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Interactive Simulation for Walk Path Planning within the Automotive Industry

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Abstract

For manufacturing industry, the increasing demand for mass-customization is currently leading to profound changes for production. As one consequence, the way in which the launch of a new product is planned, successively transforms from a hardware-based to an entirely digitized process. As one possibility to evaluate human factors in virtual environments, recent tracking and visualization technology (e.g. virtual reality) enables production planning departments to interactively validate and plan assembly processes. Furthermore, character animation and motion simulation approaches are representing a second promising area of research. Even tough offering many evident benefits, both groups reveal different drawbacks with respect to validity and completeness of the gathered results. To bridge this gap, this paper presents a generic concept unifying interactive validation and automatic simulations methods to a beneficial symbiosis. Furthermore, a rich continuum of operating modes is introduced which demonstrates the widespread options of implementation. The applicability of this novel approach is eventually evaluated for the use-case of walk path assessment in automotive production planning.

Keywords: Virtual environments; simulation; human factors; walk path planning;

1. Introduction

The manufacturing industry and automotive original equipment manufacturers, are currently facing an increasing demand for mass-customization, inevitably inducing exhaustive numbers of different product variants. As production of each derivative has to be planned beforehand, the overall-efforts for planning departments are rising significantly. This trend is expected to reinforce within the next years, since recent developments such as Industry 4.0 and vehicle electrification will profoundly change this domain. In order to nevertheless deliver products with no sacrifice in quality, the car and its corresponding assembly tasks are increasingly planned in virtual environments. For this purpose, two major areas of research can be identified: Interactive virtual environments and character animation and simulation methods.

The former enables production planning departments to interactively validate and plan manual processes and assembly tasks using recent tracking and visualization methods [1,2], such as virtual reality. Even though offering many evident benefits, interactive approaches are also accompanied by considerable efforts since each motion must be carried out by the user. Thus, it is only partly possible to analyze complex workflows, which comprise an exhaustive number of variants and execution manners. For instance, it is economically not reasonable to demonstrate the entirety of all feasible installation paths variants for each part. Instead, in practice, it is usually tested whether key-percentiles of the population can move a certain part along one plausible trajectory to its final destination.

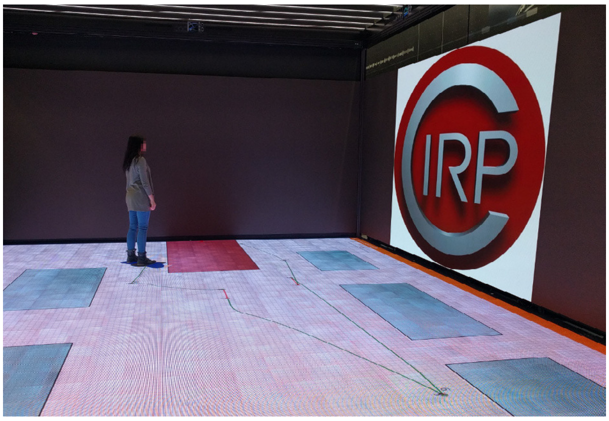

Fig. 1. Implementation of the proposed concept for the use-case walk path planning: A motion planning algorithm is coupled with a true-to-scale LED-floor.

Besides interactive virtual environments, simulation software modeling human behavior are representing a second major cluster within the context of virtual assessment of human labor. Disregarding authoring efforts, recent approaches en-

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able the automatic analysis of assembly tasks while considering various influence factors in a notably shorter time-frame (compared to purely interactive methods). The validity of the gathered results and consequently their significance for production planning, however, is widely unknown and furthermore strongly correlates to the utilized parametrization of the simulation model.

To contribute to virtual manufacturing, this paper presents a generic approach, unifying both separated clusters to a complementary system. The resulting interactive simulation concept reinforces the advantages and compensates the drawbacks of the respective groups. For the use-case of walk path planning, this concept can be implemented as depicted in Fig.1: Walk paths, stemming from a motion simulation framework, are displayed on a true-to-scale visualization system. Subsequently, a user verifies the simulation's outcome by means of re-enacting the walking tasks. In the following, the generic concept is described and its exemplary applicability for walk path analysis is evaluated.

2. State of the Art

The presented approach builds upon a significant body of recent work on motion simulation approaches and interactive virtual environments.

2.1. Motion simulation approaches

During the last decades, an exhaustive number of tools simulating human movements have been developed. Even though differing in their respective scope, each tool relies on motion generation algorithms which control the movements of the digital human model (DHM). For the use-case of human locomotion in a bird's eye view, literature presents various so-called motion planning algorithms, generating a realistic trajectory between a start and an end point while taking into account obstacles. Within this context, the human locomotor system, composing several joints and dimensions is described simplified using its two-dimensional center of mass. Appropriate approaches can be generally divided into global and local motion planners, whereby the former is used for application in which all obstacles are known a priori [3]. This group consist of roadmap-techniques [4], rapidly exploring random trees [5], cell decomposition (see [6,7]) and algorithms using potential fields [8]. In contrast, reactive local motion planners are modeling dynamic behavior while considering the desired characteristics and restrictions of the target system. Various approaches have been used for this purpose, ranging from steering behaviors [9] to velocity obstacle algorithms [10].

The mentioned approaches offer the possibility to run-time efficiently simulate human locomotion with respect to given input parameters (e.g. maximum velocity). Consequently, motion generation algorithms are ideally suited to predict the impact of different obstacle configurations, task sequences or varying percentiles of the overall-population on walk paths. Even though predominantly generating realistic results, the level of realism varies vastly with respect to the utilized parametrization. For instance, the target walking velocity of a two-dimensional virtual human strongly affects the spatio-temporal outcomes, namely, the trajectories. Simultaneously, it is difficult to predict whether the chosen parametrization and the gathered results reflect reality due to a missing possibility to validate the simulated outcomes.

2.2. Interactive virtual environments

In contrast to fully automated simulation systems, interactive virtual environments rely on user feedback to assess human labor. Motions and walk paths are not synthetically generated, but demonstrated by a participant. Therefore, these interactive systems offer the possibility to realistically plan, optimize and analyze assembly tasks in virtual environments since the results are derived from captured motions. With the dawn of commercial motion capture systems (e.g. Microsoft Kinect), head-mounted displays (e.g. HTC Vive), precise tracking devices (e.g. Optitrack or Vive Lighthouse) and dropping costs for large-scale visualization devices, interactive virtual systems are increasingly applied to manufacturing use-cases. In particular, numerous application have been presented ranging from ergonomics [11], over human activity analysis [12] and factory [13] / production [1] planning to manufacturing training [14]. In the context of walk path assessment, Visell et al. [15] present an overview of augmented floor surfaces and reviewed techniques and technologies for interaction with floor surfaces. Even though offering many benefits, it is time consuming to holistically assess assembly tasks comprising an exhaustive number of process variants as each sequence has to be performed in real-time.

3. Generic Concept for Interactive Simulation

This paper presents a generic concept to interactively simulate and plan human labor, consisting of a simulation framework generating synthetic human motion, which is coupled with a true-to-scale visualization system. Using the introduced methodology, the benefits of both independent clusters can be enhanced, while drawbacks are compensated. The novel approach can be regarded as a feedback-loop between simulation and the production planning employee interacting with the virtual model. As the synthetic and the user's motions can be compared, on one hand, invalid simulation outcomes can be detected at an earlier stage, which increases the maturity of planning-data. On the other hand, the algorithms can generate various process-variants or predict the impact of different parameters (e.g. the height of a person or the weight of a part) on the resulting human motion. Consequently, assembly tasks, being performed in the virtual environment, can be further enriched using synthesized data. Therefore, it is possible to cover a wide range of process-variants, while ensuring a high degree of realism by means of comparing the simulation model with captured behaviors.

3.1. System architecture and generic technical concept

Fig. 2 depicts the technical concept of the interactive simulation system. It becomes apparent that the overall-set-up can be sub-divided into two main groups, namely, the simulation software (left half of Fig. 2) and the visualization/interaction hardware (right half). Both units are interconnected via a motion capture device, which provides the simulation framework with recorded motions of the user/s interacting with the virtual environment. Depending on the use-case and needed level-of-detail

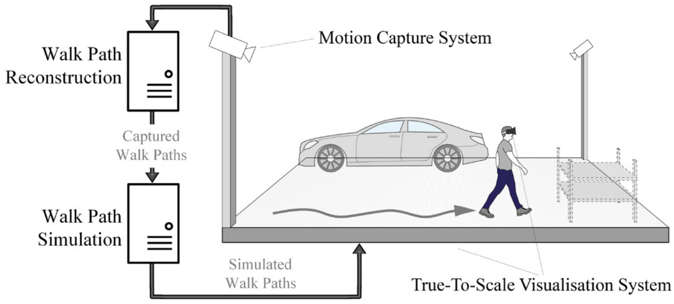

Fig. 2. Concept of interactive simulation for walk path planning: The dynamic two-dimensional walk path simulation is projected true-to-scale onto the floor, while a tracked user is simultaneously performing the identical walking tasks. Subsequently, both, the simulated and captured walk paths are merged to the final result.

(i.e. full-body tracking or center of mass), various tracking systems (e.g. Microsoft Kinect, Optitrack or Vive Lighthouse), can be utilized for this purpose. Regardless of the specific implementation, the raw data are processed by an interconnected PC, which extracts necessary information for the downstream simulation instance. For the use-case of walk path planning, the center of mass trajectory is reconstructed using the captured motions (see Fig. 2). Subsequently, the processed tracking data are relayed to the simulation instance, which utilizes these information to adapt its motion generation algorithms. Moreover, synthetically generated movements of the digital human model can thus be verified. Analogous to the interaction and visualization system, the particular software implementation strongly depends on the use-case. While the simulation of complex and fully-articulated motions requires detailed digital human models in combination with potent engines (e.g. Unity3d or Unreal), other use-cases can be addressed using light-weight software environments and abstract human models. Notwithstanding the implementation, next, the behavior of the digital human model can be enhanced and refined, while taking into account the user's captured actions. Finally, the virtual scene is rendered and provided to the interactive visualization hardware - which represents the reverse-line complementing the feedback-loop. Note that this generic concept can be applied to various use-cases such as installation path assessment, optimization of ergonomic conditions or task execution time analysis. Section 4 gives an example of an concrete implementation for the use-case of walk path planning.

3.2. Continuum of operating modes

Using this methodology, three main operating categories can be identified (see Fig. 3), differing in terms of balance between both systems and the usage of the feedback-loop.

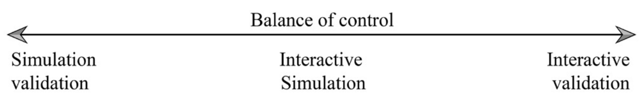

Fig. 3. Continuum of operating modes: **Simulation validation** (validation of simulation results without feedback loop), **interactive simulation** (bidirectional interplay between simulation and interactive system) and **interactive validation** (interaction without simulation support).

Simulation validation (left side). Assuming the simulation to be in full control and the communication between both instances to be unidirectional (from left to right in Fig. 2), the complementary system can be used to validate synthetic results without directly manipulating the simulator. First, the underlying algorithms generate human motions with respect to the given tasks and environment. Second, the resulting artificial outcomes are subsequently provided to the interactive visualization interface. For instance, the movements of the virtual assembly operator are displayed in a bird's-eye view using a LED-floor - as depicted in Fig. 1. Third, the results are re-enacted by the user by means of performing the identical tasks in the virtual environment. Thus, the respective person is enabled to detect inconsistencies, stemming from both, the simulation approach including its parametrization itself and improper assumptions of the planning department. Finally, these defects can be corrected by hand or the simulation is re-run utilizing manually adjusted inputs.

Interactive simulation (center). As depicted in Fig. 3, the continuum of operating modes offers nearly unlimited options for balancing the interplay between the visualization/interaction and the simulation component. Such mixed scenarios are characterized by a bidirectional communication and a close cooperation between both instances. Similar to the above-mentioned mode of operation, the simulator is used to provide synthetic human motions to the interaction system. Analogous to *simulation validation*, the user is performing the identical task, however, while being tracked by the motion capture system. Depending on the weighting between both systems, the framework hence adapts the parametrization or inputs of its algorithms with respect to the given manner of execution. Note that this adaption process can be performed instantaneously (real-time control-loop) or after each simulation run. Besides avoiding planning errors, this mode can also be used to synthetically enrich a captured motion. For instance, the user demonstrates the execution of a list of tasks, teaching the simulator a desired behavior. Based on this input, multiple variants including different task orders, human percentiles or alternative solutions are generated and presented to the user, who confirms or manipulates the results. Consequently, variant-rich tasks can be holistically assessed, without physically performing each variant.

Interactive validation (right side). This unidirectional mode of operation (right to left in Fig. 2) is characterized by the interactive system being in control. Hence, the captured motions are fed into the simulator instance, however, not transferred back to the interaction system. As no active feedback-loop is present, this mode corresponds to an independent use of the well-known interactive virtual environments (e.g. [1]) without simulation support.

3.3. Mode of visualization

Based on the mode of operation and the established feedback-loop, the simulation outcomes can be presented to the user in various forms. In general, two major concepts can be identified, which show specific advantages and disadvantages: With- and without displaying the status, position and motions of the digital human model to the user during interaction.

Side-by-side. On the one hand side, the DHM is visualized as a semi-transparent reference or ghost, which performs the identical tasks parallel to the user. The main advantage of this methodology is the possibility to easily detect inconsistencies between simulation and reality, since the user can visually compare its own and the artificial motions at any time. Moreover, this visualization concept allows to pause the DHM to demonstrate a specific manner of execution. As the user might has to carry out task sequences with a high complexity, another benefit of displaying the virtual human, is the presence of a reference motion. Consequently, the system offers a reminder to the user, how and in which sequence a list of assembly tasks are to be executed. This is especially helpful when interacting with abstract representation of workplaces (e.g. two-dimensional floor-projection) in combination with complex workflows. In contrast, the reference will also lead to the drawback that users will adapt to the behavior of the DHM. This might result in partly meaningful motions and in the suppression of alternative execution manners.

Iterative. On the other hand, the state of simulation can also be hidden from the user during interaction to exclude the presence of influence factors. In this case, the captured and the syntactical motions are presented to the employee after having performed each task. Analogously, a rich repertoire of different variants and alternatives can be obtained using either no, or only unobtrusive cues, to guide the user within the scene. For instance, the next assembly point can be highlighted during interaction, hence offering a trade-off reminder to the user. In contrast, the major drawback of this group is, that it is not possible to offer instantaneous simulation support due to the absence of the DHM.

4. Concrete Implementation and Applicability-Analysis for the Use-Case of Automotive Walk Path Planning

In general, the technical implementation of both the simulation and the interaction system, the utilized hardware and simulation algorithms strongly depend on the respective use-case. For automotive walk path planning, the following sections present and evaluates a concrete configuration.

4.1. Implementation for use-case walk path planning

The major components of the generic approach - as illustrated in Fig. 2 - were designed with respect to the given constrains of industrial walk path planning.

Simulation software. The simulation system (see left half of Fig. 2) was implemented using an animation platform, which represents the core unit to generate realistic walk paths. Its scope of application ranged from operating the virtual scene and digital human model, over processing the captured motion, to rendering of the scene. Fig. 4 depicts the implementation of this instance using *Unity3d*.

Besides choosing the simulation platform, adequate motion planning algorithms had to be defined. In general, industrial walk path planning is performed in two dimensions, while observing the assembly operator's center of mass [16]. Therefore, a global motion planning algorithm [7] was used. Moreover, this approach was complemented by an ORCA implementation of the RVO2 library [10] (local motion planner), modeling the constraints of the human locomotor system. The former was utilized to generate an optimal reference path between two consecutive assembly tasks, whereas the latter moved and animated the digital human along the obtained trajectory. The virtual scene was finally displayed using a downwards-facing orthographic camera.

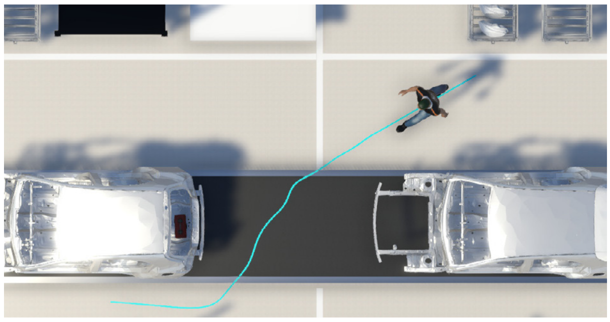

Fig. 4. Implementation of the walk path simulation system using Unity3d: A walk path between a rack and the car (turquoise line) is generated using a post-smoothed LazyThetaStar motion planner [7].

Visualization hardware. In order to implement the right half of Fig. 2, next, the visualization instance was defined. As human locomotion strongly correlates to the walking trajectory and its properties, it was significant to obtain a high spatial resemblance between the virtual- and the real environment. For instance, velocity and acceleration varies considerably with respect to the walk path length and its curvature. Therefore, true-to-scale visualization systems were predestined to be used for this purpose due to the use of preserving mappings between the real and the virtual space. A true-to-scale floor-projection system, being introduced by Otto et al. [2], was utilized consisting of four downwards-facing projectors. The setup created a virtual representation of the station layout on the ground (up to 6.0 $m \times 3.5m$). Other possible options are LED-floors (see Fig. 1) or isometric-VR [1].

Interaction hardware. To establish the feedback-loop (see Fig. 2) between both aforementioned systems, a HTC Vive tracking system was utilized. This device is able to capture the position and orientation of its controllers with an update rate of 60 *Hz* [17]. Thus, by mounting a Vive tracker on the person's front (at the landmark *umbilicus*) using an elastic belt, it was possible to track the user's center of mass. In particular, this distinctive point was determined by means of adding the half torso depth including the distance between device and skin to the controller position.

4.2. Experimental Setup

Having set-up the interactive simulation system, next, a representative workplace was designed to compare the novel with multiple state of the art approaches. Fig. 5 depicts the station layout of the final assembly workplace. It becomes apparent, that the experimental setup consisted of one body-in-white and two racks, which were positioned on one side of the car. Moreover, two shelves were placed in each rack (height of 1.0 *m* and .6 *m*), each containing one screw. As illustrated in Fig. 5, rack 2 had a distance of 2.2 *m* to the point of assembly (see 3), while the other counterpart showed an offset of 2.9 *m*.

Having defined the workplace layout, a representative list of assembly tasks was defined, including 8 sub-routes between the set of racks and the assembly point at the body-in-white. In particular, the assembly operator started at rack 2 and successively attached the screws to the car (see Fig. 5). The identical task sequence was repeated for the remaining rack. Note that each of the four screws had to be carried individually whereas walking was performed at self-selected speed.

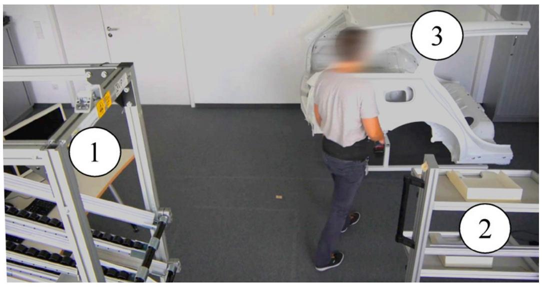

Fig. 5. Overview of the experimental setup: A participant had to successively pick up two screws at rack 1 and 2 and subsequently attach them to the workpiece (point 3).

4.3. Design of Experiments

Using the presented layout and assembly tasks, four independent scenarios were conducted to benchmark the proposed approach. In a first step, a comprehensive set of reference trajectories was captured with the help of a group of 10 participants. Note that this scenario comprised a hardware installation of the representative workplace - as shown in Fig. 5. Subsequently, the identical layout was re-planned using three virtual planning methods including the proposed approach. Comparing the planned (virtual) and captured walk paths (hardware), is it possible to draw conclusions regarding the prediction quality of the three respective methods.

Baseline. In order to model the influence of different heights and walking styles, 10 participants (9 male 1 female) could be recruited. This group showed following characteristics: Age (μ = 27.80, σ = 6.08), height (μ = 1.79 m, σ = .12 m) and weight (μ = 76.20 kg, σ = 14.18 kg). None of the participants reported vision or balance disorders. Each of the participants repeated the above-mentioned assembly tasks 10 times (in an identical order) to cover multiple spatio-temporal executions-variants. In total, the group thus generated a comprehensive database of 100 walking trajectories (10 participants, 10 trials each) for the identical set of assembly tasks.

Simulation. Having generated reference trajectories, second, the 100 trails were simulated without interactive validation support. For this purpose, the above mentioned motion planning algorithms were utilized. The two racks and the body-in-white were modeled as two-dimensional obstacles. Moreover, the mentioned motion planning algorithms were utilized to generate walking trajectories between consecutive assembly tasks using a velocity parametrization of 1.36 m/s [18]. As human locomotion comprises an infinite number of different styles and manners of execution and is further depending on the person's physical condition, the captured baseline can only be partly covered using deterministic approaches [19]. One possibility to overcome this limitation is to probabilistically manipulate input parameters of the walk path planning algorithms. Therefore, the deterministic parametrization was extended to consider statistical variations. In particular, the target velocity for each of the 100 trails was individually drawn from a normal distribution (μ = 1.36 m/s and σ = .50 m/s)

Interactive. Third, the identical scenario was solely planned interactively by one production planning employee, who was neither familiar to the workplace nor to the assembly tasks. For this purpose, the user was asked to carry out the tasks using the floor projection while being tracked by the motion capture system. Note that this experiment was conducted without simulation support and only generated a single planned walk path - in analogy with production planning practice.

Interactive simulation. Finally, the workplace was assessed using the proposed system which can be regarded as combination of both aforementioned methods. In line with the previous experiment, a second production planning employee demonstrated the sequence of tasks using the identical apparatus. In contrast, the tasks were subsequently re-simulated based on the user's maximum walking speed using the described algorithms. For this purpose, an optimization based approach presented by Wolinski et al. [20] was used. Next, the simulated results were presented to the user after each take, who either approved the artificial walk paths or repeated the procedure. In a last step, the interactively validated trajectory was probabilistically enriched with 100 probabilistically obtained routes (varying parametrization of σ = .50 m/s).

4.4. Results

Using the different methodologies, four different results could be obtained which are summarized in Fig. 6.

Baseline. During the baseline experiment, walk paths with an overall-length of approx. 2 km could be gathered. The left side of Fig. 6 shows the distribution of the 100 overall-walking times in form of a boxplot. It can be seen, that the 25^{th} percentile is located at 16.26 s, whereas the median and the 75^{th} percentile are 23.43 s and 27.67 s. The considerable delta between both reference percentiles of 11.41 s confirms the assumption that deterministic simulation approaches are only partly suitable to simulate human locomotion due to its variant-richness and statistical nature. Same applies for interactive planning.

Simulation. The second boxplot in Fig. 6 illustrates the resulting walking times for the probabilistic simulation approach. It becomes apparent that the sampling-based parametrization generates distributed walking times: 25^{th} percentile of 31.45 s, median of 37.05 s and 75^{th} percentile of 44.22 s. Even though showing a significant difference between the planned walk paths and the captured counterparts, the range between 25^{th} and 75^{th} percentile of 12.77 s corresponds to the baseline variability. Consequently, the chosen statistical sampling method is able to cover the captured range, however, with a differing mean. As the simulation is not compared to real world observation (e.g. using the interactive system) the error remains unidentified.

Interactive. The third boxplot within Fig. 6 shows the single outcome of interactive walk path planning without simulation support. It can be seen that the result of 21.67 s corresponds to

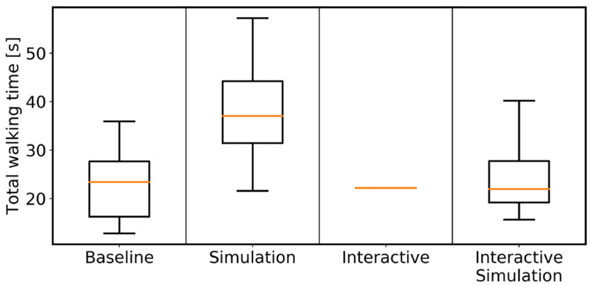

Fig. 6. Evaluation results: The first boxplot (see *reference*) depicts the reference temporal distribution of the 100 captured walk paths. The second measurement shows the 100 synthetic results for the statistical simulation approach (see *Simulation*) whereas *Interactive* illustrates the single outcomes for purely interactive planning. The last boxplot depicts the results of the proposed approach unifying both aforementioned methods.

the captured median of 23.43 s, however, it is economically not feasible for production planning departments to capture a comprehensive number of walk paths stemming from large populations.

Interactive simulation. Finally, the last measurement depicts the novel concept unifying both aforementioned approaches. As the conditions for the user were not substantially different from the purely interactive counterpart (i.e. DHM was not visible during execution) the resulting median of 21.96 s is nearly equal. In contrast, the coupled sampling-based simulation approach enriches the single captured motion with 100 artificial counterparts. Boxplot 4 and its range between the 25^{th} and 75^{th} percentile of 8.57 s underlines this assumption. Consequently, the novel approach on the one hand covers the captured variance and on the other hand produces a smaller degree of deviation between the captured and the planned median. In practical terms, the proposed method calibrates a given simulation approach to real word observations, thus significantly increasing the prediction quality of virtual planning methods.

Summarizing, the evaluation underlines the capabilities of the proposed method, as the novel approach combines the possibility to efficiently simulate variants with the reliability of real world observations. Even though this particular form of interactive simulation outperforms the tested state of the art methods, it is to be noted, that the gathered results are not of general applicability but exemplarily demonstrate the evident advantages of this generic concept.

5. Conclusion and Outlook

This paper introduces the concept of interactive simulation for industrial purposes, which combines interactive planning of human labor with motion simulation algorithms. The resulting symbiosis of both systems reinforces the individual benefits while compensating the respective drawbacks. Furthermore, methodologies, interaction and visualization concepts and modes of operation are described to span the entirety of possible areas of applications. Starting from this generic concept, a concrete implementation for the use-case of automotive walk path planning is described and evaluated. The latter demonstrates the potential of interactive simulation and outlines the evident benefits of the introduced approach.

Future work will optimize and extend both, the presented implementation and the generic method for the use-case of production planning. Moreover, in the next publications the influence of statistical motion modeling and machine learning and their interplay will be further investigated. Finally, the impact of virtual reality on human locomotion will be discussed in the future.

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