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Bringing rigid bodies to life: Immersion study in motion capture-based virtual realistic animation of vehicle movement

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ABSTRACT

Movement mapping in 3D space is a commonly applied computer technique. Due to the growing demand for games, films and cartoons, developing methods for creating and generating high-realism object animations has become essential. Current advanced methods based on motion capture systems mainly focus on humanoid figures, while rigid bodies are often animated based on the keyframes or physics of objects. This study pursues an innovative approach to producing rigid body VR animations, which utilizes data acquired from a passive optical motion capture system. The key task is to obtain high-quality recordings with continuous trajectories of markers attached to tracked objects. The great demand is put on preprocessing of c3d data in MotionBuilder software, preparing the object and rigging the 3D model to obtain the highly realistic animation. It is further transferred to a VR environment where an ablation study is performed to analyze the effect of animation baking factors on users' perception. Comprehensive ablation studies concerning the VR immersive experience, involving the 10-person research group, are performed. They verified to which extent the real environment is engaging and convincing enough. The obtained results highlight that the animation has a high level of movement realism and corresponds with great user immersion.

Keywords: motion capture, rigid body animation, realistic animation, VR animation, immersion.

INTRODUCTION

With the development of commercialization and digitization, there is an increasing need to develop techniques related to graphics. Animation is one of the most important tools of modern visualization, which plays a key role in various fields - from computer games, through films [1] and advertisements, to education and medicine [2].

Current research on 3D animation focuses on humanoid silhouettes, whose movement dynamics are complicated and require controlling many variable parameters [3–5]. There are many different methods of creating animations in 3D space, most often focusing on motion simulation using object physics [6, 7] and motion tracking using motion capture systems [8, 9]. The latter method permits for high accuracy of object trajectories and thus for reliable and realistic representation of movement in computer space. The novelty of this study is grounded in demonstrating a novel approach to creating 3D rigid body animations. Utilizing dedicated 3D model rigging, a high-quality VR animation was achieved and subjected to research participants testing. Due to the use of motion capture, this study focused on obtaining high animation realism, which impacts the level of immersion and presence of VR system users.

Motivation

Software created for cooperation with animations provides ready-made facilities for creating character animations such as marker mapping or silhouette rigging but they are limited to usage on humanoid characters. In the analysis of studies regarding 3D animation of objects with the characteristics of rigid bodies, it can be seen that this topic is very rarely discussed and focuses on the use of physic-based or keyframes methods. Thus, the main motivation of this study is to apply an innovative approach to creating rigid body animations using a motion capture system and transferring the solution to a virtual environment. The motion capture system provides data with high motion accuracy, which allows for mapping real movement in computer space. This approach is essential for VR space, where users expect high relativity and a sense of immersion. This study core endeavours deriving uninterrupted 3-D trajectories from marker-based data, into a skeleton structure and validating the result in an immersive-VR, which plays a great interest in modelling and simulation in engineering.

The main aim of this study is to develop an innovative approach to create rigid body animations. The novelty of this study is based on the use of motion capture technology to create a VR animation of a rigid body object, that is developed differently than native humanoid animations, for which most software provides a ready-made interface for mapping individual joints onto the 3D model rig. The vehicle animation was created by applying mocap recordings and processing in MotionBuilder software, which allowed the assembly of a dedicated skeleton of the object and mapping the 3D model.

Contributions

The contributions of this study are as follows:
- Recording high-quality movement paths of markers pinned to vehicle objects using a Vicon motion capture system, obtaining smooth and continuous motion recordings through postprocessing. Each of the final files consist a cloud of points in .c3d format.
- Obtaining a three-dimensional computer representation of the object in the form of a model, combined with motion recording using tools for processing motion data. Utilizing MotionBuilder's structural elements – the skeleton node and the skeleton root – a rig was created that corresponded in structure to the marker positions pinned to the vehicle, enabling the overlapping of a 3D model.
- Creating an animation based on the obtained 3D model and preparing VR environment, utilizing Unity software and importing assets in .fbx format into the graphic creator, where special routes for the riding vehicle were prepared.
- Importing the prepared animation into the VR environment to test the animation's performance and enable the presentation of the study results to the research group participating in the ablation study.
- Performing an ablation study analyzing the impact of baking animation factors on users' perception and immersion. Key settings affecting data exported by MotionBuilder were selected and the impact of their changes on user immersion, when viewing the VR animation was examined, utilizing Igroup Presence Questionnaire and 10 participants.

RELATED WORKS

3D-based animation

3D animations can be developed by utilizing various methods. Animations based on the physics of objects are characterized by a high workload to achieve more realistic animation effect [10] and they are not suitable for simulating real-time interactions [11]. One of the most popular methods are those based on motion capture technology. These solutions permit for a highly realistic representation of movement in computer space and provide great opportunities for creating 3D graphics materials for films, games and animations [9,12].

Some motion capture systems differ based on their capabilities and how they operate. There might be distinguished passive optical system, active optical system, inertial optical system, markerless motion capture and surface electromyography [13]. The passive optical system operates by capturing the movement of markers on objects or humans. It is employed by the Vicon system in various areas such as animation, sports and scientific research offering high accuracy and stability. Active optical systems work based on markers equipped with infrared light-emitting LEDs that are beneficial in different lighting conditions. It is utilized for example in the Raptor series. Conversely, inertial motion capture uses inertia sensors placed on monitored body parts like wrists or arms. Cameras or physical markers do not need to be used in this technology because sensors measure acceleration and orientation. It is widely used in systems such as Xsens MVN. There are also markerless motion capture systems that apply special cameras, image processing algorithms and artificial intelligence to record movement tracking or human biomechanics. They are incorporated into Microsoft Kinect.

Methods for creating 3D animations bases on both physics-based approaches [14, 15] and the use of realistic trajectories. For humanoid figures, the most common technique is the use of data from motion capture systems [16] due to the high complexity of the movement in various sequences. However, for other objects, such as vehicles, a simulation approach is most often used, which is not a realistic interpretation of the trajectory but merely the result of calculations based on the principles of the object's physics.

Software

The most commonly utilized software for working with data applicable to creating 3D animations was determined as part of a review. Autodesk MotionBuilder is one of the widely-used tools for tasks, such as processing data from Motion Capture systems, providing advanced features for importing, mapping, retargeting, and editing animations [17, 18]. It is prevalently utilized in creating human-like animations including dance sequences animations [9] and tennis strokes animations [19]. MotionBuilder provides the retargeting of skeleton bones onto the developed model's bones with tools for animation editing. Additionally, it was applied in investigating user interactions with a holographic sign language interpreter in a mixed reality (MR) classroom for pupils with hearing impairments [20] where MotionBuilder supported the merging of American Sign Language (ASL) raw data produced by three motion capture software.

Another tool frequently applied in 3D modeling and animation is Blender. Due to implementing some mathematical models, users managed to create many animations. Additionally, it is feasible to apply path tracing and real-time rendering methods built on ray tracing algorithms to provide high-quality animations [21]. Blender also might be employed in the development of a human body 3D model based on a motion capture system [22] or in the 3D models' creation from 2D images in its virtual environment, such as developing face of a famous person from few images [23].

Unity, a game engine, is also perceived as a prominent tool throughout the design of 3D animations due to providing high-quality graphics, scripting capabilities, real-time rendering, and cross-platform support as well as the ability to create animations based on the motion capture data [24, 25]. Due to its abilities Unity can be utilized as an environment for developing visual simulations in virtual reality technology [26–28] as well as in augmented reality applications [29, 30].

Animations in VR

Virtual reality animation introduced changes in the perspective of how the viewer engaged with the whole environment [31–34]. In traditional animation, the attention of the viewer is guided by the angles of the camera and editing abilities whereas, in animation, a VR viewer is placed within the animation environment [35, 36]. This situation presents some challenges because, during the development of the animation in VR, the additional VR-specific elements, such as spatial audio, user interactivity and navigation should be considered to enhance the viewer's level of immersion [37, 38] as well as human factors, such as age or gender [39]. Each animation has its components: scene elements, controllers, or setting panel, which features multiple usages, for example the manipulation of objects [25, 40, 41].

Motion capture systems could be utilized for data acquisition to create more realistic VR animations by integrating human motion into virtual reality [42, 43]. Some elements, such as body gestures and facial expressions could be captured. VR animations based on motion capture data might also be beneficial in capturing training data and then developing a virtual reality application to study athlete's results [44–47] or in the systems that analyze dance movements [48, 49].

MATERIAL AND METHODS

Digitization of vehicle movement

Motion capture system

The acquisition of vehicle movements was performed in the Motion Capture and Analysis Laboratory of the Department of Computer Science at the Lublin University of Technology in Poland. The basis for developing the animation was the creation of recordings using a motion capture system. The study utilized an 8-camera Vicon optical passive system that collects data from captured reflective markers. A dedicated model was developed indicating driving paths, especially in a straight line, on a curve and around a roundabout. The model consisted of 113 markers. The whole model was placed in the area of the laboratory, where each marker was visible by all cameras. The remote-controlled car was prepared for acquisition by attaching 7 retro-reflective markers: 2 markers at the front, 2 at the end, 2 on each side and 1 marker in the middle of the roof of the car. The arrangement of the markers on the car was designed in such a way that after further post-processing, a rigid body could be created.

Driving around the roundabout was recorded at a set frequency of 100 Hz. The car was placed inside a designated circular route with a radius of 35 cm and a width of 60 cm. The movement was recorded from the moment the lap began until it crossed the starting point after a full 4 laps. This kind of movement was repeated three times. The capturing was performed in the Vicon Nexus software.

Data post-processing

The data obtained from the recordings were further post-processed. This procedure removed irregularities and prepared marker signals for further use in motion models and animations. The study used the Nexus software, which permits the processing of mocap data. The post-processing consisted of four main steps (Table 1): labelling, gap filling and cleaning data. The first part consists of assigning the proper name, from the created vehicle model, to all markers. The second one involved interpolating gaps between frames in order to obtain a smooth trajectory. Missing data at the beginning and end of the recording is difficult to fill in, because the interpolation methods cannot be applied. To supplement the data, proprietary software in Python was applied [50]. The key aspect of post-processing is to obtain high-quality motion recordings, free from artifacts and gaps.

3D-based animation

Properly prepared data allow the creation of a 3D model and the development of movement animation in three-dimensional space utilizing appropriate software. In this study, MotionBuilder was used, which is a popular tool for processing c3d files [51, 52]. However, the procedure for utilizing motion capture data in the case of rigid body objects differs significantly from the most commonly used humanoid silhouettes. Software such as MotionBuilder or Maya has built-in rigging for humanoid objects and it is also possible to directly map a rigged object to a 3D model. Such features make it easier to animate silhouettes, but they do not apply to rigid bodies, for which there are no built-in options. An innovation in the approach to this process was used. The most important starting point was the use of c3d motion recordings with a continuous motion trajectory. Based on the loaded c3d file, the creation of a 3D model of the car object began. In the first step, a rig consisting of skeleton node and skeleton root elements was created. The rig included 6 bones that connect 7 points derived from motion capture system marker coordinates. Each skeleton component was manually placed at the marker location using the element inheritance process. Six skeleton node elements were used, along with one skeleton root, which serves as the central part connecting all the bones. This combination created a rigid body that represents a realistic object and also allows for the subsequent application of a 3D model to the rig. The appropriate arrangement of elements enabled the creation of a rigid body skeleton, which is shown in Figure 1.

The obtained skeleton was used to embed the 3D model. A 3D object of a vehicle was selected, which was imported in fbx format from a public library of 3d assets. MotionBuilder does not have built-in support for rigging non-humanoid models, but it permits for imposing a 3D object on the created rig. The object from the fbx file was embedded directly onto the created skeleton. It was also necessary to determine the model's affiliation to the skeleton through inheritance established in the structure of scene elements. The resulting 3D model is shown in Figure 2. The

Table 1. Post-processing stages

Post-processing step	Description
Visual inspection of recordings	It identifies missing markers, noise and other artifacts.
Marker labelling	Includes assigning labels by naming specific marker locations, grouping markers into configurations representing real objects.
Gap filling	Involves detecting and addressing gaps in the recordings. They are caused by the vehicle being positioned on the edge of the visible area (where the cameras recorded the marker's position) at the beginning and end of the movement.
Removal of incorrectly placed markers	Eliminating artifacts and unnecessary markers that could disrupt the model.

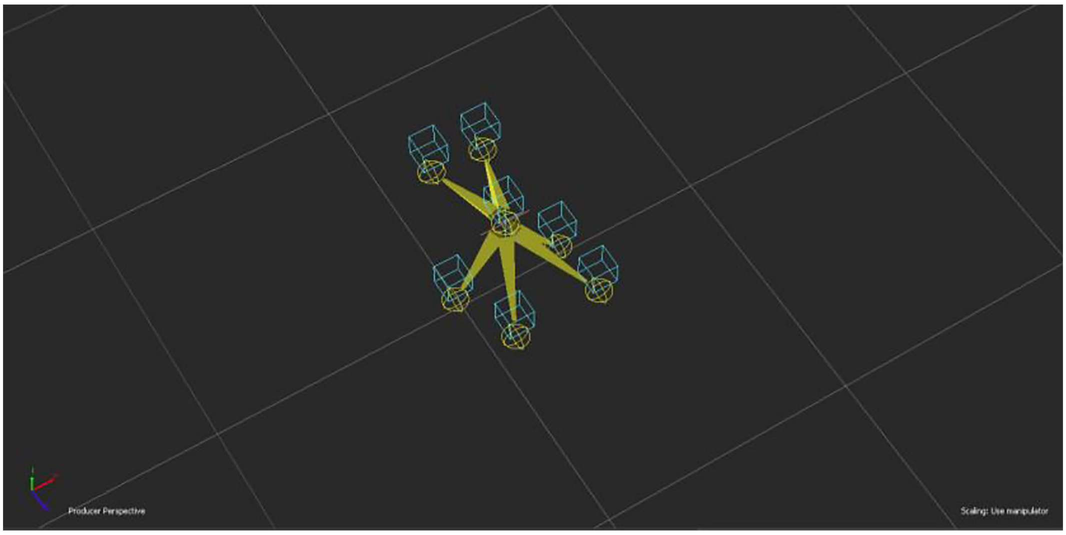


Figure 1. Skeleton of the vehicle rigid body object

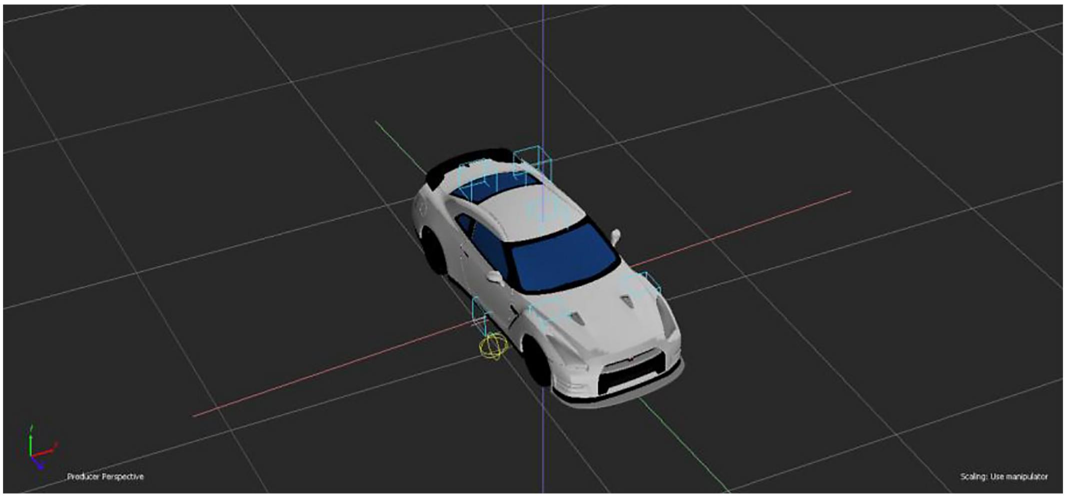


Figure 2. Three dimensional model of vehicle rigid body

last stage was to create an animation of the car through plotting and creating an animation path, which allows for the integration of data from motion capture, the built skeleton and the 3D object imported from the fbx format. To ensure high animation smoothness, it applied 100 frames per second generating frequency.

Animation in VR

The research was conducted towards the use of the obtained animation of the vehicle in the VR application (Figure 3). A VR project was created using the Unity software. The first stage was to create a virtual environment that is the background for the car animation. A scene filled with three-dimensional objects available in the public library of Unity Assets was created. Then, animation was developed in the VR environment, which consisted of the following steps:

- importing the file obtained in MotionBuilder in the fbx format to the project assets, which allows the use of animation in the created scene,
- applying a car animation object by placing the asset on the scene editor area,
- creating an animation controller, setting the input for data on the object's movement and its position,
- adding an animation to the car object by setting the controller in the animator configurator.

Unity allows for direct connection of the environment and uploading the animation to the VR goggles, due to which the created animation was used to conduct the immerse test.

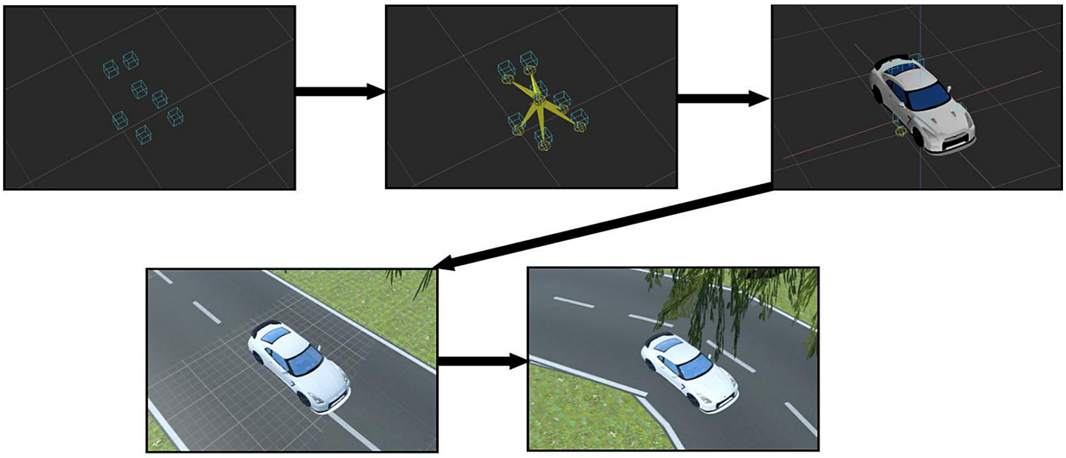


Figure 3. VR animation development process

Ablation study

In the method of creating animations, one of the key stages that influence further image processing is baking. It was performed in MotionBuilder and allows combining the motion trajectory and the 3D model into one object. During the study, it was determined to evaluate the influence of the plotting option on the realism of the obtained animations. Thus, an ablation study was conducted in combination with a user survey. The study examined the influence of individual, selected baking factors on the perception of VR animations. Two movement animations were used in the study: around a curve – animation 1 and around a roundabout – animation 2, due to the more sophisticated trajectory than driving straight forward. Each animation was baked in 4 ways, which are presented in Table 2. Individual settings were turned off in the plot option in the MotionBuilder tool, resulting in different motion characteristics in individual frames. The prepared animations were evaluated by 10 users, who were requested to watch the VR animations and rate each of them using the Igroup Presence Questionnaire (IPQ) survey criteria.

SmartPlot option enables plotting an animation without adding unnecessary keyframes, applying appropriate filters while preserving the original keyframes.

The Fidelity Keys Tolerance parameter determines the accuracy of the animation representation during plotting. Changing the parameter value affects the fidelity of the original animation by changing the number of keyframes.

Rotation Filter is a setting used to eliminate problems related to rotations, such as unwanted jumps in the animation, visible artifacts or noise.

The Gimbal Killer filter adds additional keyframes to minimize unwanted effects, improves the quality of the movement and rotation trajectory.

Survey

The study required verification of the realism level of the created VR animations depending on plotting factors. Therefore, a survey was conducted to assess the virtual reality experience of a group of 10 participants – students of Computer Science in age 20–24.

The IPQ [53, 54] is a scale for measuring the sense of presence experienced in a virtual environment. Immersion is assessed on the basis of 14 questions (Table 3) divided into three subscales (Table 4) and one additional item not belonging to any subscale, measuring the general sense of virtual reality. Each question has a scale from -3 to 3 points, where -3 means – fully disagree and 3 means – fully agree. Four of the 14 questions have

Table 2. Ablation study experiments

Ablation study experiments number	SmartPlot	Fidelity Keys Tolerance [units]	Rotation filter
AB1	True	0.25	-
AB2	True	0.05	-
AB3	False	-	-
AB4	False	-	Gimball Killer

Table 3. IPQ survey questions [53]

No. of question	Subscale	Question	Reverse point scale
1	Involvement	How aware were you of the real world surrounding while navigating in the virtual world? (i.e. sounds, room temperature, other people, etc.)?	Yes
2	Experienced realism	How real did the virtual world seem to you?	No
3	Spatial presence	I had a sense of acting in the virtual space, rather than operating something from outside.	No
4	Experienced realism	How much did your experience in the virtual environment seem consistent with your real world experience?	No
5	Experienced realism	How real did the virtual world seem to you?	No
6	Spatial presence	I did not feel present in the virtual space.	Yes
7	Involvement	I was not aware of my real environment.	No
8	General presence	In the computer generated world, I had a sense of "being there".	No
9	Spatial presence	Somehow I felt that the virtual world surrounded me.	No
10	Spatial presence	I felt present in the virtual space.	No
11	Involvement	I still paid attention to the real environment.	Yes
12	Experienced realism	The virtual world seemed more realistic than the real world.	No
13	Spatial presence	I felt like I was just perceiving pictures.	Yes
14	Involvement	I was completely captivated by the virtual world.	No

Table 4. Subscales of IPQ survey

Subscale name	What does it represent?
Spatial Presence	The sense of physical presence in the VR.
Involvement	Measures the attention devoted to the VR and experienced engagement.
Experienced Realism	Measures the subjective experience of realism in the VR.

a reversed scale, which was included in the analyzis of the results. The survey method consists of comparing animations during 4 experiments (AB1, AB2, AB3, AB4). In each experiment, participants experienced 2 animations displayed on VR goggles, the first animation concerned movement around a roundabout, the second movement on the a curve. After the individual animation had finished, the subjects completed a survey. In total, each participant completed 8 questionnaires. Thus, the survey study collected a total of 80 responses from participants that were further analyzed. The indicators for the subsequent subscales were calculated based on the average value obtained from the participants from specific questions in each experiment. The maximum value that the subscale could obtain was 3, and the minimum -3.

Metrics

The main metrics used in the study are related to sampling and image smoothness, which have a direct impact on the final quality of the built animation. Capturing frequency determines the number of image samples recorded per second. The higher the sampling value is, the greater the accuracy of the recorded images is.

FPS (Frames per second) is a basic indicator of animation smoothness. It determines the number of individual frames generated per second. The higher the value is, the smoother the animation effect is obtained.

Frame Render Time is responsible for the time it takes to render one frame in the animation. A shorter frame render time means less latency, which improves fluidity and user experience.

Metrics related to the conducted survey regarding the immersion experience:

- Spatial Presence is assessing whether the user felt physically present within the virtual environment. A high score indicates that the user had a strong sense of being inside the simulated world, rather than just observing it from the outside.
- Involvement describes the degree to which the user focused on the VR experience and disengaged from real-world stimuli. A high score indicates deep cognitive and emotional engagement with the VR environment, which is crucial for a sense of immersion.
- Experienced Realism measures how realistic and immersive the virtual environment felt. A high score suggests that the user experienced the VR environment as authentic,

believable and realistic – which contributes to the quality of immersion. General presence is an overall assessment of presence, often analyzed in isolation or as a benchmark, based on a single question in the IPQ survey.

RESULTS

VR animations

After the vehicle movements capture and post-processing steps, the data contains specific coordinates of the road paths and a vehicle in the successive frames (Figure 4). The uninterrupted motion trajectory was obtained for each marker attached to a car (Figure 5).

Going further, VR animations were created, which were supplemented with additional scene elements. Each one from 5 animations shows a different type of movement recorded by a motion capture system: curved to the left, curved to the right, roundabout to the left, roundabout to the right and driving straight ahead. Animation in Unity software required the creation of additional elements such as an animator controller and an animator, which allowed for movement to the car object. The software turned out to be an intuitive tool, which has additional interfaces enabling direct connection of the animation to VR goggles. The resulting animation (Figure 6, Figure 7, Figure 8) resembles the effects achieved by the simulation authors [14, 15], due to the inclusion of additional scene elements, such as trees and rocks, which may also contribute to a more favorable animation experience.

Ablation study

The ablation study was performed using the animation plotting options, which were then transferred to the VR environment. The study analyzed the motion trajectories of three-dimensional coordinates. Translation describes the displacement of an object in space (XYZ). It is less susceptible to sensor vibrations or registration errors, while rotation catches small nuances, determining how the angle of rotation of the object around each axis (X, Y, Z) changes over time. The translation coordinates does not have noise or artifacts and the plotting modifications are unnoticeable on the graph. Thus, the study analyzes rotation graphs (Figure 9–12), which highlights changes depending on the selected parameters. The horizontal X-axis of the graphs describes the animation time measured in frames and the vertical one, Y-axis determines the rotation value in degrees. The visual representation is created by tracking the vehicle model's movement in three

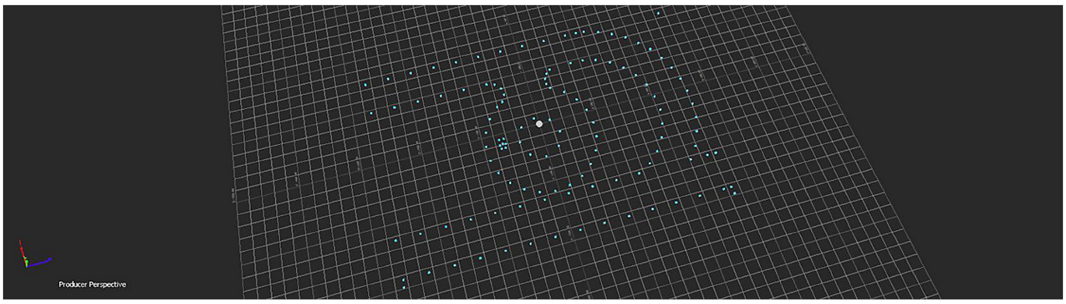


Figure 4. Graphical 3D representation of markers in Vicon Nexus after post-processing

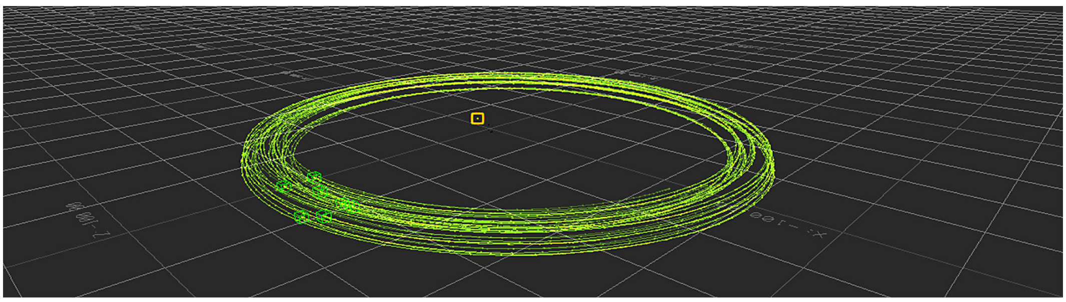


Figure 5. Continuous path of movement after post-processing

Figure 6. VR animation view of driving on the curve

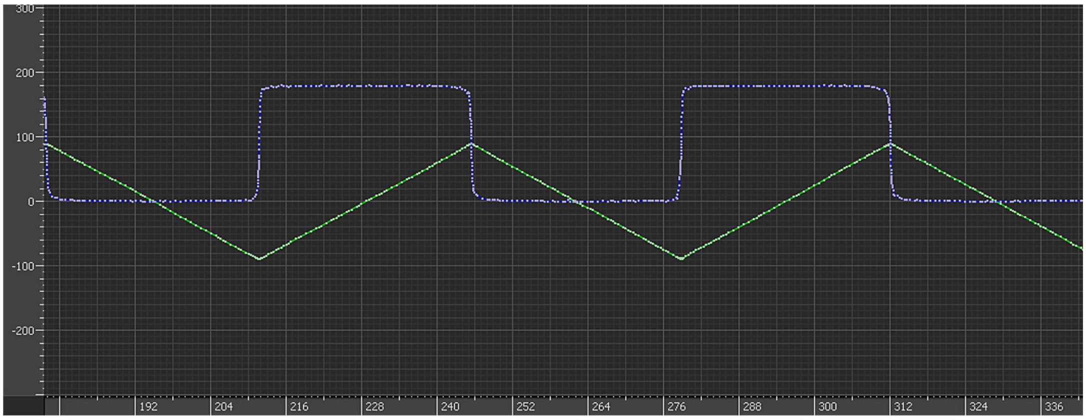
Figure 7. VR animation view of driving straight forward

Figure 8. VR animation view of driving around a roundabout

dimensions, measured as frames of the recording. They describe rotational movement within three dimensions: X, Y and Z. The following colors indicate a different axis of coordinates: X – red, Y – green, Z – blue.

Ablation experiment 1

First experiment examines objects plotted with general factors. The SmartPlot option was selected, with a fidelity of 0.25. This approach uses default filters that adjust the motion characteristics by smoothing the trajectories while maintaining the original number of keys. Adjustment is performed by interpolation between frames, avoiding noise and artifacts (Figure 9). A fidelity of 0.25 indicates high accuracy based on the distribution of keyframes. The survey participants showed a high level of presence in the virtual environment for created animation (Table 5). The average General Presence score was 2.70. In the case of Spatial Presence, the score is 1.85, which indicates a fairly high immersion in the Virtual World and isolation from the external environment. Involvement



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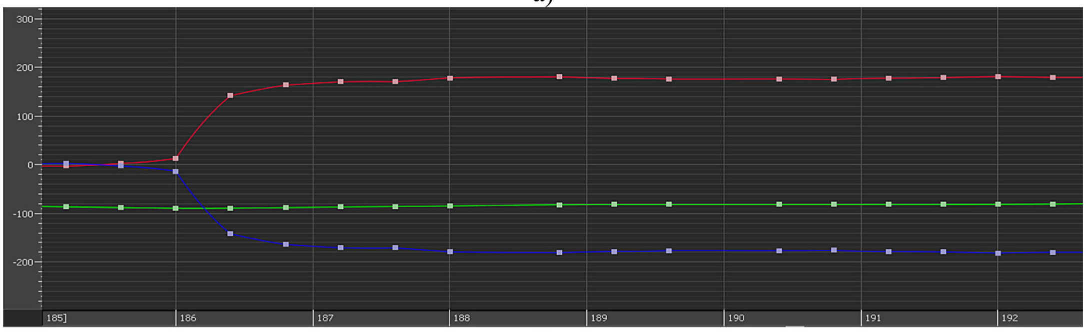
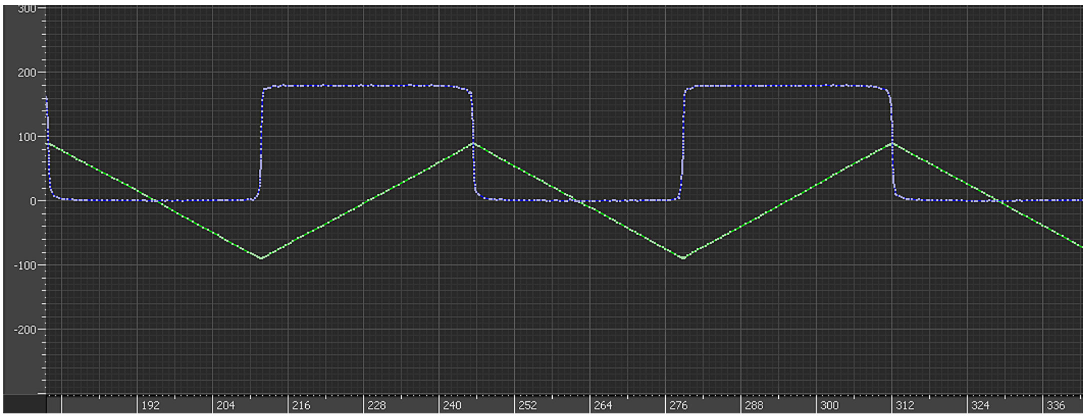


b)

Figure 9. AB1 experiment rotation trajectories for two animations (X axis – time in frames, Y axis – rotation in degrees): (a) movement around a roundabout, (b) movement on the curve to the right



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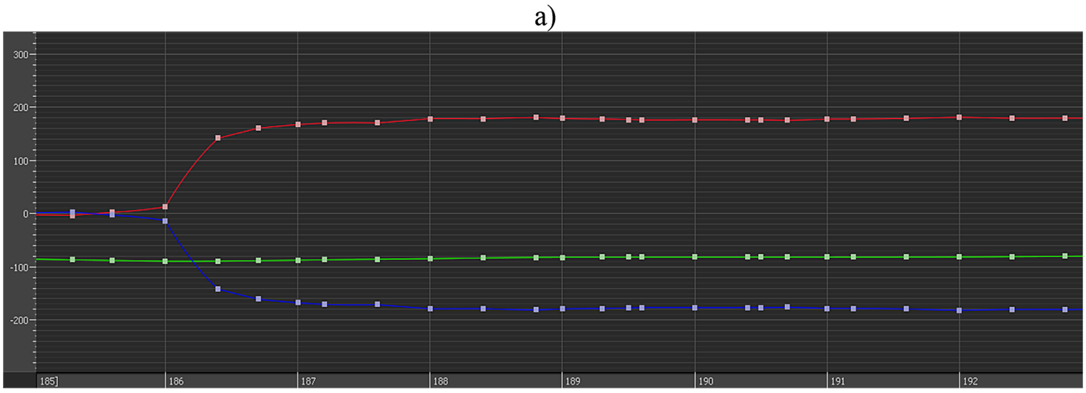

b)

Figure 10. AB2 experiment rotation trajectories (X axis – time in frames, Y axis – rotation in degrees): (a) movement around a roundabout, (b) movement on the curve to the right

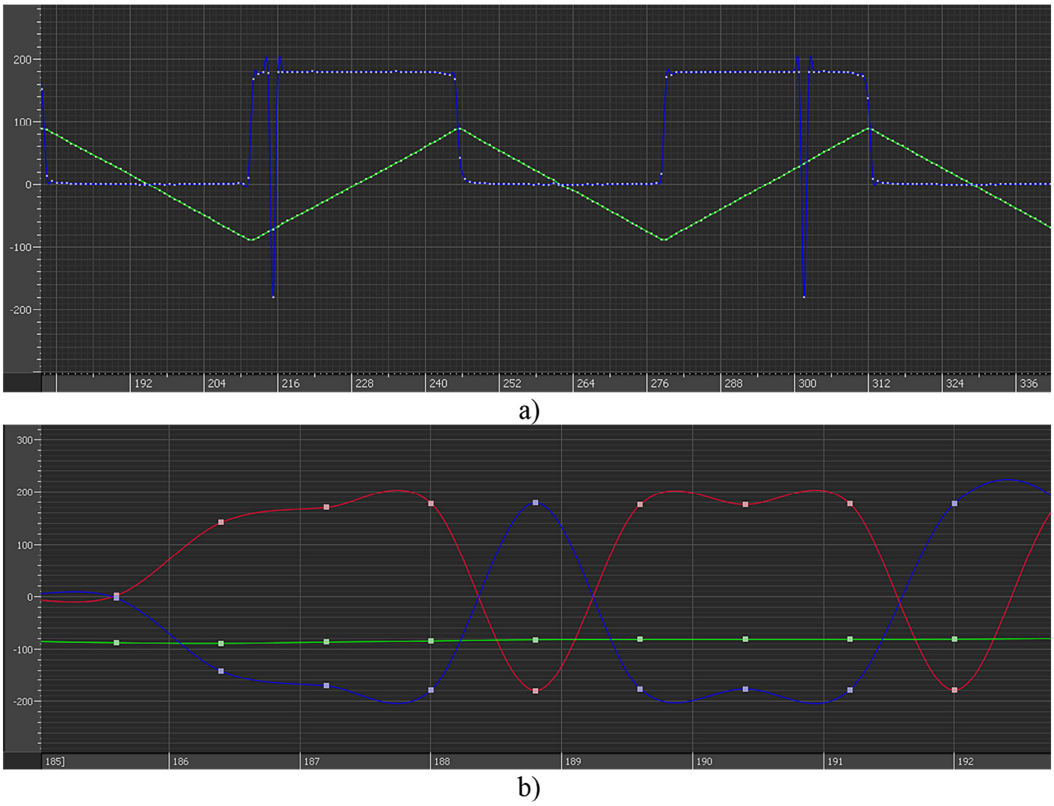

Figure 11. AB3 experiment rotation trajectories for two animations (X axis – time in frames, Y axis – rotation in degrees): (a) movement around a roundabout, (b) movement on the curve to the right

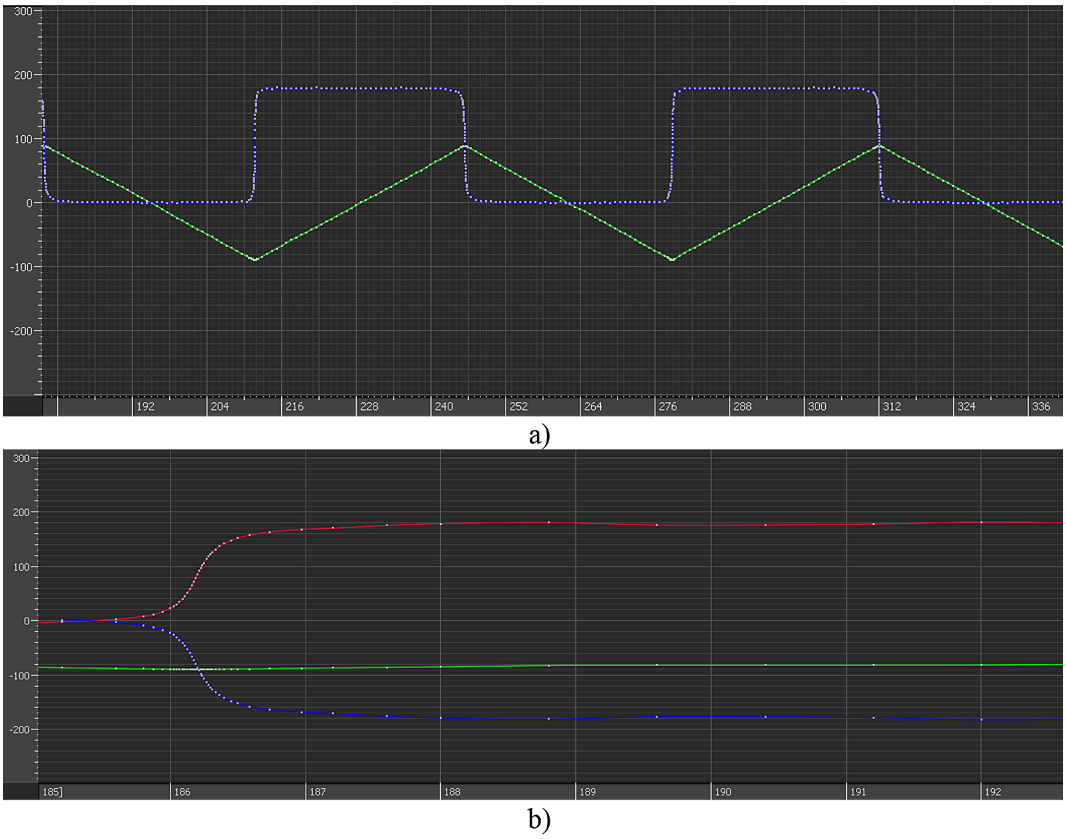

Figure 12. AB4 experiment rotation trajectories for two animations (X axis – time in frames, Y axis – rotation in degrees): (a) movement around a roundabout, (b) movement on the curve to the right

turned out to be the weakest area, with an average score of 1.01, which is still a positive result. The experience of realism is rated very high, receiving a value of 1.93, so the animation was perceived as very realistic and convincing.

Ablation experiment 2

In the second experiment, the SmartPlot option was retained, but the fidelity was changed to 0.05. This approach increases the number of keys, which should provide greater accuracy of the motion trajectory (Figure 10). General Presence achieved 2.75, which means a good match between the technology and the environment and their perception, the result is close to the maximum value of the scale. Spatial Presence obtained 1.83, which is a high result and within the study represents the best setting for this area. The result for Involvement (1.13) also turned out to be better than in the case of Ablation experiment 1. Experienced Realism was 1.68, which indicates that participants assessed the VR environment as quite realistic. Comparing ablation experiment 1 and 2 (Table 5), it turns out that the differences are small, so changing the value for Fidelity to a lower one may slightly improve the results for user immersion, especially in terms of Involvement, but it does not make a big difference in General Presence, so the change in animation plotting was not significant.

Ablation experiment 3

In the third ablation study, the SmartPlot option was eliminated and no additional filters were set. This approach results in vibrations and noise, so the trajectories are not smoothed and the keys in individual frames are mixed (Figure 11).

In this experiment, users overall rated their score on the level of General Presence subscale on 2.15, while that score for spatial presence subscale was 1.53. For the involvement subscale, the mean score rated by users was 0.95. Experienced realism achieved 1.26. The obtained results (Table 5) are lower than in the rest of ablation experiments. It could be considered that noise, vibrations and jumps present in the 3D model's motion characteristics have reduced the realism and immersion of the subjects.

Ablation experiment 4

The fourth ablation study eliminates SmartPlot option, but adds an additional Gimball Killer filter that allows to eliminate noise, gimbal lock, jitter and jumps. It smoothes the motion characteristics and densifies the frame keys (Figure 12). The respondents achieved a result for General Presence 2.65, which indicates a strong overall impression of being "inside" the VR experience. The average of 1.65 for Spatial Presence shows that participants clearly felt physically present in the VR space – although not as intensely as in the aspect of general presence. The result for the Involvement subscale (1.10) suggests that some participants were more easily distracted or were not completely absorbed by the VR environment. A fairly high result was also obtained for Experienced Realism (1.53). The obtained results for ablation study 4 (Table 5) are high, but not the best, which may suggest that very smooth movement trajectories do not guarantee high user immersion, the movement obtained from such characteristics may seem idealized and artificial. The ablation study highlighted differences in the reception of VR animations depending on plotting factors. The participants of the study rated the variant from experiment AB3 the worst. Despite subtle visual differences, which were manifested by vibrations or the occurrence of artifacts, the subjects were able to indicate differences between perception and the sense of immersion in subsequent animations.

DISCUSSION

The study conducted a comparison with state-of-the-art animation creation methods (Table 6). The input data processed during the animation development process, the animation object, software and the utilized techniques were taken into

Table 5. Ablation study results for individual experiments

Ablation study experiments number	Spatial Presence [units]	Involvement [units]	Experienced rRealism [units]	General Presence [units]
AB1	1.85	1.01	1.93	2.70
AB2	1.83	1.13	1.68	2.75
AB3	1.53	0.95	1.26	2.15

Table 6. Comparison with the state-of-the-art regarding the methods of animation creation

Ref.	Animation technique	Animation object	Software	Data input
[14]	SUMO based on rigid-body, mixed reality (MR)	Vehicle	Unity	SUMO trajectories, symulated sensors
[15]	Rigid-body based and simulation	Vehicle	Unity	SUMO trajectories, unity controller
[5]	MetaHuman library, keyframes, performance capture, Human IK rigging	Humanoid	Unreal Engine, Maya	Keyframe and motion capture data
[16]	Human model with joint linkage	Humanoid	Unreal Engine, 3DMAX	Motion recordings from inertial system
[9]	Built-in interface for assigning points to model bones	Humanoid	MotionBuilder	Motion capture data
[6]	Rigid bodies with rotational springs, position-based-dynamics-inspired solver with analytic spring solutions	Botanical trees	Unity	Procedural tree model, physical parameters (stiffness/damping)
[7]	Physic-based, deep reinforcement learning, imitation learning	Humanoid, paddle, ball	Unity	Motion capture clips of strokes, physics of ball, reinforcement learning states
Our work	Dedicated rigging	Vehicle	Unity	Motion capture data

consideration. Significant publications analyze humanoid silhouettes, utilizing data from optical [5, 9] and inertial [16] motion capture systems. This approach resulted in high-quality and high-fidelity animations. An important improvement for humanoid silhouettes is the support of software, such as MotionBuilder or Maya with built-in interfaces that allow for the application of skeletal points to a pre-built model of joint connections for a 3D object. However, such an improvement is not available for rigid bodies, which cannot be defined by translation into a humanoid model. The animation of rigid bodies such as trees [6] are physic-based. They assume physical parameters, which, through calculations, create a simulation that animates the movement of leaves and branches. To achieve high-quality mixed animation [7] consisting of a humanoid and rigid bodies, the authors combine techniques. A major trend is the use of reinforcement learning methods, which enable object adaptation to environmental factors. This combination with physics-based animation of a ball and paddle produces reliable 3D motion animation, but requires greater integration of mixed data – physics parameters, motion capture data, reinforcement learning policies and states. Animations of vehicles, are based on simulations based on ready-made physics-based interfaces [14, 15]. An example is SUMO, used by Unity, which allows the creation of vehicle motion animations. This solution relies on a different technique than motion capture acquisition. It provides high motion fidelity, but the impact of this technique on immersion and user presence has not been compared.

Therefore, this study uses a motion capture data and dedicated 6-rig skeleton created using MotionBuilder software. It replaces the pre-built interface from humanoid silhouettes, enabling the integration of the object with the prepared 3D model, giving high possibilites of realistic representation of movement.

Methods of creating VR animations

VR animation techniques primarily rely on reproducing realistic behaviour of objects in the real world. The level of detail has a significant impact on the quality of the perceived image. Motion capture is a technology that allows for the most faithful reproduction of real-world movement, which is used not only for complex sequences such as dance moves [9], but also for achieving precise control simulation [41]. Mirroring real-world movement is often impossible using traditional animation methods, such as physics-based or keyframe animation. The use of motion capture technology is the direction chosen in the latest methods not only in animation, but also in cinematography, which proves its great importance.

Article [34] compares the use of two animation techniques: Inverse Kinematics (IK) and motion capture. Significant differences in user immersion were found based on perceived animation realism. Using a 6-question questionnaire, the authors assessed the reception of VR animation. Motion capture achieved a better result, as it allowed users to have a greater level of engagement with the animation. A subsequent publication [33] compared three VR animation technologies:

Unity Inverse Kinematic (Unity IK), Final Inverse Kinematic (Final IK) and motion capture. The created character avatars were tested by users who experienced the VR environment. The authors noted that each technique affected the level of animation fidelity, for which motion capture provides the highest result. The study showed that motion capture achieved a high score in the user study, but Final IK can also offer a similar level of sense of agency, which translates into a higher level of immersion. The examples presented in [33, 34] demonstrate the significant importance of using motion capture technology in enhancing the immersion of VR animation users. However, it's worth noting that the above-mentioned research compares the creation of animations and their impact on the immersion of humanoid objects, such as avatars and human characters. The study, presented in this paper, examines this issue from the perspective of rigid bodies, which represents elements of VR in environments, such as games, animations and simulations. Their creation methods can also significantly impact user perception and immersion, so it's worth noting that this study undertakes a novel approach: investigating the immersion and perception of rigid body animations in VR. Therefore, the research presented in this article is of great value.

Immersion in VR animations

Immersion in a virtual world is a complex concept that depends on many factors [38], including both the software to the VR environment and the techniques used to implement the virtual world. The realism of animation is associated with immersion [36], but sense of agency and factors related to faithful reproduction of behaviours in a VR are also of great importance [33, 34]. There are many techniques for assessing user immersion, based on questionnaires. The preference of a specific solution depends on the characteristics of the study and its complexity, as well as the chosen goal.

The study [35] describes a comparison of four various questionnaires. Authors utilized the survey developed by Slater, Usoh and Steed, known as SUS, Presence Questionnaire (PQ), IGroup Presence Questionnaire (IPQ), Bouchard questionnaire. These metrics analyse various aspects of presence and user perception, which is crucial for assessing the impact of animation on immersion. The IPQ was found to be the most capable of detecting differences in the virtual reality experience between various types of animation and VR environments. That is why in this study the authors decided to apply this questionnaire. However, other tools, such as the Bouchard Questionnaire or the Presence Questionnaire, may also prove useful information about assessing immersion.

CONCLUSIONS

The main aim of the study was to present an innovative approach to the production of VR animations of rigid bodies. Due to the high realism of the motion mapping, data from the motion capture system was used, which was postprocessed using tools such as Vicon Nexus and MotionBuilder. The novelty of the presented process was to create a custom rigging for the vehicle object and mapping the skeleton to the 3D model, without using pre-made mapping interfaces, which are available in graphical environments only for humanoid characters. Based on the results it could be stated that the chosen method of data acquisition and their further use in order to create 3D animations is very effective. The study enables to determine the difficulties in creating solid animations using a method based approach on data from the motion capture system. Utilized method could be perceived as an innovative approach to creating rigid body animations, not seen in the previous literature. A high realism of motion mapping was obtained, which was evaluated and confirmed by an IPQ survey.

The present study extends passive-optical motion capture science beyond articulated humanoid figures to encompass rigid-body vehicles, showing that non-articulated dynamics can be reconstructed in virtual reality with spatial fidelity comparable to the best human captures. To achieve this, the authors developed an end-to-end empirical pipeline in which a radio-controlled vehicle, instrumented with seven reflective markers and sampled at 100 Hz, is processed by a bespoke gap-filling algorithm that yields uninterrupted three-dimensional trajectories and removes the dropout artefacts that commonly afflict rigid-body tracks. Based on these trajectories the study creates a rigging of a recorded vehicle, enabling a single rigid object to inherit both rotation and translation from marker clusters and thus bridging bone-based animation methodologies with solid-body kinematics.

The influence of animation stages on user experience was tested in the ablation experiment that compared SmartPlot at two key-frame densities, an unfiltered raw-key condition and a Gimball-filtered variant, all evaluated with the Igroup Presence Questionnaire across 80 virtual-reality trials.

Quantitative psychophysical analysis shows that SmartPlot with moderate key-frame density produces the highest perceived realism (1.93 on a 3-point scale) and general presence (2.70), while excessive smoothing by the Gimball Killer, although it lowers noise, also reduces realism – evidence of an optimal rather than maximal filtering threshold. Leaving the data unfiltered decreases all presence metrics by roughly 25%, highlighting their decisive role. The performed ablation study highlighted differences in the perception of VR animation, impacted by changed plotting factors.

Research related to the animation creation suggests a variety of methods for achieving interesting visual effects. Motion capture technology enables achieving high realism of movement, thus it is often applied in the animation of humanoid figures. Utilization of this technology to rigid bodies, instead of a physics-based simulation approach, can deliver results as good as those for humanoids. Greater realism in movement translates into a better user experience and consequently, increases immersion and presence rates. This study presents a novel approach to creating realistic VR animation using motion capture technology. High realism was confirmed utilizing the IPQ questionnaire, which indicated high rates of immersion and presence in each ablation study setting.

The study involves detailed motion trajectories obtained from motion capture recordings, transforming the data into a skeleton structure and then a 3D model and verifying the results in a VR environment. This methodology is the essence of modeling and simulation in engineering, which clearly aligns with the fields of image analysis, numerical techniques, computer graphics and adaptive algorithms.

Further research could explore a wide range of innovative areas, each contributing to the evolution of animation and immersive virtual environments. One potential solution contains developing games using advanced game engines such as Unity or Unreal Engine. These powerful platforms offer robust tools for creating interactive and visually captivating virtual worlds, allowing researchers to apply dynamic animation techniques that increase user engagement and interaction. Another area is the utilization of motion retargeting processes in virtual reality, which involves adapting animations to different characters or objects, making them more realistic. Thus, researchers can create more immersive experiences by enabling avatars or in-game characters to move fluidly and naturally, responding to player input in real time. Integration of reinforcement learning to develop social agents is a direction worth considering. Social agents are virtual characters designed to interact with users in a meaningful way. They could be powered by reinforcement learning techniques. Using machine learning algorithms could improve problem-solving ability and overall interactivity, offering users a dynamic experience in virtual environments.

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All data generated during the current study are available in the repository https://github.com/anik0o/VR-animation-based-on-motion-capture-data.

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