The Simulation and Animation of Virtual Humans to Better Understand Ergonomic Conditions at Manual Workplaces

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ABSTRACT

This article extends an approach to simulate and control anthropomorphic kinematics as multiagent-systems. These "anthropomorphic multiagent-systems" have originally been developed to control coordinated multirobot systems in industrial applications, as well as to simulate humanoid robots. Here, we apply the approach of the anthropomorphic multiagent-systems to propose a "Virtual Human" - a model of human kinematics - to analyze ergonomic conditions at manual workplaces. Ergonomics provide a wide range of methods to evaluate human postures and movements. By the simulation and animation of the Virtual Human we develop examples of how results from the field of ergonomics can help to consider the human factor during the design and optimization phases of production lines.

Keywords: Virtual Human, Ergonomic Analysis, Workplace Simulation and Multiagent-Systems

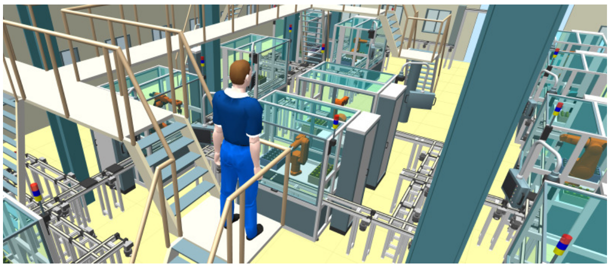

Fig. 1. The "Virtual Production" – the simulation of complex, highly automated production lines.

1. INTRODUCTION

The initial idea of the Virtual Human arose from experiences related to the "Virtual Production" - the simulation of complex, highly automated production lines (see Fig. 1). Virtual Production is used for the planning of modern production lines. It allows for the easy evaluation of alternative designs and scheduling schemes in order to decide on an optimum layout and control for the final installation.

Most systems used for Virtual Production today were originally developed to provide tools for the programming and simulation of automated components and industrial robots. Thus, these simulations focus on technical elements, mainly neglecting the human factor so far. Although manual workplaces still are a common element even in modern production lines.

This paper proposes new contributions to make manual workplaces an integral part of the methodology to plan, simulate and evaluate manufacturing installations. The Virtual Human presented here extends an approach to program, control and supervise anthropomorphic kinematics as multiagent-systems (MAS). These "anthropomorphic multiagent-systems" have originally been developed to control coordinated multirobot systems in industrial applications [8][3], as well as to simulate humanoid robots, such as Justin [1][2]. In these MAS, the individual agents manage the motion of kinematic chains representing the limbs and the torso of the human body. An supervisory control layer of the MAS coordinates the motions of the individual agents in order to generate characteristic anthropomorphic motions in realtime (see section 2).

The main advantage of the concept of anthropomorphic MAS is the depth of the conceptual and technical integration with the simulation of the technical components of the surrounding production line. Modeling, programming and simulating the Virtual Human is basically achieved by the same set of tools that is used for industrial robots. Users may seamlessly apply their know-how in robotics to prepare the simulation and animation of the anthropomorphic MAS (see section 3). Using the Virtual Human, common ergonomic evaluations of postures, movements, stresses and strains have been implemented for the Virtual Production (see section 4).

2. THE CONCEPT OF ANTHROPOMORPHIC MAS

The central idea of anthropomorphic MAS is the humanlike coupling of individual kinematic chains which represent the limbs and the torso of the human body (see Fig. 2). The individual kinematic chains are driven by agents which are well-prepared to control real robots in multirobot applications in automation. In order to meet the requirements of sophisticated human-like motions the interaction of these agents is supervised and controlled on the level of the MAS.

Motion control of the individual agents
Each of the individual kinematic chains is guided by a control which exhibits the characteristic features of an agent[9]. The agents accomplish given tasks independently by evaluating models of their environment and the kinematic chains assigned

to them. At first, the agents provide motion control for the kinematic chains without any knowledge of the anthropomorphic properties of their configuration as a MAS. They only consider parameters and descriptions of kinematic chains which are also used to describe the range of properties of common industrial robots.

Fig. 2. The concept of anthropomorphic MAS.

Since motion control is the most important service that is carried out by the agents, the core of each agent consists of a module for path interpolation. The module supports motion control for a multitude of kinematic configurations. It is based on velocity kinematics, solving the inverse kinematic problem using the Jacobian. The module also supports advanced abilities that exceed the need of industrial applications, but that have been identified as being essential to meet the requirements of anthropomorphic kinematics:

- *Reaching of targets given in joint coordinates*, in modes Point-to-Point and Synchro-PTP
- *Reaching of targets given in Cartesian coordinates*, along linear paths, circular paths and paths defined as B-Splines and NURBS
- *Path control via guiding objects*, based on kinematic and dynamic (force/torque) guidance
- *Motion control of highly redundant kinematic chains*, where the number of joints decidedly exceeds the Cartesian degrees of freedom
- *Motion control of bidirectional kinematic chains*, where the meaning of "Base" and "Tool-Center-Point" changes frequently during operation

Beyond the scope of motion control, other tasks can be delegated to the agents as well. The agents can be enabled to use enhanced sensory, to handle complex gripping tasks or to command robot hardware in real-time by the instantiation of additional control modules.

Coordinated motions of the MAS

The module for path interpolation supports abilities that are essential to enable human-like motions. Especially the ability to move bidirectional kinematic chains along freeform curves in Cartesian space is important, as one can see in the motion of walking. The motion of walking composes natural paths and the periodical change of supporting leg and free leg. Such anthropomorphic motions can be carried out by the agents without additional effort. But there are also kinematic couplings between the agents that can only be supervised and solved on the level of the superordinated MAS. For the control of the Virtual Human, two particular classes of these kinematic couplings have to be taken into account:

- *Body-Forward-Dependency*. The motion of the limbs depends on the motion of the torso, e.g. when gripping an object, leaning forward will further reduce the distance between the object and the hand
- *Body-Backward-Dependency*. The motion of the torso can also be conditioned by the motion of the limbs, e.g. when gripping an object, leaning forward or making a step towards the object would solve the situation, if the length of the arms is not sufficient to bridge the distance between the object and the hand

A supervisory module for the anthropomorphic coordination of the motions of the individual agents addresses such kinematic couplings on the level of the MAS. A basic strategy to solve the Body-Forward-Dependency is given by restarting path interpolation for the agents every time the torso moves. Then, recalculation of the paths automatically adjusts to the shifted relative positions of the hands and the torso. Building on this basic approach, more intelligent solutions can reduce the load of the necessary calculations, e.g. by monitoring the motions and predicting the final relative positions in advance. Situations of Body-Backward-Dependency are harder to solve than that, since there is no central event like the motion of the torso that could be forwarded to the limbs. In the case of Body-Backward-Dependency, potentially any of the limbs could request supporting motions of the torso in order to reach its target.

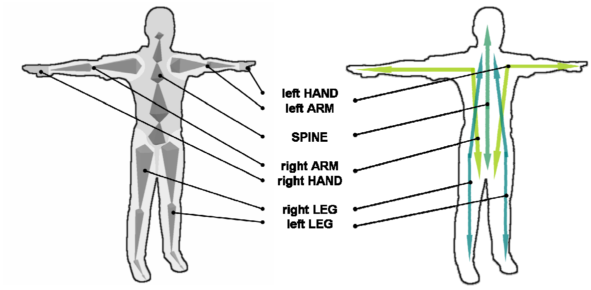

Fig. 3. Influence of the limbs on the torso, according to the concept of "Multiple Redundancy".

In conventional kinematic chains, a well-known method to manage redundancy is given by considering the redundant joints as "additional axes" - e.g. industrial robots are mounted to be moved on rails or complex grippers provide additional axes that can be picked up to achieve specific tasks. In order to solve the problem of Body-Backward-Dependencies for anthropomorphic MAS, the concept of "Multiple Redundancy"[3] is based on methods to control such additional axes. Using Multiple Redundancy, multiple agents are allowed to access the same set of additional axes in parallel. In the case of the Virtual Human, the multiple redundancy methodology is applied by enabling the limbs to superimpose desired movements on the torso to extend their ranges (see Fig. 3). The gain of this systematical introduction of mutual, multiple redundancies is a smooth, human-like superposition of the motion of each of the agents.

A common approach to control redundancy is using the nullspace. The motion control is performed by the path interpolation of the individual agents, based on velocity kinematics using the Jacobian.

$$\begin{aligned} \underline{\dot{x}} &= \underline{J}\,\underline{\dot{q}} & \Leftrightarrow \quad \underline{\dot{q}} &= \underline{J}^{+}\underline{\dot{x}} \\ \underline{\ddot{x}} &= \underline{J}\,\underline{\ddot{q}} + \underline{\dot{J}}\,\underline{\dot{q}} & \Leftrightarrow \quad \underline{\ddot{q}} &= \underline{J}^{+}\left(\underline{\ddot{x}} - \underline{\dot{J}}\,\underline{\dot{q}}\right) \end{aligned} \tag{1}$$

with $\underline{J}^{+}$ being the generalized pseudo-inverse to $\underline{J}$. The null-space of a matrix $\underline{J}$ with the dimension n is the vector space consisting of all vectors $\underline{z}$ satisfying the condition

$$\underline{J}\,\underline{z} = \underline{J}\left(\underline{P}\,\underline{w}\right) = \underline{0} \tag{2}$$

where $\underline{z} = \underline{P}\underline{w}$ creates elements of the nullspace using the null-space projection matrix $\underline{P}$ by multiplying arbitrary vectors $\underline{w}$ with the nullspace projection matrix. This is typically chosen as the orthogonal projection matrix

$$\underline{P} = \underline{I} - \underline{J}^{+}\underline{J}\,. \tag{3}$$

According to Eq. (1), nullspace motions $\underline{\ddot{q}}_{nsp}$ can be superimposed on the joint accelerations $\underline{\ddot{q}}_{spec}$ resulting from the commanded Cartesian motion $\underline{\ddot{x}}_{des}$ without changing the path of the agent:

$$\underline{\ddot{q}}_{des} = \underline{\ddot{q}}_{spec} + \underline{\ddot{q}}_{nsp} = \underline{J}^{+}\left(\underline{\ddot{x}}_{des} - \underline{\dot{J}}\,\underline{\dot{q}}\right) + \left(\underline{I} - \underline{J}^{+}\underline{J}\right)\underline{w}\,. \tag{4}$$

Using Eq. (4), the concept of Multiple Redundancy can be formulated for anthropomorphic MAS by super-imposing null-space motions not only to cope with the possible redundancy of the kinematic chain of the torso, but also to enable the limbs, *ext* ("extremities"), to control the torso as a set of additional axes

$$\underline{\ddot{q}}_{nsp} = \underline{\ddot{q}}_{torso} + \sum_{i=1}^{4} \underline{W}_{ext\,i}\,\underline{\ddot{q}}_{ext\,i} \tag{5}$$

where weighting matrices $\underline{W}_{ext\,i}$ are introduced to restrict the influence of each limbs on the joints of the torso to adjacent joints only. The concept of Multiple Redundancy is implemented in the modules for path interpolation of the individual agents, which perform the motion control of the resulting, highly redundant kinematic chains using the nullspace. The supervisory module for the anthropomorphic coordination of the MAS monitors and controls the usage of the additional axes in order to manage other aspects of the Body-Backward-Dependency as well, such as triggering a walking movement towards objects out of the range of the hands.

Layered architecture of the simulation and control

The components of the Virtual Human are ordered in a layered architecture. The fundamental layers of this architecture are formed by the anthropomorphic MAS. The first layer consists of the individual agents that control the kinematic chains of the limbs and the torso. On top of this, a second layer holds the coordinating control of the MAS (see Fig. 4).

Agents to control the hands are managed in an extra layer, since anthropomorphic grasping is an extensive topic of its own. Separation of the control of the hands allows for the implementation of alternative solutions, such as controlling the hand as simple grippers or the control of the hands with an underlying, independent MAS.

The visualization of the Virtual Human is separated into an extra layer as well, since alternative levels of detail may be used in different situations. In some situations, e.g. when programming the Virtual Human, it is suffcient to work with only rough renderings of the structure of the kinematic chains. To see the finished animation, one might want to render the human body using advanced visual effects of skinning, texturing and lighting.

The main advantage of the layered architecture is the ability to extend the set of applications of the Virtual Human by new layers. These new layers are optional and provide a framework to implement additional analytical views and extended simulations. Using the framework, new applications can directly interact with the simulation of the Virtual Human.

During the early phases of planning of production lines in the Virtual Production, the Virtual Human is initially shown as an abstract placeholder. These dummies hold only a few parameters to estimate the time needed to conduct a given task at a manual workplace. Along with the progress in finalizing the surrounding production line, the functionalities of the manual workplaces are simulated and visualized in more detail. Each of these levels of detail is maintained through separate, optional layers – starting with icons representing the steps of production that are carried out at the workplaces up to the full animation and visualization of working persons. During the later phases of planning with the Virtual Production, other layers are made available to the user which allow for evaluation of ergonomic conditions at the manual workplaces. Based on the simulation and animation of the Virtual Human, these layers provide evaluation of postures and movements, but also evaluation of the field of view and the range of the hands.

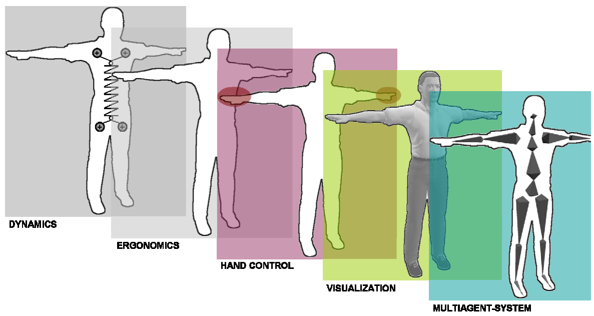

Fig. 4. The layered architecture – from the fundamental control layers to evaluations manual workplaces.

On the one hand, the analysis of stresses and strains is beyond the scope of an approach based on kinematics, since the detailed dynamic properties of the human body have to be considered in order to get accurate results. On the other hand, splitting up the kinematic chains to model the degrees of freedom of the human body in full detail would mean to give up the efficiency of the motion control and the intuitive handling of the kinematic chains of the MAS. Thus, new layers are introduced to perform the simulation of dynamics at any desired detail, without influencing the existent applications too much. These layers provide detailed models of parts of the human body, taking into account the kinematic and dynamic properties that are necessary to evaluate temporary and permanent stresses and strains in a simulation. To link these evaluations to the animation of the Virtual Human, the forces and torques occurring at "anchors", such as the shoulders and hips, are calculated based on methods well-known in robotics[5]. These forces and torques are forwarded to the layer of the dynamic simulation, where they are interpreted as given influences, twisting and compressing the body in the detailed dynamic model. Using the layers of dynamic simulation, the dynamic models can be modeled at any desired level of detail, without compromising the configuration of the underlying MAS.

3. SIMULATION AND PROGRAMMING OF ANTHROPOMORPHIC MAS

State-oriented modeling of the simulation

The technical integration of the anthropomorphic MAS is prepared by the underlying realtime simulation system, where applications such as the Virtual Production are enabled by the systematical simulation and control of discrete event systems. For the development of its applications, the simulation system implements standardized procedures and accompanying tools. According to the method of state-oriented modeling[10][4], the simulation of a discrete event system is prepared in three steps (see Fig. 5):

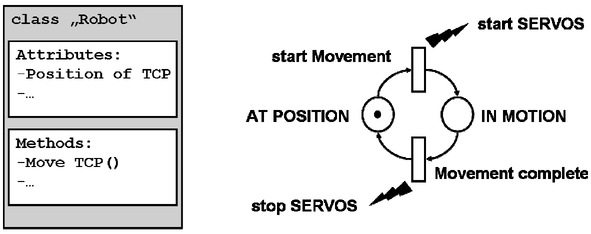

Fig. 5. The method of state-oriented modeling – example of a simple class describing "Robots" (left) and its dynamic behavior (right), generating commands for an external system "SERVO".

- *Analysis of system components*. The discrete event system is separated into components. In the process, instances of similar parts of the system are combined to be represented by classes. According to the principles of object-oriented design, these classes describe separable sub-systems or independent functionalities within the complete system. Classes have attributes and methods, describing the inner processes of the components.

- *Modeling of system dynamics*. The dynamics of the classes are modeled using petri nets. Places in these petri nets represent possible states of the component, where transitions describe the conditions and action that precede and follow from changes in the state of the component. Instantiations of the classes are inserted as markers into the petri nets for animation.

- *Observation of system state*. The entirety of the petri nets, attributes and methods, is the database for the animation of the discrete event system. With the observation of the petri nets and the individual animated markers, the dynamic behavior of the system can be observed as a whole. External systems that interfere with the simulated system are connected via interfaces, e.g. robot hardware controllers.

To apply the method of state-oriented modeling, the simulation system provides a scripting language which combines aspects of the object-oriented and the state-oriented design. The technical components of the Virtual Production as well as the anthropomorphic MAS are implemented using the scripting language. Thus, the anthropomorphic MAS become an integral part of the simulation - existing in the same database and accessing models of the environment in as the same way as the components of the Virtual Production.

State-oriented programming of MAS

Starting from the classes of components, the scripting language supporting the method of state-oriented modelling allows the implementation of more general concepts of simulation and control. For example, using the object-oriented instruments of the scripting language, the internal complexity of components is abstracted to "building blocks". Without having to consider all the internal details, building blocks make a simple selection, configuration and usage of components available to users of the Virtual Production. Not only the object-oriented but also the state-oriented instruments of the scripting language where applied to develop a coherent basis to program the anthropomorphic MAS - a combination of well established concepts to program robots in industrial applications and new approaches based on the potentialities specific to petri nets (see Fig. 6):

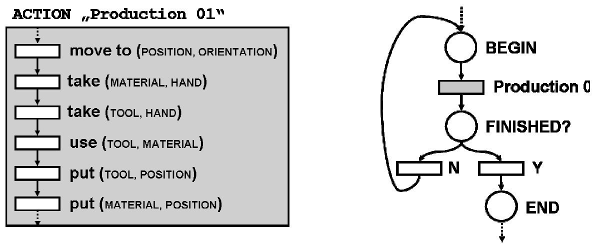

Fig. 6. State-oriented programming – example of an action consisting of sequences (left) and its application within an action-net (right).

- *Targets.* Targets are defined either as a set of Cartesian coordinates or a joint vector. In addition, targets provide a convenient way to configure the numerous options of path interpolation for the agents.

- *Sequences.* Where targets address only an individual agent, in a MAS potentially all agents are on the move at the same time. To dispatch several targets to the agents of a MAS, sequences describe the concurrent execution of targets as well as dependencies in the order of their execution.

- *Actions*. Sequences are defined as one specific type of actions. In addition to these actions of motion, there are other pre-defined actions, e.g. actions to handle and manipulate tools and materials. Users are also enabled to create their own, user-defined actions.

- *Action-Nets.* Actions are organized in action-nets to enable the development of flexible libraries of descriptions of complex processes of tasks and motions. Using the instrument of state-oriented design, action-nets combine and link actions for serial, concurrent and conditional execution.

The programming of targets and sequences is achieved by using well established tools for the 3-D offlineprogramming of robots. To program tasks and motions for the Virtual Human, the user chooses desired actions from the pool of available actions. Then the chosen actions are appropriately configured, combined and linked in action-nets. Actions and action-nets are suitable for the visual programming of the Virtual Human, since the graphical representation of places and transitions is instrinsic to the concept of petri nets.

4. METHODS OF ERGONOMICS FOR THE VIRTUAL HUMAN

NIOSH equation

The "National Institute for Occupational Safety and Health" of the United States (NIOSH) developed the "NIOSH equation for the design and evaluation of manual lifting tasks"[11]. The equation allows for the estimation of a recommended weight limit (*rwl*) for the lifting of loads:

$$rwl = lc \times hm \times vm \times dm \times am \times fm \times cm \qquad (6)$$

The multipliers *h*(orizontal)*m*, *v*(ertical)*m*, *d*(istance)*m* and *a*(symmetric)*m* are used to adapt the equation to the geometric conditions of the lifting task. The multipliers *f*(requency)*m* and *c*(coupling)*m* define how often the task is carried out in a given time and how handles etc. support lifting the weight. The constant *l*(oad)*c* is used to adapt the equation to different target groups.

In situations at manual workplaces, the result of Eq. (6) is a recommendation that should be obeyed in order to protect workers from injuries. Applied to simulations of the Virtual Human, the NIOSH equation can help to detect potential stresses and strains in the kinematic chains that may occur during similar lifting tasks.

Rapid Upper Limb Assessment

The "Rapid Upper Limb Assessment" (RULA) was initially developed at the University of Nottingham in England[7]. The RULA method focuses on the evaluation of potential risks for the arms, hands and the back. The basis of the RULA method is to categorize the postures of the arms into "zones" - angles of the upper and the lower arm in relation to the torso. In order to describe potential stresses and strains, values are assigned to the zones, ranging from 1 (natural postures) to 4 (extreme postures). Similar values are assigned to the postures of the wrists, the back and the neck and additional rules are evaluated to consider specific circumstances, e.g. the weights of carried loads and the stability of the stand.

With the help of tables, the values are incorporated into a final evaluation of the given posture, ranging from 1 (comfortable posture) to 7 (unacceptable posture, calling for immediate action).

In contrast to the NIOSH equation, the RULA method is ready to perform evaluations of postures at run-time. In simulations of the Virtual Human, the categorization of the postures of the upper limbs can be achieved solely on the basis of the joint vectors of the individual kinematic chains. A color coded visualization of the evaluation rendered on top of the normal visualization of the Virtual Human can help to detect strenuous postures.

Methods-Time Measurement

The "Methods-Time Measurement" (MTM) was developed at the "Methods Engineering Council" of the United States[6]. In fact, MTM is not an ergonomic analysis in the direct sense, but it is closely related to the evaluation of manual workplaces and is a well established part of the methodology of the Virtual Production. The MTM method focuses on the estimation of the time needed to carry out a given task.

For the analysis of MTM, the typical steps of the production process at a manual workplace are divided into so-called "methods", such as (approach), (take), (push), (put) or (walk). A time value is allotted to each of the methods, reflecting the average time that is needed to fulfil the according movement in production. The time values are also adjusted to the actual distances, loads and other conditions that may change for each of the methods. The time values are given in "Time-Measurement-Units" (TMU), which allows for the adjustment of the general duration of methods of different target groups. In order to maintain realistic time values in corresponding catalogues, empirical studies are periodically conducted in selected facilities.

The results of the analysis of MTM are estimates of the total time needed to carry out the evaluated task. In subsequent higher-level assessments, MTM estimates are associated with the achievable throughput of the individual workplaces. In the Virtual Production, MTM estimates are directly involved in the optimization process of planned production lines - an important aspect of the optimization of the technical components is the adjustment of their schedules and control schemes to the potential working load of interspersed manual workplaces.

With regard to the simulation of the Virtual Human, the MTM analysis provides an elaborate catalogue of methods that have been identified as being recurring actions in manual production processes. Thus, MTM methods can be an exhaustive source for the definition of common actions for the Virtual Human. Such libraries of common actions in place, action planning and path planning can be improved by basing the decision for alternative plans on MTM estimates.

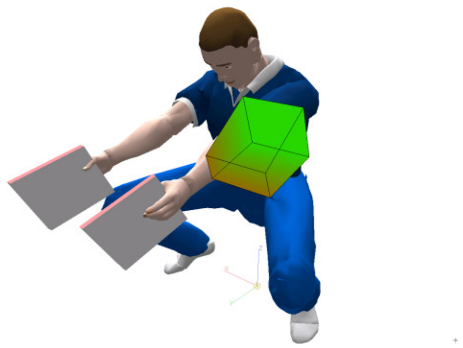

Fig. 7. Analysis of stresses and strains in the back during lifting tasks.

5. CONCLUSION

The foundations of the Virtual Human are based on our previous works for multi-robot systems in industrial applications. In order to coordinate human-like motions for the multi-robot systems, e.g. the two-armed handling of bulky objects, we program and control these anthropomorphic kinematics as multi-agent systems. Here, we extend the approach of the anthropomorphic MAS to propose a Virtual Human - a model of human kinematics for the evaluation of ergonomic conditions at manual workplaces. Manual workplaces are a common element even in modern production lines, but they are mainly neglected in the methodology of the Virtual Production so far.

From the point of view of the users, the setup of the Virtual Human can be carried out with the same tools as for the offline-programming of industrial robots. In addition to the known toolset, the Virtual Human can also be programmed using customizable actions, e.g. "go", "take", "put", that can be composed in action-nets. Actions and actions-nets are implemented in a scripting language that supports object-oriented and state-oriented programming techniques and is well-prepared to support the visual programming of the Virtual Human.

The Virtual Human is organized in a layered architecture that is open for modular extensions. The fundamental layers are formed by the control of the anthropomorphic MAS, additional layers provide optional simulations, visualizations and evaluations. First layers for the analysis of ergonomic conditions implement the NIOSH equation (for lifting tasks), the RULA method (for the evaluation of postures) and MTM (for the scheduling of manual workplaces). Additional layers provide the analysis of stresses and strains based on the dynamic properties of the human body. By extending this set of layers, the Virtual Human has the potential to support the early and easy integration of a wide range of manual workplaces in simulations of the Virtual Production.

Fig. 8. Analysis of ergonomic conditions – driven by the simulation and animation of anthropomorphic MAS

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