likely that this component will be removed in the next step and consequently unlikely that in the next step the tools will be changed and work will continue on another component. An open question is how these probabilities can be determined without a significant increase of modeling effort. One solution to this problem could be the use of machine learning algorithms to recognize patterns and connections between work steps in the way workers work. The resulting information can be used for the constant improvement of existing work plans or the creation of new ones.

The extension of the observation types, however, allows a better modelling of the work steps as further aspects of the work situation can be covered. This also includes, for example, the consideration of several pieces of information regarding the same observation type. For example, in order to record not only one point in time of the work situation but whole sequence of the working situation and thus improve the activity or work step detection.

In our further research, the developments of the combined model will be examined more closely and tested with the help of the manual working station. In addition, the model will be further developed through improvements such as those mentioned above.

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