Abstract

The gap between technical capability and practical application of service robotics increased constantly within the last years, especially regarding small and medium-sized enterprises. In order to facilitate the transfer of knowledge to the shop floor, a methodology for the formal modelling of originally manual work processes was developed. Here, specific work processes can be characterized under consideration of automation relevant parameters what serves as a basis for a subsequent determination of applicable and suitable service robotic solutions. By utilizing this approach, industrial operators will be considerably supported regarding the planning and implementation of automated and especially hybrid robot-assisted work systems.

Keywords: Design of work systems; Process and production planning for variety; Adaptive manufacturing; Formal process modelling; Service robotics

1. Introduction

The environment of modern manufacturing companies is characterized by internationally expending markets, new technologies and a continuous development of new customer-oriented products which lead to shortened product lifecycles and an increasing process variety and complexity. Due to resulting high flexibility requirements, the trend towards fully automated processes has declined in the recent years [1, 2]. Instead, technical assistance applications for human beings as well as collaborating human-robot systems are used increasingly to support an ageing workforce to cope with the substantial current requirements regarding industrial work. In particular, the application of service robots allows for the combination of the employee’s cognitive-analytical and sensori-motorical abilities with the advantages of a robot system (e.g. high accuracy and velocity). For that reason, an integration of service robots into manual work processes is of outstanding importance and depicts a promising approach [3].

Despite the various provided applications of service robots for the support of employees in industrial work processes, only few industrially implemented applications can be found. In fact, a substantial gap between the evolved potentials and the degree of service robotic applications currently exists in practice, especially regarding small and medium-sized Enterprises (SMEs) [4]. Reasons therefor are among others the user’s difficulties in accessing information and their concerns about possibly high implementing costs [2]. In order to overcome the affiliated obstacles and the presently prevailing barriers of acceptance, an easily applicable and formal methodology for planning and integrating service robots into formerly manual work processes becomes even more necessary. The methodology’s objective is to support industrial users in analyzing their specific manual work processes and planning appropriate service robotic solutions. As a central precondition therefor, data concerning the underlying manual work processes including information on automation requirements needs to be collected within a formal and systematic way.
2. Formal modelling of manual work processes

The evaluation and assessment of currently manual work processes regarding their possible automation levels require a formal process modelling language whereby all automation relevant parameters concerning product, process and work system environment can be identified initially and transformed into clear and precise semantics afterwards. Based on this formal manual process modelling, hybrid or fully automated manufacturing and assembly systems using industrial service robots can be designed.

In industrial environments, a large number of different process languages exist (e.g. Business Process Model Notation (BPMN), Value Stream Mapping (VSM), VDI 2860, Robot Time and Motion (RTM), Methods Time Measurement (MTM)). These mainly differ in their accuracy and the effort necessary to record and document the manual work processes. In addition, current process languages also vary in their complexity and are often designed for very specific applications (e.g. assembly planning).

Although there are mentioned differences afore, any process modelling language serves as a tool for documentation, analysis and modelling of processes. The main objective is a reduction of complexity as well as an increase of transparency and comprehension of processes, for identifying existing vulnerabilities and for deriving improvement measures [6].

The evaluation of existing manual processes concerning their possible automation level as well as the subsequently use case-based selection of service robotic applications require an adapted process modelling language. The selection of an appropriate process modelling language is determined by certain performance criteria. Exemplary valid quality criteria are among others [6]:

- Relevance (focus on the central information concerning the application)
- Modular approach (possibility of reducing or increasing the level of detail by hierarchical variation)
- Objectivity and reliability (minimal inter- or intrapersonal fluctuations concerning process analysis; repeatability)

In general, a well-structured approach during process evaluation and a relatively low training effort is of particular importance so the process modelling language can be learnt and applied easily. Furthermore, there are additional requirements that arise from the specific application context:

- Considering various, extensive manual operations
- Integration of automation relevant parameters (e.g. object symmetry, grasping surface)
- Little effort for data collection
- Representation of respective process input and output parameters
- Representation of sequence relationships between consecutive processes

In this context, MTM appears as a particularly suitable system of predetermined times. This system is explicitly used for modelling and analyzing manual work processes while documenting relevant factors which affect human motion sequences in general and fulfills several of the given criteria to a large extent. In order to ensure the criteria objectivity and reliability, e.g. the MTM process building blocks are described by an unambiguous syntactic and semantic standard [6]. Based on the MTM system, in 1979 the RTM (Robot Time Motion) process modelling language was developed for the purpose of modelling and evaluating robotic processes. As true for the MTM system, RTM also divides the overall process and defines fundamental elements as well [7]. Based on these substantial similarities, the compiled contents concerning RTM were also taken into account for adapting the MTM notation.

3. MTM/MTM-1

The MTM system is considered as one of the most important systems of predetermined times concerning the scientific and industrial application [8]. MTM serves as an instrument for the formal modelling, analysis, planning and design of work systems. Hereby, the focus of MTM lies on the formal modelling of manual work processes as a set of motions in combination with corresponding influencing factors and the subsequent determination of time values. As a main precondition for the utilization of MTM, the examined work operations need to be completely influenceable by human beings, i.e. process times conducted by machines (e.g. automatic cutting processes) or extensive mental operations (e.g. utilizing CAD software) cannot be considered [9].

As a superior system, MTM consists of various methods which may be utilized depending on the characteristics of the underlying manual work process. For the production of medium to large product series (characterized by e.g. moderate cycle times, several repetitions), the MTM-UAS method may be applied as it ensures a relatively low effort regarding the process analysis. This can be realized by comprising numerous different motions within relatively long single motion sequences (e.g. reaching, grasping, positioning and releasing an object). For a highly standardized production (characterized by e.g. short cycle times, high degree of repetition), utilizing the MTM-1 method can be very advantageous. Here, the effort for conducting a process analysis is relatively high, because manual motion sequences need to be modelled by so-called basic motions in a fundamental and elementary way (e.g. reaching for an object corresponds to one basic motion). However, the MTM-1 method hereby considers the highest level of detail so that the data quality regarding the manual work process is higher compared to other MTM methods [6].

The five fundamental basic motions considered within MTM-1 are depicted in Figure 1 and can easily be explained by the example of manually sticking a screw into a hole. The initial arm motion towards the screw is considered by the basic motion Reach. Closing the fingers in order to control the screw physically is regarded as Grasp. Taking the screw from the initial position to the hole is considered as a Move. Manually sticking the screw into the hole corresponds to Position. Finally, detaching the fingers from the screw is regarded within the basic motion Release.

To characterize a given motion sequence in detail, well-defined time influencing factors are assigned to each basic
A MTM-1 motion sequence may include five different basic motions. Exemplary referring to the basic motion Grasp, the most important influencing factors are the kind of grasp as well as the position and shape of the object. In this context, the kind of grasp refers to the motion of the fingers required to physically control the object (e.g. simply joining the fingers). The position refers to the presence of additional material within the surroundings of the object (e.g. selecting a single screw from a container), whereas the shape is mainly characterized by the size of the workpiece (e.g. small). Hereby, the time necessary for manually executing a basic motion strongly depends on the characteristics of the influencing factors.

Overall, MTM-1 is a widely spread method that allows for the creation of high-quality data concerning industrial work processes. Particularly for these reasons, MTM-1 will be utilized as a foundation for the formal process modelling. However, this method was designed to model and analyse manual working operations and therefore does not consider key topics like automation and especially the application of industrial service robotics. Therefore, an adaptation of MTM-1 in respect of automation relevant parameters needed to be conducted.

4. Identification of automation relevant parameters

For this adaptation, parameters that are relevant for the automation of manual working processes and not considered within the original MTM-1 method needed to be identified and structured at first. Besides technical parameters (e.g. component dimensions), various other subjects like economical (e.g. investment costs) and ergonomic issues (e.g. physical load) were examined as well. As indicated in Figure 2, the parameter identification was mainly conducted within three steps.

Initially, automation relevant parameters were identified based on a comprehensive literature review. Here, especially works regarding the analysis of a suitable level of automation were important [1, 10, 11, 12, 13]. Besides, additional parameters could be identified by the analysis of scientific publications concerning the automation of processes in general [14, 15, 16, 17]. In parallel, interviews with scientific and industrial experts in the field of automation were conducted to discuss the revealed parameters and to find additional ones.

As a second step, the identified parameters were classified in order to obtain a comprehensible and transparent structure. Therefore, the found criteria were compared to each other whereby some redundant parameters could be removed. Subsequently, a classification of the remaining factors was conducted. For this purpose, the required classes were defined based on the REFA model for the formal modelling of work systems [18]. This model differentiates between seven main elements of work systems:

1. Work task
2. Process
3. Input
4. Output
5. Human being
6. Manufacturing equipment
7. External influences

Hereafter, each parameter was matched to those elements showing the highest content-specific coherence. For instance, ergonomic parameters especially focus on preserving the physical capabilities of employees which is why they were assigned to the class Human being.

As a third step, each of the parameters was analysed in detail based on an additional extensive literature review. Hereby, the aim was to define rationally structured parameter characteristics. Taking the solidity of a component as an example, the three defined characteristics are rigid, elastic and non-rigid. Here, rigid parts are generally easier to handle for...
robots or other machines than non-rigid ones in terms of automation. Altogether, the generated structure of automation relevant parameters is a main precondition for each of the following actions.

5. Adaption of the process modelling language

Based on the defined classification, the adaptation of the selected process modelling language MTM-1 can be conducted subsequently. In order to ensure a reasonable and sustainable integration of the automation relevant parameters within MTM-1, expert interviews were performed. Thereby, each basic motion within MTM-1 was analyzed and adapted separately, whereas the underlying scientific approach was the same for all basic motions. Concerning this adaptation, the influencing factors within MTM-1 as well as the automation relevant parameters are of outstanding importance, because the characteristics of each analyzed motion sequence are hereby defined.

Therefore, the relevance of every MTM-1 specific influencing factor for each basic motion was evaluated at first. For instance, the MTM-1 influencing factor Kind of grasp regarding the Grasp of an object was focused. This parameter refers to manual grasping motions whereas the way automated grasps are conducted by machines or industrial service robots is not considered. This aspect is much better regarded within the automation relevant parameter gripping surfaces. Therefore, the influencing factor Kind of grasp could be ruled out in this case.

After the analysis of the original influencing factors, the matching of the identified automation relevant parameters was performed. Hence, the relevance of each factor within the classification was discussed and evaluated for the five basic motions. Regarding the grasp of an object as an example again, the existence of gripping surfaces was identified as a central factor. The reason for this is that depending on the amount and position of gripping surfaces, there is a substantial influence on the available technical gripper units. For gripping surface on the exterior sides of an object, contact can be established by simply reducing the radius, which is a standard motion that can be performed by numerous technical devices. In contrast, the requirements regarding to grippers are significantly higher if an object does not feature any gripping surfaces. In that case, gripping can exclusively be ensured by the utilization of substance properties (e.g. magnetic, adhesive) for what the corresponding characteristics need to be determined for grasping.

Another important aspect that facilitates the application of the process modelling language in practice is the development of a formal, short process code for each basic motion. Herewith, especially the creation of well-defined codes was a main requirement to avoid any possible ambiguous or ambivalent codes.

To illustrate the defined code structure, an exemplary process code for grasping is shown in Figure 3. The first character, which is highlighted in the black box, codes for the underlying basic motion. As the adapted process modelling language differs from the original MTM-1 method, the basic motion was renamed to grasp+. Moreover, each code segment within the remaining seven blue boxes corresponds to an automation relevant parameter. The letters in the first position of each code segment refer to the underlying automation relevant parameter. For instance, F obtains to the solidity of the components and O represents the surface sensitivity. The numbers within the second position of each segment correlate to the specific characteristic of the particular parameter. As can be seen in comparison with Table 1, e. g. the code segment F1 indicates a rigid object, whereas the segment O1 refers to insensitive surface material.

Based on this adaptation of the original MTM-1 process modelling language, the industrial user is supplied with fundamental tools for modelling manual working processes to evaluate a suitable level of automation and the reasonableness factors. By this means, especially the effort for analysing a process in practice remains on a medium level as only seven characteristics need to be determined for grasping.

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Table 1. Automation relevant parameters for the basic motion grasp.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>solidity of the component (F)</td>
<td>rigid</td>
<td>elastic</td>
<td>non-rigid</td>
<td>-</td>
</tr>
<tr>
<td>surface sensitivity (S)</td>
<td>insensitive</td>
<td>sensitive</td>
<td>contaminated</td>
<td>-</td>
</tr>
<tr>
<td>material allocation (L)</td>
<td>ordered</td>
<td>partially ordered</td>
<td>disordered</td>
<td>-</td>
</tr>
<tr>
<td>mass (M)</td>
<td>m ≤ 1 kg</td>
<td>1 kg &lt; m ≤ 10 kg</td>
<td>m &gt; 10 kg</td>
<td>-</td>
</tr>
<tr>
<td>aspect ratio (V)</td>
<td>uniform aspect ratio</td>
<td>one extension large or small</td>
<td>two expansions large or small</td>
<td>all expansions large or small</td>
</tr>
<tr>
<td>symmetry (S)</td>
<td>rotationally symmetric</td>
<td>surface symmetric</td>
<td>strongly symmetric</td>
<td>seemingly symmetric</td>
</tr>
<tr>
<td>gripping surfaces (G)</td>
<td>gripping surfaces outside</td>
<td>gripping surfaces inside</td>
<td>no gripping surfaces (vacuum gripper)</td>
<td>no gripping surfaces (adhesive bond)</td>
</tr>
</tbody>
</table>

Fig. 3. Formal process code for the basic motion grasp.
of implementing service robotic solutions in a subsequent step. In this context, the utilization of the formal process modelling in practice will be focussed in the following segment.

6. Application within a manual work process

The application of the presented process modelling approach is conducted within three main steps. Therewith, general data on product, process segment and important framework conditions are collected at first. After that, the process needs to be modelled sequentially by utilizing the basic motions, which particularly includes identifying the characteristics of the correlating automation relevant parameters. As a last step, the collected data needs to be processed and depicted within the formal process code to facilitate further operations. To clarify the practical importance of this approach, the three addressed steps are outlined in detail for an exemplary manual work process.

Regarding the first step, the considered use case which is visualized in Figure 4 concerns the manual assembly of a metal driving shaft for a gear box. The work content for the shaft assembly includes sequentially attaching two plastic gear wheels, two lock rings as well as two metal ball bearings to the basic shaft and finally delivering it to a subsequent workstation. Special framework conditions concerning this process did not apply.

Referring to the second step, one motion segment will be described as an example. In this context, the grasping of an assembled shaft in order to deliver it to the subsequent workplace will be focussed. As indicated within the left picture regarding the workflow, the shaft is stored vertically in a standard device as a starting position and is grasped at its very top. The determination of the parameter characteristics was conducted in the following way:

- **Solidity of the component**: The grasping area is made of rigid metal
- **Surface sensitivity**: As the surface material is sturdy and no special quality-related requirements have been defined, the shaft can be determined as insensitive
- **Material allocation**: The shaft is individually stored in a standard container so it can be identified as ordered
- **Mass**: By weighing the workpiece a mass in the range of 1 kg < m < 10 kg was determined
- **Aspect ratio**: The shaft features a cylindrical structure so one extension is large compared to the other workpiece dimensions
- **Symmetry**: The driving shaft has a rotationally symmetric structure
- **Gripping surfaces**: As indicated within the picture, the gripping surfaces are located on the outside of the workpiece

As a last step, the determined basic motions, automation relevant parameters as well as their characteristics were composed and transformed into the formal process code. Here, the approach can be comprehended by comparing the table with the process code depicted in Figure 4.

7. Conclusion

The presented concept is of outstanding importance for the formal modelling and analysis of manual work processes for automation with special regard to relevant process, product and framework parameters. In this context, achieving a high quality concerning the input data was determined as a central requirement. Therefore, the MTM-1 method was selected as a fundamental process modelling language.

Referring to MTM-1, the determination of time values for the conduction of manual work processes is an important aspect. However, this feature was not integrated in the adapted process modelling language, because it is not inevitable in terms of technical feasibility for automation. Nevertheless, potential time savings are an important factor within the manufacturing industry which is why the subsequent consideration of time aspects is to be analysed within future research.

Moreover, the required degree of input data quality has to be focussed as well. Depending on central conditions like the quantity, the degree of standardization or the extent of work content, input data of lower quality might be reasonable for gaining a lower effort concerning the process modelling. In this context, the adaptation of other methods like MTM-UAS may become important issues.

Besides, the presented approach serves as a foundation for the modelling of manual work processes in terms of automation. Indeed, an additional methodology that utilizes the generated data base needs to be developed to identify possible applications for service robotics for specific manual work processes. Herewith, a suitable interface between both methodologies and especially a high compatibility of the underlying data is a main challenge which needs to be focused in future works.

Furthermore, the adapted process modelling language needs to consider appropriate and technically applicable service
robotic solutions. Therefore, the detailed analysis of numerous manual industrial work processes regarding the implementation of service robotics can be a suitable approach. Hereby, new findings on robot characteristics and especially possible fields of application can be acquired. This can be achieved by especially examining processes for different working areas (e.g. assembly, setting-up of machines). Based on these processes and the corresponding findings, the process modelling language may be improved further.

Concluding these aspects on a more general perspective, the importance of implementing automation and especially robotic assistance systems for the manufacturing industry will considerably underline the major relevance of corresponding research activities. Hereby, especially man-machine-interaction and the composition of hybrid work systems are main issues within the German Industry 4.0 program that have to be substantially enhanced [19].

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References