# ema – a Software Tool for Planning Human-Machine-Collaboration

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**Abstract.** Digital human models are already in use for validating manual work in terms of risk prevention and ergonomics. However, modelling different work activities is mostly very time-consuming and inefficient. This is because digital human models are considered as machines with more than 100 degrees of freedom to be specified for one pose. ema, however, the so called editor for manual work activities, treats its digital humans as virtual workers. By defining work instructions, the modelling process is much faster and more intuitive compared to efforts specifying individual poses. Furthermore, the implemented work instructions are more accurate and realistic as a result of theoretical development and empirical validation by means of motion capturing technologies. Newest work operations also allow the planning of human-machine-collaboration leading to the validation of interactive human-robot-scenarios. In this paper, features of ema are presented, including manual work modelling, time analysis and ergonomic evaluation.

## Introduction

With the increasing digitalizing of product development processes more than 200 digital human models have been introduced on the market. Those models can be used for anthropometric as well as muscle stress analyses. A detailed register can be found in Mühlstedt [1] and Duffy [2]. The most significant digital models are Ramsis (Human Solutions), Human Builder (Dassault Systémes) and Jack (Siemens PLM). They are represented by an internal skeleton model and an envelope and have similar characteristics and functionalities in terms of evaluating human workspace. Ergonomic analyses is based on anthropometric data, i.e. percentiled body measurements, as well as on individual poses.

However, motion modelling is similar to this of machines, i.e. individual poses are obtained by manipulating specific degrees of freedom to desired target positions. In contrast to robots with only 6 degrees of freedom, this modelling approach is mostly very time-consuming and inefficient – considering the fact that those digital human models consist of 100 degrees of freedom and 50 segments on average. Furthermore, modelled human work activities do not refer to any standardized performance level and thus cannot be used to evaluating cycle time.

## 1 Developing ema

Facing the stated issues, the editor for manual work activities (ema) was developed by the imk automotive GmbH in cooperation with the Technical University Chemnitz, Volkswagen AG, the German MTM Association as well as Dassault Systémes [3]. The primary objective was to create a digital human model acting on the basis of a standardized process language in terms of work instructions. In addition, it should be used for evaluating cycle time requirements. After five years of brainstorming and development, the first version of ema was presented in 2011. Since then, ema is constantly being further developed.

### 1.1 Design Principles

ema uses a modular approach for describing and generating human work activities. The editor is based on so called complex operations representing an aggregation of single elementary movements originally formulated by the MTM-method. MTM is a predetermined motion time system that is used to analyse human work tasks based on five elementary movements, i.e. reach, grasp, move, position and release. Those elementary movements were empirically provided with standardised execution times dependent on influencing variables such as movement length or level of difficulty [4].

By applying highly automated algorithms for generating a workflow based on MTM, the modelling approach in ema is not only faster but also a premise on a standardised method.

### 1.2 Complex Operations

As mentioned before, ema uses complex operations for generating human work activities as a function of elementary movements. Thus, complex operations are aggregated single elementary movements in a logical sequence to fulfill a specific task. For instance, the operation 'get and place part' consists of the following single movements: steps forward – bend – hand to object – pick object – straighten body – object to body – step backward – turn – steps forward – bend – place object – release object – hand back – straighten body.

Complex operations are divided into 2 groups consisting of 36 human and 10 object operations. Human operations include picking and placing objects, using tools, grasping, manual screwing, visual control, waiting, walking, turning, sitting down, bending down, kneeling, etc. whereas object operations include moving, turning, waiting, establishing and resolving connections, inverse and forward kinematics. One major challenge in the development of ema was the definition and implementation of complex operations that can be found in various manufacturing environments. In the end, the team from imk succeeded in a logical separation of operations and an additional parameter setting for adjusting boundary conditions of individual tasks, e.g. the weight of the object to be handeled.

### 1.3 Empirical Validation

As there was no sufficient theoretical method that was able to fully describe the complexity of human motion generation, an empirical approach was applied to validate the implemented algorithms in ema. Therefore, a motion capturing system was used to record experienced operators from real production lines in an artificial testing environment. For each operation, external parameters that may influence task execution were systematically varied and recorded, e.g. working height, force direction, weight of handeled object, and body height of operator.

In this sense, the biomechanical correctness as well as a high accuracy of movements could be verified for the implemented modules in ema.

## 2 Workflow

Simulating human work activities in ema reduces the effort for modelling of up to 90 % compared to manual step-by-step simulation. While manipulating individual degrees of freedom for simulating 1 minute of human work requires about 230 minutes, only 25 minutes of effort are needed with ema.

The workflow for generating a simulation in ema can be divided into 3 steps: defining the scenario, modelling the behaviour and analysing the simulation. The individual steps are presented in more detail in the following.

### 2.1 Scenario Definition

Within the scope of defining the scenario, products and resources are implemented and positioned in the simulation environment. Products represent objects that are handeled as well as reference objects, whereas resources respresent human models, tools, machines, tables, containers, layouts, etc. Digital human models describing specific percentiles are selected from the comprehensive library. User defined geometries as well as collision objects are also either selected from the comprehensive library or imported through the CAD interface (Figure 1). At the moment, the comprehensive library consists of 360 objects. Furthermore, object characteristics are specified, such as weight or motion assignment.

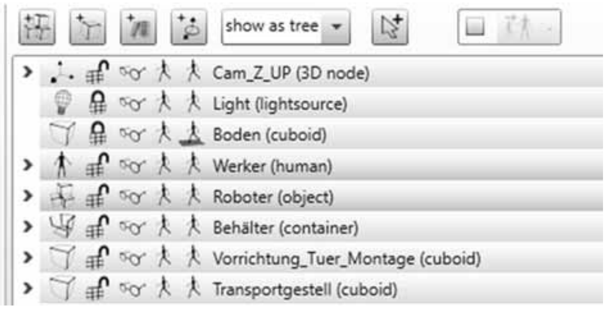


**Figure 1:** Object tree with library button.

### 2.2 Behaviour Modelling

After the scenario has been defined, the behaviour is modelled for each digital human model as well as for objects with previously assigned motion characteristics. The predefined complex operations are formulated to a task sequence by drag-and-drop (Figure 2). For each operation, parameters need to be specified, such as object to be handeled, automatic walk, target position or body posture.

Parameters like 'object to be handeled' or 'target position' can be easily set by selecting the required object or reference object in the 3D-environment. Thus, a complex operation is really formulated as a process language in terms of 'go and get the container and place it on the shelf at the end of the hall'.

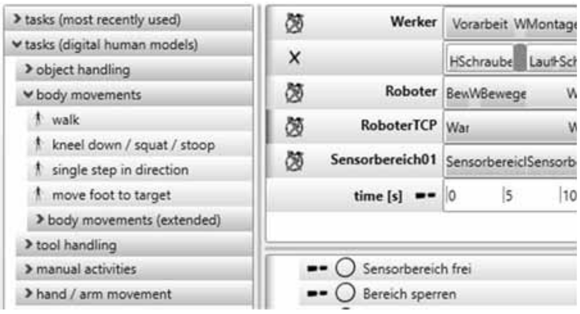


**Figure 2:** Task library and behaviour workflow

### 2.3 Analysis and Reporting

Basically, there are three analysing tools in ema with a focus on cycle time, ergonomics and motion path. Cycle time analysis corresponds to the MTM-method as each implemented human work activity is modelled complying with the standardised time of MTM. Thus, a comprehensive time analysis based on MTM-UAS (Universal Application System), an aggregated MTM-system, is available in ema (Figure 3).

UAS analysis

| # | type | code | hand | TMU | c x f | TMU infl. |
|---|---|---|---|---|---|---|
| 1 | place | PA3 | | 25.0 | 1 * 1 | 25.0 |
| 2 | movement cycle | ZB1 | | 10.0 | 1 * 15 | 150.0 |
| 3 | body movement | KA | | 25.0 | 1 * 3 | 75.0 |
| 4 | place | PA1 | | 10.0 | 1 * 1 | 10.0 |
| 5 | movement cycle | ZB1 | | 10.0 | 1 * 5 | 50.0 |
| 6 | place | PA1 | | 10.0 | 1 * 1 | 10.0 |
| 7 | movement cycle | ZB1 | | 10.0 | 1 * 5 | 50.0 |
| 8 | place | PA2 | | 20.0 | 1 * 1 | 20.0 |
| 9 | process time | PT | | 38.9 | 1 * 1 | 0.0 |
| 10 | body movement | KA | | 25.0 | 1 * 2 | 50.0 |

**Figure 3:** Integrated MTM-UAS analysis

Furthermore, ema includes an ergonomic risk assessment according to NIOSH, OCRA (Occupational Repetitive Action) and EAWS (European Assembly Worksheet).

| | Werker |
|---|---|
| information | 50th percentile, male, German, 79kg, age: 40 |
| **whole body [pts]** | **19.5** |
| postures [pts] | 7.7 |
| trunk rotating [pts] | 7 |
| trunk bending [pts] | 2.7 |
| far reach [pts] | 1.7 |
| **postures sum [pts]** | **19.5** |

**Figure 4:** Integrated EAWS analysis

EAWS is a standardised tool for evaluating repetitive assembly tasks taking into account static postures, action forces, load handling and short, repetitive loads. Within the scope of the ergonomic risk assessment, joint angles and positions of the body segments are recorded throughout the entire simulation cycle, i.e. simulation time. Based on this data, each posture is categorised according to EAWS. However, information regarding action forces and object weights need to be specified manually. In the end, ema calculates a total risk score that is rated according to the traffic-light system green – yellow – red (Figure 4). Additionally, so called spaghetti diagrams visualising the motion paths, workflow reports as well as cycle time diagrams can be directly obtained from the simulation (Figure 5). All simulation results can be either saved as videos, screenshots or exported as Excel or CSV files.

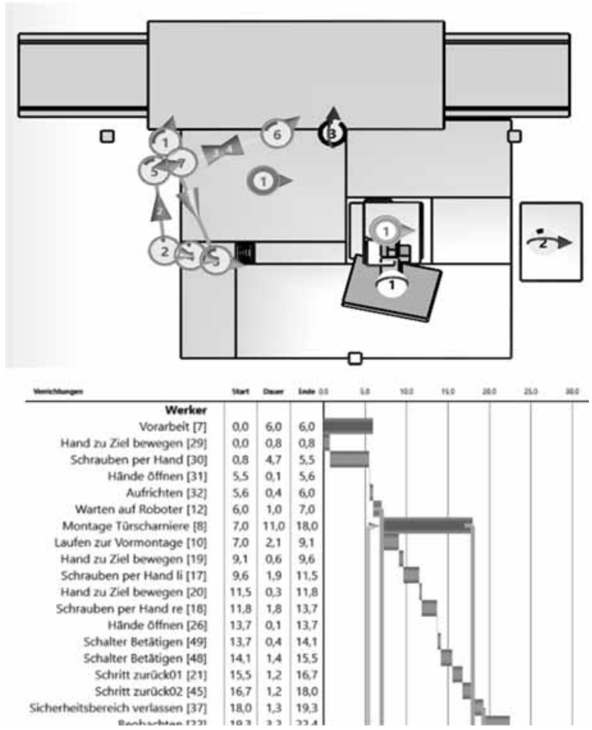


**Figure 5:** Spaghetti diagram showing motion paths (above) and cycle time diagram (below)

## 3 Planning Collaborative Work

With the introduction of human-machine collaboration, human workers are subject to a number of potential risks. Due to absent safety guards, humans work in the middle of highly dynamic enviroments where collision objects are not stationary any more. This leads to dangers arising from different sources, such as:

- planned and technological required collisions within the scheduled process, e.g. human-machine collaboration for a specific task within the collaborative space
- technical failure, e.g. collisions with out-of-control

objects
- machine dynamics, e.g. collisions with moved objects
- misbehavior, e.g. unattention, unintentional collision with objects

Those dangers challenge the planning and the design of collaborative working scenarios and make simulations prior to commissioning important than ever. ema, with its realistic human task modelling and its potential in incorporating also machine tasks, prepares a new era for validating human safety in the field of automation [5].

### 3.1 Design of collaborative scenarios

The design process for implementing collaborative working scenarios begins with a theoretical division of tasks between humans and machines and leads to the layout, tools and periphery design. Within the detailed planning phase, special tools for designing PLC-code, machine-code as well as human work activities are applied. As the following phase deals with the design and planning of scheduled collaborative tasks, a tool including PLC, machine and human tasks is urgently needed. Currently, research and development focuses on consecutive phases of generating misbehaviour and validating safety despite of misbehaviour – also as a basis for acceptance reports.

### 3.2 Analysing Regular Sequences

In order to efficiently analyse collaborative working scenarios, PLC, machine as well as human tasks need to be visualised in one simulation environment. Thus, the regular sequence of a collaborative work incorporates:

- Individual motions of the system, e.g. safety gate open – close
- Motion connections within the system, e.g. move machine only at closed safety gate
- Sensor reaction of the system, e.g. close safety gate only when light curtain is free
- Regular machine movement
- Sensor reaction of machine, e.g. force control
- Motion behavior of machine in case of sensor reaction, e.g. safety regulated stop
- Regular human motion
- Human motion for non-periodic tasks, e.g. tool change

### 3.3 Validating Safety at Misbehaviour

For validating safety at misbehaviour, the interaction between human misbehaviour and system reaction needs to be analysed. Furthermore, danger arising from excessive demand because of the system's dynamic needs to be taken into account. Even though, safety regulations are defined on the basis of risk assessments, human behaviour is analysed as a consequence of generated tasks. However, planning experience shows that validation requires an analytical approach.

Thus, misbehaviour can either result from FMEA (Failure Mode and Effects Analysis) or from random generators [6]. Both approaches have advantages and disadvantages in terms of objectivity and computation time. For instance, FMEA allows the analysis of a scenario with acceptable risk level where the robot moves an object with reduced velocity in close proximity to the human worker. The simulation of the scenario shows a collision between the object moved by the robot and the hand of the human worker (Figure 6). The next step would be a calculation and an evaluation of the applied and tolerable forces. There already exist tools for calculating forces during collision but those models are not yet implemented in ema. The physiological impact of collisions with the human body was already investigated by the BGIA in the past couple of years [7]. The results of this research are planned to be integrated in ema soon.

Even though, FMEA is an established method for failure analysis, the generation of misbehaviour is dependent on the engineer's imagination. In this sense, developers of ema are working on a so called numerical model for human behaviour which automatically generates collaborative scenarios [8].

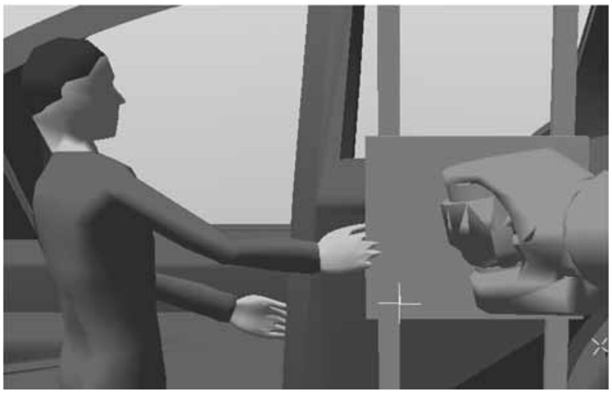

**Figure 6:** Collision between object and human body

For instance, the human worker is unconcentrated and enters the safety zone. The robot stops as fast as possible. The human worker is surprised by the reaction of the robot and almost falls over. The simulation of the scenario shows an unexected result, i.e. the human does not fall over as he reflexively supports himself on the workpiece (Figure 7).

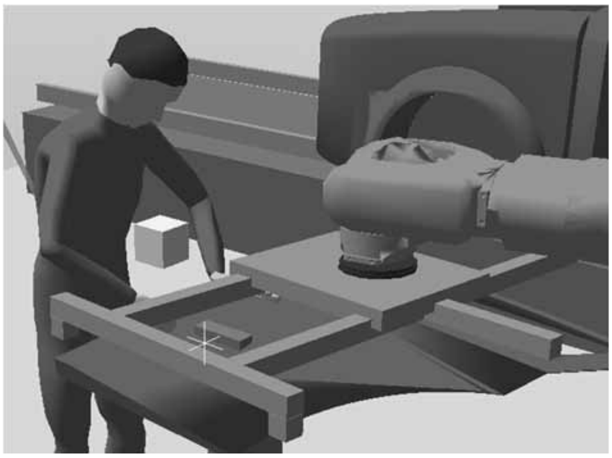

**Figure 7:** Simulation of misbehaviour

## 4 Discussion and Outlook

ema is an advanced simulation tool for intuitively generating and analysing human work activities. As the application of human-machine collaboration is of major interest now, ema was further provided with functionalities enabling the simulation of collaborative working scenarios.

Due to the development of universal exchange formats, ema not only comprises an interface for importing CAD data of machine objects but also for importing motion bevahviour in 3D space. Even though there exist exchange formats for geometries and motion data, logical connections to safety equipment are not yet integrated.

However, ema is able to simulate safety equipment on the basis of objects with their own active behaviour, i.e. sensors can be switched on and off. Furthermore, they are able to communicate to the system environment in case of specific events, e.g. human entering safety zones. This functionality expands ema to an event-based simulation system also allowing the validation of collaborative scenarios.

Even though ema is well-advanced in generating human activities, operations on moved objects in terms of following the moved object during task execution is not possible yet. For instance, objects moving on a conveyor belt or moved by a robot cannot be picked by the human worker during motion.

Furthermore, the integration of risk assessment analyses in terms of FMEA or random generators is still in focus of research and development. However, the examples show, that the integration of both methods is essential for the validation process.

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**Note.** At the moment, 4 editions of ema are available, i.e. Demo, Standard, Time&Ergo and Professional. The Demo edition is a fully featured software and can be installed for free. Compared to the Professional edition the only difference is in a watermark, a flag on each human model and in the only availability of the $5^{th}$ female and $95^{th}$ male percentile (Figure 8). The current version of ema is 1.6.0.0 including edition dependent functionalities like:

- Male and female digital human models representing the $5^{th}$, $50^{th}$ and $95^{th}$ percentile (Standard)
- Comprehensive task library for describing manual workflow (Standard)
- Comprehensive object library for different geometries, e.g. tables, shelves, containers, tools, etc. (Standard)
- CAD data interface for importing user defined geometries in Collada (.dae), JT (.jt), VRML (.wrl) and Wavefront (.obj) (Standard)
- Analysis tools, such as spaghetti diagrams, workflow reports including ErgoChecks and cycle time diagrams (Standard)
- Collision avoidance (Standard)
- Data interface for importing and exporting results as CSV or XLSX (Standard)
- Comprehensive ergonomic analysis based on the EAWS method (Time&Ergo)
- Comprehensive time analysis based on the MTM-UAS standard (Time&Ergo)
- Dynamic work station simulation including complex kinematic animation, e.g. robots (Professional)
- Motion capturing interface (Professional)
- Welding simulation (Professional)
- Assembly line balancing in terms of cycle variation analysis (Professional)

**Centauro GmbH.** The Centauro GmbH provides services in the field of simulating and analysing automation production lines. Currently, Centauro uses ema for planning human work activities within a research project – especially in the field of human-robot-collaboration – and is an essential partner for the further development of ema regarding task execution on moved objects.


**Figure 8:** User interface Demo edition. 1 menu bar, 2 tabs, 3 simulator, 4 task library, 5 behaviour workflow, 6 property settings, 7 3D settings, 8 3D view, 9 status area