Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 72 (2018) 768–773

www.elsevier.com/locate/procedia

51st CIRP Conference on Manufacturing Systems

Presenting a Modular Framework for a Holistic Simulation of Manual Assembly Tasks

Felix Gaisbauer[a,b], Philipp Agethen[a,b], Michael Otto[a,b], Thomas Bär[a], Julia Sues, Enrico Rukzio[b]

[a]*Daimler AG, Wilhelm-Runge-Straße 11, 89081 Ulm, Germany*
[b]*Ulm University, James-Frank-Ring, 89081 Ulm, Germany*

[*] Corresponding author. Tel.: +49-731-505-2414; fax: +49-711-3052156294. *E-mail address:* felix.gaisbauer@daimler.com

Abstract

Within automotive industry, the importance of simulating manual assembly processes is currently increasing due to recent trends such as Industry 4.0. Even though market provides various tools, their scope is solely limited to specific aspects. Consequently, holistic simulation approaches satisfying all heterogeneous requirements of production planning are not available, yet. This paper presents a novel concept in which arbitrary motion simulations can be integrated into a common framework by introducing standardized motion model units (MMUs). The novel concept builds upon the established FMI standard, enabling autonomous generation of realistic human motions by using heterogeneous simulation approaches. The applicability of this concept is further validated based on the simulation of an assembly related scenario.

Keywords: Modular Simulation; Human Simulation; DHM; FMI; MMU; Animation; Production Planning

1. Introduction

Within the global economy, digital modeling activities and simulation of human motion have emerged during the last decades in various domains ranging from automotive over health to the gaming industry. Even though differing in their respective scope, the ability to realistically predict real-world observations have shown to be a key technology in order to remain competitive. Within the automotive industry and in particular within production planning departments, different assessment goals such as build-ability, ergonomics and task execution times are assessed with digital simulation approaches [1]. For assessing complex production scenarios, currently a large repertoire of separate tools must be utilized. Since these heterogeneous simulation tools are realized as individual expert systems, no holistic simulation and assessment of comprehensive production scenarios within a common environment are possible yet. For mechanical and mechatronic components, the incorporation of heterogeneous simulation approaches has already been solved by the FMI standard [2]. This standard allows to couple diverse simulation approaches into a single framework utilizing a standardized interface and a co-simulator.

Build upon this approach, in this paper a novel concept is proposed, which allows to incorporate heterogeneous motion simulations into modular units within a common framework. Utilizing the novel approach, task sequences such as displayed in Figure 1 can be simulated by subdividing the processes into modular blocks, in which specialized motion generation and simulation approaches are embedded.

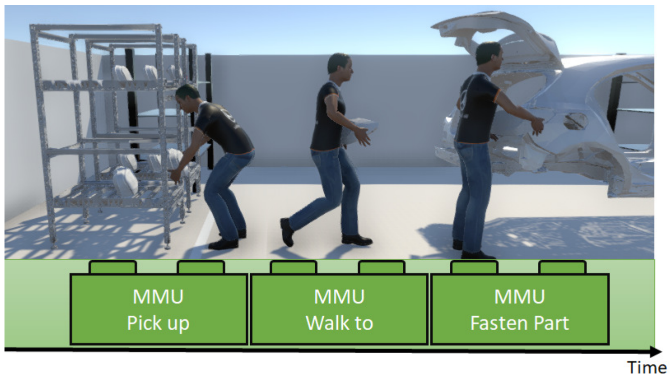

Fig. 1. Overview of the modular Motion Model Unit (MMU) approach. With the proposed approach, motions can be decomposed of other sub-motions in a building block manner. These blocks can contain heterogeneous simulation approaches which are specialized on the respective tasks.

The remainder of the paper is structured as follows: First the state of the art respective to simulation approaches targeting human motions and the FMI standard is revisited. Second, the novel framework and the concept of the so called Motion Model Units is proposed in detail. Subsequently the applicability and validity of the proposed framework are evaluated based on a simulation within an assembly scenario. Finally, a further conclusion and an outlook are given.

2212-8271 © 2018 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the scientific committee of the 51st CIRP Conference on Manufacturing Systems.
10.1016/j.procir.2018.03.281

2. Related work

Digital Human Simulation. Digital human simulations are nowadays increasingly important for various branches such as the automotive industry, since these simulations offer the possibility to virtually assess manual processes without relying on actual hardware setups. An exhaustive number of tools for simulating human motion has been developed for various scopes of application ranging from ergonomics-, over musculoskeletal- and biomechanical-simulation to animation purposes.

Tools like Delmia [3], Ramsis [4], IMMA [5], Santos [6], Ema [7] and Siemens Jack [8] focus on the analysis, design and arrangement of workplaces, products and systems. The tools use Digital Human Models (DHMs) comprising varying level of details, in combination with specialized motion generation approaches. Musculoskeletal and biomechanical modeling tools like AnyBody [9] and OpenSim [10] utilize highly-detailed DHMs including a fine-grained representation of musculoskeletal- or organ-system. These tools precisely model motions of the human body, however, at the expense of the real-time capability.

Besides analyzing human factors and the wellbeing of individuals, others present approaches focusing on the optimization of workflows - such as the simulation of an assembly workplace including the order of assembly tasks or the position of racks (see [11]). In general, these approaches are holistically covering overall-workflows on an abstract level, however, neglecting important factors to a large extent.

Another cluster, which received significant attention during the last years, is the group of character animation systems and game engines like Unity Mecanim [12] and CryEngine [13]. These tools provide gaming-related platforms to easily animate human motion. Even though achieving outstanding results in terms of naturalness, difficult movements in collision-afflicted setting can only be scarcely simulated. Smartbody [14] provides an animation system which is focused on the generation of human motion utilizing hierarchical motion controllers. These controllers are tightly embedded in the Smartbody platform, thus being limited in its usage and integration. The proposed concept in this paper enhances the core idea of layered motion controllers, whereas heterogeneous simulations can be incorporated into different platforms.

Even though obtaining excellent results within their respective domain, the vast majority of the mentioned approaches fails when being transferred to another context. Moreover, neither a holistic simulation framework nor an approach investigation the modularization of motion generation algorithms is currently existent. Therefore the proposed approach within the paper bridges the gap, allowing to incorporate various specialized digital human simulation approaches into a common framework.

Functional Mock-up Interface. For exchanging motions between different simulation tools, there are various formats such as Biovision Hierarchy (bvh), C3D and Filmbox (fbx) available. Whereas bvh is mainly used for storing animations of humanoid models, the proprietary fbx format can be also utilized to store additional scene information. Even though both formats are widely used, they are only capable of storing pre-generated motions (e.g. recorded by a motion capture system). Hence it is not possible to integrate motion generations algorithms and simulation approaches within the files itself.

For exchanging simulation functionality in a different domain than motions, a widely used solution is available. Functional Mock-up Interface (FMI) is a standard that supports the exchange of dynamic simulation models as well as its co-simulation while being tool independent. This standard is based on a combination of xml-files and compiled C-code [15]. An instance of a FMI component is called a Functional Mock-up Unit (FMU). This FMU is represented by a zip archive which contains several files describing a simulation model and its parameters. The functions within the archive itself can be stored either as source code or in binary form as dynamic link libraries. Using the FMI standard, it is possible to perform a simulation of different FMUs, containing appropriate solvers, where only the simulation results of the FMUs are exchanged after defined time steps. This approach is called *FMI for co-simulation* [16], [2]. The proposed concept of modular motion units builds upon the idea of FMUs and its interfaces to further extend the standard to simulate human motions.

3. Proposed Concept

The main objective of the proposed framework is to generate realistic human motion without being limited to a certain use case and individual motion generation techniques, ultimately incorporating various advanced simulation approaches. The core concept which enables the utilization of heterogeneous motion synthesis approaches within a common framework is the so called Motion Model Interface (MMI) and its corresponding implementations, called Motion Model Units (MMU). In the following, first the basic principles of these units are introduced, whereas subsequently the realization and usage within a proposed architecture is further described.

3.1. Concept of Motion Model Unit

The core idea of the Motion Model Units is to encapsulate arbitrary motion generation approaches and digital human simulations into a standardized component structure being incorporated into a generic framework. The MMI approach builds upon the established FMI standard which is mainly used for the simulation of mechatronical components. With FMI, complex systems such as a vehicle can be simulated by incorporating various specialized co-simulations, being encapsulated by the FMUs. For instance, separate FMUs for modeling tire abrasion, engine or spring systems can be combined in a single simulation framework to simulate the mechanical behavior of a vehicle. In principle, complex human process sequences such as tasks occurring within manual assembly scenarios can be simulated in an identical manner. A sequence in which a worker has to mount a tail-light at the car can be subdivided into several tasks such as walking to the tail-light, picking up the tail-light, walking to the car and mounting the tail-light (see Figure 1). Instead of modeling the overall process with one single approach, which might be limited, these sub-tasks could be modeled by different MMUs which are specialized on the respective context. Consequently those units (or co-simulations) could be incorporated into a comprehensive simulation framework to simulate a complete assembly sequence.

As indicated by the name Motion Model Unit, the proposed units comprise in-build models, which generate context sensi-

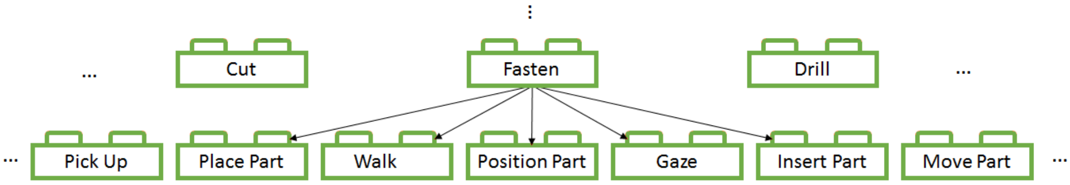

Fig. 2. Overview of the modular Motion Model Unit (MMU) approach. With the proposed approach, motions can be decomposed of other sub-motions in a building block manner.

tive output motions. These units can contain vastly heterogeneous implementations. For tasks in highly collision afflicted environments such as fasten or drill within the engine compartment of a car, simulation approaches such as Imma [5] could be best suited. These approaches utilize specialized path planning algorithms and inverse kinematics to compute collision-free and ergonomically feasible motions. However, these tools are not specialized on simulating realistic human walk behavior yet. In contrast, for simulating walking behavior of humans, motion blending approaches being widely used in computer games could be applied. These performance optimized approaches use motion capture data and produce natural motions in real-time. Since a large amount of motion capture data is necessary to address collision afflicted environments [17], these approaches are not practically applicable for those scenarios. The symbiosis of both methods, could eliminate the respective disadvantages.

The granularity of the specific MMU implementation can vary depending on the use case and required level of detail. Whereas for two-dimensional walk path simulations the modeling of the center of mass point might be sufficient [18], for simulating an assembly scenario in three dimensional environments, full body motion synthesis is required. In particular, the MMUs can manipulate full body motions, solely individual joints of the DHM, or contain time information of the respective processes. Consequently, simulations with different scopes and requirements can be carried out with the novel approach.

In general, complex human motions, such as occurring in manual assembly tasks, can be subdivided into smaller motions. For analyzing human motions and work tasks, the Methods Time Measurement (MTM) system [19] is a widely used approach in industrial settings. This system portions motions like picking up an object into smaller, context independent blocks such as reach, grasp and retrieve, particularly describing the required times. The MTM approach is limited in its expressiveness, only being able to model the expected time of the respective human tasks. Using the novel MMU concept, these blocks can be extended to simulate human motions in a detailed way. Since the MMUs share the same interface, the units can be recombined to more complex motions, while being modeled in a hierarchical way. Figure 2 illustrates this concept based on typical work-tasks in an assembly line. The modular system contains individual bricks which can be reused in higher aggregated MMUs. Tasks such as fasten therefore can contain various sub-motions like place part, walk, position part, gaze or insert part. Whereas highly specialized or use-case dependent motions could be modeled within a distinct MMU (e.g. cut motion), other motions like picking up or putting down an object, which are use case independent, could be modeled in analogy to the MTM approach. Since a vast amount of human motions and assembly tasks can be segmented into those fundamental primitives, a basic repertoire of MMUs could be recombined for the realization of those motions. Consequently the overall idea is to provide various use case independent motions in a MMU library (such as Figure 2 bottom layer), which can serve as the basis for modeling more complex and specific motions.

Despite the pure simulation of specific motions, the sequence planning of individual tasks is also a major aspect of a realistic simulation of digital avatars. Commonly, the motion generation and sequence planning are positioned in one single layer. Therefore the parametrization and characteristics of each individual motions have to be considered while generating logical sequence plans. This induces a high complexity for generating task sequences, while the sequence plans only hold for the specifically considered implementations. By utilizing the novel MMU approach, the logical sequence planning can be encapsulated from the actual motion generation. Therefore logical sequences can be planned without relying on the specific implementation. Moreover, even if a task sequence is available and no specific implementations for the motions are existent yet, time placeholders like MTM can be used within a MMU to ensure workflow and process continuity.

3.2. Motion Model Unit Interface

To transfer the FMI concept to the domain of simulating human motion, a common interface, capable of encapsulating heterogeneous motions, must be specified. In principle, the FMI approach distinguishes between FMI for Co-Simulation and FMI for Model Exchange. While within the first, each FMU contains an individual solver, within the latter the simulation environment provides the solver and performs a numerical integration. For coupling various motion generation approaches, the FMI for co-simulation approach seems best suited, since the components communicate at discrete points in time, whereas in the time between two communication points, the subsystems are solved independently by their individual solvers. As part of this approach, the co-simulator acts as master, whereas the individual FMUs act as slave. The master controls the data exchange between the subsystems and the synchronization of all FMUs. The FMI functions and parameters can be defined utilizing the FMI Description File (in XML format) and the actual C sources of the FMU. Since the source code within FMI for Co-Simulation implementations does not have to be exchanged, the intellectual property of the specific technology providers can be protected. In general, the FMUs contain an input as well as an output block which can comprise functions of various types such as Real, Integer and String.

Figure 3 shows the proposed MMU interface with the corresponding input and output blocks. Since the generation of human motion is mostly context sensitive, the specific context in which the motion has to be performed (e.g. state of digital

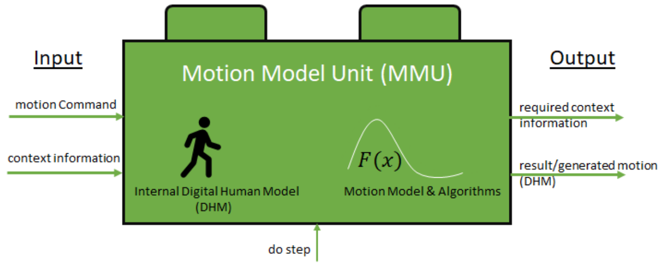

Fig. 3. Overview of the principal component structure of a Motion Model Unit. The component contains an intrinsic DHM as well as an internal model and logical descriptions to generate the respective motions.

human or scene) must be provided by the master. Furthermore, a so called motion command is provided as an input value in order to describe the desired motion, its constraints and characteristics in detail (e.g. grab object 1 with left hand for 5 seconds). These commands can be principally modeled using languages and formats like the behavior markup language (bml) [20]. The main output of the proposed units is the generated motion which is provided as a separate output signal. This output comprises the actual representation of the digital human and its motion after the specific update step. Formats such as bvh or fbx can be used for exchanging these information. Since the MMU may require additional scene dependent information or services such as path planning, the MMU also provides a description of the required resources in before each update step. The co-simulator can consequently evaluate the required information and assign it as context input to the respective MMU. Additionally, to incorporate heterogeneous DHMs with different skeleton hierarchies into a common framework, each MMU has to provide a representation of the internally used DHM. Thus, the differing skeletons can be mapped to a global reference avatar with the help of automatic retargeting tools like provided by the Unity3D engine.

3.3. Co-Simulation

An important aspect of the FMI approach is the co-simulator. This component is responsible for the behavior realization and sequencing of the respective units. For creating continuous human motions from discrete MMUs, analogically, a co-simulator is required. This MMI co-simulator triggers and executes the respective MMUs and contains a reference representation of the digital human, which can be used as simulation result.

Figure 4 illustrates the proposed communication workflow describing the interaction between the co-simulator and a specific MMU. Initially, a motion command is set, describing the desired characteristics of the motion. Afterwards a sequence of actions is cyclically performed until the specific MMU is finished. Note that the MMUs comprise an additional status function to determine the current status. Within the cyclical routine, the descriptions of required resources are fetched from the MMU and are evaluated using the knowledge and services of the co-simulator. This derived information is subsequently provided to the MMU as input context. With the execution of the do step routine, the actual motion is computed in the MMU. The provided result is fetched afterwards and mapped to a global reference skeleton by utilizing retargeting algorithms. Finally the gathered motion in the reference DHM representation can be further processed by the co-simulator.

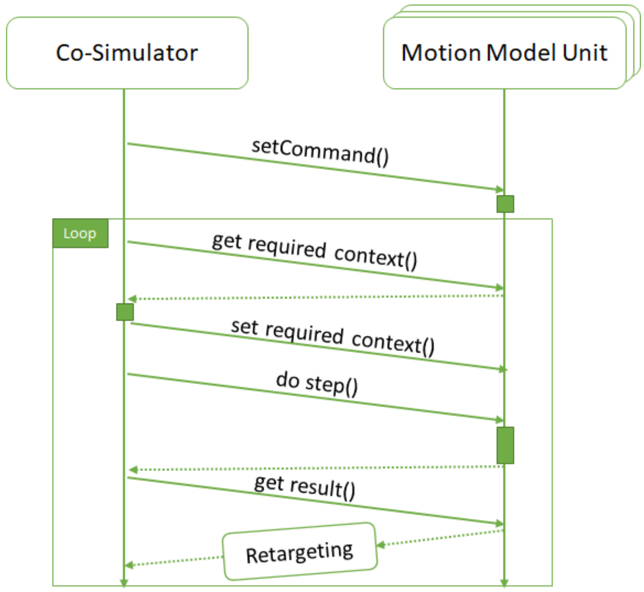

Fig. 4. Sequence diagram of the update cycle of the co-simulator. Initially a "setCommand" instruction is performed. Subsequently the MMU is updated and the result is processed within a retargeting stage. This update and retargeting steps are cyclically executed within each frame until the motion is finished.

For realizing complex MMUs such as displayed in Figure 2, which might comprise several sub-motions, the co-simulation can be directly integrated into the respective MMU. In this case the co-simulation is carried out by the specific MMUs itself which leads to a hierarchical co-simulation.

Tasks such as drilling, which commonly requires both hands, can be principally modeled in different ways. On the one hand, these motions can be modeled by a single MMU, while the component internally controls both hands (e.g. hierarchical co-simulation). On the other hand, the drilling motions can be modeled by two ore more distinct MMUs. In this case, one MMU could model the handling of the electric drill, while the other MMU could model the positioning of the screw with the other hand. In this context, avatar masks which are commonly used in animation system can be utilized. These components mask out the areas which are not used by the particular MMUs (e.g. only left hand relevant). Given this information, the co-simulator is able to process and merge the separate motions.

By executing the discrete MMUs in a sequential manner, without any further processing, the respective motions might be unrealistic while lacking in smoothness. For instance, two consecutive MMUs might end or start with an entire different pose of the digital human. A direct transition between these two consecutive MMUs therefore leads to an unnatural gap within the overall motion. To avoid this and generate continuous motion from a sequence of discrete MMUs, the transition must be explicitly considered. The transition between MMUs can be modeled by applying widely used motion blending and interpolation approaches such as [21]. During each transition the interpolation weight of the previous MMU is continuously decreased while the weight of the subsequent MMU increases according to a predefined weight-function. Since the heterogeneous avatars of the respective MMUs are mapped to reference avatar, the interpolation can be carried out using the reference avatar. Moreover, the transition between MMUs can be realized by using statistical approaches as proposed by Min et. al [22].

4. Applicability for Simulating Human Assembly Tasks

After having outlined the concept of the novel approach, in the course of this section the applicability for simulating human assembly tasks is validated. The evaluation has been carried out for a pick & place scenario in a collision-afflicted environment. Overall, the setting is simulated with three different simulation approaches, whereas one approach builds upon the proposed MMI concept. The results of the respective simulation approaches are evaluated based on a survey conducted with 16 production planning employees (4 females, 12 males, age: $\mu = 28.95$, $\sigma = 9.10$). Since the production planning employees are experienced at evaluating human motions, a survey has been preferred over quantitative metrics such as smoothness, which only partially evaluate naturalness and realism.

4.1. Apparatus

In the experiment a pick & place scenario which frequently occurs in automotive assembly scenarios was chosen. Figure 5 visualizes the experimental setup. Initially the virtual worker walks to a rack (size 0.40 x 2.00 x 1.50 m) consisting of three shelves. The virtual avatar has to pick up a spherical shaped object (diameter 0.10 m) from the intermediate shelf which is partially occluded by a vertically aligned cover with a size of 1.50 x 0.20 x 0.02 *m*. Subsequently the digital avatar walks to a table (0.60 x 1.00 x 1.60 m) and places the spherical object on the desk. The process is simulated using three different simulation approaches within a common simulation environment in which videos for all approaches have been recorded:

Implementation A (Smartbody). The state of the art digital human animation tool Smartbody has been used to simulate the above mentioned scene. The system focuses mainly on interaction, walking and behavior modeling. The implementation contained in the Virtual Human Toolkit [23] has been used, whereas Smartbody is integrated within the Unity3D engine. The respective locomotion commands describing the walk behavior, as well as the reach commands being necessary to control the digital avatar are set using the behavior markup language.

Implementation B. Beside the Smartbody implementation, a tailored solution which covers path planning within highly collision afflicted environments is used. The approach is implemented within the Unity3D engine and utilizes path planning algorithms such as RRT [24] as well as inverse kinematics functionality to model human assembly tasks. Moreover, the walk animations are realized by translating the digital avatar while playing humanoid animations provided by the Unity3D engine.

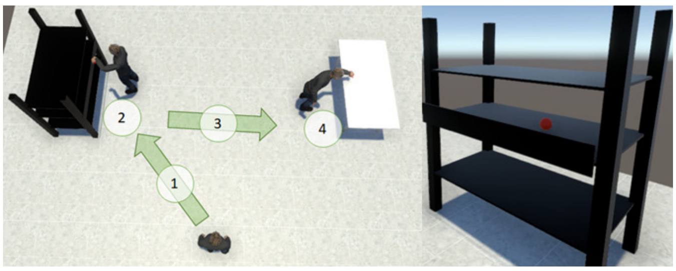

Fig. 5. Experimental setup of the performed evaluation. On the left, the overall task sequence is illustrated, while the right image shows the utilized rack.

Implementation C (MMI Approach). As third simulation system, an approach has been implemented which incorporates the functionality of both previously mentioned systems. Whereas the path planning and inverse kinematics capabilities of implementation B are used within distinct MMUs for modeling the pick and place tasks, the Smartbody implementation is incorporated within a separate MMU to cover the walk simulation. Both MMUs have been integrated into a common framework following the explained MMI concept. Moreover, an implementation of a co-simulator according to 3.3 is utilized which triggers the respective MMUs. The transition between the individual MMUs is realized by linearly interpolating the motions. Since the Smartbody approach internally uses a different avatar, a retargeting to the Unity3D Mecanim avatar is carried out.

4.2. Procedure

For validating the perceived realism of the simulations, a questionnaire containing a five point Likert scale has been used. Whereas 1 corresponds to a strong disagreement, 5 corresponds to a very strong agreement. The performed task is split into the four different sub-tasks: Walk to rack, pick up, walk to table, put down. For each sub-task the question targets the realism of the specific task (e.g. realism of walking/pick up motions). The complete clip which comprises all four tasks is visualized afterwards to allow an assessment of the realism of the overall simulation. During the evaluation, initially a video of the state of the art human simulation tools Delmia [3] and Imma [5] is demonstrated. Afterwards a video is shown which explains the task to be performed and the simulation environment. Subsequently the recorded videos, which display the simulation results of the three different systems are shown to each participant. To control sequence effects, the order is randomized for each participant and all systems are presented in total twice.

4.3. Results

After having performed the evaluation with 16 participants, in total 160 questions have been edited. Figure 6 illustrated the results of the performed survey. Since the identical videos are shown twice, the value of both ratings is averaged. Moreover, the two contained walking tasks in the experiment are combined to a single walking score. In general, it can be seen that the three simulation approaches received different ratings. While system A achieved a median score of 4.0 for walking realism, pick up (1.0) and put down realism (1.25) are rated as poor. In contrast, implementation B scores well at pick up (4.0) and put down (4.5), whereas the median walk path realism is rated rather poorly (2.0). The MMI approach which combines both implementations can achieve overall better median scores (4.0), compared to A (2.5) and B (2.5). The significance level of the datasets has been tested using the non-parametric Wilcoxon test. The overall rating of the novel system is significantly higher than implementation A (one sided p-value (p) = 0.00, effect size (r) = 0.89) and B (p = 0.01, r = 0.78). Furthermore, the realism of walking within implementation C is significantly higher than B (p = 0.00, r = 0.88), whereas the realism of pick-up (p = 0.00, r = 0.89) and put-down (p = 0.00, r = 0.89) tasks are significantly higher than within implementation A. All mentioned effect sizes can be denoted as high.

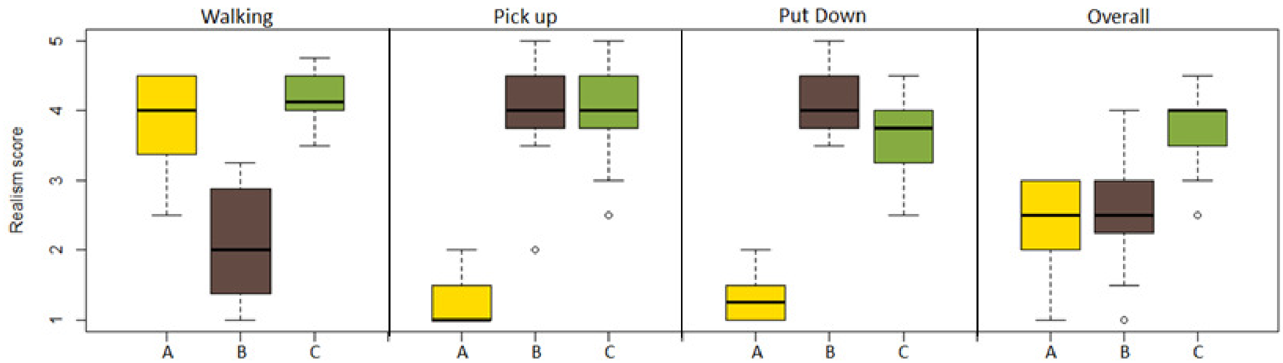

Fig. 6. Boxplots which illustrate the results of the performed survey. The realism ratings for the different tasks as well as the overall ratings are visualized for each tested implementation. Implementation C combines implementation A and B within a common framework by utilizing the proposed MMI approach.

4.4. Discussion

The evaluation shows that the novel approach (C) can significantly improve the overall realism by incorporating the specialized approaches of implementation A and B into a common framework. The distinct systems A and B have disadvantages in respective aspects. Whereas system A lacks the capability to generate collision-free reach motions, B tends to produce unrealistic walk motions. By combining both approaches using the MMI concept, the overall result can be improved. The overall high rating for walking in implementation C indicates that the specialized approach of A can be successfully embedded into a MMU. Moreover the rating for put-down and pick up approves that the MMU concept can also incorporate path planning and inverse kinematics approaches. Since the motion generation is strongly context sensitive (e.g. a put down motion relies on the end-pose of the previous motion), nevertheless differences in the rating such as between put down of system B and C might occur. In this case, the walking motion of A ended in a different pose than in B. This caused a motion which was rated slightly worse compared to put down of B. Moreover, the significantly better overall rating of implementation C shows, that the MMI approach and the co-simulation can generate smooth and realistic motions even though using discrete MMU components.

5. Conclusions

Within this paper a novel concept to combine heterogeneous motion generation approaches in analogy to the FMI standard is introduced. A basic interface and a co-simulation approach is proposed which enables to transfer the FMI standard to the simulation of human motion. The evaluation approves that the concept can combine heterogeneous implementations in order to generate realistic human motions. Since the presented approach is still subject of research, within future publications novel co-simulation approaches and strategies will be examined. Moreover, other motion generation approaches and their interplay in a common system will be analyzed.

References

[1] Otto, M., Prieur, M., Agethen, P., Rukzio, E.. Dual reality for production verification workshops: a comprehensive set of virtual methods. Procedia CIRP 2016;44:38–43.
[2] Blochwitz, T., Otter, M., Akesson, J., Arnold, M., Clauss, C., Elmqvist, H., et al. Functional mockup interface 2.0: The standard for tool independent exchange of simulation models. In: Proceedings of the 9th International MODELICA Conference; September 3-5; 2012; Munich; Germany. Linkping University Electronic Press; 2012, p. 173–184.
[3] DELMIA website. 2017. URL: `www.3ds.com`.
[4] Human Solutions website. 2017. URL: `www.human-solutions.com`.
[5] Hoegberg, D., Hanson, L., Bohlin, R., Carlson, J.S.. Creating and shaping the DHM tool IMMA for ergonomic product and production design. International Journal of the Digital Human 2016;1(2):132. doi:10.1504/IJDH.2016.077413.
[6] Santos digital human - website. 2017. URL: `www.santoshumaninc.com`.
[7] Imk automotive - ema website. 2017. URL: `www.imk-ema.com`.
[8] Siemens plm software - website. 2017. URL: `www.plm.automation.siemens.com`.
[9] Anybody technology - website. 2017. URL: `www.anybodytech.com`.
[10] Opensim website. 2017. URL: `www.opensim.stanford.edu`.
[11] IPO.Log - website. 2017. URL: `www.ipoplan.de/software/ipolog/`.
[12] Unity technologies - website. 2017. URL: `www.unity3d.com`.
[13] CRYENGINE - website. 2017. URL: `www.cryengine.com`.
[14] Thiebaux, M., Marsella, S., Marshall, A.N., Kallmann, M.. Smartbody: Behavior realization for embodied conversational agents. In: Proceedings of the 7th international joint conference on Autonomous agents and multiagent systems-Volume 1. International Foundation for Autonomous Agents and Multiagent Systems; 2008, p. 151–158.
[15] 07006 ITEA Project MODELISAR - website. 2017. URL: `www.itea3.org/project/modelisar.html`.
[16] Functional Mock-up Interface. 2017. URL: `www.fmi-standard.org`.
[17] Manns, M., Mengel, S., Mauer, M.. Experimental Effort of Data Driven Human Motion Simulation in Automotive Assembly. Procedia CIRP 2016;44:114–119.
[18] Agethen, P., Gaisbauer, F., Froehlich, P., Manns, M., Rukzio, E.. Towards Realistic Walk Path Simulation in Automotive Assembly Lines: A Probabilistic Approach. Procedia CIRP 2017;.
[19] MTM Association for Standards and Research, . Website MTM Association. 2017. URL: `www.mtm.org`.
[20] Kopp, S., Krenn, B., Marsella, S., Marshall, A.N., Pelachaud, C., Pirker, H., et al. Towards a common framework for multimodal generation: The behavior markup language. In: International Workshop on Intelligent Virtual Agents. Springer; 2006, p. 205–217.
[21] Rose, C., Cohen, M.F., Bodenheimer, B.. Verbs and adverbs: Multidimensional motion interpolation. IEEE Computer Graphics and Applications 1998;18(5):32–40.
[22] Min, J., Chai, J.. Motion graphs++: a compact generative model for semantic motion analysis and synthesis. ACM Transactions on Graphics (TOG) 2012;31(6):153.
[23] Hartholt, A., Traum, D., Marsella, S.C., Shapiro, A., Stratou, G., Leuski, A., et al. All Together Now: Introducing the Virtual Human Toolkit. In: 13th International Conference on Intelligent Virtual Agents. Edinburgh, UK; 2013,.
[24] LaValle, S.M.. Rapidly-exploring random trees: A new tool for path planning 1998;.