Universität Bremen

Faculty 3: Mathematics and Computer Science

Bachelor's Thesis

Dust Devils and Dust Storms on Planet Mars
Animation and Simulation of Natural Phenomena

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Abstract

This bachelor's thesis addresses the implementation of realistic natural phenomena in the virtual Mars environment of the Valles Marineris Exploration - Virtual TestBed (VaMEx-VTB) project. This includes animated dust devils, simulated dust storms, and a simulated atmosphere. The natural phenomena are used to extend the virtual Mars environment of the VaMEx-VTB project to provide a more realistic experience in consideration of the environmental influences and to extended the test scenarios for the testing of autonomous, heterogeneous swarm behavior on Mars terrain.

Contents

1 Introduction

The introduction chapter serves as an explanatory section to highlight the motivation and goals of this bachelor's thesis and to provide an overview about its structure.
Chapter 2 contains the fundamentals and previous work.

1.1 Motivation

This thesis is written as a part of the VaMEx-VTB initiative of the Institute of Computer Graphics and Virtual Reality of the University of Bremen as a part of the VaMEx initiative of the German Aerospace Center (DLR) and the Federal Ministry of Economic Affairs and Energy (BMWi). The goal of the initiative is to provide a realistic simulation framework for the testing of autonomous, heterogeneous swarm behavior on Mars terrain. Therefore, the VaMEx-VTB provides a virtual environment that includes a realistic looking Mars terrain with rocks and caves. The motivation of this bachelor's thesis is to extend the VaMEx-VTB. This extension should consider natural phenomena like dust devils, dust storms, and an atmosphere to provide a virtual environment that includes the possible influences of these natural phenomena on the swarm behavior. Test scenarios, like the limitation of vision through a dust storm that changes the captured data of the visual sensors of a device of the robotic swarm, or the recognition of a natural phenomenon, like a dust devil as a landmark, should be included to test the reaction of the swarm and to eliminate possible errors.

1.2 Goals

The goal of this bachelor's thesis is the implementation of realistic animated and simulated natural phenomena inside the virtual Mars environment of the VaMEx-VTB project. These natural phenomena are used to extend the virtual testbed and to and provide a wider range of more realistic test scenarios for the autonomous, heterogeneous swarm behavior inside the VaMEx-VTB. This includes the animation of several dust devils by using different implementation methods. They are implemented according to the characteristics of a real dust devil, which includes the shape, look, and movement. The idea behind this is that dust devils can be recognizable as landmarks by the visual sensors of the robotic swarm inside the VaMEx-VTB, which could cause problems with the navigation. This kind of test scenario could be provided through the integration of dust devils into the virtual Mars environment. Furthermore, the different dust devil implementations are compared in a user study to gather the opinions of a wide range of participants. These collected data are used to choose the best possible dust devil implementation for the integration into the virtual testbed. The natural phenomenon dust storm is also implemented to simulate different kinds of dust storms like local, regional, and planet-encircling to extend the virtual Mars environment. Dust storms can be used inside the virtual environment to develop test scenarios like the limitation of view of a device that causes the loss of the orientation or the darkening of the sun that results in a decrease of solar polar, which is used to charge the devices. An atmosphere is the third natural phenomenon that is implemented. Floating dust particles are generated to simulate the dusty atmosphere of planet Mars in order to test the influences of dust on the sensors and mechanics of the devices of the robotic swarm.

1.3 Structure

Chapter 2 of this bachelor's thesis contains the fundamentals and previous work. This includes a detailed description of the later animated and simulated natural phenomena in section 2.1, the software and the methods used later for the implementation in the sections 2.2 and 2.3, materials, textures, and 3d models in 2.4, information about the VaMEx-VTB initiative in section 2.5, and an insight into two computer games taking place on Mars in 2.6. The following chapter 3 deals with the implementation of the natural phenomena presented in section 2.1 and their integration into the virtual Mars environment of the VaMEx-VTB. First, the implementation process of three different animated dust devils is described in section 3.1, followed by the explanation of two dust storm simulations in 3.2, and the implementation of a Martian atmosphere in section 3.3. Chapter 4 is about the conducted user study. It contains an overview of the structure of the online questionnaire in section 1.3, the presentation of the collected data in 4.2, and the analysis of these data in section 4.3. This study is mainly used to evaluate the three animated dust devils from section 3.1. The results of the thesis are summarized in chapter 5. Section 5.1 presents the outcomes of the implementation from chapter 3 and section 5.2 the findings of the user study from the previous chapter 4. To finish this thesis, chapter 6 consists of the conclusion of the thesis in section 6.1 and the ideas for future work regarding the topic of the thesis in section 6.2.

2 Fundamentals and Previous Work

The previous chapter 1 contains the motivation, goals, and overview of the structure of this bachelor's thesis. In this chapter, the fundamentals and previous work are presented. These are needed for the implementation chapter. The chapter begins with an introduction of the natural phenomena dust devil, dust storm, and atmosphere on planet Mars in section 2.1. Afterwards, the software and methods used for the implementation of the natural phenomena are listed and described in 2.2 and 2.3. This is followed by a brief explanation of materials, textures, and explicit and implicit 3D models in section 2.4. Next, the VaMEx-VTB initiative, which this bachelor's thesis is part of, is presented in 2.5. At the end of the chapter, two online computer games taking place on the planet Mars are mentioned in section 2.6.
The following chapter 3 is about the implementation of the natural phenomena. It includes three animated dust devils, two kinds of dust storms, and atmospheric dust, which is used to imitate the atmosphere of Mars.

2.1 Natural Phenomena

In the first section of chapter two, an overview of the natural phenomena, which are implemented in chapter 3, is given. This includes dust devils in section 2.1.1, dust storms in section 2.1.2, and atmosphere in section 2.1.3. Because experiments and observations regarding these natural phenomena on Mars are rare and expensive, the amount of provided information is limited. Therefore, information about the same natural phenomena on Earth can be used to complement the knowledge, if the differences between the planets are considered. To underline these differences, a short comparison of Mars and Earth is provided in 2.1.4.
Section 2.2 includes brief explanations of the software used in the practical part of the thesis.

2.1.1 Dust Devils

In this section, information about dust devils on planet Mars and Earth like wind speed, height, and shape is provided. Furthermore, a list that summarizes important characteristics of a dust devil is attached in 2.1.1.1. This list is used for the implementation of animated dust devils in section 3.1. The next natural phenomenon dealt with in this chapter is dust storms in section 2.1.2.

Figure 2.1 A large dust devil in the desert near Eloy, Arizona - credit: (NASA 2005)

In accordance with Balme and Greeley dust devils are defined as small whirlwinds made visible by whirled up dust and sand, in other words, particle-loaded vertical convective vortices (Balme and Greeley 2006). Similar definitions can be found in the work of Singh (Singh 2019) and Horten et. al. (Horton et al. 2016). They form when the ground and the air close to the surface get heated up through insolation, which causes the spiral, convective rising of air into the atmosphere. This results in a swirling helical structure. On earth, dust devils occur mostly in hot, flat or sandy areas. For example in the desert near Eloy, Arizona, as it can be seen in figure 2.1. These regions offer the best conditions for a strong insolation, like being arid, with less trees or buildings, having a lot loose surface material and maybe even a gentle slope (Balme and Greeley 2006). As the surface of the planet Mars and its climate conditions are similar to those in the desert landscapes on Earth, these conditions are fulfilled.

The shape of dust devils can vary from tall and thin to wide and short. In general, according to Balme and Greeley, most dust devils are five times higher than wide, have a higher particle density near the ground than in the higher regions, start narrow at the ground and get broader at the top, and some have a defined columnar core, which can tilt towards the direction of motion (Balme and Greeley 2006). Balme and Greeley divided the structure of a typical dust devil, as they call it, into three parts. The first part is called vortex boundary layer, which is located close to the ground. It has a high particle density, thanks to the turbulent inflow of loose surface material towards the center of the dust devil. The second part of a dust devils' structure describes the column of rotating dust and defines the general shape and look of the whirlwind. Different to the second part, showing just a little exchange of dust between the columnar core and the surrounding air, at the top of the dust devil the material gets expelled into the atmosphere. This is where the spiral flow dissolves and the rotation speed lessens, marking the visible height of a dust devil. A picture of a dust devil on planet Mars can be seen in figure 2.2, taken by the rover 'Spirit'.

Figure 2.2 A dust devil on Mars photographed by the rover 'Spirit' on sol 486 - credit: (NASA 2005)

Compared to those on the Earth, dust devils on Mars show larger dimensions. They can have a diameter up to one kilometer and an altitude up to ten kilometers according to Singh (Singh 2019). This fact is supported by information provided by the European Space Agency (ESA). The ESA has recorded dust devils tracks that are hundreds of meters wide and a few kilometers long on the red planet (European Space Agency 2019). Dust devils with these dimensions could possibly lift as much loose surface material as a Martian global dust storm at its peak. This is also caused by the differences in atmosphere between the Earth and Mars. As the atmosphere on planet Mars is thinner than the one on Earth, the dust and sand can be lifted higher into the atmosphere and carried further. More information about the atmosphere of the Mars is provided in chapter 2.1.3. On Earth, dust devils normally don't pose a big risk and their destructive power is rated relatively low. The biggest problem is usually the air quality in dry regions, worsening through dust devil activity (Balme and Greeley 2006). Even if the dust devils on Mars are significantly bigger with a high wind speed about 100 m/s, according to Balme and Greeley, the destruction power is reduced because of the thin atmosphere. They could possibly pose a risk to the robotic devices of a swarm exploration, because of high dust loads, which could cause a limitation of view, or if the huge potential gradients of terrestrial dust devils also occur on Mars, which could result in problems with their electricity.

2.1.1.1 Characteristics of a Dust Devil

The following list summarizes the characteristics of a dust devil, to provide an orientation for the implementation of this phenomenon. Dust devils:

-are particle-loaded vertical convective vortices, made visible by whirled up dust and sand (Balme and Greeley 2006)
-develop through spiral, convective rising of the air (Singh 2019)
-have a swirling helical structure (Horton et al. 2016)
-own a vortex boundary layer, which causes a higher particle density near the ground (Balme and Greeley 2006)
-have a shape that starts narrow at the ground and gets broader at the top (Balme and Greeley 2006)
-look like a column of rotating dust tilting towards the direction of motion(Balme and Greeley 2006)
-loose their rotation speed at the top, where the rotation dissolves and the particles get expelled into the atmosphere (Balme and Greeley 2006)
-have a body that is about five times higher than wide (Balme and Greeley 2006)

2.1.2 Dust Storms

After the description of dust devils in the previous section 2.1.1, this paragraph contains an overview of dust storms on planet Mars. This includes the reasons for the development of dust storms, the dimensions they can reach and their effects on the atmosphere. Some of the information provided is based on facts about dust storms on Earth, because of the amount of information available about dust storms on Mars. Compared to dust devils, dust storms differ mainly in extension and shape.
In the next section, 2.1.3, the atmospheric conditions of the red planet are summarized.

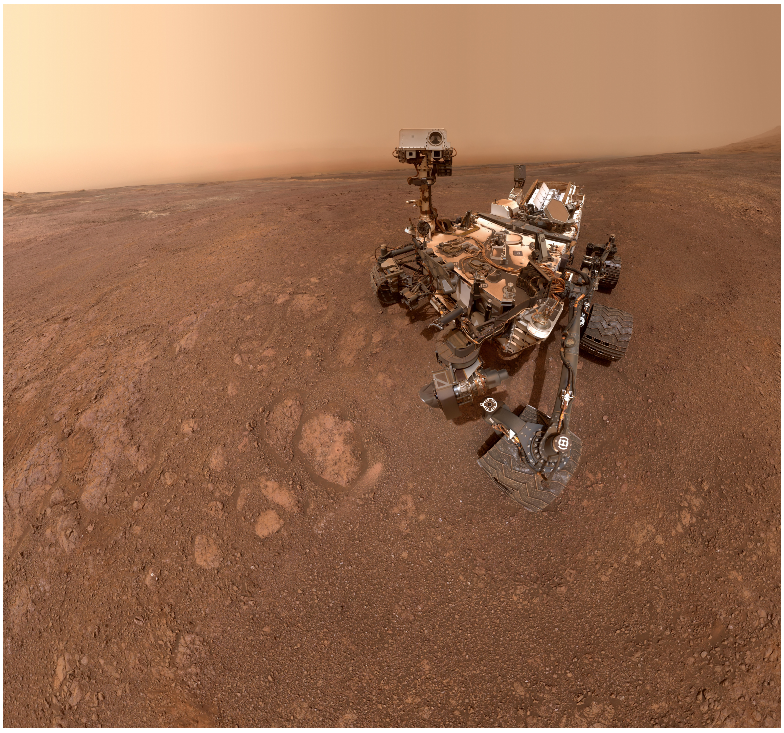


Figure 2.3 Mars rover 'Curiosity' in front of a dust storm, January 2019 - credit: (NASA/JPL-Caltech/MSSS 2019)

The thin and dusty atmosphere of planet Mars aids the development of dust storms. Thanks to the thin atmosphere, dust is lifted easily into the air. The dust, in turn, influences the circulation of the atmosphere, because the dust particles absorb solar radiation and cause the surrounding air to warm up. This supports the development of enhanced temperature gradients resulting in increased local circulation, which leads to stronger winds and even more dust that is lifted into the atmosphere (Cantor, James, et al. 2001). The result is dust storms, like the one visible in the back of the picture of the Mars rover 'Curiosity' in figure 2.3.

Dust storms can vary a lot regarding size and duration. Cantor and Pickett divide the dust storm activity on planet Mars into local and regional dust storms. Local ones last for up to three sols and cover up to 1.6x106 square-kilometers surface areas. Whereas, regional storms last more than three sols and cover more than 1.6x106 square-kilometers surface areas (Cantor, Pickett, et al. 2018). In the article 'The origin, evolution, and trajectory of large dust storms on Mars during Mars years 24–30', Wang and Richardson provide a similar classification, but they add planet-encircling dust storm as a third category (Wang and Richardson 2015). According to them, large regional and global dust storms are categorized as large-scale dust storms. These could last for weeks or months and exert a significant influence on the global atmospheric structure and circulation on Mars. Global planet-encircling and large regional dust storms arise from a union of local and small regional dust storms (Cantor 2007). One reasons for this kind of aggregation of many dust storms are dust storms that occur repeatedly on the same route and cause the affected region to stay dusty. Another reason can be one dust storm that influences the circulation of its border regions, which in turn increases the circulation till another dust storm develops, causing the development of more and more dust storms. Also, two storms that started independently and merge with each other can be an origin (Wang and Richardson 2015).

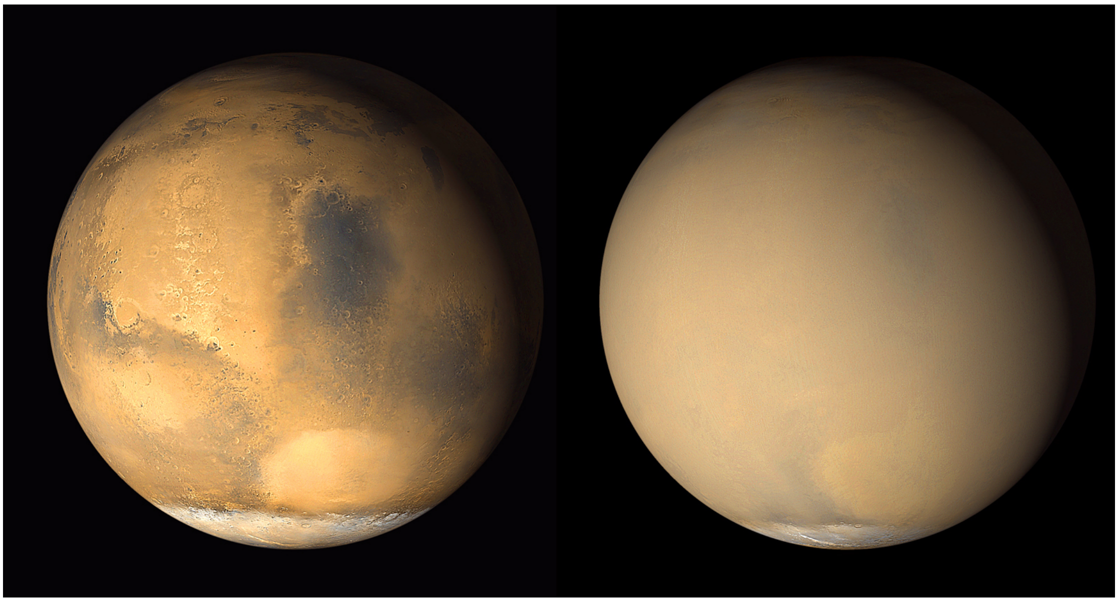


Figure 2.4 The 2001 great dust storms, Hellas/Syrtis Major - credit: (NASA/JPL-Caltech/MSSS 2018)

An example for a planet-encircling dust storm is the Martian global dust storm from 2001. Figure 2.4 shows Mars under mostly clear conditions on the left and the planet being enveloped by the dust storm on the right. It resulted from a series of local dust storms, which generated a dust cloud reaching sixty kilometers above the surface of mars and covering both hemispheres.

The storm disturbed the seasonal weather patterns by influencing the dust storm and dust devil activity and caused a warming of the atmosphere (Cantor 2007).

In general, it should be differentiated between dust storms and dust clouds. Zurek and Martin classify clouds as well-defined clouds or hazes without motion or expansion. Storms are characterized through movement (Zurek and L. J. Martin 1993). Cantor goes more into detail by describing a dust cloud as a visible body of dust particles floating in the air of an unknown density, which can vary in its extension from a discrete layer to a height of more than seventy kilometers. Dust storms, in turn, are defined as a moving atmospheric disturbance, which lifts loose surface material, like dust and sand, up into the atmosphere, forming a dust cloud (Cantor 2007). According to Cantor, it is not possible to differentiate between these two types of dust clouds from an orbital view.

2.1.3 Atmosphere

After the dust devils in section 2.1.1 and dust storms in 2.1.2, this section provides information about the atmosphere of Mars. It differs from the one of the Earth especially in the atmospheric pressure and its chemical composition.
More differences between Earth and Mars are outlined in the following section 2.1.4.

The Martian atmosphere consists of 95.32% CO2, 2.7% N2, 1.65% Ar and 0.13% O2. Mars is commonly known as the red planet, because of the amount of dust in its atmosphere and the presence of Fe2-O3 (Cantor, James, et al. 2001). Next to light-scattering properties, dust also absorbs solar radiation. That influences the temperature of the atmosphere, supports local gradients and enhances atmospheric circulation. This could lead to the development of dust storms, as already mentioned in the previous section 2.1.2 (Tomasko et al. 1999). The amount of dust in the atmosphere could also influence vision, depending on the opacity and optical depth. This is shown in figure 2.5, where a series of images simulates the possible changing of the view of NASA's rover 'Opportunity' during the dust storm in 2018 according to the increasing measures of dust opacity (T. Z. Martin 1994).
Other characteristics of the Martian atmosphere is the low atmospheric pressure of about 6.5 mbar, which is less than 1% of the pressure on Earth. In combination with the temperature gradients, the pressure gradients boost the local and regional circulation of the atmosphere. This, in turn, could lead to increased wind speeds and more dust, that gets lifted into the atmosphere. Then again, dust increases the circulation through solar radiation. This proves the important role of the dust in the circulation system of Mars (Cantor, James, et al. 2001).

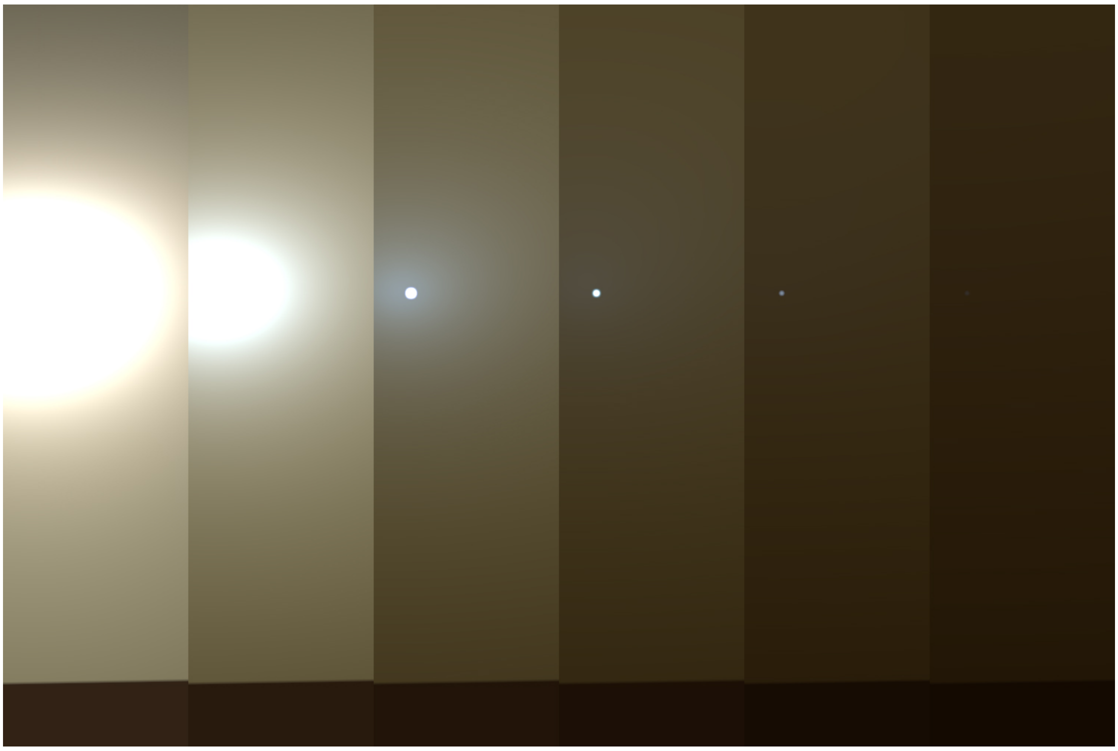


Figure 2.5 This series of images shows simulated views of a darkening Martian sky blotting out the sun from NASA's Opportunity rover's point of view. Each frame corresponds to a measure of opacity: 1, 3, 5, 7, 9, 11 (from left to right) - credit: (NASA/JPL-Caltech/TAMU 2018)

2.1.4 Differences between Earth and Mars

In the previous section 2.1.3, some information about the atmosphere on planet Mars is provided, which already show some significant differences compared to Earth. These kinds of differences are further discussed in context with the afore mentioned natural phenomena.
The next section of the fundamentals and previous work chapter, 2.2, is about the software which was used for the implementation in chapter 3.

An important difference between Mars and Earth is the duration of a day. One Mars day, called sol, lasts 24 hours, 39 minutes and 35 seconds. Because the Mars is further away from the sun than the earth, it needs more time to circle the sun. This is why one Mars year has six-hundred-sixty-nine sols, which is equal to six-hundred-eighty-seven days on Earth. Furthermore, the red planet has only 28% of the surface of the Earth. About two thirds of it is made up of mountains and craters, including huge volcanoes. The other third of Mars' surface is made up mostly of plains (Carr 2007).

As mentioned before, a dust devils' size is one of the biggest differences between Earth and Mars. On Mars, a dust devil can reach up to a few kilometers altitude with a diameter of up to several hundred meters. On Earth, a dust devils' diameter, in general, is about one-hundred meters and reaches a height about five times the diameter (Balme and Greeley 2006). In addition, the regions of the Mars where dust devils occur are often rough, whereas the most active dust devil areas on Earth are hot, flat surfaces.

Unlike dust devils, the characteristics of dust storms are similar on both planets. For example, the main seasons for dust storms on Earth and Mars are spring and summer, the dust in the atmosphere can cause changes in the temperature, because of the reflected sunlight, and a dust storm can cause reduced visibility (Ghosh and Pal 2014). The biggest difference is that the global dust storms, which cover both hemispheres, only occur on planet Mars (Wang and Richardson 2015).

The atmospheric pressure on Mars is less than 1% of the pressure on Earth. Another significant difference of the atmosphere is its chemical composition. On earth, dry air contains 78.09% nitrogen, 20.95% oxygen, 0.93% argon, 0.04% carbon dioxide, and small amounts of other gases (Ahrens 2012). The atmosphere on Mars consists of 95.32% carbon dioxide, 2.7% dinitrogen, 1.65% argon, and 0.13% oxygen (Cantor, James, et al. 2001). Oxygen has a natural occurrence on Earth that is more than one-hundred-fifty times higher than on Mars.

2.2 Software

The first section of chapter two, 2.1, provided a brief introduction into the different natural phenomena, which are realized in chapter 3.

This section deals with the software used for the implementation, further explained in chapter 3. It includes an introduction into 3ds Max in section 2.2.1, Blender in section 3.1.2, and Unreal Engine 4 in section 2.2.3. 3ds Max is a 3D modeling and animation software, mostly used in the fields of design and architecture (Autodesk Inc. 2019). The 3D creation software Blender offers features for 3D modeling, animation, and simulation, for example in game development and film making (Blender Foundation 2019). Unreal Engine 4 is known as a game engine used inter alia for material editing, simulation, visual effects, and animation, especially in the field of game development (Epic Games 2019). Additionally, Unreals' particle editor Cascade and Blueprints are presented in the sections 2.2.3.1 and 2.2.3.2.

In the following section 2.3 the methods used for the implementation of the natural phenomena are described.

2.2.1 3ds Max

The first software tool to be introduced is the 3D modeling and animation software 3ds Max (Autodesk Inc. 2019). For this thesis the student version of 3ds Max was used. This paragraph contains an overview of the developer, the most important features, and the provided file formats, as well as a screenshot of the user interface in figure 2.6.
Afterwards, the 3D creation software blender is presented in 2.2.2.

3ds Max is used as a 3D modeling and animation tool and was developed by Autodesk Inc. It offers an education license for free use for students. Its main features include splines, quarder maps, fase-modification, fluid generation, motion paths, rigging tools, animation tools, particle effects, and rendering tools. 3ds Max can among others be used for design visualization, 3D animation and dynamic, 3D modeling, texturing, 3D rendering, game design, visual effects, and virtual reality design. Thanks to this wide rage of functions, this software is used in game design, film making, graphic design, visual effects design, and in architecture for example. 3ds Max works with a build-in scripting language called MAXscript and is available for the operating system of Windows.

It supports the following file formats:

for import: .fbx, .3ds, .prj, .abc, .ai, .catpart, .catproduct, .cgr, .dae, .dem, .xml, .ddf, .dwg, .dxf, .flt, .htr, .ige, .igs, .iges, .ipt, .iam, .jt, .model, .mdl, .session, .exp, .dlv, .dlv3, .dlv4, .obj, .prt, .neu, .g, .asm, .prt, .rvt, .sat, .shp, .skp, .sldprt, .sldasm, .stl, .step, .trc, .wire, .wrl, .wrz, .xml,

for export: .fbx, .3ds, .abc, .ai, .ase, .ass, .dae, .dwf, .dwg, .dxf, .flt, .htr, .igs, .obj, .pxproj, .sat, .stl, .svf, .wrl.

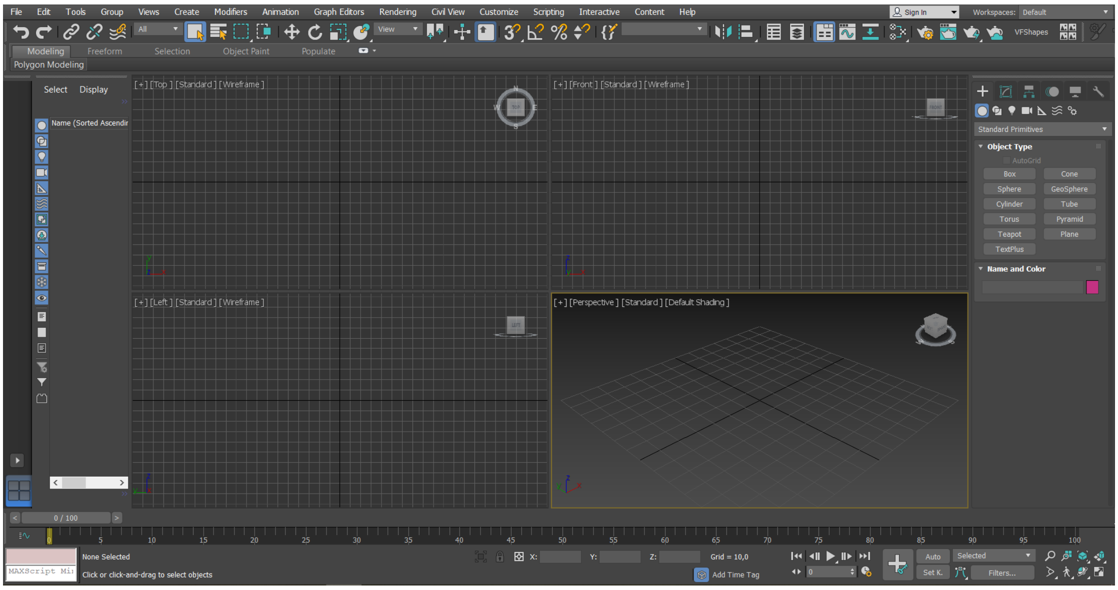


Figure 2.6 User interface of 3ds Max 2019

2.2.2 Blender

A similar introduction as into the 3D modeling and animation software 3ds Max before in section 2.2.1 is given for the 3D creation software Blender (Blender Foundation 2019). In addition to the information like the developer, features of the software, and fields of use, a screenshot of the user interface is shown in figure 2.7.
The game engine Unreal Engine 4 is presented in the following section 2.2.3.

The developer of the free and open source 3D creation suite Blender is the Blender Foundation. For this thesis version 2.81 is used. The main features are real-time view port preview, CPU & GPU rendering, PBR shaders, high dynamic range (HDR) lighting support, virtual reality (VR) rendering support, full N-Gon support, sculpting tools, 3D painting, Python scripting, camera reconstruction, real-time preview, auto & manual tracking, b-spline interpolated bones, curve editor, and onion skinning. Blender is normally used in fields like visual effects (VFX), animation, game development, and modeling, for example for modeling, rigging, sculpting, scripting, simulation, rendering, compositing, motion tracking, and video editing. The 3D creation tool supports various platforms, like Windows, Linux, macOS, Solaris, FreeBSD, and IRIX, and uses Pyhton, C, and C++ as programming languages.

Supported by Blender are the following file formats:

for import: .dae, .abc, .fbx, .bvh, .ply, .obj, .x3d, .wrl, .stl, .svg, .glb, .gltf,

and for export: .dae, .abc, .fbx, .bvh, .ply, .obj, .x3d, .wrl, .stl, .svg, .glb, .gltf.

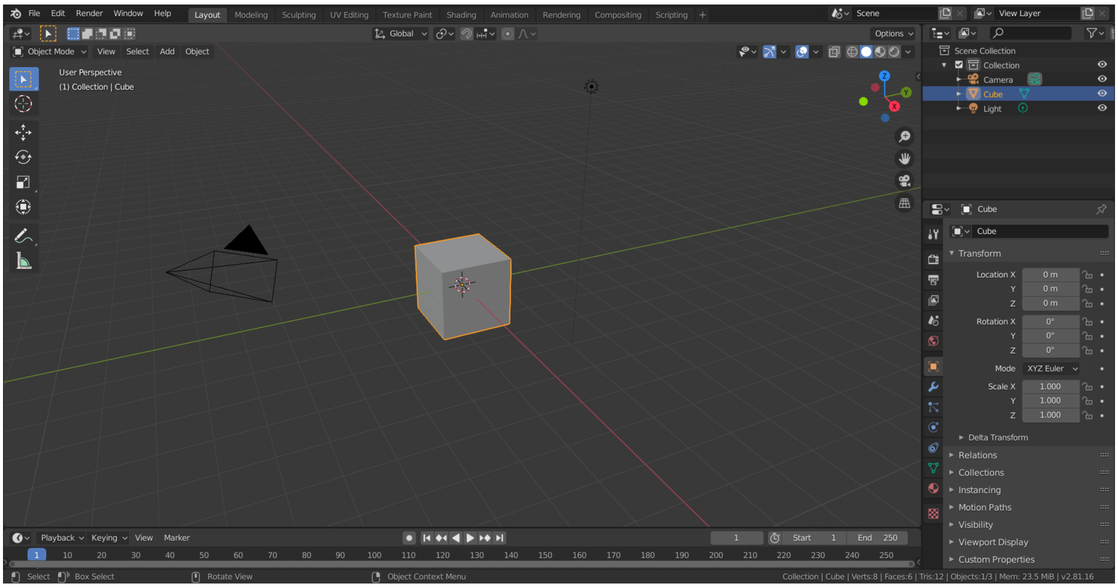


Figure 2.7 User interface of Blender 2.81

2.2.3 Unreal Engine 4

The last software tool to be presented is the game engine Unreal Engine 4. An overview of 3ds Max and Blender are already provided in 2.2.1 and 3.1.2. Information like the features, supported platforms, and file formats of Unreal Engine 4 are summarized in the following paragraph. Additionally, Unreals' particle editor, Cascade, and Blueprints, the gameplay scripting system used in the engine, are introduced. For this thesis, version 4.23 of Unreal Engine 4 is used. A screenshot of its user interface can be found in figure 2.8.
In the next section of the fundamentals and previous work chapter, 2.3, the methods used for the implementation of the natural phenomena in chapter 3 are described.

Developed by Epic Games, Unreal Engine 4 is available to everyone for free as long as commercial sales do not exceed $3000. It supports a big range of platforms, for example Windows, Linux, SteamOS, macOS, PlayStation (2, 3 und 4), Xbox (360 und One), Android, Dreamcast, iOS, Nintendo Switch, webOS, tvOS, WebGL, HTML5, WebAssembly, Google Native Client, and Windows Mixed Reality. The game engine is used in fields like game development and film making, architecture, automotive and transportation, broadcast and live events, and training and simulation. Unreal Engine 4 offers features like C++ source code & Python scripting, a multiplayer framework, photo-realistic rendering in real time, blueprints, VR & AR & MR experiences, a material editor, post-process effects, simulation and visual effects, artificial intelligence (AI), an editor in VR mode, an animation toolset, an editing and animation tool, an audio engine, perforce integration, and terrain & foliage building. A detailed overview of the supported software and file types can be found in the documentation (Epic Games, Inc. 2020b). Furthermore, does it use the programming languages C++ and the build-in Blueprint Visual Scripting system, mentioned in detail in 2.2.3.2.

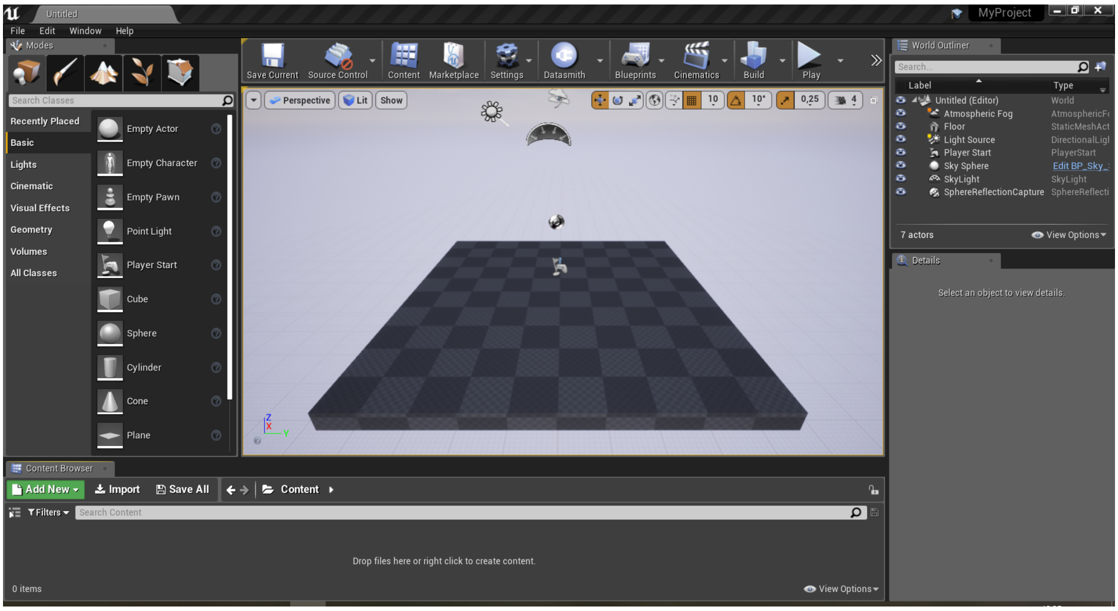


Figure 2.8 User interface of Unreal Engine Version 4.23.1

2.2.3.1 Cascade

Cascade is the integrated, modular particle effects editor of Unreal Engine 4. It is used for the creation of visual effects like smoke, sparks, and fire, the creation of CPU-, GPU- and mesh-based particle systems, beam, and ribbon particles (Tavakkoli 2015). Features like real-time feedback and modular effects editing offer a fast and easy way to create complex visual effects. While material and texture mostly decide the look of the particles, the particle system is responsible for the behavior of the particles. A screenshot of Cascades' user interface is provided in figure 2.9.

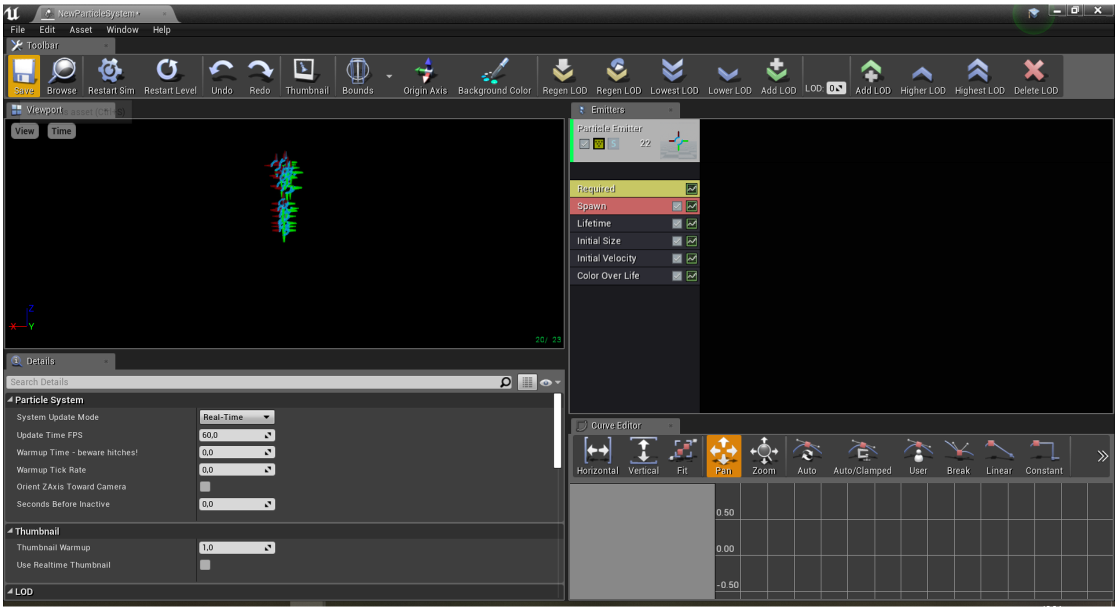


Figure 2.9 User interface of Cascade - Unreal Engine 4.23.1

2.2.3.2 Blueprint Visual Scripting

The gameplay scripting system, blueprint visual scripting, works with a node-based interface, which is used to create gameplay elements, define object-oriented classes or objects, and to create customizable prefabs with construction scripts, playable game characters, and head-up displays. Level blueprint, blueprint class, data-only blueprint, blueprint interface, and blueprint macro library are among the different blueprint types.

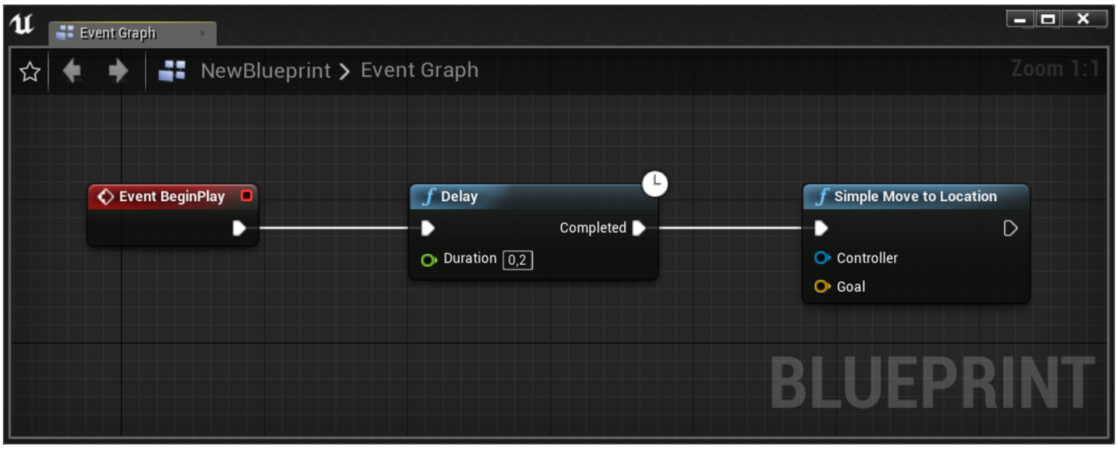


Figure 2.10 Blueprint example of an actors' event graph - Unreal Engine 4.23.1

A big advantage of blueprints is that no coding skills are needed to use the powerful blueprint editor. Samples and tutorials are available in the documentation of Unreal Engine 4 (Epic Games, Inc. 2020a). By connecting nodes, events, functions, and variables with wires, behavior and other functionalities can be implemented. An example of an event graph is shown in figure 2.10. A disadvantage of the blueprints is, that they can't be transferred to other engines or software tools. Another disadvantage comes up with the increasing complexity of a blueprint, because it gets harder to follow the graph node. To give a short overview of the different node types, the most important colors are explained in figure 2.11. A summary of the color code of the variables is provided in figure 2.12.

Color	Type
Red	Event node: events are nodes that are called from gameplay code to begin the execution of an individual network within the event graph
Green	Pure function node: usually associated with get[something]
Blue	Function node: if it's a function a 'f' icon is placed in the nodes header, for an event node, an arrow is placed instead
Purple	Node can't be deleted, this type is found in the construction script or in functions
Gray	Macro, collapsed, or flow control node
Cyan	Cast node

Figure 2.11 Color code of the node types of the blueprint visual scripting - Unreal Engine 4.23.1

Color	Maroon	Sherpa blue	Sea green	Moss green	Yellow green	Mauve	Magenta	Pink	Gold	Cornflower blue	Orange	Blue
Type	Bootlean	Byte	Integer	Integer64	Float	Name	String	Text	Vector	Rotator	Transform	Object

Figure 2.12 Color code of the variables of the blueprint visual scripting - Unreal Engine 4.23.1

2.3 Methods used for the Implementation of the Natural Phenomena

After the presentation of the software tools in the previous section 2.2, the methods that are needed for the implementation of the natural phenomena in chapter 3 are explained. These methods include vector fields in section 2.3.1, fluid simulation in 2.3.2, particle systems in 2.3.3, and exponential height fog in 2.3.4.
The next section 2.4 of the fundamentals and previous work chapter provides an overview of

materials, textures, and 3D models.

2.3.1 Vector Fields

Vector fields are the first method of the methods used for the implementation of the natural phenomena that is described. Two vector fields are used in the implementation of the dust devils, later in section 3.1.1.1.
It is followed by fluid simulation in section 2.3.2.

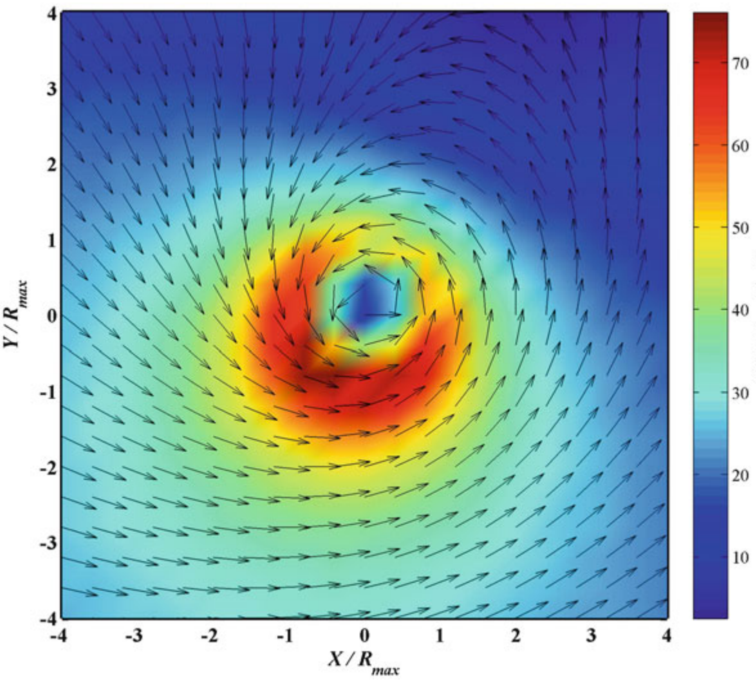


Figure 2.13 Wind vectors and isotachs representing a wind velocity field of a tornado - credit: (Peng et al. 2016)

A vector field offers the possibility to allocate a vector to every single point in a defined space (Königsberger 2004). These vectors are represented by arrows placed at a regular distance inside the space. The length of the arrow defines its strength. Vector fields can be used in many different ways. For example, to describe flow directions and the speed of fluids to visualize the local flow direction (Peng et al. 2016). Another example are vector fields as a part of weather maps to describe the strength, speed, and the direction of the wind as shown in figure 2.13. Also magnetic and gravitational force can by described with a vector field.

For this thesis, the vector fields are used to influence the behavior of particles in a particle system. Therefore, each vector assigns a direction and speed to a specific point inside the particle system.

2.3.2 Fluid Simulation

After vector fields in the previous section 2.3.1, fluid simulation is presented in this paragraph. This method is used for the implementation of one of the dust devils in section 3.1.2.
The next method used for the implementation of the natural phenomena are particle systems in section 2.3.3.

There are many different ways to implement fluids like water, smoke, or fire. One of them is fluid simulation. In the following implementation chapter 3, the 3D creation software Blender is used for the fluid simulation. An example of a fire simulation in Blender is provided in figure 2.14. This is why the focus of this paragraph lies on the Lattice Boltzmann method (LBM), which the Blender fluid simulation is based on. Other methods used for fluid simulation are the Smoothed Particle Hydrodynamics method, Euler equations or Navier-Stokes equations.

Figure 2.14 Example of a fire simulation in Blender - credit: (Blender Foundation 2020)

The LBM is based on a numeric flow simulation. This is a numerical simulation of a time-, space-, and velocity-discrete Boltzmann-type equation (Bernsdorf et al. 2003). The basic idea of the LBM is the construction of simplified kinetic models. Special about the LBM is that its convection operator in phase space is linear. Other differences to other numeric simulations are that the pressure is calculated by using an equation of state and that the LBM uses a minimal set of velocities in phase space (Chen and Doolen 2003). An important advantage of the Lattice

Boltzmann method is the low computing and storage demand for each cell. This offers a cheap and easy way to calculate the thermodynamic processes of fluids and solid objects.

2.3.3 Particle Systems

In the previous section 2.3.2 fluid simulation is introduced. The third method used for the implementation in chapter 3 are particle systems. These are later used for the implementation of the natural phenomenon dust devil in 3.1.
In the next section, 2.3.4, information about exponential height fog, a tool of Unreal Engine 4, is provided.

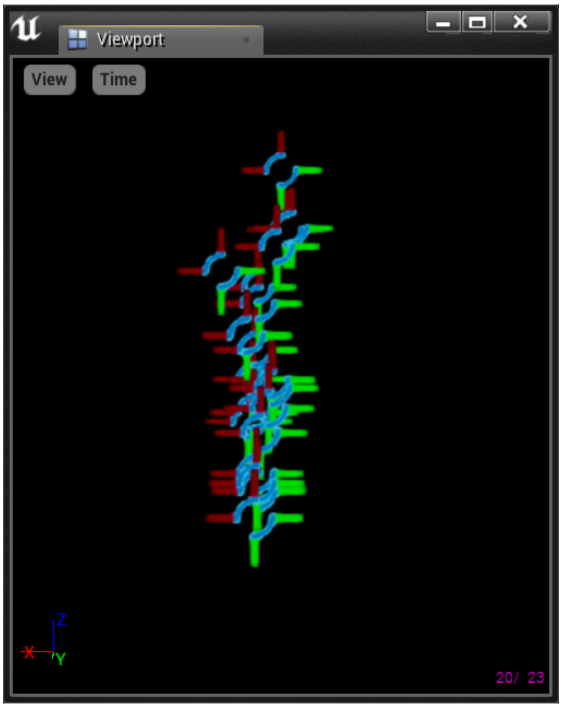


Figure 2.15 Default particle system - Unreal Engine 4.23.1, Cascade

Similar to fluid simulations, particle system can be used to create real-time effects, also called fuzzy objects, like water, fire, or smoke (Reeves 1983). A particle system consists of 3D points in a 3D space. Its attributes, like position, speed, movement, and color, are mostly declared as vectors. Particles aren't static because they are generated into the particle system where they move, change and die as if they where going through a life cycle (Lander 1998). The emitter is the source of the particles, it controls the global settings, such as the number, size, lifetime, direction of movement, and speed of the particles (Lachner and Vorderleitner 2017). To provide a short impression of how a particle system could look, figure 2.15 shows a default particle emitter inside Cascade (2.2.3.1), the particle editor of Unreal Engine 4.

2.3.4 Exponential Height Fog

After particle systems in the previous section 2.3.3, the last method used for the implementation of the natural phenomena that gets presented is the exponential height fog. This section is than extended with a short overview of the volumetric fog settings. Exponential height fog and volumetric fog are used for the implementation of the dust devils in section 3.1 and dust storms in 3.2. Information provided in this section is based on the documentation of Unreal Engine 4 (Epic Games, Inc. 2020c).
The next section of this chapter, 2.4, is about materials, textures, and 3D models.

Figure 2.16 Example scene of exponential height fog with volumetric fog enabled - credit: (Epic Games, Inc. 2020c)

In general, fog effects are used to add ambiance to a scene. Unreal Engine 4 supports exponential height fog. If integrated into an environment it creates a fog with a higher density in the lower areas that gets thinner the higher it goes. Next to parameters like density and height fog offset, also the maximum fog opacity or the start distance, which controls the distance between the camera and the beginning of the fog, can be adjusted. Furthermore, the exponential height fog provides two different fog colors. The color depends on the directional light. An example scene of an environment with exponential height fog integrated can be seen in figure 2.16. Additional to the default exponential height fog, volumetric fog can be enabled in its settings to compute participating media density and lighting at every point in the camera frustum so that varying densities and any number of lights affecting the fog can be supported.

2.3.4.1 Volumetric Fog

By checking the box inside the exponential height fog settings, the volumetric fog can be enabled. Below the checkbox, the properties of the volumetric fog that control things like the light scattering distribution, the extinction scale, or the view distance globally in the scene can be found. Additional settings are available in the settings of the light source of the scene. The volumetric inscattering intensity controls how much light contributes to the volumetric fog.

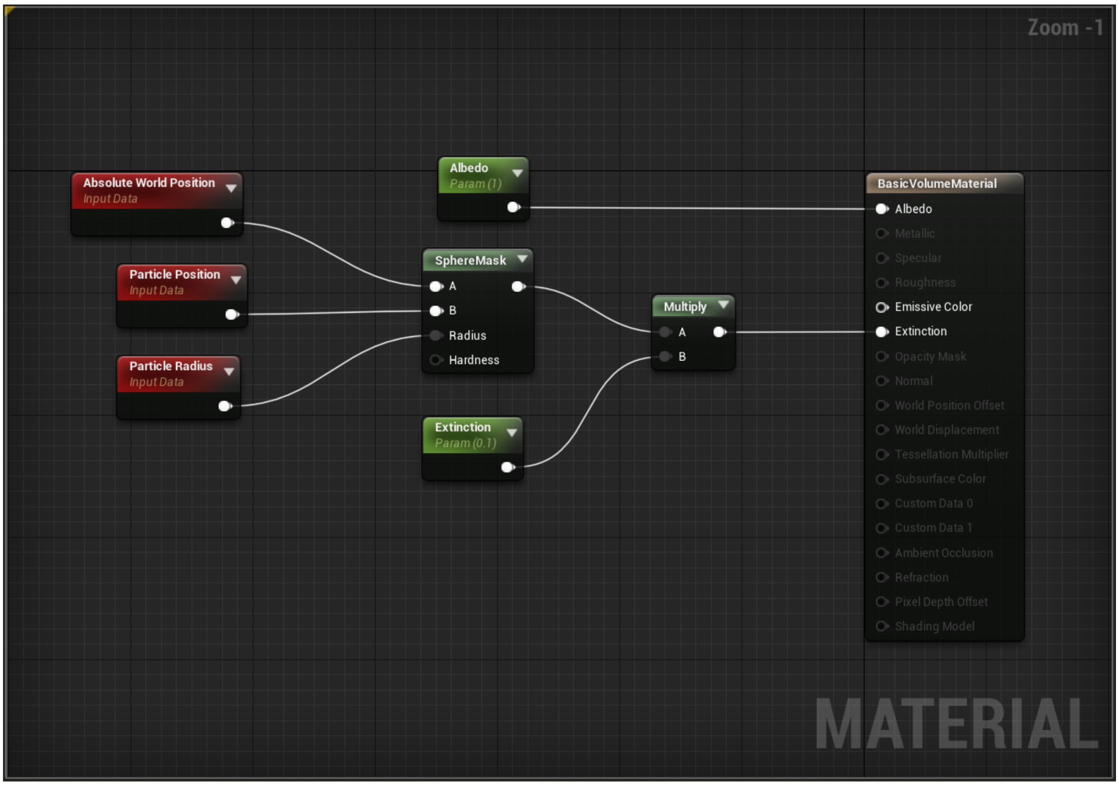


Figure 2.17 Screenshot of a basic volume material for local control of volumetric fog - Unreal Engine 4.23.1, Material Editor

To control the volumetric fog locally, a particle system with an applied volume material is needed. An example of a basic volume material is shown in figure 2.17. The albedo, emissive, and extinction settings of a volume material can be used to add a sphere of density to the volumetric fog by influencing the local fog settings through the particle system. This effect is fully three dimensional and makes the area of the particle system look like an independent fog cloud like the one in figure 2.18.

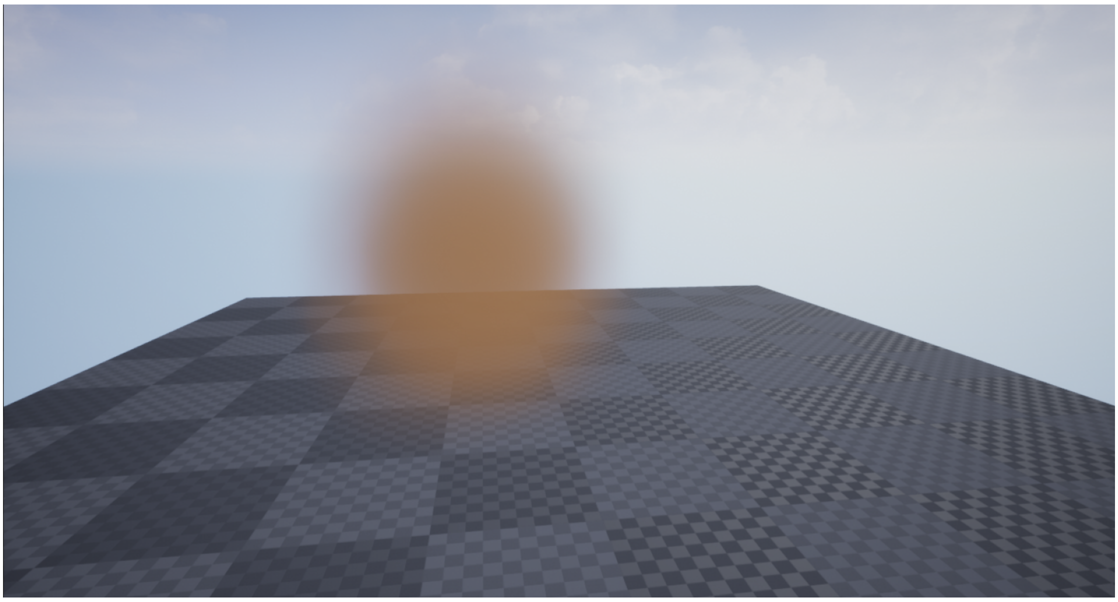


Figure 2.18 Screenshot of a particle system using a basic volume material for local control of volumetric fog - Unreal Engine 4.23.1

2.4 Materials, Tetxures and 3D Models

The last section, 2.3, included a brief introduction of the methods used for the implementation of the natural phenomena dust devil, dust storm and atmosphere. This section provides information about materials in 2.4.1, textures in 2.4.2, and 3D models in 2.4.3.
Then, an overview about the VaMEx-VTB initiative is given in section 2.5.

2.4.1 Materials in Unreal Engine 4

The first part of this section is an overview of materials, especially materials in Unreal Engine 4. Later these materials are used for the implementation of the natural phenomena in chapter

3. After a brief introduction, detailed information about the properties and inputs used inside the material editor is provided in the subsections 2.4.1.1 and 2.4.1.2. This section is based on the documentation of Unreal Engine 4 (Epic Games, Inc. 2019a). As the documentation of the materials isn't yet updated to the version 4.23, which was used in this work, there could be some differences in settings and properties.
The following section 2.4.2 is about textures and their use in the game engine.

A material defines the look of an object. The simplest explanation of materials is that a material has the same function as color or wallpapers. Because, just like color or wallpapers it gives an object another paint or imitates a structure. In addition to color, materials are also used to define properties such as shininess or transparency of an object. It calculates how the light that hits a surface, interacts with that surface.

In Unreal Engine 4, materials are constructed with visual scripting nodes (2.2.3.2) within the material editor. An example of a basic black material with a black color node applied to its base color input is shown in figure 2.19. Each material owns a list of properties that can be manipulated, after selecting the main material node, according to the wanted result. Changing the properties leads to changes of the inputs of the main material node. To apply a material to an object in Unreal Engine 4, it can be chosen in the material slot of a mesh.

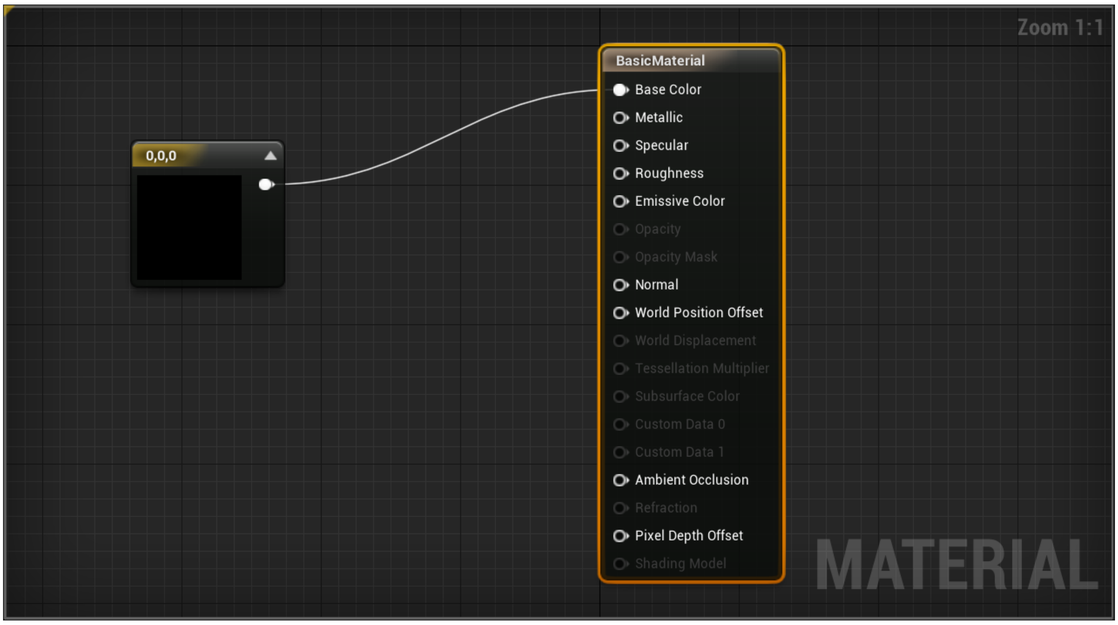


Figure 2.19 Basic material with the color black applied as the base color - Unreal Engine 4.23.1, Material Editor

2.4.1.1 Properties

As shown in figure 2.20, the properties of a material in Unreal Engine 4 are accessible inside the material editor. To provide a basic knowledge about materials some of the properties are explained in detail.

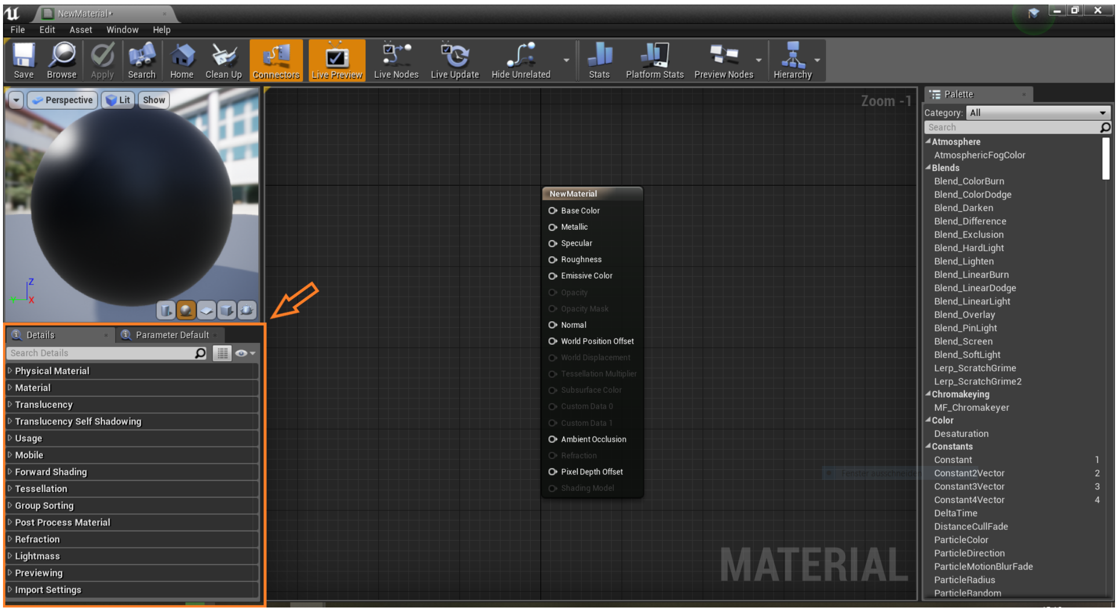


Figure 2.20 User Interface of the material editor - Unreal Engine 4.23.1

The physical material settings have no influence on the appearance of a material. Instead, they are used to define its physics properties. In the material tab, the material domain is listed as a property. It designates how the material will be used and includes the options surface, deferred decal, light function, post process, volume, user interface, and virtual texture. Choosing surface, for example, makes the material usable on an objects surface, while a volume material domain can be applied to a particle system to generate a local fog cloud inside a scene. Certain material functionalities are therefore only valid in certain domains. The blend mode property controls the interaction of the current material with the background, or, in other words, how the material will be processed with the destination color that is already saved in the frame buffer. A translucent blend mode, for example, could result in a transparent material, according to the value of opacity. Other blend modes are opaque, masked, additive, and modulate. The property shading model defines how material inputs are combined to result in the final color. More available properties of a material are translucency, translucency self shadowing, usage, mobile, forward shading, tessellation, group sorting, post process material, refraction, lightmass, previewing, and import settings.

2.4.1.2 Inputs

The inputs of the main material node change according to the settings in the properties. For example, with the material domain set to surface, blend mode set to translucent, and the shading model chosen as unlit the available inputs are emissive color, opacity, world position offset, and refraction. In this paragraph the inputs important for the implementation of the natural phenomena are described.

Setting the albedo of a material defines its overall color. Each color channel has a value set between zero and one. The emissive color input controls the glowing of a material, which means that parts of the material emit light. To define the glowing parts, normally a masked texture is applied. Depending on the value the opacity input receives, the transparency of a material is set. The extinction input also controls the translucency.

2.4.2 Textures in Unreal Engine 4

After the introduction into materials in 2.4.1, this section provides a detailed look at textures. As textures are only used for the implementation with Unreal Engine 4 in chapter 3, the following information is limited to textures used in the game engine. Therefore, the documentation of Unreal Engine serves as the reference work in this section (Epic Games, Inc. 2019b).
The next section, 2.4.3, contains a brief overview of explicit and implicit 3D models.

Textures are commonly used for the creation of materials. By adding a texture sample node to the material editor, the texture image can be used directly as an input of the base color or indirectly as a mask for other inputs. In the second case, the pixel values of the texture are used. Various textures can be applied to one material. Besides the material generation, textures can also be used to draw to the heads-up display. To preview or edit a texture, Unreal Engine 4 offers a build-in texture editor. A screenshot of the editor's user interface is shown in figure 2.21.

The texture formats supported by Unreal Engine 4 are .bmp, .float, .pcx, .png, .psd, .tga, .jpg, .exr, .dds, and .hdr

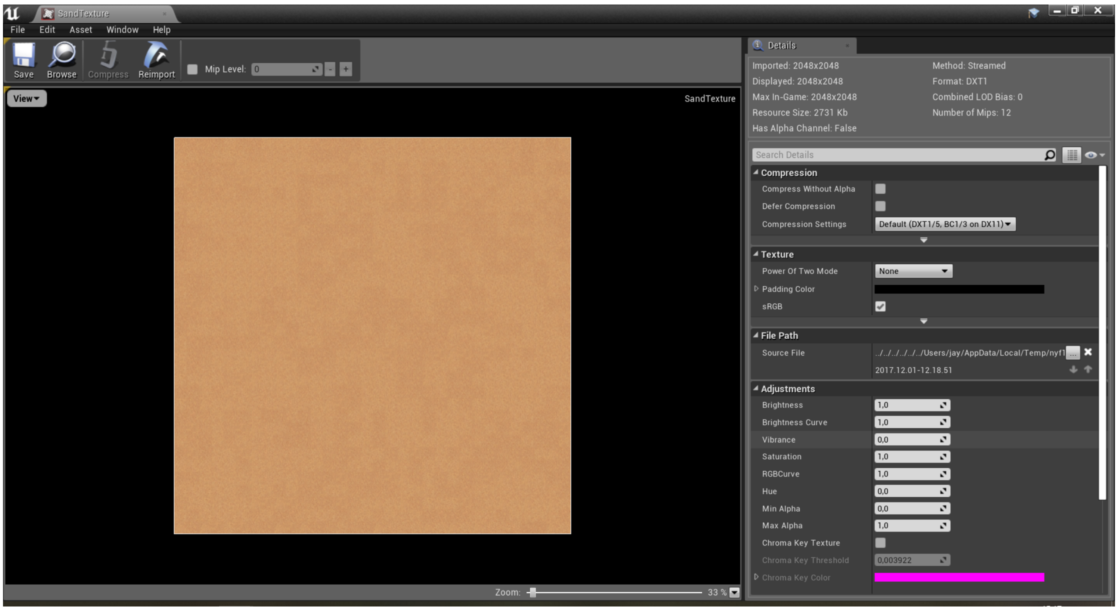


Figure 2.21 Sand texture of the VaMEx-VTB project opened in the texture editor - Unreal Engine 4.23.1

2.4.3 Explicit and Implicit 3D Models

The previous section 2.4.2 provided information about the use of textures in Unreal Engine 4. In this paragraph, the topic 3D models is covered. The three-dimensional reconstruction of visible surfaces is an important part of computer graphics. 3D models are used in various fields like visualization, animation, and modeling. They can be separated into explicit and implicit surfaces. An example of both, an explicit and an implicit 3D model, can be seen in figure 2.22
Afterwards, section 2.5, contains an overview of the VaMEx-VTB initiative.

2.4.3.1 Explicit 3D Models

Polygon meshes, which are defined as a collection of vertices, edges, and faces that build a 3D model, and spline patched and triangulated meshes are examples for explicit surfaces. One of the advantages of explicit surfaces is its easy manipulation. This can be done directly by moving the vertices of the mesh or indirectly with a free form deformation approach (Ilic and Fua 2003). Furthermore, the easy rendering and the intuitive handling are additional benefits of the explicit 3D models. Even though, it works well for graphic purposes and is therefore preferred by graphic designers, it's not recommended for fitting and automated modeling, because the process of finding the facets closest to the 3D data points is time consuming (Ilic and Fua 2003).

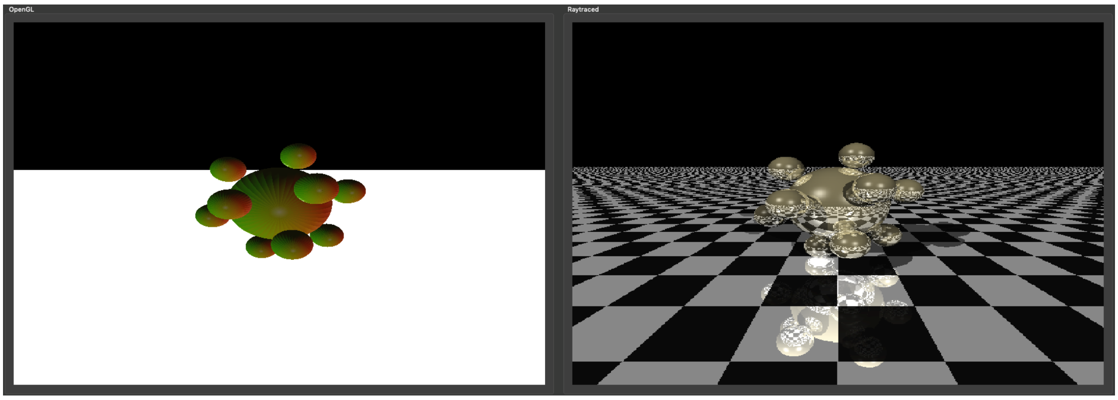


Figure 2.22 Example of an explicit (left) and an implicit (right) 3d model, Ray-Tracing Framework - credit: (Zachmann 2007)

2.4.3.2 Implicit 3D Models

In math, an implicit surface is a surface in Euclidean space defined by an equation. In comparison to the explicit surfaces, implicit surfaces aren't well-suited for graphic purposes, but rather for the modeling of smooth objects, noisy image-data or the simulation of physically based processes (Ilic and Fua 2003). They allow fitting without search, because they only need an evaluation of a differentiable field function at every data point instead of the time-consuming approach of explicit surfaces. A disadvantage of implicit surfaces is that it is quite difficult to control their shape. To manipulate the space in which a implicit 3D model lives, a suitable warping function is needed, but deformations like twisting, bending and tapering only work for parametric surfaces like spheres and cylinders (Ilic and Fua 2003).

2.5 VaMEx-VTB Initiative

In the previous section 2.4, the tools needed for the implementation of the natural phenomena are introduced, including materials, textures, and 3D models. This part of the fundamentals and previous work chapter contains an overview of the Valles Marineris Exploration - Virtual TestBed (VaMEx-VTB), a virtual test bed for autonomous, heterogeneous robotic swarm exploration of the Valles Marineris. Additionally, a brief explanation of the Visual Simultaneous Localization and Mapping (VSLAM) algorithm is attached.
Afterwards, the last subsection of this chapter, 2.6, contains the presentation of two computer

games taking place on planet Mars.

The Valles Marineris Exploration - Virtual TestBed (VaMEx-VTB), developed by the Institute for Computer Graphics and Virtual Reality of the University of Bremen (University of Bremen - Institute for Computer Graphics and Virtual Reality 2020), is a sub-project of the Valles Marineris Explorer (VaMEx) initiative, which was funded by the DLR (Deutsches Zentrum für Luft- und Raumfahrt e.V. 2020) and the BMWi (Bundesministerium für Wirtschaft und Energie 2020). Next to the University of Bremen, various other institutes in Germany are a part of the VaMEx initiative, for example, the Technical University of Braunschweig Institute of Automotive Engineering (TU Braunschweig 2020), the Modern Aerospace Systems Instiute of the University of Würzburg (Universität Würzburg 2020), the Chair of Media Technology of the Technical University of Munich (TU München 2020), and the Institute of Space Technology and Space Applications of the Bundeswehr University of Munich (Universität der Bundeswehr München 2020).

VaMEx-VTB wants to provide an infrastructure-less navigation technology for autonomous, heterogeneous robotic swarm explorations of the Valles Marineris on the planet Mars. The goal is to develop a virtual test bed which is as realistic as possible but still calculable, to analyze and evaluate the performance of various concepts, algorithms and scenarios.

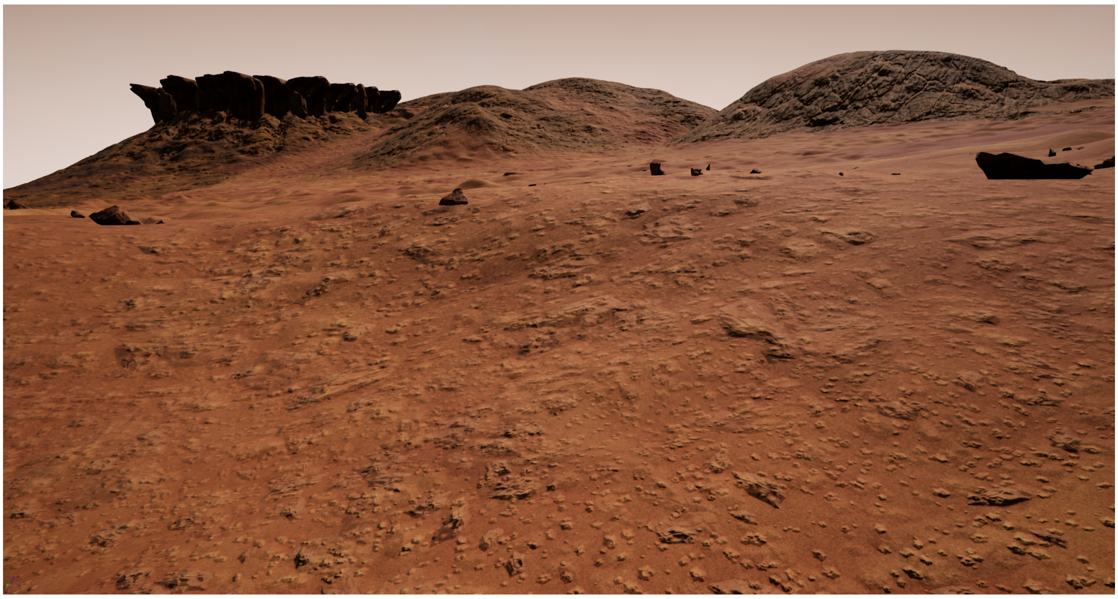


Figure 2.23 Section of Mars HiRise terrain with textures, foilage (rocks) and other features - credit: VaMEx project page of the University of Bremen (University of Bremen - Institute for Computer Graphics and Virtual Reality 2020)

The virtual test bed offers a realistic Mars terrain with different terrain types, including diverse textures, physics, and a sky with day-and-night-cycle. Furthermore, it contains a communication framework that connects the simulation and integration parts build with ROS. The communication framework connects autonomous navigation, exploration systems, sensor data processing, error models, and swarm behavior of various swarm units with the visualization and integration parts like the simulation of environmental aspects, the synthesis of data for various sensors, the visualization of data, and the user interaction. The robotic swarm found inside the test bed provides three different devices, rovers, unmanned aerial vehicles (UVAs) and hominid robots, which are called Charlie. A picture of the Mars terrain of the VaMEx-VTB can be found in figure 2.23.

A virtual test bed, like VaMEx-VTB, offers many advantages compared to real testing environments. Next to the facts that it is less time-consuming and cheaper to test various scenarios in virtual reality, no agent-hardware is needed, and a virtual test bed is also easier to build than a real suitable environment. Furthermore, in a virtual test bed, the environmental circumstances are adjustable and can be set according to the needs of the scenario. Also, it offers the possibility of easy repetition and parallelism.

2.5.1 Visual Simultaneous Localization and Mapping (VSLAM)

For the navigation of the robotic swarm of the VaMEx-VTB, a SLAM framework called ORB-SLAM based on the ORB-SLAM2 library (Yousif et al. 2015) is used. Thanks to this algorithm and with the help of visual sensors the robots of the swarm exploration should be able to create a map of their surroundings using landscape features as points of recognition. The ORBs' feature detector and descriptor, feature tracking, mapping, re-localization and loop closing let the robot collect the environmental data. This data helps it to localize itself by recognizing landscape features from different viewpoints and send relevant data, like new discovered features and landmarks, to the central processing unit, where overlapping maps are merged, to create one shared map for the swarm (Mur-Artal et al. 2015). The overall goal is to build a map where every single device of the robotic swarm can localize itself and contribute new discoveries to, to keep the map up to date and expand it as far as possible.

2.6 Existing Mars Games

After the introduction into the VaMEx-VTB initiative in section 2.5, the last section of chapter 2 offers brief overviews of two computer games that both take place on planet Mars. These games are used as examples for existing virtual Mars environments to provide a comparison to the Mars terrain of the VaMEx-VTB. The first game, described in section 2.6.1, is a single-player strategy game called Surviving Mars. Mars Tomorrow is the second one. This online science-fiction economy simulation game is presented in section 2.6.2.
The following chapter 3 deals with the implementation of the natural phenomena dust devil, dust storm and atmosphere.

2.6.1 Surviving Mars

Surviving Mars is a single-player strategy and economy simulation game that was developed by Haemimont Games (Haemimont Games AD 2020) and published by Paradox Interactive on the 15th march 2018. It is available for Microsoft Windows, Linux, Mac OS, Playstation 4, and Xbox One.

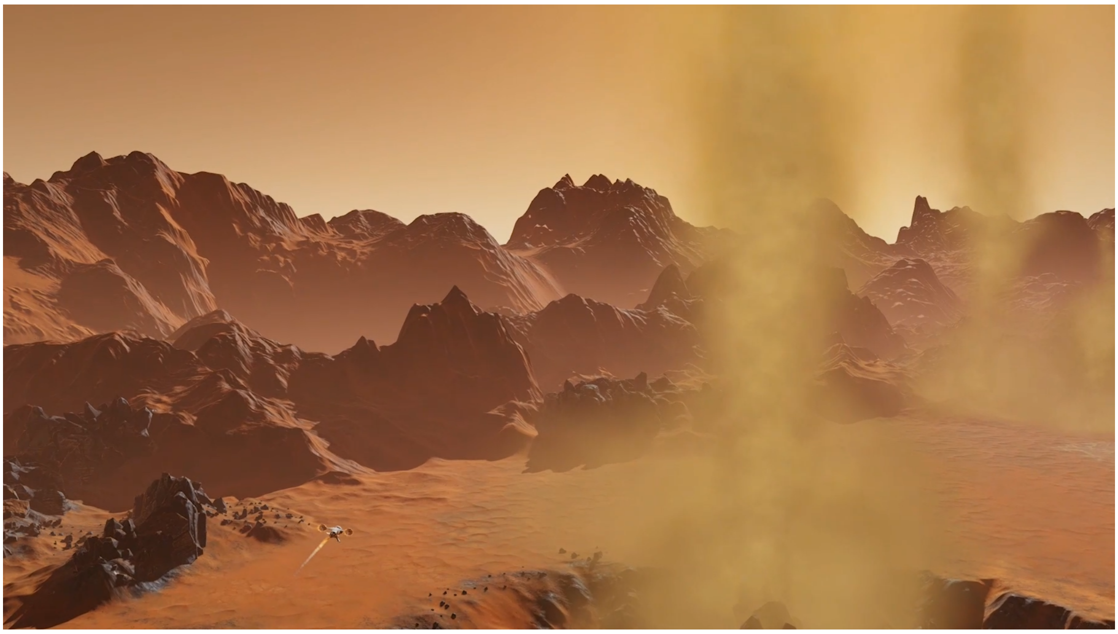


Figure 2.24 Screenshot of dust devils in the Surviving Mars game trailer, minute 00:47 - credit: (Haemimont Games 2018)

The goal of the sciene-fiction-builder is to colonize the Mars and to make the colony survive. To start the game the player needs to choose a space-agency that will support him/her with money and resources to start the colony by building domes and infrastructure, start the drone exploration, and grow food. The player tries to solve different tasks, like the building of a sustained colony or the exploration of the secrets of the red planet. Challenges the player will face are, for example, the natural phenomena taking place on the planet. These include dust devils and dust storms. Dust devils exist in two sizes and disappear relatively quickly, but they can cause maintenance work on domes and reduce the speed of the rovers. They appear as rotating vertical columns of dust that create a dust cloud at the ground. This is shown in the screenshot of the game's trailer in figure 2.24. Dust storms, in turn, can cause increased dust accumulation which can lead to problems like buildings that stop functioning, rockets that can't land or take off, or leaks on pipes and power cables. Also, electrostatic dust storms are possible. An electrical shock during a dust storm could result in building shut downs, drone battery drain, loss of fuel from fuel refineries and storage, loss of resources from universal depots, power loss of power accumulators or atomic accumulators, or colonists that die instantly. Different to dust devils, the dust storms do look like red fog that restricts the view, as show in figure 2.25.

Figure 2.25 Screenshot of a dust storm in the Surviving Mars game trailer, minute 00:42 - credit: (Haemimont Games 2018)

2.6.2 Mars Tomorrow

The online science-fiction economy simulation game Mars Tomorrow was developed by Bytro Labs GmbH. Building his/her own habitat in a colony on Mars is the player's main goal. Therefore, he/she needs to explore new technologies and challenge the requirements of the logistic, the provision for the population, and the conditions of the environment. One habitat offers thirteen building sites for the player to use. An example of such a habitat is shown in figure 2.26. The game works with rounds. Each round is split into eight phases of ten days. Each phase offers different resources and tasks for the player. At the end of the eight phases the player has to face the endgame where the Mars is destroyed.
Mars Tomorrow has its focus on the economic development and logistical issues of a Mars colony. Natural phenomena, like dust devils, dust storms or the conditions of the different atmosphere do not influence the development of a colony.

Figure 2.26 Screenshot from Mars Tomorrow Game, (Gamefabrik 2017)

3 Implementation

The previous chapter 2 is about the fundamentals and previous work. It includes introductions into the natural phenomena in section 2.1 that are animated and simulated in this chapter, the software needed for the implementation in 2.2, the different methods used for the animation and simulation in section 2.3, materials, textures, and 3D models in 2.4, the VaMEx-VTB initiative in section 2.5, and two computer games taking place on planet Mars in 2.6.
In this chapter, a detailed description of the practical part of this thesis can be found. It is split into several sections according to the three different natural phenomena. The implementation process of the dust devils is provided in section 3.1, of the dust storms in 3.2, and of the atmosphere in section 3.3. Three dust devils are provided. The implementation of the first and second dust devil includes the generation of two vector fields with 3ds Max, two materials made with the material editor of Unreal Engine 4, and the creation of a particle system with the particle editor Cascade. The third dust devil is build with Blender. It uses a particle system and fluid simulation. Two different versions of the natural phenomenon dust storm are simulated inside Unreal Engine 4. The first one is generated with exponential height fog and the second one combines volumetric fog, a material, and a particle system. Last, atmospheric dust is created to simulate the existence of an atmosphere in the virtual Mars environment. Therefore, a material and a particle system are generated in Unreal Engine 4.

One of the basic ideas of the implementation chapter is the animation and simulation of realistic looking natural phenomena. They are mostly implemented in Unreal Engine 4 to offer an easy integration into the VaMEx-VTB to extend the test bed and the test scenarios.

The following chapter 4, presents the conducted user study of this bachelor's thesis about the valuation of the implemented dust devils, including the structure of the online questionnaire, the collected data, and their analysis.

3.1 Dust Devils

Dust devils are the first natural phenomenon that is dealt with in this chapter. The goal is to create animated dust devils according to the facts about real dust devils that are provided in 2.1.1. This includes the shape, appearance, and behavior of a dust devil. The list of characteristics that should be considered by implementing a dust devil, shown in section 2.1.1.1, is used as an orientation for the implementation process. Three different dust devils are provided in this section. In section 3.1.1, the first and second one are described. They use 3ds Max (2.2.1) for the creation of vector fields and Unreal Engine 4 (2.2.3) for the generation of particle systems and materials. Blender (2.2.2) is used for the third dust devil, which is based on a particle system, force fields, and fluid simulation. Its implementation process is described in 3.1.2.
Afterwards, the implementation process of the natural phenomenon dust storm is summarized in section 3.2.

3.1.1 3ds Max 2019 & Unreal Engine 4

In this section, the implementation of two of the three dust devil animations is described in detail. The structure of these two dust devils is nearly identical, except for the used materials and some settings of the particle system. Each dust devil uses two vector fields, one material, one particle system, and a basic AI movement structure. First, the generation of the two vector fields is explained in 3.1.1.1. These are used for both dust devils. Afterwards, the creation of two different materials is shown in 3.1.1.2. The vector fields and the materials are applied to the particle systems of the dust devils. Both particle systems consist of three emitters. The generation of the particle systems is described in 3.1.1.3. As the last step of both dust devil implementations, a basic AI movement is added to the particle systems, which is explained in 3.1.1.4. An overview of the implementation structure can be found in figure 3.1.
The implementation of the third dust devil, which is made with Blender, can be found in the following section 3.1.2.

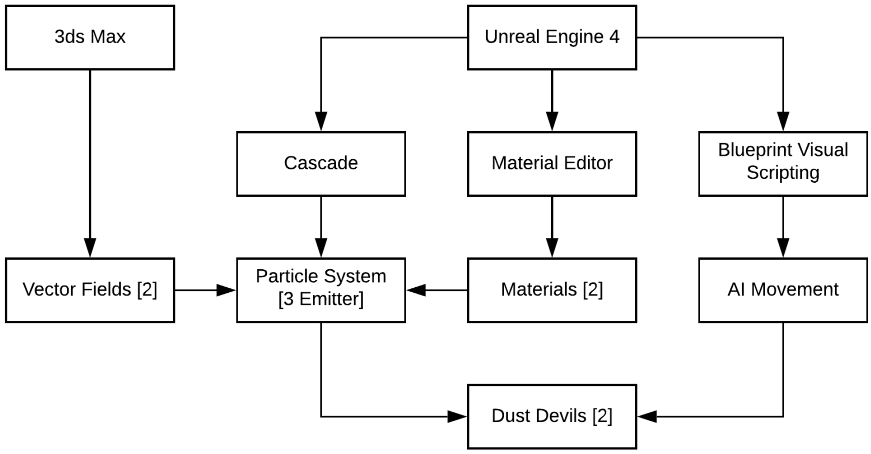


Figure 3.1 Flow chart of the implementation process of the first and second dust devil

3.1.1.1 Vector Field Generation in 3ds Max 2019

For the implementation of each of the two dust devils two vector fields are needed. An introduction into vector fields is provided in section 2.3.1. To create these vector fields, the student version of the 3D modeling and animation software 3ds Max is used, which is already introduced in section 2.2.1. A plugin called VFShapes is installed inside 3ds Max, which is used to add a vector field to an editable spline (Ruben Henares 2014). The vector fields are later applied to the particle systems of the first and second dust devil in Unreal Engine 4 to provide their basic shape. This implementation step is explained in section 3.1.1.3.
Next, the creation of two materials is described in section 3.1.1.2.

3.1.1.1.1 First Vector Field

The first vector field created with 3ds Max is used to build the body of the first and second dust devil. Having a look at the list of characteristics used as an orientation for the dust devils implementation in section 2.1.1.1, the shape of a dust devil is described as an upward-moving, swirling helical structure with a defined columnar core (Horton et al. 2016), or a vertical column of rotating dust (Balme and Greeley 2006). Therefore, a helix is chosen as the basic spline object. With the lower radius of the helix chosen smaller than the upper radius, an upward-moving, swirling helical structure can be imitated. Furthermore, if the radii are chosen close to each other, the shape of a columnar core is formed. The height of the helix depends on the scene in which the dust devil is later inserted. Same goes for the number of turns of a helix. The relation between the height and the number is important for the final look of the dust devil. If the turns of the vector field are too close together, the swirling structure can get lost. Keeping some distance between the turns also creates a less structured look, which is important, because a dust devil is a natural phenomenon and should not look too smooth. The helix applied to the particle system of the first and second dust devil has 50 turns with a total height of 200, to provide an even distribution. To create a higher particle density in the lower part of the dust devil, as mentioned in the characteristics list in 2.1.1.1, the bias of the helix is set negative, but close to 0, to increase the number of turns in the lower part of the helix and to decrease the turns at the top. Furthermore, less turns support the dissolution of the rotation at the top of the dust devil.

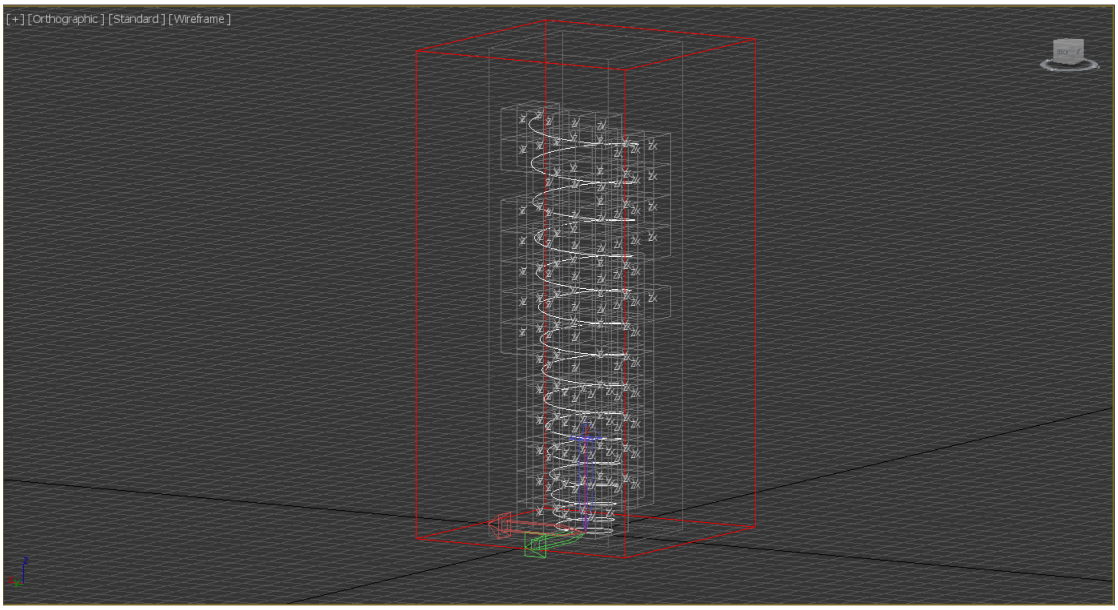


Figure 3.2 Updated helix with vectors of the first vector field - Autodesk 3ds Max 2019, Student Version

For the generation of the vector field of the helix, the VFShapes plugin of 3ds Max is needed (Ruben Henares 2014). By opening the plugin, a cube, called VoxelGridTemplate, appears in the center of the 3D space. The size of the cube should be adjusted according to the dimensions of the helix, with some space kept between the helix and the frame of the cube. When the helix is converted to an editable spline it can be chosen inside the VFShapes menu. To increase the number of vectors of the vector field, the density can be adjusted in the plugin menu. It should be considered, that the more vectors inside the vector field, the higher the performance. The force of the vectors needs to be set to attract, so later when the vector field is applied to a particle system, the particles are attracted by the helix to form the vertical column of rotating dust. After the helix has been updated the vectors are visible inside the 3D space, as shown in figure 3.2. The vector field can then be exported as a .fga file and imported into Unreal Engine 4.

3.1.1.1.2 Second Vector Field

To create the turbulent inflow of loose surface material at the bottom of the dust devil, mentioned in the list of characteristics of a dust devil in 2.1.1.1, a second vector field is created. It is used to add a dust cloud at the ground, arising from the sand stirred up by the dust devil, to provide the look of a turbulent inflow and to support the higher particle density in the lower part of the dust devil. Similar to the first vector field, a helix is used as the basic spline object to keep the idea of an upward swirling behavior. Different to the first helix, the upper radius of the second helix is a bit smaller than the lower radius. This shape is used to push the particles towards the rotating columnar core, simulating the attractive force of the dust devil. Also, both radii must be bigger than the ones of the first helix, because the dust cloud encircles the column. The height of the helix is set to a quarter of the height of the first one in order to keep the dust cloud in the lower part of the dust devil. Again, a negative bias close to 0 increases the turns in the lower part of the helix to create a higher particle density near the ground and to simulate the dust, which gets lifted up from the ground because of the vortices.

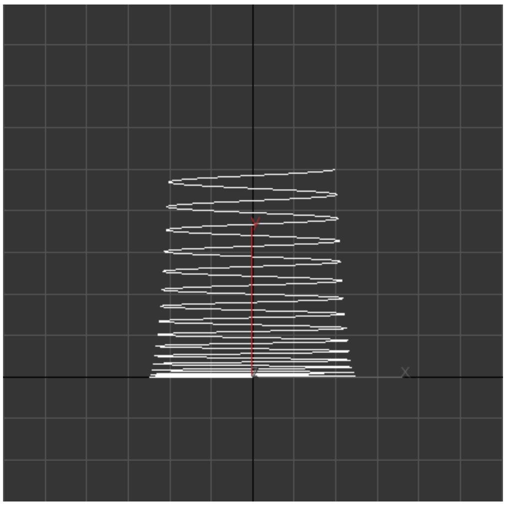


Figure 3.3 Helix of the second vector field - Autodesk 3ds Max 2019, Student Version

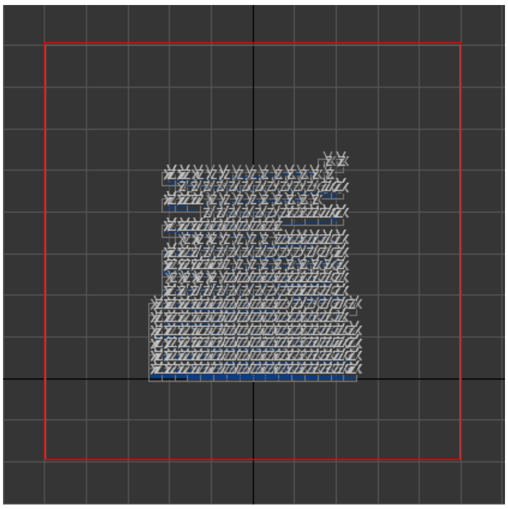


Figure 3.4 Updated helix with vectors of the second vector field - Autodesk 3ds Max 2019, Student Version

The process of the vector field generation of the second helix with the VFShapes plugin is the same as for the first vector field. Figure 3.3 shows the helix before the generation of the vector field and figure 3.4 shows the updated version with the vectors.

3.1.1.2 Materials

After the generation of two vector fields in 3.1.1.1, this section describes the second step of the implementation of the dust devils, the creation of the materials. Each of the two dust devils, that are built with Unreal Engine 4, need its own material. Therefore, two different materials are provided. The material editor of Unreal Engine 4 and blueprints are used for the generation. A short introduction into the topic materials is given in section 2.4.1. Information about Unreal Engine 4 can be found in 2.2.3 and an overview of its visual scripting language in subsection 2.2.3.2.
The creation of the particle systems of the first and second dust devil, which the materials are applied to, is described in the following section 3.1.1.3.

3.1.1.2.1 Material of the first Dust Devil

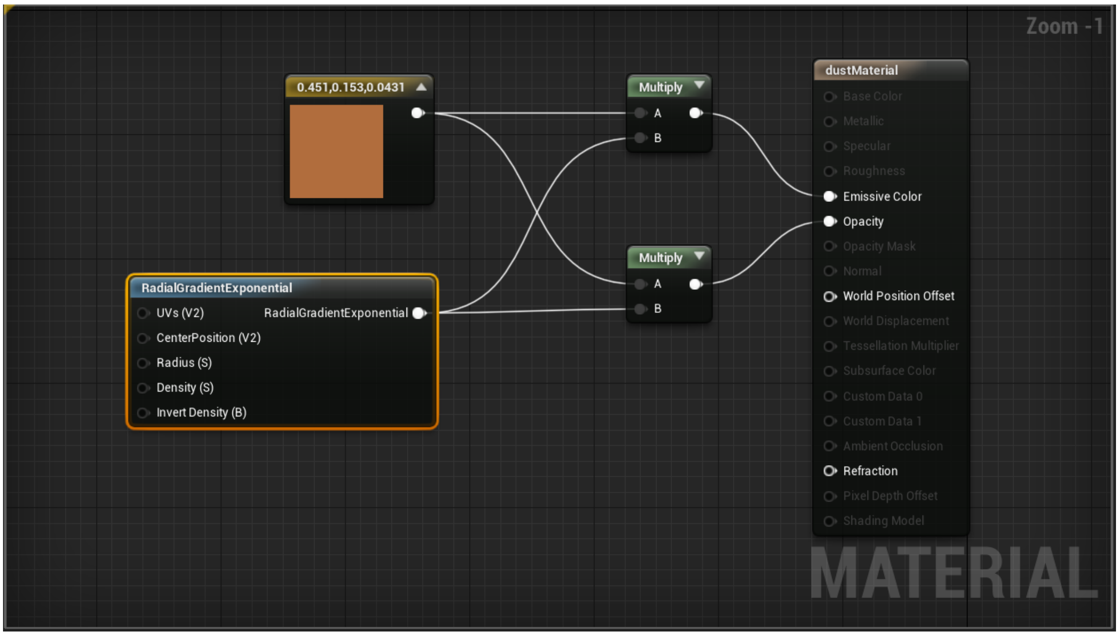


Figure 3.5 Screenshot of the blueprint of the material used for the first dust devil - Unreal Engine 4.23.1, Material editor

The blueprint of the first material is shown in figure 3.5. Through the rest of this thesis, this material is called the surface material. The reason for this name is the material domain that is set to surface material, which makes is applicable on an object's surface. To make the material transparent, the blend mode is set to translucent. Furthermore, the shading model is chosen as unlit. These settings result in a material main node with the inputs emissive color, opacity, world position offset, and refraction. The inputs world position offset and refraction are left empty, while the inputs emissive color and opacity are used to create the final look of the material. A 'constant3Vector' node is used to define the color of the material. Its value is picked from the virtual environment of the VaMEx-VTB, to provide a matching color concept for the integration of the dust devil. The 'RadialGradientExponential' node offers a function that uses UV channel 0 to produce a radial gradient, giving the user the ability to adjust the radius and offset the center point. Figure 3.6 shows the default output result of the node. The default values of the 'RadialGradientExponential' node are multiplied with the values of the 'constant3Vector' node and used as an input as well for the emissive color as for the opacity. The result of the material blueprint can be seen in the preview of the material in figure 3.7.

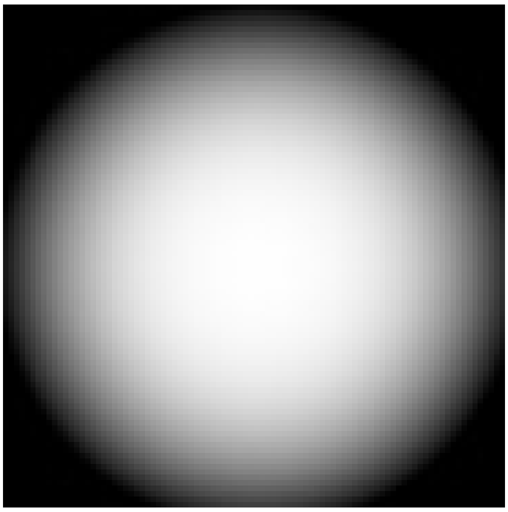


Figure 3.6 Default output result of the 'RadialGradientExponential' node - credit: (Epic Games Inc. 2020)

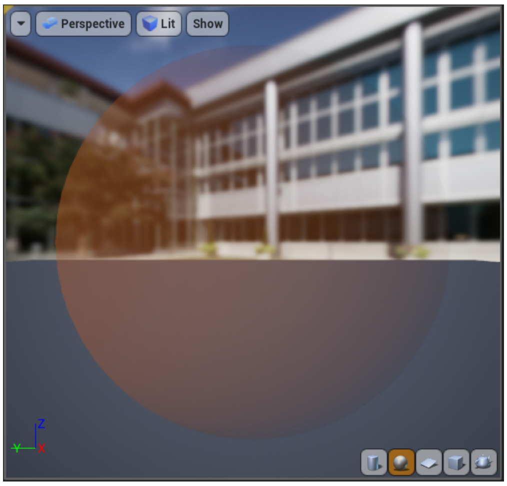


Figure 3.7 Preview of the material used for the particle system of the first dust devil - Unreal Engine 4.23.1, Material editor

3.1.1.2.2 Material of the second Dust Devil

Different to the first material, the second material is based on a volume material domain. Therefore, it is called the volume material. A screenshot of the materials' blueprint is shown in figure 3.8. A volume material is only visible inside a scene in Unreal Engine 4, if the exponential height fog is integrated and the volumetric fog enabled. More information about exponential height fog and volumetric fog is provided in section 2.3.4.

Next to the material domain, the blend mode and shading model of the second material receive different settings than the first material. The blend mode is set to additive, while the shading model is chosen as default lit. These settings cause the inputs of the main material node to be albedo, emissive color, and extinction. The emissive color input is left empty, while the albedo gets a 'constant3Vector' node as an input. The color of the 'constant3Vector' node is also picked from the virtual Mars environment of the VaMEx-VTB to offer a harmonic color concept for the integration of the second dust devil. The 'Absolute World Position' node provides the position of the current pixel in world space, while the 'Particle Position' node outputs Vector3 (RGB) data, representing each individual particle's position in world space. A 'Particle Radius" node defines the radius in Unreal units of each particle individually and the constant node '0' outputs 0 as a single float value. The values of these four nodes are set off against each other with the 'SphereMask' node, which outputs a mask value that gets multiplied with 0.05 and is then used as the value of the extinction input. There is no preview provided of the material, because a volume material, as already mentioned above, is only visible inside a scene with the exponential height and volumetric fog integrated.

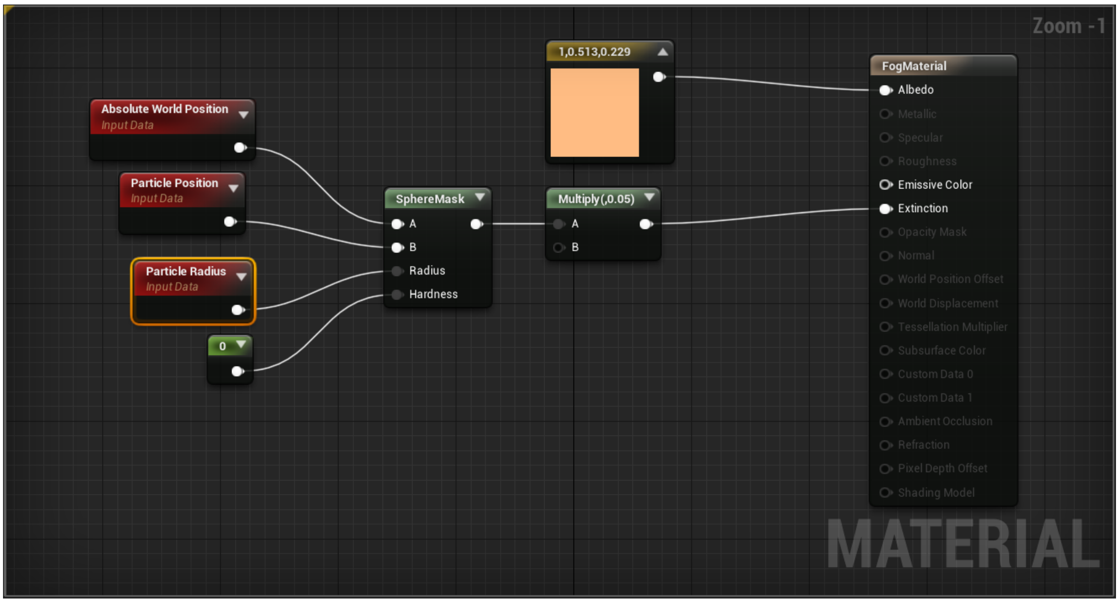


Figure 3.8 Screenshot of the blueprint of the material used for the second dust devil - Unreal Engine 4.23.1, material editor

3.1.1.3 Particle Systems

The previous section 3.1.1.2 deals with the material creation. In this paragraph the particle systems of the first and second dust devil are built. The particle systems determine the final look of the dust devils. Therefore, the generation is oriented on the characteristics list provided in 2.1.1.1. An overview of the implementation process of the particle systems is shown in figure 3.9. The outcomes of the previous two sections, the vector fields (3.1.1.1) and materials (3.1.1.2), are applied to the particle systems. Each particle system uses both of the vector fields and one of the two materials. The vector fields define the basic shape of the dust devil, while the material, in each case, determines the look of the particles, including color and opacity. For the generation of the particle systems, the build-in particle editor of Unreal Engine 4, Cascade, is used. An overview of the topic particle systems can be found in 2.3.3 and an introduction into Cascade in section 2.2.3.1. Because the particle systems of the two dust devils share the same base structure, it is described only once in section 3.1.1.3.1. Afterwards, the settings specific for each dust devil are explained in detail in 3.1.1.3.2 and 3.1.1.3.3.
In the following section 3.1.1.4 the AI movement of the first and second dust devil is handled.

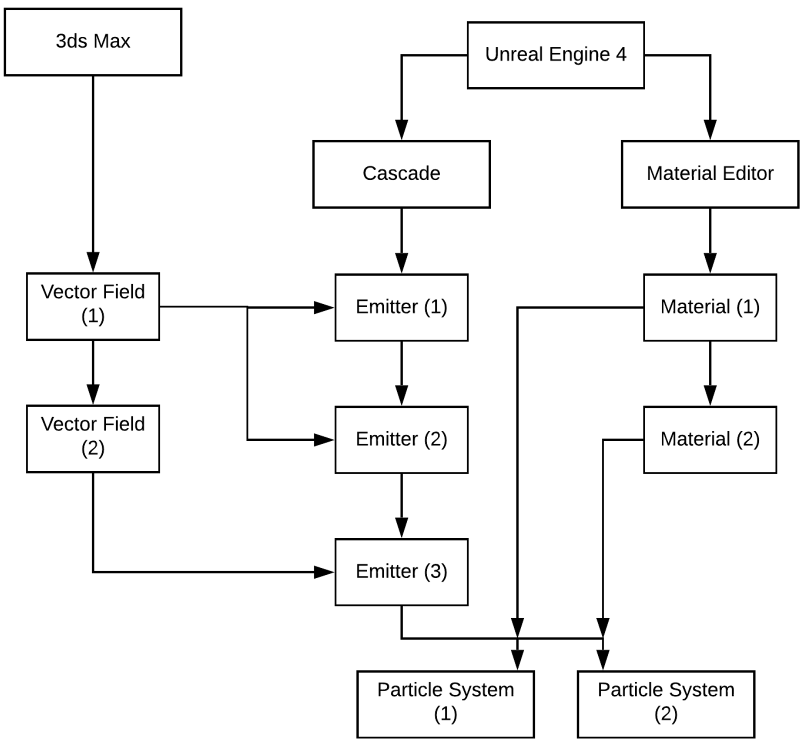


Figure 3.9 Flow chart of the generation of the particle systems of the first and second dust devil

3.1.1.3.1 Base Structure of the Particle Systems

Both particle systems consist of three emitters. The first and second emitter are used to define the upward moving, vertical column of rotating dust and the dust expelling top of the dust devils. Whereas, the third emitter creates a moving dust cloud at the bottom that simulates the higher particle density and the turbulent inflow of loose surface material as mentioned in the dust devils' characteristics list in 2.1.1.1. An overview of the modules of the emitters of the particle system of the first dust devil is shown in figure 3.10.

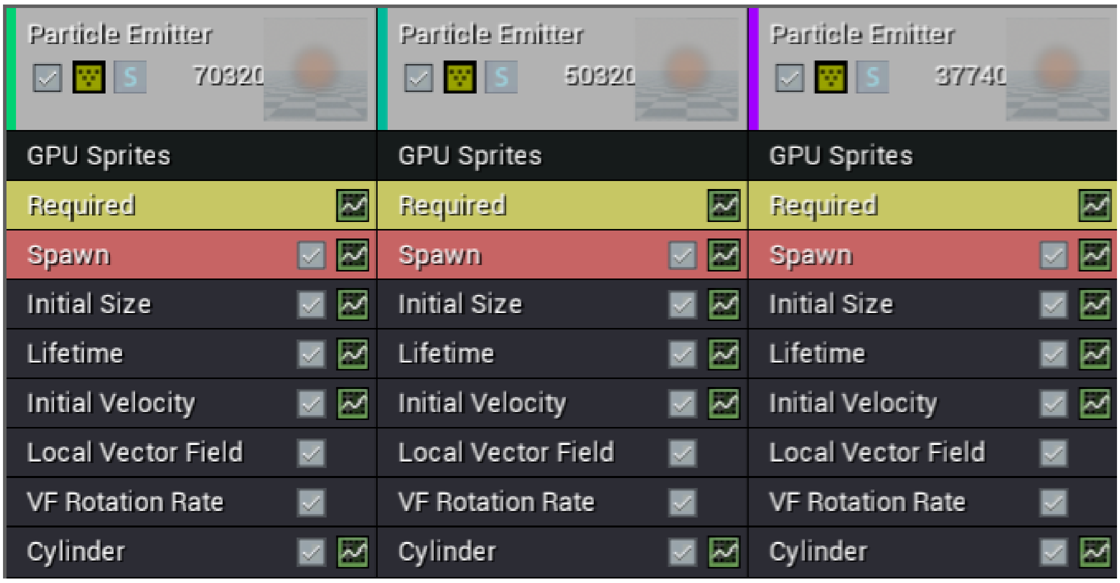


Figure 3.10 Details of the particle system of the first dust devil using the surface material - Unreal Engine 4.23.1, Cascade

The first emitter of the particle systems is set to GPU sprite, which means it is only generated if the dust devil is located in the visible area of the scene, to save GPU work. As the dust particles of a dust devil keep their color, the default 'ColorOverLife' module can be deleted. To apply a vector field to an emitter a vector field module is needed. There, the vector field from section 3.1.1.1.1 is selected to define the shape of the emitter according to the vertical column. The scale of the vector field can be adjusted according to the size expected for the integration into the virtual Mars environment of the VaMEx-VTB. To increase the force of the vector field, the intensity is set to 1000 and the tightness to 0.03. A tightness of 0 means that the vector fields force influences the particles velocity additively, whereas a value of 1 would cause the particles velocity to be replaced by the vector fields force. To generate a realistic spiral dust column with a smooth transition between the turns of the helical base structure, the tightness is chosen close to 0, providing a natural degree of chaos. Choosing the tightness closer to 1 would cause the particles to follow the structure of the vector field more accurate and result in a too organized and too structured emitter. Adding the 'VFRotationRate' module to the first emitter and setting the z value to 1.5 increases the overall rotation rate of the particles around the z-axis and supports the impression of high rotating wind speeds (2.1.1.1). A cylinder is chosen as the initial location of the emitter. It can be adjusted to match the shape and dimensions of the bottom of the helix of the vector field and provide a smooth transition from generation to movement inside the particle system. This also supports the idea of the dust particles getting lifted up from the ground. As a dust devil is described with upward moving flows, the minimum and maximum of the z value of the first emitters velocity is set to 30 and 70. Also, the lifetime of the particles is increased, depending on the height of the generated dust devil and its vector field. The higher the dust devil, the longer the lifetime should be, to ensure that the particles reach the full height of the dust devil without fading and its total shape can be seen.

All in all, the second emitter of the particle systems is mostly identical to the first emitter. Its aim is to add another rotating column of particles to reach a higher density and increase the irregularity of the dust devils. To make the emitters differ from each other, some settings of the second emitter are adjusted. The lifetime is reduced, which causes the particles to vanish earlier and not necessarily reach the altitude of the first emitter. This results in an increased particle density in the lower parts of the dust devil, which meets the characteristics of a higher particle density near the ground and a smooth dissolution of the particles at the top as described in section 2.1.1.1. That simulates that the center of speed and force of the dust devil is in the lower part of it and that the particles seem to get spread wider the higher they come, which results in a decreased density at the top. Also, the z value of the vector rotation rate is decreased to add more visible irregularity to the behavior of the dust devil and to simulate some inclination in the rotating movement. Additionally, the height of the initial location cylinder is increased to add some variation to the particles from the origin of the dust devil.

The third and last emitter is used to simulate a dust cloud at the bottom of the dust devil. This is used to support the higher particle density in the lower part of the dust devil, and to imitate the turbulent inflow of the loose surface material, which gets whirled up by the dust devil (2.1.1.1). Just like the first and second emitter, the third emitter is set to GPU sprite. Again, the 'ColorOverLife' module isn't needed, as the particles of a dust devil keep their color. The second vector field created in section 3.1.1.1.2, is applied to this emitter, to give it the basic structure of a helix which is wider and shorter than the helical vector field of the first two emitters. Intensity and tightness of the vector field are identical to the first and second emitter. Though, the rotation rate of the vector field gets a lower value than the other two emitters (0.1). This clear difference in the rotation speed simulates the decrease of the wind speed from the dust devils' core towards the surrounding air. The initial location of the third emitter is also set to a cylinder, which, again, matches the shape of the dust devil, or rather the structure of the vector field. Therefore, the start radius of the cylinder is adjusted according to the dimensions of the second vector field, so the particles are also generated around the rotating column of the first and second emitter. The velocity of the particles is set to the same values as the velocity of the other two emitters, which provides the upward movement also for the third emitter. But, the lifetime of the third emitter has a larger range between maximum and minimum to give the dust cloud some irregularities and random behavior, which makes it seem more realistic and supports the idea that the force of the dust devil gets lower and varies the larger the distance to the center is.

3.1.1.3.2 Particle System of the first Dust Devil

Different materials are the main difference between the particle systems of the first dust devil and the second dust devil. The surface material created in section 3.1.1.2.1 is applied to all three emitters of the particle system of the first dust devil. Thanks to this material, the particles get a semi-solid look, imitating real dust and sand particles. Semi-solid means that the particles aren't opaque, thanks to the opacity input of the materials blueprint. As dust or sand particles are quite tiny in reality, the initial size of the particles is set to a minimum of 0.5 and a maximum of 1.0. To make the silhouette of the first dust devils vertical, rotating column still visible despite the small size of the particles, the first and second emitter need a high spawn rate of about 100000 particles per second. As the dust cloud produced by the third emitter is lower in height and density than the column of the dust devil, it's spawn rate should be less. The lifetime of the the first emitter is set to a minimum of 5 seconds and a maximum of 7 seconds, the second emitter is set to a minimum of 3 seconds and a maximum of 5 seconds, and the values of the third emitters' lifetime are 1 second and 5 seconds. Figure 3.11 shows the first emitter, figure 3.12 the second one, figure 3.13 the third, and figure 3.14 all three emitters of the particle system of the first dust devil enabled.

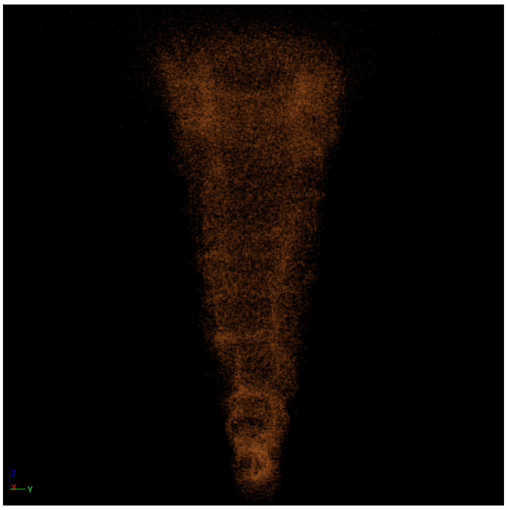


Figure 3.11 First particle system with the first emitter enabled - Cascade, Unreal Engine 4.23.1

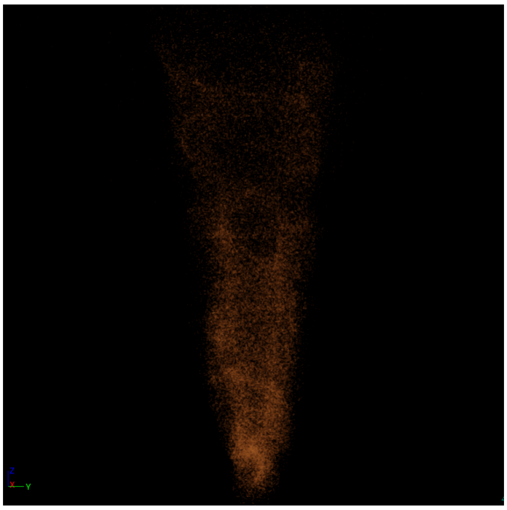


Figure 3.12 First particle system with the second emitter enabled - Cascade, Unreal Engine 4.23.1

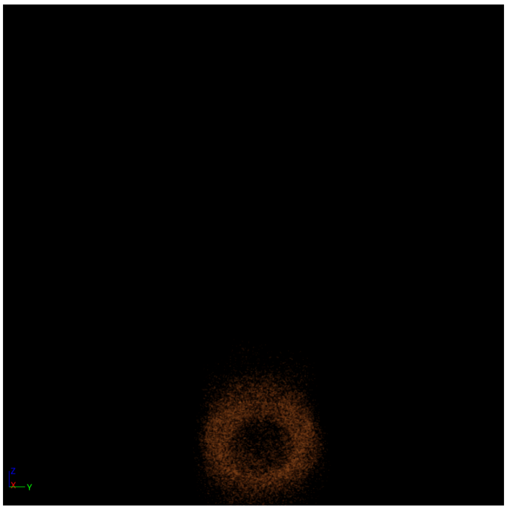


Figure 3.13 First particle system with the third emitter enabled - Cascade, Unreal Engine 4.23.1

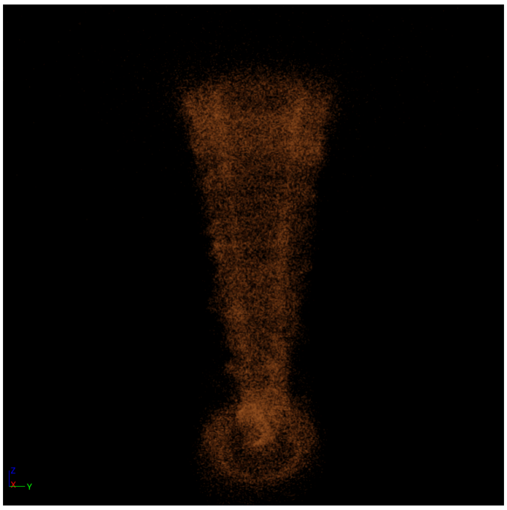


Figure 3.14 First particle system with all emitters enabled - Cascade, Unreal Engine 4.23.1

3.1.1.3.3 Particle System of the second Dust Devil

The particle system of the second dust devil uses the volume material created in section 3.1.1.2.2 for all three emitters. This material, as already mentioned before, is only visible if the exponential height fog is integrated into the scene and the volumetric fog is enabled in its settings. Unlike the particle system of the first dust devil, the initial size of the particles is set to a much higher value for all three emitters. The minimum of 100 and the maximum of 200 is based on the different behavior of the volume material. Each particle generates a kind of little sphere of dust, in other words, a little dust cloud. To make it visible inside the scene, the size of the particles needs to be significantly higher than the size of the first particle system. An advantage of the bigger dust spheres is that the transition of one particle to the others gets lost, thanks to the transparent cloud effect. The result is that the particles look like one connected dust cloud that moves according to the vector fields' forces, instead of many single particles. A bigger initial size of the particles leads to a much lower spawn rate. The spawn rate of all three emitters is set to 150 particles per second. Different to the particle system of the first dust devil, the spawn rate of the third emitter is identical to the first and second emitter. A reason for this is the different behavior of the particles. The particles are much bigger and if the lifetime is over and the particle vanishes, the influence on the look of the dust devil is totally different than the result if one of the small particles of the first particle system disappears. On the one hand this adds more irregularity to the dust devil, providing a more natural and less organized look. On the other hand, the spawn rate needs to be high enough, so if one particle vanishes, other particles have already been created and moved into this space, to avoid holes in the rotating column of dust. The lifetime of the first and second emitter is set lower, compared to the particle system of the first dust devil, because the bigger dust sphere particles don't need as much time to reach the top of the dust devil as the tiny semi-solid particles. Figure 3.15 shows the first emitter, figure 3.16 the second one, figure 3.17 the third, and figure 3.18 all three emitters of the particle system of the first dust devil enabled.

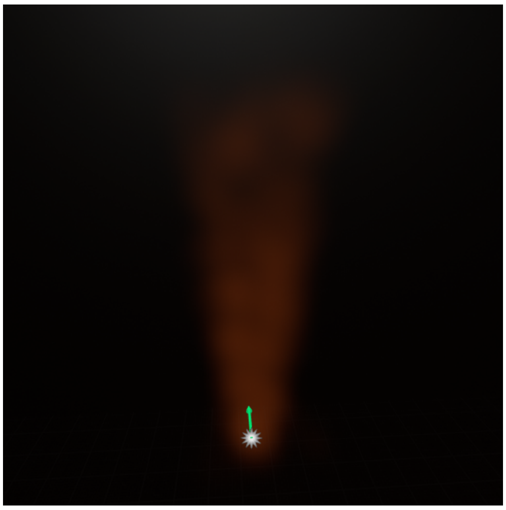


Figure 3.15 Second particle system with the first emitter enabled - Cascade, Unreal Engine 4.23.1

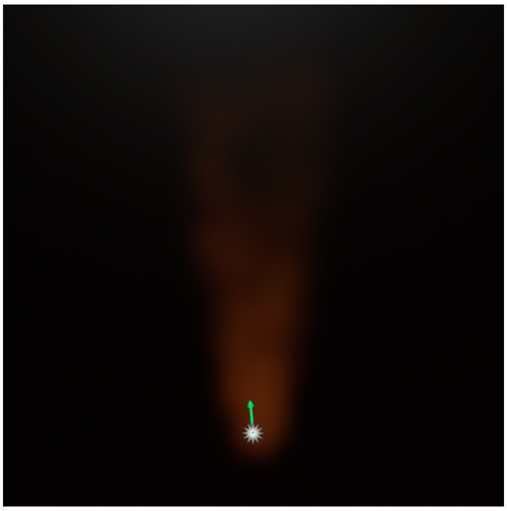


Figure 3.16 Second particle system with the second emitter enabled - Cascade, Unreal Engine 4.23.1

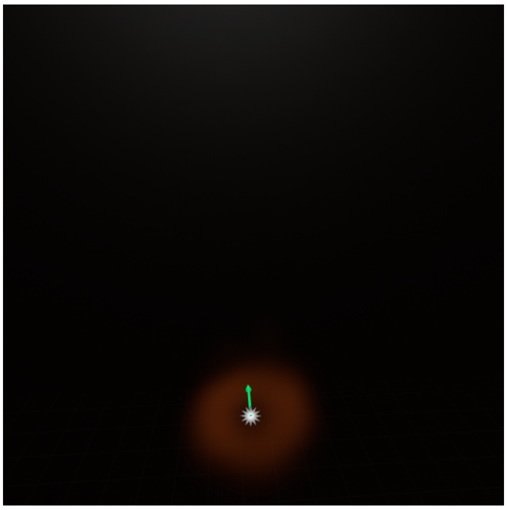


Figure 3.17 Second particle system with the third emitter enabled - Cascade, Unreal Engine 4.23.1

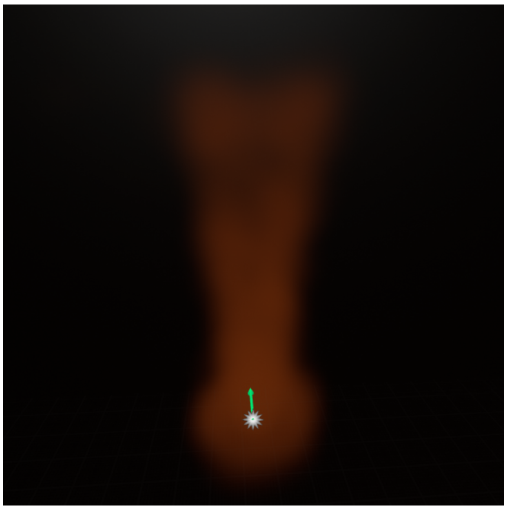


Figure 3.18 Second particle system with all emitters enabled - Cascade, Unreal Engine 4.23.1

3.1.1.4 AI Movement

In the third step of the implementation of the first and second dust devil the generation of particle systems is presented in section 3.1.1.3. The fourth and last step is about the movement of the dust devils. An AI movement is created for both dust devils with the help of blueprints inside Unreal Engine 4. More information about blueprints is provided in 2.2.3.2. To make the AI movement work, a 'NavMeshBoundsVolume' needs to be integrated into the scene. Its bounds limit the range of movement of the dust devils. As the structure of the AI movement is identical for both dust devils it is only explained once.
The next section in this chapter, 3.1.2, deals with the implementation of the third dust devil with the 3D creation software Blender.

To set up the AI movement a character blueprint, an AI controller, a behavior tree, a service, and a blackboard are needed. The character blueprint functions as the physical representation of the dust devil within the world. Therefore, the particle system of the dust devil is added as a component to the blueprint. The origin location of the particle system should be checked, so the particle system won't be spawned too high or too low. Inside the event graph of the characters' blueprint, a 'Set Character Movement' node is added after the 'Event BeginPlay' node with the maximum walk speed value set to 100. By connecting the 'Get Character Movement' node to the target input of the setter node, the walk speed of the character movement is set to the new value.

An AI controller is assigned to the character blueprint to make the dust devil able to gather information of the world in the scene in order to make decisions and react according to the situation without explicit input from a human player. It responds to the input from the virtual environment and controls the performing actions of the character. Its main task is to run the behavior tree of the dust devil, which is set inside the event graph.

A behavior tree is a tool of Unreal Engine 4 to create artificial intelligence for characters and a blackboard is used to store values or other information from the behavior tree as so called 'Blackboard Keys'. The nodes of the behavior tree graph execute from left to right and from top to bottom, which is similar to the logic of blueprints. Furthermore, a behavior tree is event-driven, which avoids unnecessary work, and it listens passively for events to trigger changes in the tree graph without constant checking. The black nodes are composite nodes that define the root of a branch and its basic executing rules. Purple nodes represent task nodes, which are used to perform actions for the AI. Green nodes, in turn, are services, which are executed in a defined frequency as long as the branch is active. These are often used to do checks and to update the blackboard. The behavior tree of the dust devil consists of a 'Root' node, a 'Sequence' node, and a 'Move To' node, which makes use of a custom service. Its goal is to provide a random location where the dust devil could move to. Both, the 'Root' node and the 'Sequence', are composite nodes. The children of the sequence node are executed from left to right and stop executing when one child fails, causing the whole sequence to fail. The 'Move To' node is a task node, which causes a character blueprint with a character movement component to move to the provided location vector. In this case, the vector is a blackboard key provided by a custom service.

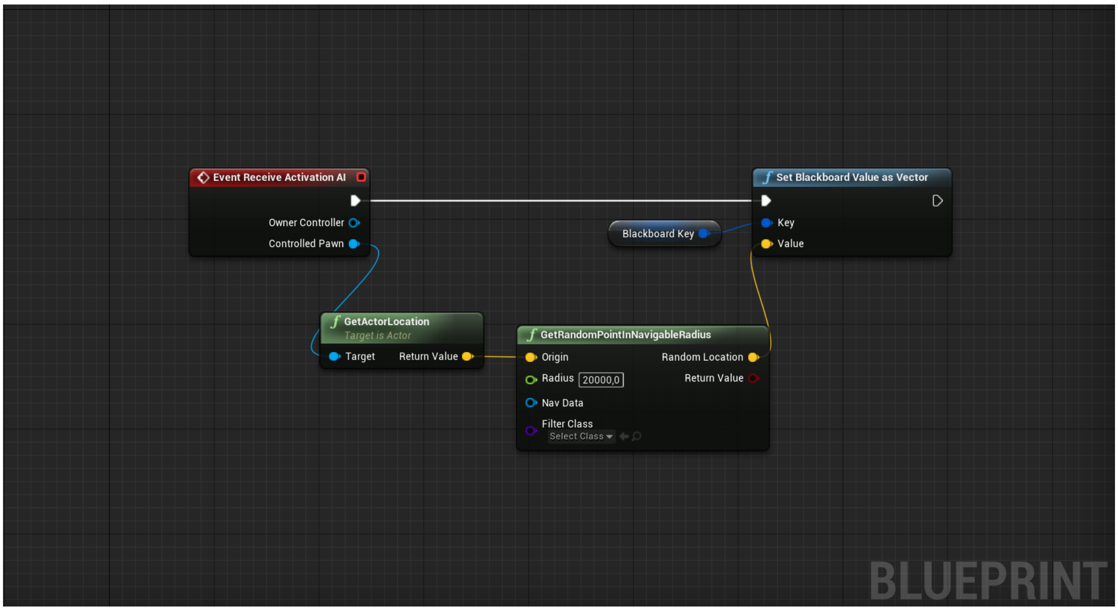


Figure 3.19 Screenshot of the event graph of the custom service- Unreal Engine 4.23.1

The custom service is used to generate a random location vector. A screenshot of the blueprint of the service is shown in figure 3.19. Thanks to the 'Event Receive Execute AI' node, the service starts executing when its task is activated inside the behavior tree. The 'GetActorLocation' node returns the location of the root component of its actor, in this case, the location of the dust devils' character blueprint. This location vector is needed as an input for the 'GetRandomPointInNavigableRadius'. With the location of the dust devils as an origin input and the radius set to 20000, a vector with a random location in the reachable radius is the output. The 'Set Blackboard Value as Vector' node stores the random location vector in a blackboard key. This blackboard key, in turn, is provided to the 'Move to' node of the behavior tree, which causes the dust devils' character blueprint to move to this random location vector.

If the character blueprint with the first particle system is then integrated into the virtual environment of the VaMEx-VTB, the random moving first dust devil is added to the scene. The same procedure works for the second dust devil.

3.1.2 Blender

In the previous section 3.1.1, the generation of two dust devils with the 3D modeling software 3ds Max and the game engine Unreal Engine 4 is described. This section is about the implementation of a third animated dust devil using the 3d creation software Blender (2.2.2). Again, the implementation of the dust devil is based on the list of characteristics of a real dust devil provided in section 2.1.1.1. The third dust devil also uses a particle system, but in contrast to the first and second dust devil, the particle system is only needed to provide the basic shape of the dust devil. Fluid simulation, or rather smoke simulation, is used to imitate the actual dust. An introduction into the topics particle systems and fluid simulation can be found in section 2.3.3 and 2.3.2. Additionally, to influence the motion and behavior of the dust generated by the smoke simulation, force fields are added to create rotation and form the shape of the dust devil. The disadvantage of using the fluid simulations in Blender is that it isn't yet possible to integrate the rendered smoke simulation into Unreal Engine 4 and the virtual environment of the VaMEx-VTB. More information about the VaMEx-VTB is provided in section 2.5.
Next, the implementation of two dust storm simulations is explained in section 3.2.

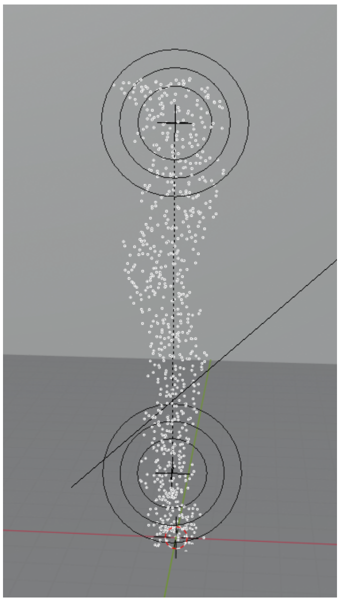


Figure 3.20 Particle System of the dust devil - Blender 2.8

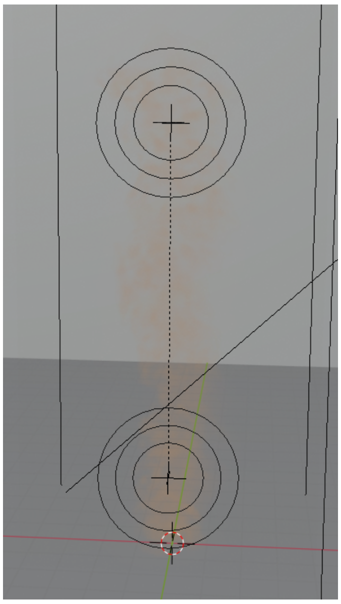


Figure 3.21 Smoke domain of the dust devil - Blender 2.8

Figure 3.22 Rendered view of the dust devil - Blender 2.8

To create the basic structure of the rotating dust column of the third dust devil a particle system is needed. A filled circle mesh is used as the initial location of the emitter. The emission number depends on the wished density of the dust devil. A value around 2000 as the maximum amount of parent particles used in the simulation results in a semi-transparent dust column, as it can be seen in figure 3.22. To make the particles rise instead of fall, the gravity of the particle systems needs to be set to 0. The lifetime of the particles influences the height of the dust devil. It is set to 100 frames. Figure 3.20 shows the particle system in solid view mode.

The spiral flows of the shown particle system are added by using a vortex force field. To simulate the rotating wind speeds forming the rotating dust column, the force field is placed at the same x- and y-coordinates as the filled circle mesh, the initial location of the particle system, but at a higher z-coordinate, so the particles move upwards. It is set to plane, with a minimal negative inflow of -0.5 and a strength of about 7. Normally the force field attracts the particles and gives them an inward flow. By setting the inflow negative, the particles will flow outwards and start to circle around the middle. This will give the particle system the needed basic movement to form the column of rotating dust.

To support the upward movement and to influence the behavior of the particles two more force fields of the type 'Force' are added, with their shape set to plane. One of the two is placed close above the emitter, with a low negative strength of -1, while the second one is placed at the same coordinates as the vortex force field and its negative strength is set to -3. Force fields with a negative strength attract the particles. This is used to keep the particles from spreading too far by limiting the influence of the vortex force field through another force.

Next, to make the dust devil look more realistic, some random movement is implemented. For this purpose, an animation is added to the particle system. First, the vortex force field is set as the parent of the other two force fields, which makes them stick together and move dependent on one another. Then, a location keyframe is added at the beginning of the timeline. In the graph editor the z-location is locked and the x- and y-location receive a noise modifier, which changes the x- and y-graph to wavelike lines. The two graphs should differ from each other to make the movement look more random. When the animation is started, the force fields move along the x- and y-axis according to the wavelike graphs. The result looks like the particle system tilts towards the direction of motion, because the top of it moves randomly as if it is influenced by the rotating wind gusts.

To add the fluid simulation, or rather the smoke simulation, smoke is added in the physics of the circle mesh, with the type set to flow and the flow source set to the particle system. This sets the smoke origin to the particle system, which causes smoke spheres to evolve at the location of each particle in the particle system.

A smoke domain is needed to make the smoke visible. Therefore, a cube can be used, whose size is changed to frame the particle system and the force field. The size of the cube influences the final size of the dust devil, because the smoke won't reach above the cubes' outlines. In the physics of the cube, a smoke simulation can be added. The resolution division influences the time the animation needs to bake, so the higher the value, the longer the baking time. Adaptive domain and the high resolution should be checked, as well as dissolve and the additional slow checkbox. The dissolution time is set to a value around 4. This decides how long smoke, which is generated at the position of each particle, needs to dissolve again. If the value of the dissolve time is set too low the particles won't exist long enough to blur into each other and create the impression of one connected dust cloud instead of many single smoke spheres. Choosing a high dissolution time, in turn, could cause the smoke to become too dense, because the new smoke spheres mix up with the old ones and the smoke becomes too thick. The density of the smoke simulation is set slightly negative, like -0.0001, making it a little bit transparent, which supports the impression of dust.

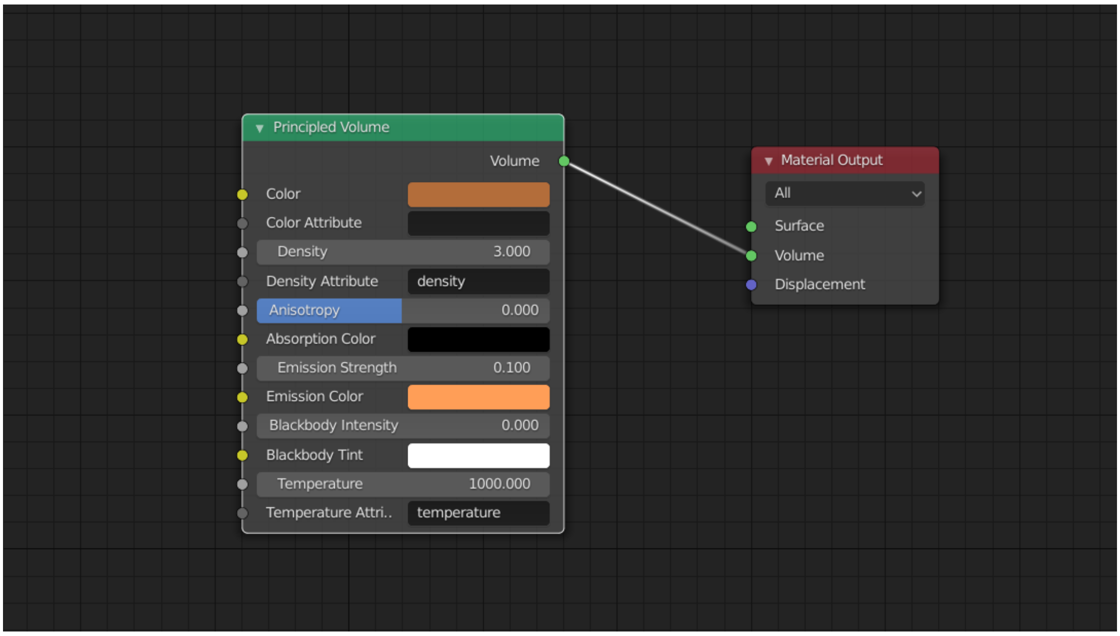


Figure 3.23 Material of the dust devil - Blender 2.8

To make the smoke of the smoke simulation look like dust, the material of the smoke domain needs to be adjusted inside the shader editor. The default 'Principle Shader' node can be deleted and the 'Principled Volume' node is added instead. Its density value is set to 3.6, the anisotrophy to 0, and the emission strength to 0.1. The color is picked from the virtual Mars environment of the VaMEx-VTB, so the dust devil matches the color concept of the environment. A screenshot of the material used for the dust devil is provided in figure 3.23.

The smoke becomes visible after the baking of the scene. Therefore, the particle system of the circle mesh and the cube, which represents the smoke domain, need to be baked. Figure 3.21 shows the particle system with the final, baked smoke simulation in solid mode, while figure 3.22 provides the view in rendered mode.

3.2 Dust Storms

After the implementation of the three animated dust devils in 3.1.2, two different dust storm simulations are described in this section. An overview about the natural phenomenon dust storm can be found in section 2.1.2. Both dust storm implementations are build with Unreal Engine 4 (2.2.3) and are based on exponential height fog. The second one also makes use of a particle system and a basic AI movement structure. Information about exponential height fog and particle systems can be found in the sections 2.3.4 and 2.3.3. The first approach simulates a scene inside a large regional or global dust storm in 3.2.1, while the second one creates a local or small regional dust storm in 3.2.2.
In the following section of the implementation chapter, 3.3, the simulation of a Martian atmosphere is presented.

3.2.1 Exponential Height Fog and Volumetric Fog

With the use of exponential height fog and volumetric fog, a simulation of an occurring large-scale dust storm is built. As exponential height fog, if integrated into a scene, occurs in the whole environment, it can best be used to simulate large regional or even global dust storms, as described in section 2.1.2. The fog won't move or change its look and that's why it can't be used to simulate a moving dust cloud or the beginning or end of a storm. Next to the exponential height fog and the volumetric fog, the settings of the light actor need to be adjusted to provide the wanted look of a dust storm.
The following section 3.2.2 deals with the generation of a moving, small, regional dust storm.

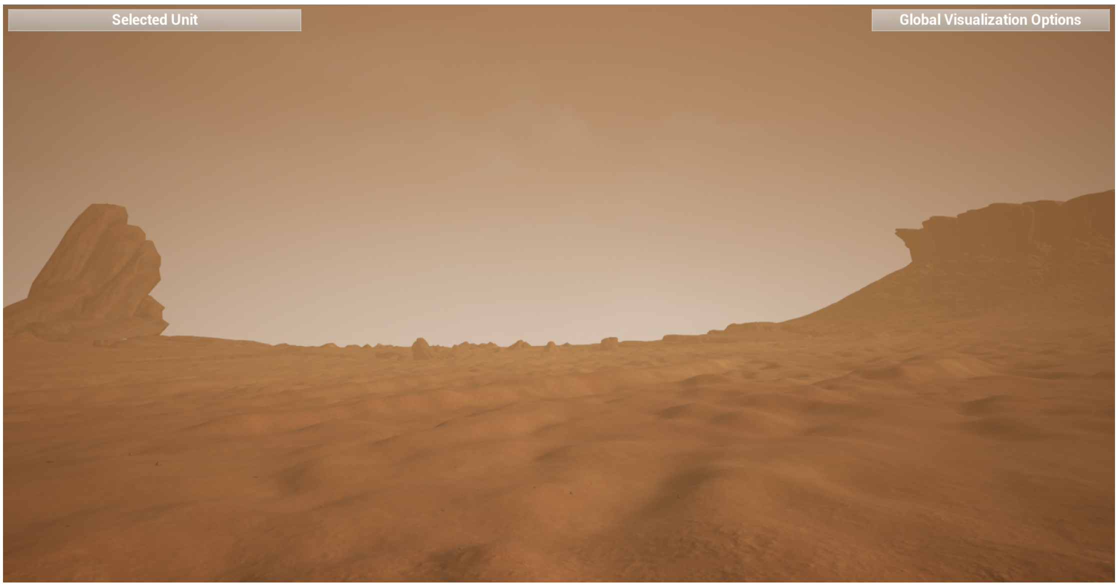


Figure 3.24 Example scene virtual environment of the VaMEx-VTB with exponential height fog enabled its the extinction scale set to 10 - Unreal Engine 4.23

After the integration of the exponential height fog into the scene, both density factors, the global one and the one of the second fog layer, are increased to give the fog a higher thickness and support the feeling of dust particles floating through the air. The global density is set to 0.05, while the second fog layers' density is changed to 0.02. Using a second fog layer makes the fog seem denser and the dust storm more intense. Because the dust storms on planet mars can get pretty large in height and surface, the fog height falloff of the first and second fog layer, which control how the density of the fog increases as the height decreases, should be set pretty low to make the visible transition larger. This results in a smooth transition from the fog area to the fog-free area and increases the overall height of the fog. To give the fog a similar color as the ground of the virtual Mars environment of the VaMEx-VTB (2.5), the fog inscattering color property is used. To simulate dust that has been lifted up from the ground and whirled up into the air the color is picked directly from the Mars terrain. The fog max opacity influences the transparency of the fog. A value of 1 stands for fully opaque and 0 would make the fog invisible. Therefore, the chosen value of 0.5 offers a semi-opaque look, which limits the vision, but leaves the surroundings recognizable.

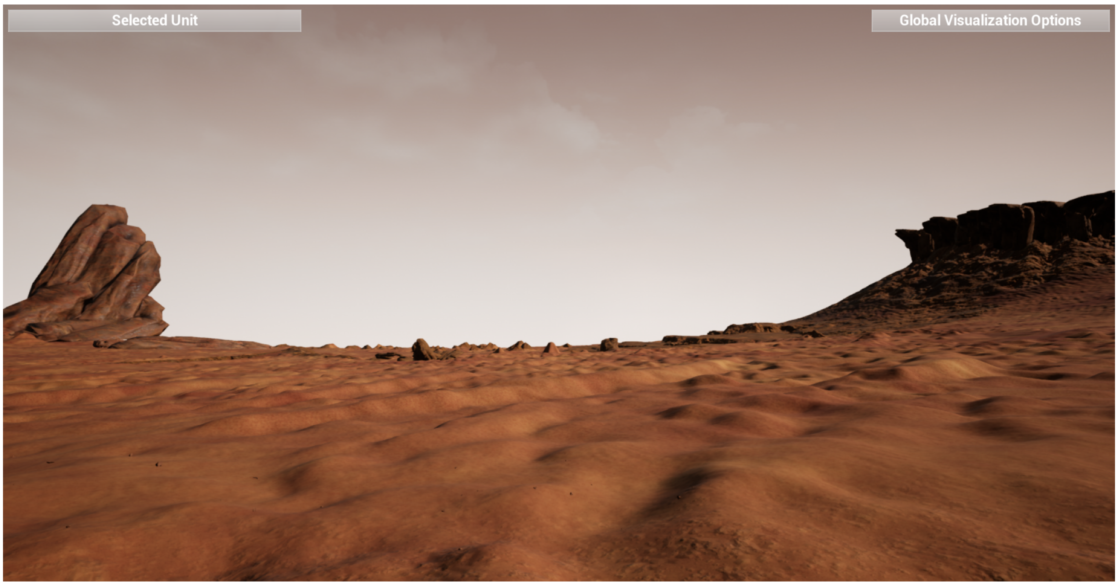


Figure 3.25 Example scene virtual environment of the VaMEx-VTB with exponential height fog disabled - Unreal Engine 4.23

Volumetric fog should be checked inside the exponential height fog settings to support a more realistic look of the dust storm. It computes participating media density and lighting at every point in the camera frustum and supports varying densities and any number of lights affecting the fog. Furthermore, the volumetric fog offers some more settings which can be used to influence the final look of the dust storm. For example, the albedo influences the color of the fog in the scene, by setting the overall reflection of the participating media. The default color of the albedo is white, which can be used for clouds, fog, and mist, in other words, everything that consists of water particles. Dust particles need instead a slightly darker albedo. Therefore, the values of the albedo are set to R = 200, G = 200, B = 200, and A = 250. The higher the extinction scale the more intense the fog seems to be. With values above 1 the fog particles begin to absorb more light. By increasing the extinction scale, the fog seems thicker and the scenery darker. Figure 3.24 shows the virtual environment of the VaMEx-VTB with exponential height fog integrated and its extinction scale set to 10. Figure 3.26, in turn, provides the same scene with an extinction scale of 1. To demonstrate the effect of the exponential height fog better, figure 3.25 offers a screenshot of the scenery with no fog effects enabled.

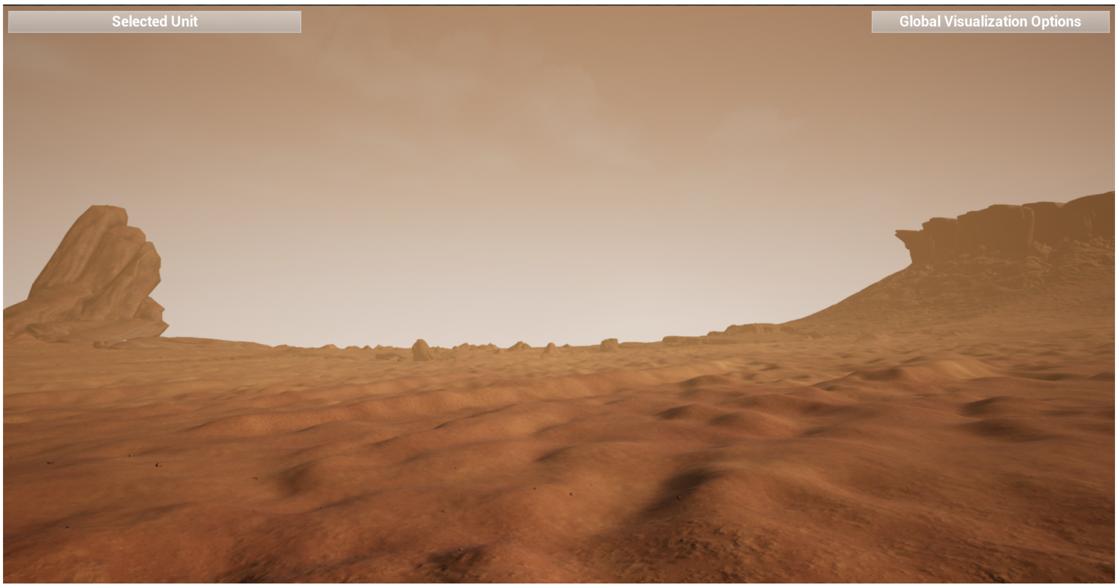


Figure 3.26 Example scene virtual environment of the VaMEx-VTB with exponential height fog enabled its the extinction scale set to 1 - Unreal Engine 4.23

The light settings also need to be adjusted inside the scene to create the effect shown in figure 3.24 and 3.26. In the skylight object of the VaMEx-VTB the volumetric scattering intensity is set to 4. A value higher than 0 makes the light contribute to the volumetric fog. By increasing the value, the light seems to break more through the fog, which makes the scene more realistic. A denser dust storm would probably need a lower value.

3.2.2 Particle System

The previous section 3.2.1 describes the generation of a large-scale dust storm with exponential height fog and volumetric fog. For the second dust storm version these fog effects are combined with a particle system and AI movement, to create a local or small regional, moving storm. Information about local and small regional dust storms is provided in section 2.1.2.
In the last section of this chapter, 3.3, the simulation of an atmosphere for the virtual Mars environment of VaMEx-VTB is described.

Similar to the first dust storm in the previous section, the exponential height fog is integrated into the scene. Also, the volumetric fog needs to be enabled to offer local and global fog control. This approach is described in section 2.3.4.1. The particle system, which is created below, uses a volume material to generate a sphere of fog at its location in the scene. An example of a local fog sphere integrated into the virtual environment of VaMEx-VTB can be seen in figure 3.27. In comparison to the dust storm in section 3.2.1, the settings of the exponential height fog and volumetric fog are mostly identical, except the density factors of the global and second fog layer and the extinction scale of the volumetric fog. For both fog layers, a value of 0.01 is enough, because it only needs to be higher than 0 to make the fog sphere of the particle system visible. Also, the extinction scale is set to a minimum of 1 in order to provide the visibility of the local fog.

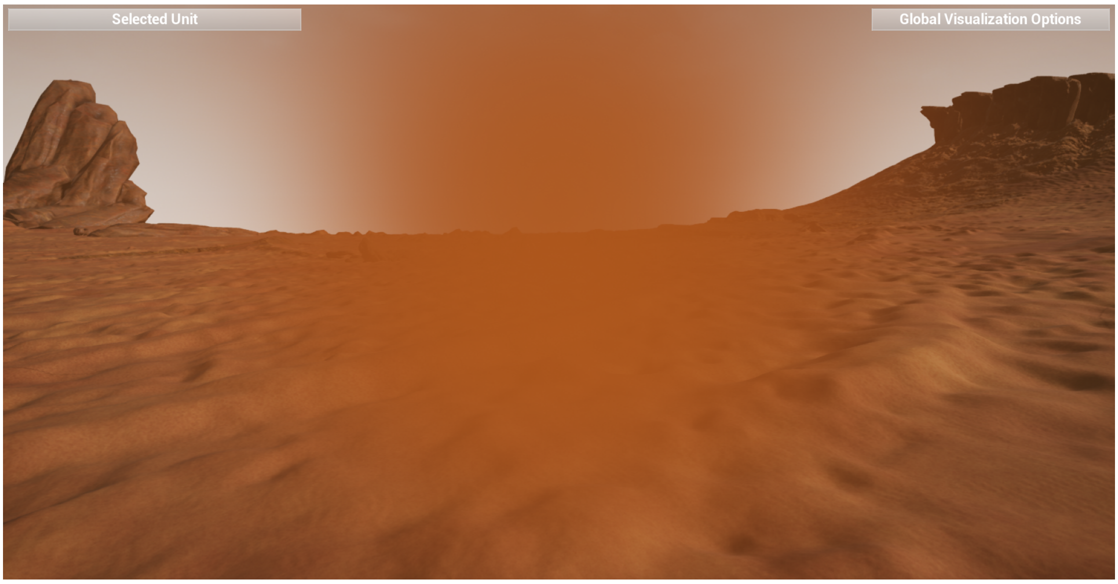


Figure 3.27 Example scene of the virtual environment of the VaMEx-VTB with a local fog sphere shown from the close - Unreal Engine 4.23

The volume material, which is applied to the particle system, has the same structure as the one of the second dust devil that is built with Unreal Engine 4 in section 3.1.1.2.2. It only differs in the color picked for the 'constant3Vector' node. A screenshot of the material is provided in figure 3.28. A cylinder is chosen as the inital location of the particle system, to form the shape of a cloud. The start radius and the height of the cylinder define the size of the final dust cloud. For the simulation of the small local dust storm inside the virtual environment of the VaMEx-VTB the radius is set to 10000 and the height to 400. Because the atmosphere on planet Mars is thinner than the one on Earth (2.1.3), the particles during a dust storm can easily be raised high into the air. Therefore, the start height of the cylinder should be set high enough to match the height of a Martian dust storm in relation to the scene. The size of the particles in combination with the spawn rate influence the density of the dust cloud. If the particles are too small with a low spawn rate, the particle system looks like many little dust spheres floating around. Therefore, the size of the particles needs to be big enough and the spawn rate high enough to make the single spheres blur into each other with no visible transition to create the impression of one big dust cloud. Another factor influencing the look of the particle system is the lifetime of the particles. The longer a particle exists, the less irregularities develop inside the fog cloud. Therefore, the size of the particles is set to x = 3000, y = 50, and z = 50, the spawn rate is increased to 400 particles per second, and the lifetime is changed to a minimum of 10 and a maximum of 12 seconds.

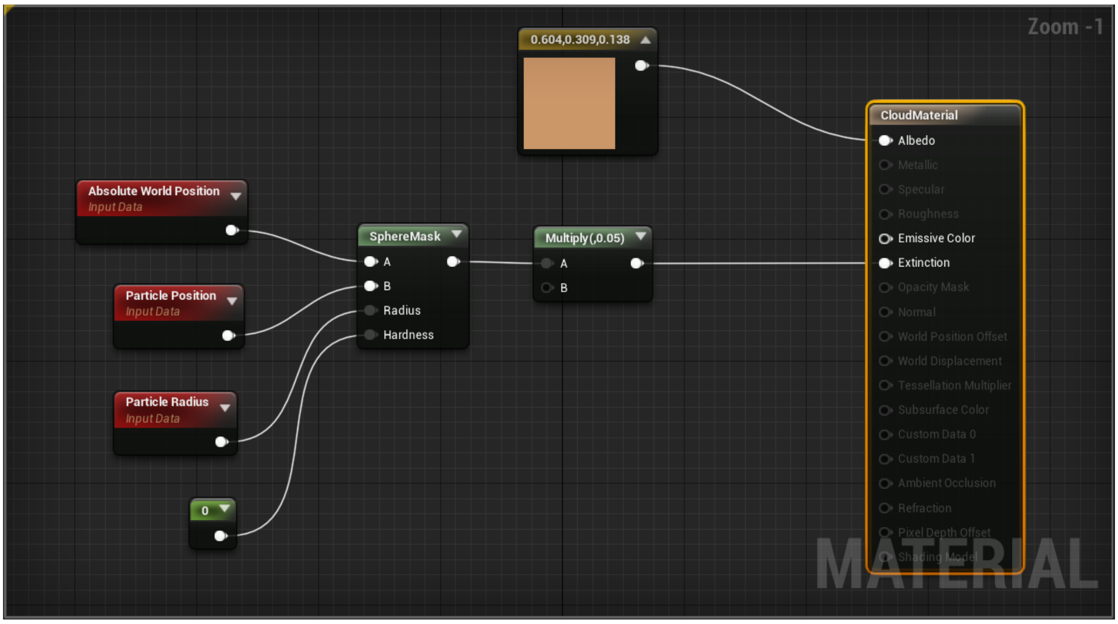


Figure 3.28 Example of a volume material used for the particle system of the fog cloud - Unreal Engine 4.23, Material Editor

To make the particle system move independently in the scene AI, movement is added. The dust storm uses the same AI movement structure as the two dust devils build with Unreal Engine 4, which is described in detail in section 3.1.1.4. A character blueprint, an AI controller, a blackboard, a behavior tree, and a custom service are needed as well as the integration of a 'NavMeshBoundsVolume' into the scene. The maximum walk speed inside the character blueprints' graph editor can be decreased to 50. This independent movement turns the simple static dust cloud into a moving, local dust storm. Figure 3.29 shows a scene of the virtual Mars environment of the VaMEx-VTB from the inside of the particle system.

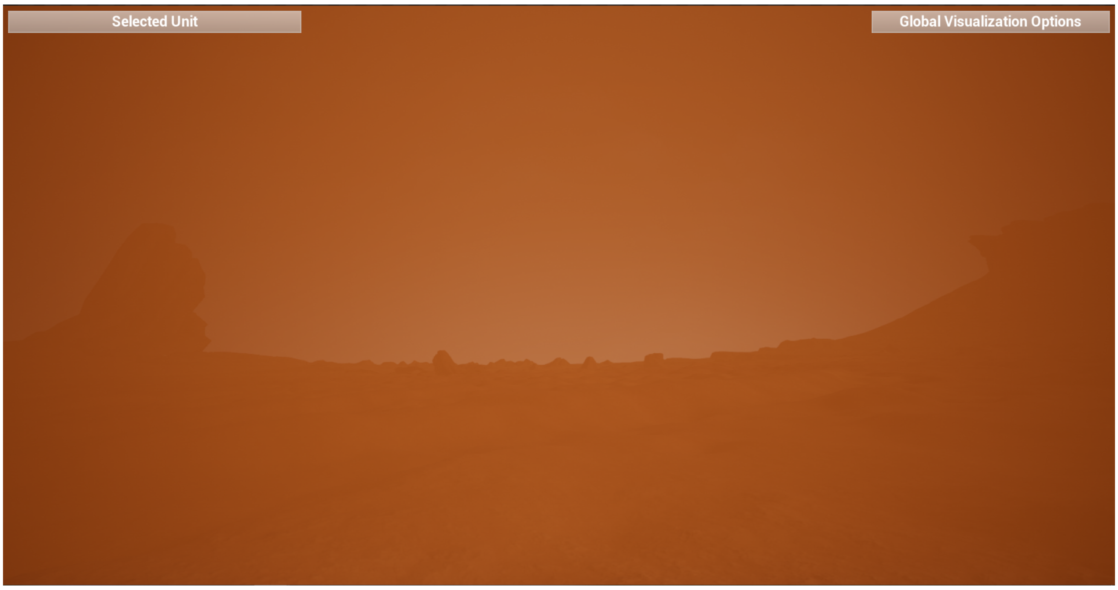


Figure 3.29 Example scene of the virtual environment of the VaMEx-VTB with the exponential height fog and the particle system integrated - Unreal Engine 4.23

3.3 Atmosphere

A simulated atmosphere is the last natural phenomena that is implemented and explained in this chapter. The animated dust devils and simulated dust storms are already described in section 3.1 and 3.2. To simulate the dusty Martian atmosphere for the virtual environment of the VaMEx-VTB in Unreal Engine 4 a particle system and a surface material is used for the generation of atmospheric dust. Information about the atmosphere on planet Mars is provided in section 2.1.3.
The following chapter 4 is about the conducted user study of this thesis, including its structure, the collected data, and the analysis of these data.

Cascade, the particle editor of Unreal Engine 4, is used to create the particle system. An introduction into Cascade can be found in section 2.2.3.1. Only one emitter is needed for the generation of the atmospheric dust. The material applied to it is the one that is created for the first dust devil in section 3.1.1.2.1. This surface material creates semi-opaque dust particles, which means that the particles aren't fully opaque, but a bit transparent. The dust particles floating through the air should look like they could have been lifted up from the ground of the virtual Mars environment of the VaMEx-VTB. This leads to the idea that the properties of the atmospheric dust particle system should be similar to the one of the first dust devil. Details about the generation of the particle system of the first dust devil can be found in section 3.1.1.3.2. The reason for this similarity is, that the dust devil is also implemented to simulate dust particles that have been whirled up from the ground. Therefore, the particles forming the shape of the dust devil should be of the same kind as the particles floating through the air as a part of the regular atmosphere. According to this, the size of the particles of the atmospheric dust is set to a minimum of 0.5 and a maximum of 1.0 to match the settings of the first dust devils' particle system. Also, the emitter is set to a GPU sprite.

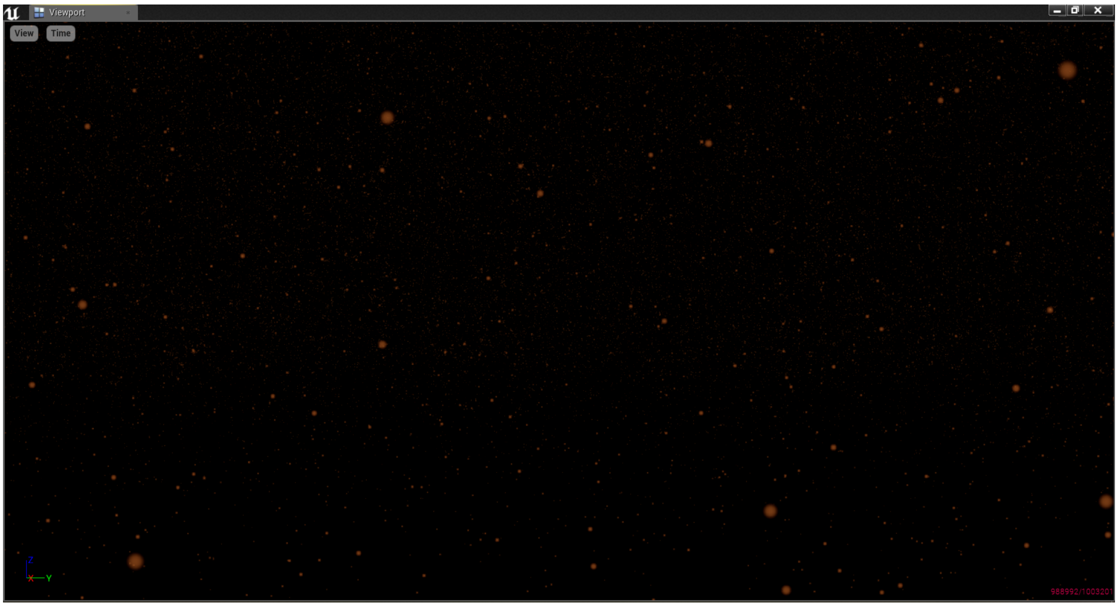


Figure 3.30 Viewport example of the atmospheric dust particle system - Cascade, Unreal Engine 4.23

The start location of the initial location of the emitter is set to a minimum of -1000 for the x- and y-coordinate, -100 for the z-coordinate and a maximum of 1000 for all three coordinates. Therefore, the spawn rate is increased to 100000 particles per second in order to provide an even distribution of dust particles in the defined space. A lifetime between 8 and 10 seconds supports the impression that the dust particles move through the air and are just out of sight when they disappear, to simulate a natural behavior. By adding a collision module to the emitter, it can be determined that a particle gets killed whenever it hits another object in the scene. For this, the resilience constant is set to 0.75, the resilience scale over life to 1.0, and 'Kill' is chosen as the respond value. To add some random behavior to the floating dust particles, an orbit module is added to the emitter. The particles start to orbit around a fixed point with the orbit amount set to a maximum of x = 2.0, y = 4.0 and z = 3.0 and a minimum of 1 for all three coordinates to define the bounds of each particles movement, a rotation amount of a maximum of 1 for x, y, and z and a minimum of x = 0.1, y = 0.3, and z = 0.2, and the rotation rate set to a maximum of x = 0.1, y = 0.3 and z = 0.2 and a minimum of 0 for all three coordinates. Figure 3.30 provides a screenshot of the viewport of the particle system of the atmospheric dust.

4 User Studies

In the previous chapter 3, the implementation of the natural phenomena dust devil, dust storm and atmosphere is described. This chapter contains the structure of the conducted user study in section 4.1, a summary of the collected data in section 4.2 and the analysis of the data in section 4.3. The study is provided as an online survey, which can be filled out by using a computer or any mobile device (Döring et al. 2015). Online questionnaires are known as efficient, discrete and easy ways for anonymous participation, which is great to gather quantitative data (Brosius et al. 2008). Furthermore, the online study fulfills the quarantine conditions during the COVID-19 pandemic. The user study is about the evaluation of the three animated dust devils that are implemented in section 3.1. Next to the valuation of each dust devil, a comparison of the animated dust devils with a real dust devil is included. Afterwards, scenes that show each of the three dust devils integrated into the virtual mars environment of the VaMEx-VTB are rated and also compared to each other. An overview of the VaMEx-VTB initiative can be found in section 2.5. Also, the use of exponential height fog inside a dust devil scene is rated in the study. More information about exponential height fog is provided in section 2.3.4. Screenshots of the study are attached in appendix A.5.
The following chapter 5 contains the results of this bachelor's thesis.

4.1 Structure

First, the structure of the user study is presented. The study is divided into five parts: introduction, first part, second part, third part and farewell. Its structure is based on the structure of a standardized questionnaire by Döring and Bortz, regarding quantitative written surveys, or rather fully structured surveys (Döring et al. 2015). According to them, a standardized questionnaire starts with the questionnaire title, followed by the questionnaire instruction. Third come the content question sets. Next comes the gathering of statistical data. Fifth is the questionnaire feedback and the sixth and last structure element is the farewell.
In this study the questionnaire title, the introduction, and the statistical data are summarized as

one structure element. It is used to welcome the participant, to give a short overview above the topic, to provide the needed information for participation and to gather first information about the participant. The first and second part are content question sets. In the first question set, the three animated dust devils implemented in section 3.1, are valuated regarding the closeness to reality of each animation. In the second question set, the same dust devils are rated regarding their integration into the Mars environment of the VaMEx-VTB (2.5) and the use of exponential height fog in one of the dust devil scenes is valuated. The questionnaire feedback can be found in the third part. It offers the possibility to rate the study and give individual feedback. The farewell represents the end of the study.
Most of the questions used for the study are closed questions, which means that the participant can only choose from the given answers (Döring et al. 2015). This provides a good base for the collection of quantitative data. The open questions in the study are all optional and can be used to give individual feedback. A progress bar is available at the bottom of each page. It shows the participant how far in the study he/she has already progressed.
The following section 4.2 of this chapter presents the data that has been collected during this study.

4.1.1 Introduction

In the beginning of the study the language needs to be chosen, English or German. Depending on the chosen language the following page shows the start of the English study or the first page of the German study. The language question is used to filter the questionnaire, so participants only see the questions relevant for them. Both versions, English and German, share the same structure, questions, and media. For this chapter, just the English version is considered, because the German translations aren't relevant for the results of the collected data. If a question is marked with a star the question must be answered to proceed in the questionnaire. The advantage of an online form is that the participant can't go to the next page if a marked question isn't answered. This helps that no incomplete questionnaires are submitted in the end.

After the choice of the language, a welcoming text for the participants comes up. This includes a short introduction into the topic of the study and information about the duration, to give the participant the possibility to decide if he/she has the time to go through the study or if he/she may choose to participate later. Next comes the privacy statement. It provides information, like how the data of the participant is used and that the participation is anonymous. A similar structure can be found in 'Forschungsmethoden und Evaluation' (Döring et al. 2015), where the first two items of the structure of the standardized questionnaire are the title and its introduction, including the aim of the study and its procedure.

The third item of the structure of the standardized questionnaire by Döring and Bortz are the content question sets (Döring et al. 2015). A content question set handles questions of a similar topic and mostly stays with the same question style. After the welcoming text and the privacy statement, the first content question set comes up. It consists of three easy dropdown-questions, which are quick to answer, to offer the participant a relaxed start in the study. These questions should not require too much effort of the participant, so he/she won't lose interest in the very beginning (Brosius et al. 2008). In this study, this kind of questions is used to gather some information about the participant, the age and his/her professional field. According to Döring and Bortz, statistic data should be collected after the content question sets (Döring et al. 2015). Because there are just these two questions, they have been moved to the front, to avoid an extra page in the study. The third and last question of this question set leads the way towards the topic of the study. It asks the participant about his/her knowledge regarding dust devils on planet Mars (Brosius et al. 2008). These three questions represent the first easy and quick question set.

On the next page of the study some information about dust devils on planet mars is provided. This includes three different videos and a paragraph with a short summary of the most important facts about dust devils on Mars. This information is provided to every participant, doesn't matter if he ever heard about dust devils on planet mars before or not. Because, even if one has already heard about them, there's no guarantee that he/she has knowledge that is helpful for the participation in this study. If all participants share the same basic knowledge, everyone has the same preconditions to fill out the rest of the study.

4.1.2 First Part

As recommended in 'Forschungsmethoden und Evaluation' by Döring and Bortz, the next question set of the study has its own title (Döring et al. 2015). The following page introduces the 'First part' of the study, to make clear that the main questions about the topic are about to start now. Screenshots of the pages of this part of the user study can be found in section A.5.2 in the appendix. First, a short paragraph is shown, which offers information about the different methods used for the implementation of the three animated dust devils, a short explanation about the structure of the following questions, and how to answer them.

The next three pages of the study have an identical structure. Each page consists of two questions. The first question always includes a list of seven characteristics. This list is based on the list of characteristics of a real dust devil on planet Mars provided in section 2.1.1.1. To offer a better overview for the questionnaire, the characteristics of the list are summed up as follows:

'Upward movement', 'Spiral movement', 'The height is about five times larger than the width', 'Higher particle density at the bottom', 'Vertical columnar core', 'Tilts towards the direction of motion', and 'Narrow base & broad top'. For all three dust devils, each characteristic needs to be rated, to check if the animated dust devil meets the requirements of a real dust devil. Therefore, each of the characteristics has its own five-step, bipolar rating scale, which means that each end of the scale represents a different, opposite feature (Döring et al. 2015). This should lead to a higher accuracy of the judgements. The labels used for the scales are ' Agree' and 'Disagree', which means that the rating of '1' is labeled as 'Disagree' and '5' as 'Agree'. The steps in between aren't labeled, but can be interpreted as '2' = 'rather disagree', '3' = 'neither disagree nor agree', '4' = 'rather agree'. This kind of questions is called attitude- or opinion-question (Brosius et al. 2008). If only the ends of the scales are labeled, some space is saved in comparison to scales where each step has its own label. This is helpful if one uses the mobile version of the study with a small display or low resolution. Using a five-step rating scale instead of a seven-step rating scale also saves space and offers a better look on small displays. Furthermore, rating scales with uneven step numbers offer the possibility of a neutral middle, which can be helpful if the participant isn't sure about the answer. A neutral middle can be used as a kind of passing place, or just if one can't decide if he/she agrees or not (Brosius et al. 2008). The second question is optional. It's an open question, which can be used to give feedback about each dust devil and its realization. This kind of feedback question offers the possibility of an individual expression of the participants opinion. It helps to avoid frustration and to provide the feeling that everything that concerns the participant can be communicated.

After these three pages, the last question of the this content question set comes up. It is a drop-down question, which asks the participant to compare the three virtual dust devils with a picture of a real dust devil. This question is used as a control question. Control questions can be found in the work of Döring and Bortz and in 'Methoden der empirischen Kommunikation' of Brosius, Haas and Koschel (Döring et al. 2015), (Brosius et al. 2008). The results of the rating of the characteristics should give an answer which dust devil seems the most realistic, if considered separately. This means that the focus is on the realization of the characteristics and each dust devil should be considered independent from the other two dust devils. Whereas, the result of the control question targets the comparison of all three dust devils to a real dust devil at once. The idea behind this question is that just because one animated dust devil seems most realistic regarding the characteristics, it doesn't have to be the most realistic one in comparison to a real dust devil.

4.1.3 Second Part

The third content question set is introduced with the title 'Second part' to show that the following questions relate to another aspect of the study (Döring et al. 2015). Section A.5.3 on the appendix contains screenshots of the pages of the third question set. The 'Second part' has its own introduction, like the paragraph of the 'First part', to provide some information to the participant that may be needed to answer the questions of the question set. Because the topic of the study isn't really common, this extra information at the beginning of the question sets is reasonable, to make sure that every participant can follow the study easily and without problems of understanding.

In this part of the study the three dust devils are shown integrated into the virtual environment of the VaMEx-VTB, which was already introduced earlier in section 2.5. Again, the following three pages of the study have an identical structure. The top of each page is filled with the current dust devil scene with the questions shown below. This time, the participant is asked if the three characteristics 'Color scheme', 'Proportions', and 'Material' of the dust devil match with the implementation of these characteristics of the virtual environment. The question is the same for all three dust devils. Also, the same bipolar rating scale is used as in the question set of the 'First part' (Döring et al. 2015). Furthermore, the second question on each page is again an open question, which allows the participant to give individual feedback for each scene.

After the individual rating of each dust devil, there is another question, which compares the three scenes of the virtual Mars environment. Each virtual environment scene has one of the three dust devils integrated. With a drop-down the participant can choose the scene that conveys him/her as the most harmonic one. This question is a control question, like the one used in the 'First part'. It is used to compare the results of the ratings of the characteristics to the direct comparison of the scenes (Brosius et al. 2008). The last question of the 'Second part' is about the use of exponential height fog. Therefore, the scene of the first dust devil integrated into the virtual environment without exponential height fog is shown again. Below, the same scene is provided with exponential height fog enabled. The participant is asked to decide which of the two scenes seems more realistic. Therefore, an attitude-question is used like recommended in 'Methoden der empirischen Kommunikation' (Brosius et al. 2008).

4.1.4 Third Part

The 'Third part' of the study is based on the fifth step of the standardized questionnaire structure by Döring and Bortz, the questionnaire feedback (Döring et al. 2015). It is used to collect some feedback for the study and to redirect the participants that used the English version to the end of the study. Therefore, the closed question ”Did you like the study?” is used as a filter question. If the participant of the English study version answers the question, he/she is directed to the last page of the study and skips the pages of the German study version.

4.1.5 Farewell

As recommended in the questionnaire structure of Döring and Bortz, the last page of the study is used to thank the participant for the participation. This signals the end of the study and works as a goodbye (Döring et al. 2015). Furthermore, the page provides a short reminder that the answers are only valid if the participant presses the ”Send” button at the end, to submit the answers.

4.2 Collected Data

In the previous section 4.1, the structure of the online questionnaire of the user study is described. This paragraph presents the raw data collected within this study. The data is organized according to the studies' structure into introduction, first part, second part, and third part. Forty-two persons participated in the study. The data of the English and German study version are summarized. Because both versions share the same structure, questions, and media, the answers are valuable for both languages. In this study five-step rating-scales are used. The scale ends are labeled with 'Disagree' and 'Agree', while all five steps are also labeled with numbers. '1' stands for 'Disagree', '2' for 'rather disagree', '3' means 'neither disagree nor agree', '4' is defined as 'rather agree', and '5' means 'Agree'. Furthermore, this study contains some open questions, which could be used by the participants to give individual feedback. Because the amount of answers is pretty low and their content matches the results of the quantitative questions, they won't be considered in the following. The tables containing the results for each answer of the study are provided in appendix A.6.
The next and last section of this chapter, 4.3, contains the analysis of the collected data of the study.

4.2.1 Introduction

In the beginning, forty-one of the forty-two participants choose the German version of the study and only 1 decides to go for the English one. The first content question set is used to offer an

easy start into the study and to gather some statistic data about the participants. According to the answers of the first question about the age of the participants, 71.43%, in other words thirty of the forty-two persons, are between eighteen and thirty years old. Four participants, which is 9.52%, are between thirty and forty and eight, 19.05%, are older than forty.
The second question of the first question set is 'In which professional field do you work?'. Because the answers are wide spread, the highest number of participants working in one professional field are eight persons in the computer science & information technologies field, followed by Marketing, PR & Design with six workers.
For the last question of the first question set, which is used to make a smooth shift from the statistical data collection to the actual topic of the study, figure 4.1 shows that just 28.57% have ever heard about dust devils on planet Mars before the start of this study, which are twelve of forty-two participants.

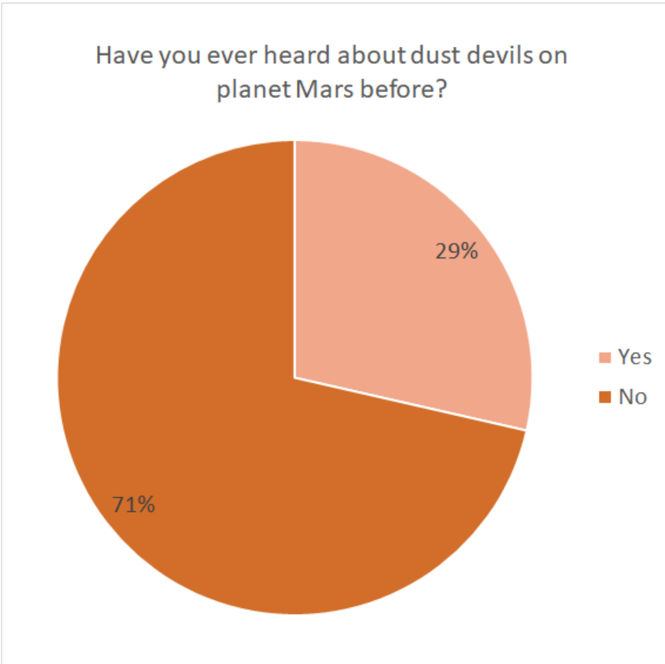


Figure 4.1 Circle chart showing the answers of the question: 'Have you ever heard about dust devils on planet Mars before?'

4.2.2 First Part

The first dust devil, that is rated, is the first dust devil that is implemented in section 3.1.1.3.2. It shows a total arithmetic mean of 3.9, which means that the participants 'rather agree' that the dust devil fulfills the characteristics of a real dust devil. The rated characteristics are 'Upward movement', 'Spiral movement', 'The height is about five times larger than the width', 'Higher particle density at the bottom', 'Vertical columnar core', 'Tilts towards the direction of motion', and 'Narrow base & broad top'. As shown in figure 4.2 all characteristics have an arithmetic mean between 3.95 and 4.48 except one. 'Tilts towards the direction of motion' only has an average of 2.76, which means it is the only characteristic, where participants 'neither disagree nor agree' that the dust devil fulfills it.

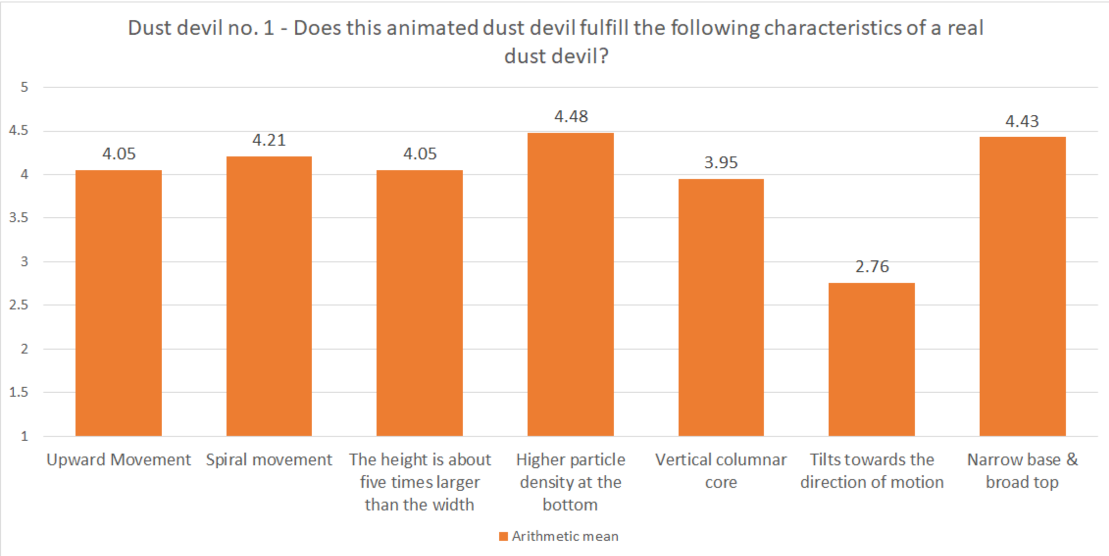


Figure 4.2 Diagram showing the arithmetic mean of the answers for the first dust devil regarding the question: 'Does this animated dust devil fulfill the following characteristics of a real dust devil?'

The standard deviation values of the characteristics range from 0.63 to 1.09. This is shown in the tables provided in section A.6.2.1 of the appendix. The characteristic 'The height is about five times larger than the width' has the highest standard deviation with 1.09. In figure A.28 the total numbers of this characteristic show that about 88% of the ratings can be found in the range of the standard deviation starting from the arithmetic mean of 4.05, from 2.96 to 5.14. Furthermore, the distribution of the ratings is focused on '4' and '5'. A similar distribution shows the summary of the ratings of the characteristic 'Upward movement'. 78% of the participants rated with 'rather agree' and 'agree' for this characteristic, though it still shows a standard deviation of 1.02. The medians of the characteristics resemble the values of the arithmetic means. 'Higher particle density at the bottom' and 'Narrow base & broad top' each have a median of 5, 'Tilts towards the direction of motion' shows a median of 3, while the other four characteristics all have a median of 4. The modes of the characteristics are even higher in comparison. 'Tilts towards the direction of motion' has a mode of 3 and 'Spiral movement' and 'Vertical columnar core' a mode of 4. For 'The height is about five times larger than the width', the participants give the same amount of 'rather agree' and 'agree' ratings. For the other characteristics 'agree' is rated most frequently. Overall, the results of the ratings of the first dust devil are quite high. This is underlined by the fact, that for all characteristics summarized just four 'disagree'-ratings are given.

Second, the second dust devil described in section 3.1.1.3.3 is rated. The rated characteristics are the same as in the question before. In total, the characteristics of the second dust devil show an average of 3.69. Rounded up, the result can still be counted as a 'rather agree', which means that the participants rather agree that the dust devil meets the requirements of a real dust devil than disagree. All characteristics summarized have a median of 4 and a mode of 5. Figure 4.3 shows that only three of the seven characteristics have an arithmetic mean higher than '4'.

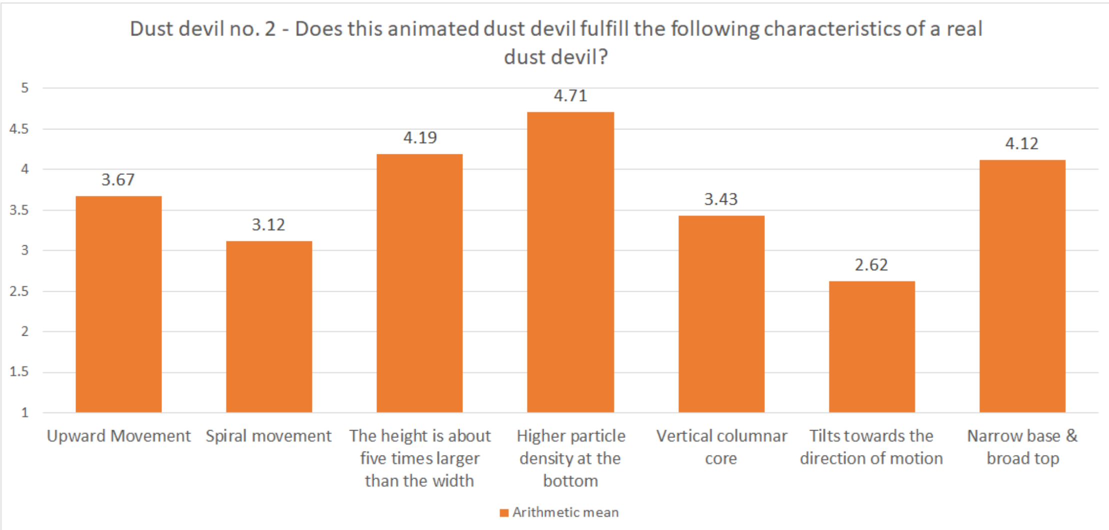


Figure 4.3 Diagram showing the arithmetic mean of the answers for the second dust devil regarding the question: 'Does this animated dust devil fulfill the following characteristics of a real dust devil?'

The rating of the 'Upward movement', with an arithmetic mean of 3.67, can be rounded up to a value of '4', which is equivalent to the statement that the participants 'rather agree' that the dust devil fulfills the characteristic. 'Spiral movement' and the 'Vertical columnar core' are both rated as 'neither disagree nor agree' instead. Figure A.34 shows a mostly similar distribution of the ratings 'rather disagree', 'neither disagree nor agree', and 'rather agree' for the 'Spiral movement', which causes the standard deviation value of 1.2. Also, the number of ratings in figure A.37 shows that ten people rated the characteristic 'Vertical columnar core' with a 'rather disagree', while twenty choose 'rather agree'. This results in a standard deviation value of 1.05. An overview of the distribution of the ratings, the arithmetic means and the standard deviations is provided in section A.6.2.2 in the appendix. Similar to the first dust devil, the characteristic 'Tilts towards the direction of motion' is the only characteristic of the second dust devil with an arithmetic mean lower than '3'. This value can still be ranked as 'neither disagree nor agree' if rounded up.

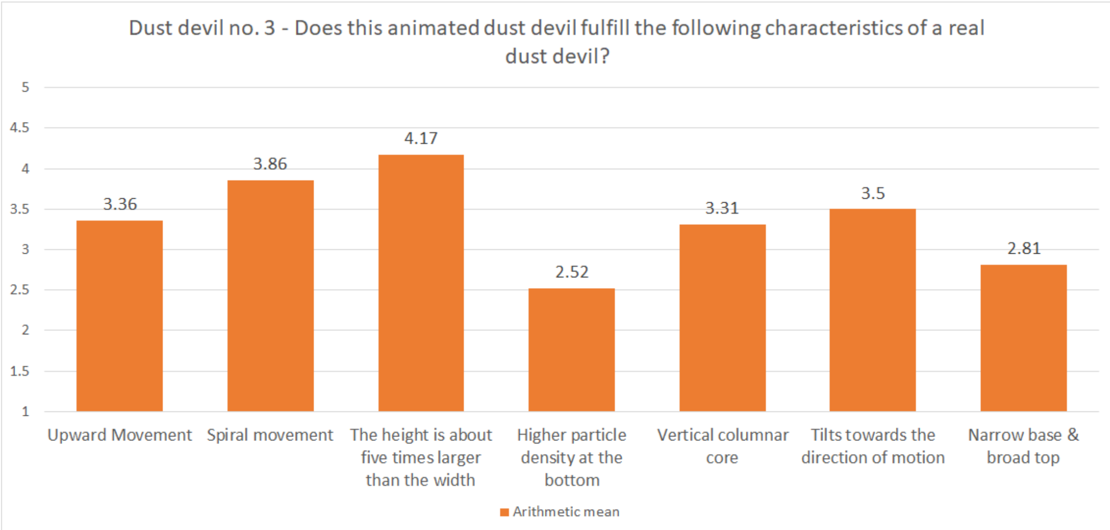


Figure 4.4 Diagram showing the arithmetic mean of the answers for the third dust devil regarding the question: 'Does this animated dust devil fulfill the following characteristics of a real dust devil?'

The third dust devil that is provided in the user study is built with Blender and its implementation process is described in section 3.1.2. As explained in the structure in section 4.1, the third dust devil is rated regarding the same characteristics as the two dust devils before. The arithmetic mean of all characteristics of the third dust devil summarized is 3.36. This is the lowest value compared to the arithmetic means of the first and second dust devil. Also, it is the only one of the dust devils that the participants rate with 'neither disagree nor agree' regarding the question if it fulfills the characteristics of a real dust devil. Furthermore, all characteristics of the third dust devil have a standard deviation higher than 1. This can be seen in the tables in section A.6.2.3 of the appendix. The characteristics 'Upward movement' in figure A.40 and 'Tilts towards the direction of motion' in figure A.45 show the most significant distributions. 'Tilts towards the direction of motion' has an arithmetic mean of 3.5. As is can be seen in figure 4.4, the characteristic 'The height is about five times larger than the width' has the highest arithmetic mean of all characteristics of the third dust devil with a value of 4.17. 'Spiral movement' shows an average of 3.86. Summarized, three of the seven characteristics are rated as 'rather agree'. The characteristics 'Higher particle density at the bottom' and 'Narrow base & broad top' both have an arithmetic mean lower than '3', but still, with averages of 2.81 and 2.52, they can be rounded up to a value of 'neither disagree nor agree'. Furthermore, the ratings 'neither disagree' and 'agree' are the most frequent ones.

Compared to each other, the first dust devil has the highest arithmetic mean of all seven characteristics summarized, the second dust devil the second highest and the third dust devil the lowest. The first dust devil has the best rating regarding the characteristics 'Upward movement' (4.05), 'Spiral movement' (4.21), 'Vertical columnar core' (3.95) and 'Narrow base & broad top' (4.43). This means that it shows the highest ranking for four of the seven characteristics. Whereas, the second dust devil has the best rating regarding the characteristics 'The height is about five times larger than the width' (4.19) and 'Higher particle density at the bottom' (4.71). The third dust devil, in turn, has only one characteristic that is ranked higher than the other dust devils, 'Tilts towards the direction of motion' (3.5). Regarding the standard deviation, the first and second dust devil show lower values than the third dust devil. The range of the standard deviations of the single characteristics of the first dust devil goes from 0.63 to 1.09. Only two values are higher than 1. In comparison, the range of the second dust devil goes from 0.55 to 1.2, with three values higher than 1. The standard deviations of the third dust devil are all higher than 1, with a range from 1.04 to 1.24.

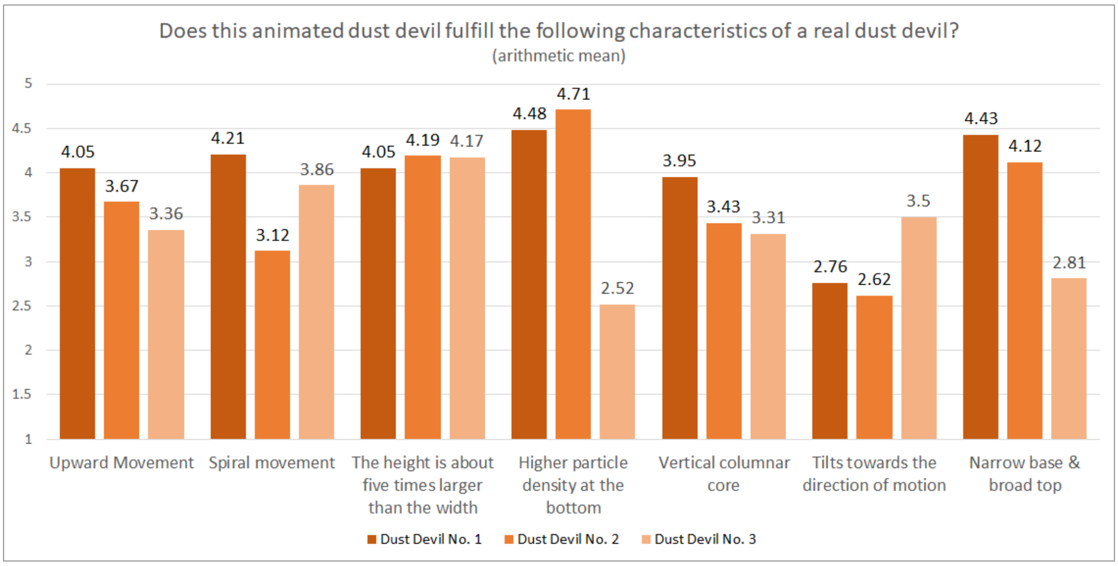


Figure 4.5 Comparison of the arithmetic means of the three dust devils regarding the question: 'Does this animated dust devil fulfill the following characteristics of a real dust devil?'

Still, most of the results of each characteristic regarding all three dust devils are quite similar. This can be seen in figure 4.5. It shows the arithmetic means of each characteristic of all three dust devils compared to each other. An exception represents the rating of the 'spiral movement' of the second dust devil, which has an average of 3.12, while the first dust devil has 4.21 and the third one 3.86. Another outlier is 'the higher particle density at the bottom' arithmetic mean of the third dust devil, which shows a difference of almost two full rating-scale steps compared to the other two dust devils. Also, the 'narrow base & broad top' arithmetic mean of the third dust devil is significant lower, with a value of 2.81, than the values of 4.43 and 4.12 of the first and second dust devil. The last notable exception represents the arithmetic mean of the characteristic 'Tilts towards the direction of motion' of the third dust devil. With 3.5 it is more than 0.7 higher than the averages of the first and the second dust devil.

The last question of the first content question set is used as a control question to check whether the results of the valuation of the characteristics of the dust devil do match the results of a direct comparison with a real dust devil. Figure 4.6 shows that the second dust devil is chosen as the most realistic dust devil in comparison to the picture of a real dust devil, that was provided in this question. It receives more than 50% of the votes of the forty-two participants. The third dust devil has 36%, which means the second place regarding the comparison to the real dust devil. Therefore, the first dust devil seems the least realistic one in compared to a real dust devil. This result differs from the result of the rating of the characteristics.

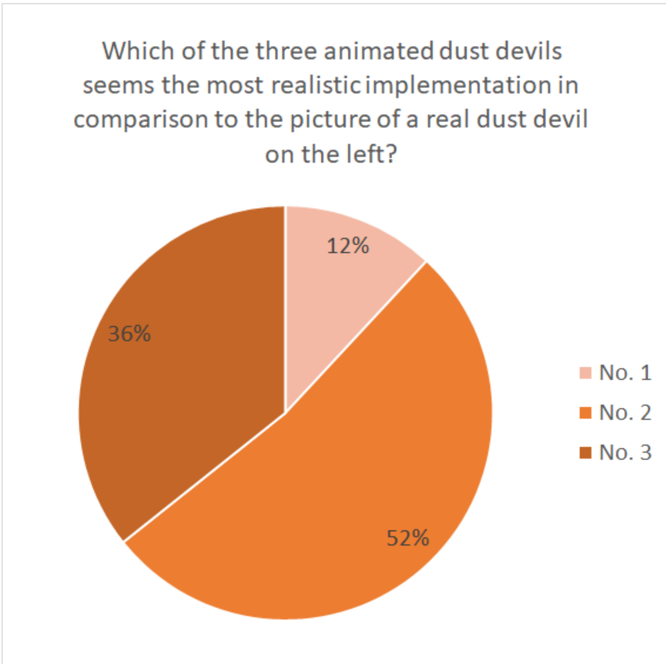


Figure 4.6 Circle chart showing the answers of the question: 'Which of the three animated dust devils seems the most realistic implementation in comparison to the picture of a real dust devil on the left?'

4.2.3 Second Part

In the third content question set, with the title 'Second part', the three dust devils, implemented in section 3.1, are shown integrated into the virtual Mars environment of the VaMEx-VTB. They are rated regarding the question if the characteristics 'Color scheme', 'Proportions' and 'Material' of the dust devils match these characteristics of the environment. The dust devils are shown in the same order as in the 'First part' of the study.

Figure 4.7 provides an overview of the arithmetic means of the characteristics regarding the first dust devil. All three arithmetic means lie inbetween the values 3.5 and 4.4, which is synonymous with 'rather agree'. This means that the average of the participants has the opinion that the characteristic of the dust devil matches the one of the virtual environment. 'Color scheme' shows an arithmetic mean of 4.29, 'Proportions' of 3.79, and 'Material' is rated with an average of 3.64. Regarding the standard deviation, all three characteristics have a value lower than 1. These values can be found in the tables in section A.6.3.1 in the appendix of this thesis. Furthermore, each characteristic has a median and a mode of 4. For example, regarding 'Color scheme' and 'Proportions', exactly 50% of the participants rate with 'rather agree'. The average of all three characteristics of the first dust devil summarized is 3.9. This shows that the participants 'rather agree' that the characteristics of the first dust devil and the virtual environment match.

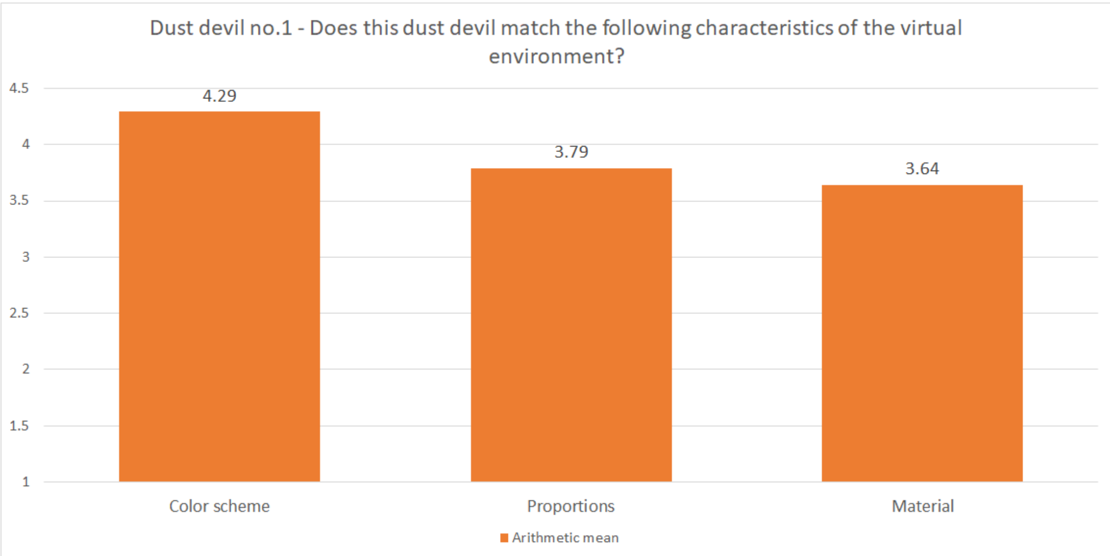


Figure 4.7 Diagram showing the arithmetic mean of the answers for the first dust devil regarding the question: 'Does this dust devil match the following characteristics of the virtual environment?'

Having a look at the second dust devil integrated into the virtual environment, the arithmetic mean of all three characteristics show a value between 'neither disagree nor agree' and 'rather agree'. This can also be seen in figure 4.8. While the average of the 'Color scheme' and the 'Proportions' ratings of 3.67 and 3.98, can still be rounded up to 4 and are therefore rated as 'rather agree', the average of 3.43 of 'Material' stands for 'neither disagree nor agree'. Still, both, the median and the mode of all three characteristics, result in a value of 4. This means that the rating of 'rather agree' is the most frequent rating. Furthermore, the standard deviations of the characteristics 'Color scheme' and 'Material' are similar, with values of 1.2 and 1. Whereas, the standard deviation of the 'Proportions' characteristic has a value of 0.74. The total average of all ratings regarding the three characteristics summarized comes to 3.69. This means that the participants 'rather agree' that the characteristics of the second dust devil match them of the virtual Mars environment. Rating results, standard deviation, and arithmetic mean are also presented in section A.6.3.2 of the appendix.

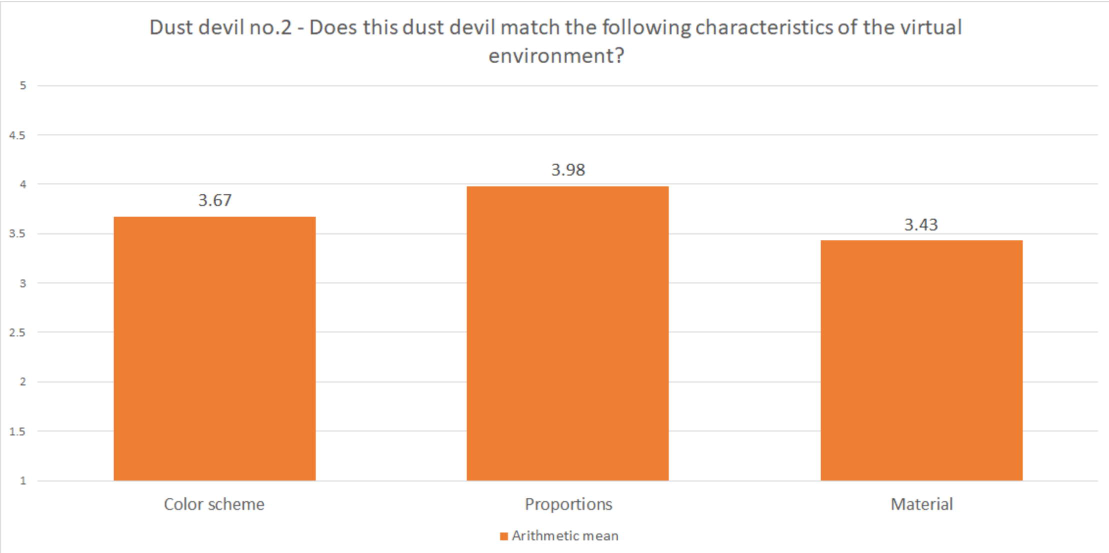


Figure 4.8 Diagram showing the arithmetic mean of the answers for the second dust devil regarding the question: 'Does this dust devil match the following characteristics of the virtual environment?'

The third and last dust devil that is shown integrated into the virtual environment in this study, has an average rating of 2.57 for 'Color scheme', 3.48 for 'Proportions' and 2.79 for 'Material'. An overview of the arithmetic means can be found in figure 4.9. This means the participants of the study 'neither disagree nor agree' that all three characteristics of the dust devil match with the virtual environment. The total numbers, that can be seen in the tables in section A.6.3.3, show that 'Color scheme' has a mode of 2, while the mode of the other two characteristics is 3. While only nine participants rate 'Proportions' with 'disagree' or 'neither disagree', the amounts of ratings for 'neither disagree nor agree', 'rather agree' and 'agree' are quite similar. 'neither disagree nor agree' has twelve ratings, 'rather agree' eleven, and 'agree' ten ratings. In comparison, only eleven participants rate the 'Material' with 'rather agree' or 'agree' and ten people the 'Color scheme'. The rest of the participants rate 'Material' and 'Color scheme' between 'disagree' and 'neither agree nor disagree'. This distribution of the ratings can also be seen in the standard deviations. All three characteristics show a standard deviation higher than 1. With a 2, the 'Color scheme' also has the lowest median. The 'Material' shows a median of 3 and the 'Proportions' of 3,5. The arithmetic mean of all ratings of the three characteristics summarized is a 2.94. So, the participants 'neither disagree nor agree' that the characteristics of the third dust devil match the characteristics of the virtual environment.

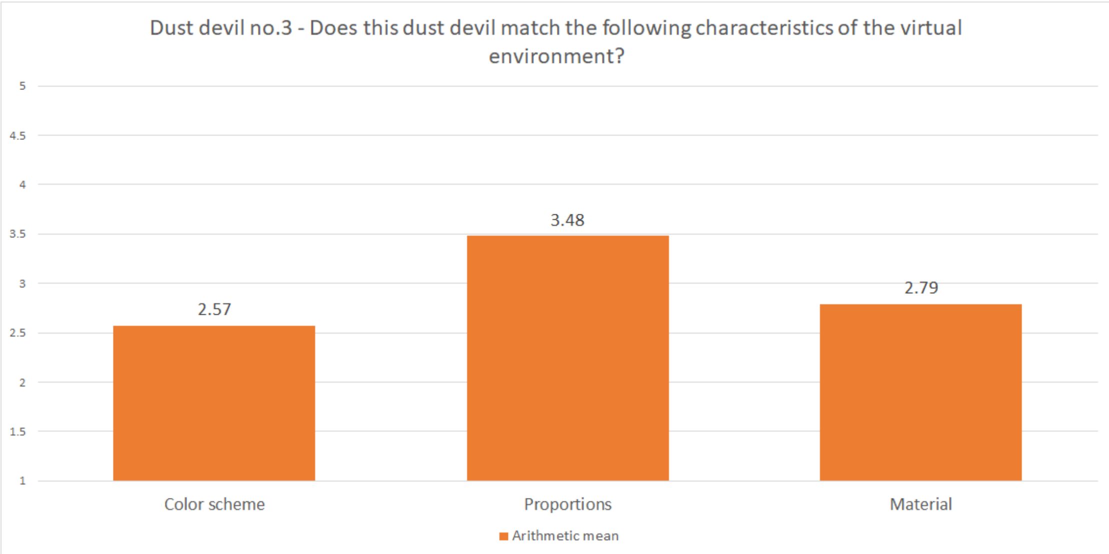


Figure 4.9 Diagram showing the arithmetic mean of the answers for the third dust devil regarding the question: 'Does this dust devil match the following characteristics of the virtual environment?'

In comparison, the first dust devil, with all three arithmetic means classified as 'rather agree', has the highest total average of the three dust devils, regarding the question 'Does this dust devil match the following characteristics of the virtual environment?'. The second dust devil is in second place, with a total average of 3.69 and two of three arithmetic means rated as 'rather agree'. The third dust devil comes last with all three arithmetic means classified as 'neither disagree nor agree' and a total average of 2.94. As shown in figure 4.10 the first dust devil has the highest ratings according the characteristics 'Color scheme' and 'Material', while the second dust devil scores best for the characteristic 'Proportions'. The third dust devil has the lowest arithmetic mean for all three characteristics. Furthermore, the third dust devil shows the highest values regarding the standard deviation. Its values range from 1.09 to 1.19. Whereas, the values of the second dust devil range from 0.74 to 1.02 and the first dust devil shows the lowest standard deviations with a range from 0.7 to 0.96.

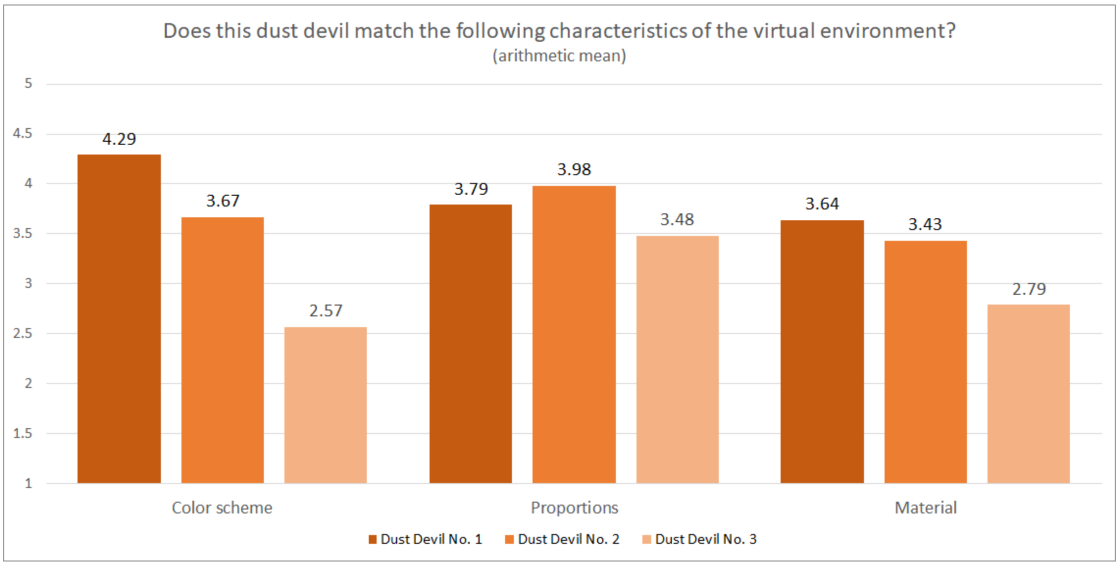


Figure 4.10 Comparison of the arithmetic means of the three dust devils regarding the question: 'Does this dust devil match the following characteristics of the virtual environment?'

The control question 'Which of these three scenes conveys the most harmonic overall impression in your opinion?' is used to compare its results with the outcomes of the questions if the characteristics of the dust devil match the characteristics of the virtual environment of the VaMEx-VTB. As shown in figure 4.11, the first scene, with the first dust devil integrated, receives 40.48% of the votes. Exactly 50% of the participants vote for the second dust devil and 9.52% vote for the last scene with the third dust devil integrated. The total numbers can be found in figure A.57. This result shows that the scene with the second dust devil is rated as the most harmonic one of the three.

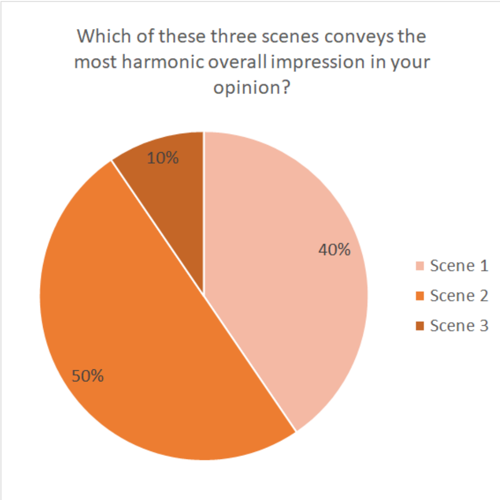


Figure 4.11 Circle chart showing the answers of the question: 'Which of these three scenes conveys the most harmonic overall impression in your opinion?'

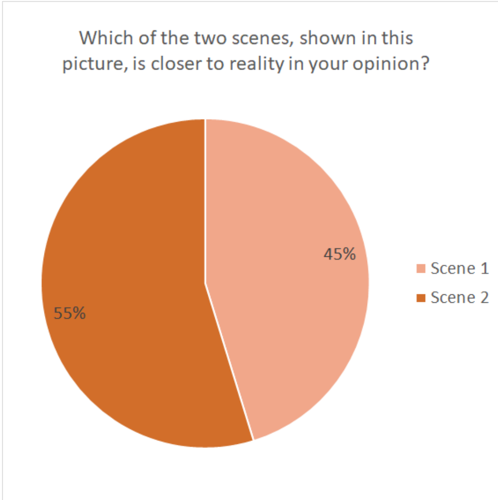


Figure 4.12 Circle chart showing the answers of the question: 'Which of the two scenes, shown in this picture, is closer to reality in your opinion?'

'Which of the two scenes, shown in this picture, is closer to reality in your opinion?' is the last question of the 'Second part' of the study, which is also the last content question set. It refers to the use of exponential height fog in the scene. Therefore, scene one shows the scene of the first dust devil integrated into the virtual Mars environment without exponential height fog and the second scene with exponential height fog. In figure 4.12 can be seen that scene one gets 45.24% of the votes and scene two gets 54.76%. Having a look at total numbers in figure A.58, the second scene wins the voting with four votes difference.

4.2.4 Third Part

The last part of the study is used to gather some feedback about the study. Therefore, 'Did you like the study?' is the only obligatory question. As shown in figure **??**, 95.24% of the participants answer with 'Yes' and 4.76% with 'No'. In total numbers does that mean that only two participants doesn't like the study.

4.3 Analysis

After the presentation of the collected data in section 4.2, this section is about the analysis of these data. Again, the section is organized according to the structure of the user study.
Next, the results of this thesis, including the outcomes of the implementation chapter and the findings of this study, are provided in chapter 5.

4.3.1 Introduction

At the beginning of the study, the statistical data is gathered, to offer an easy start into the study as recommended in 'Forschungsmethoden und Evaluation' (Döring et al. 2015). The high percentage of participants between 18 and 30 can be explained with the fact that the people that participate in the study are collected through social media and online messenger. Because there are no special limitations in the recruiting of the participants, the high distribution of the professional fields is plausible. The highest percentages in the field of computer science and design are reasonable, because the topic of the study is also classified in the computer science and design sector. There are no significant trends in the collected data regarding the different age groups or professional fields. To check whether these groups would show any tendency the number of participants needs to be higher, to provide larger groups. The highest number of participants in one professional field is eight people that work in the computer science and information technology sector. The question 'Have you ever heard about dust devils on planet Mars before?' shows that about 29% of the participants have ever heard about dust devils on planet Mars before. As this question doesn't give any details about the actual knowledge of a participant about this topic, except that he/she has heard about it, it should not be used to compare these participants with the ones that answered with 'No'. To use the differences in previous knowledge, a more complex question set would need to be integrated to check the amount of knowledge, which goes beyond the scope of this study. An information page is provided to every participant, doesn't matter which answer he/she choose for this question, to make sure that all participants have the same basic knowledge about dust devils on planet Mars. The percentage of about 71% that had never heard about dust devils on planet Mars before, supports the integration of this information page.

4.3.2 First Part

The first three questions of the first content question set of the study, called the 'First part', have an identical structure to provide a reasonable base for the comparison of the three dust devils. Each dust devil is rated regarding seven different characteristics, based on the list of characteristics of a real dust devil provided in section 2.1.1.1. These are 'Upward movement', 'Spiral movement', 'The height is about five times larger than the width', 'Higher particle density at the bottom', 'Vertical columnar core', 'Tilts towards the direction of motion', and 'Narrow base & broad top'.

Regarding the summary of all ratings of the seven characteristics and the total arithmetic mean of 3.99, the first dust devil has the highest ratings. Five of the seven characteristics show a standard deviation lower than 1, which shows that the distribution of the ratings is focused close to the value of the arithmetic mean. Even if the standard deviations of the characteristics 'Upward movement' and 'The height is about five times larger than the width' are both slightly higher than 1, does a closer look at the total numbers in figure A.26 and A.28 show that the distribution of the ratings focuses at '4' and '5'. This almost even number of 'rather agree' and 'agree' ratings isn't clearly visible by looking at the arithmetic means of 4.05. Still, it should be considered that the rating of both characteristics has a noticeable strong positive tendency. The first dust devil is the one built with Unreal Engine 4 and equipped with the surface material, which implementation is described in section 3.1.1. Its shape is based on two vector fields. Thanks to the semi-solid look of the particles that form the dust devil according to the vector fields, this basic structure can easily be recognized. The visible basic structure is probably the reason why the single characteristics of the dust devil are also easy to recognize and therefore easy to rate. This, in turn, can be a reason for the relatively high ratings.

In section 3.1.1 the implementation of the second dust devil is shown. The first and the second dust devil have many things in common. They are both build with Unreal Engine 4, use the same vector fields, and the particles systems have quite similar main settings. The biggest difference between these two dust devils is the material. While the first dust devil got a surface material applied to it, the particle systems of the second dust devil uses a volume material. This volume material generates particles, which look like little dust spheres. Because these particles have no clear outlines, the transition between them is smooth. This causes the dust devil to look like one interrelated dust cloud, which makes the outlines and the structure of the dust devil harder to recognize. The fact that the basic structure and its shape are blurred can be a reason why the total arithmetic mean of the second dust devil of 3.69 is lower than the one of the first dust devil, even if their basic structure is the same. This theory is supported by the results of the ratings of the characteristics 'Upward movement', 'Spiral movement' and 'Vertical columnar core' of the second dust devil. The ratings are lower than the one of the characteristics of the first dust devil, despite the fact that the vector fields and its rotation rate is identical for the first and the second dust devil. Having a look at the standard deviation of these three characteristics, it shows that three of the seven values are higher than 1. The standard deviations of the other four characteristics are lower than 1, which supports the representative function of their arithmetic mean. 'Spiral movement' has the highest standard deviation with 1.2. The almost identical numbers of ratings for 'rather disagree', 'neither disagree nor agree', and 'rather agree' show that the participants' opinions are divided. 'Rather agree' has only one rating more than 'rather disagree', while 'agree' earned two ratings more than 'disagree'. This divided valuation with a slight positive tendency is shown in the arithmetic mean of 3.12. Therefore, the arithmetic mean is still representative, despite the relatively high standard deviation. The second highest standard deviation presents the characteristic 'Upward movement' with 1.08. This value is caused again by a mostly even distribution of three different ratings. In this case, the ratings are 'neither disagree nor agree', 'rather agree', and 'agree'. The fact that the number of ratings for 'rather agree' and 'agree' represents almost 60% of the total number of ratings makes clear that this characteristic has a strong positive tendency. Therefore, its arithmetic mean of 3.67 could be considered with the rounded value of '4' regarding direct comparison to the other dust devils. The standard deviation of 1.05 of the characteristic 'Vertical columnar core', in turn, is caused by the clearly split opinion of the participants. In comparison to the characteristic 'Spiral movement', the neutral value 'neither disagree nor agree' has only six ratings, while 'rather disagree' has ten and 'rather agree' twenty. Still, the arithmetic mean of 3.43 is representative, because it underlines the divided valuation, but also shows the positive tendency. A clearer result could probably be achieved with a higher number of participants. With a difference of 0.3 in the total arithmetic mean of all characteristics summarized, compared to the first dust devil, and an average rating of 'rather agree' for four of seven characteristics, the second dust devil is still classified as 'rather agree' in total. Therefore, the participants rather agree that the first and second dust devil fulfill the characteristics.

The third dust devil shows a total arithmetic mean of all characteristics summarized of 3.36. This doesn't seem too low compared to the value of the second dust devil. The difference between the average value of the third and second dust devil is 0.33. Compared to the first dust devil, the difference to the third dust devil is 0.63. Also, the standard deviation of all seven characteristics is higher than 1. Having a look at the tables in section A.6.2.3 of the appendix, the characteristics 'Spiral Movement', 'The height is about five times larger than the width', 'Higher particle density at the bottom', and 'Narrow base & broad top' show clear negative or positive distribution tendencies regarding the rating. The arithmetic mean of 'The height is about five times larger than the width' represents the positive tendency with a value of 4.17. Whereas, the arithmetic means of 'Higher particle density at the bottom' and 'Narrow base & broad top' could be rather classified as 'rather disagree' considering the numbers of ratings of '1' and '2' in figure A.43 and A.46. Also, the arithmetic mean of 3.86 of the 'Spiral movement' doesn't show clearly that 66% of the participants rated it with 'rather agree' and 'agree'. The high standard deviation values of the other three characteristics 'Upward Movement', 'Vertical columnar core', and 'Tilts towards the direction of motion' are caused by divided opinions of the participants. All three characteristics show similar numbers of ratings for four of the five rating options. 'Rather disagree','neither disagree nor agree', 'rather agree', and 'agree' don't show a significant difference in the number of rating. Still, the fact that 'disagree' doesn't count more than two ratings for each of the characteristics, the tendency of the rating shifts in the positive range. This positive tendency is represented in all three arithmetic means. Still, the divided opinion of the participants regarding the rating of the characteristics of the third dust devil, causes relatively low averages in total. The third dust devil is the only one of the three dust devils that is ranked as 'neither disagree nor agree' in the total average of all characteristics summarized. Different to the other two dust devils, the third one isn't implemented with Unreal Engine 4, instead the 3D creation software Blender is used. A description of the implementation process can be found in section 3.1.2. A particle system, influenced through force field, provides the base structure for the shape of the dust devil. Because the smoke of the used fluid simulation gets generated at the location of every particle, the distribution is quite even. The first and the second dust devil use two particle emitters with different lifetimes and a third emitter that produces a dust cloud close to the ground, to provide a higher particle density at the bottom of the rotating column of dust. As the third dust devil uses only one emitter and has no variation in the dissolution time of the smoke, the density of the dust column stays mostly unchanged until the top. That's probably the reason why the rating for the characteristic 'Higher particle density at the bottom' of the third dust devil is significantly lower than the results of the first and second dust devil. The characteristic has an average rating of 2.52, while the first dust devil got 4.48 and the second one 4.71. Furthermore, the lower rating regarding the 'narrow base & broad top' could also be explained by the different implementation methods. As described in section 3.1.1, the first and second dust devil use vector fields based on a helix shape. These vector fields provide the shape of the particle system. In other words, the vector fields easily form the dust devils' smaller bases and wider tops. The behavior of the particle system of the third dust devil is influenced through force fields. These are used to track the particles upwards, force them to a spiral movement and to push them apart when they reach the top of the dust devil, to make the top broader than the base. Different to the particles that follow the direction and strength of the vector field, the force fields work like winds that influence the movement of the particles. Therefore, it is plausible that the shape of the third dust devil won't show the same accuracy as particles of the first and second dust devil and therefore results in lower ratings of this characteristic. An advantage of the missing accuracy is that the particles move in the direction they get tracked and won't follow a concrete form. The result is that the column of dust of the third dust devil looks like it tilts according to the rotational movement. Thanks to this, the third dust devil has the highest rating for the characteristic 'Tilts towards the direction of motion', despite the spread distribution of the ratings. The difference is more than 0.7 compared to the averages of this characteristic of the first and second dust devil.

'Which of the three animated dust devils seems the most realistic implementation in comparison to the picture of a real dust devil on the left?' is used as a control question to check whether the results of the characteristics' ratings match the results of the direct comparison to a real dust devil. In other words, the question is if the dust devil that is rated highest regarding the fulfilled characteristics of a real dust devil also the one that seems most realistic compared to a real dust devil. Regarding the fulfilling of the characteristics of a real dust devil, the first dust devil has the highest arithmetic mean, the second dust devil is in second place and third dust devil shows the lowest average rating. Whereas the second dust devil is rated as the most realistic one compared to a real dust devil, with the third dust devil following in second place and first dust devil having the lowest number of votes. The first dust devil has the fewest votes for this question, even though it is rated the one that fulfills the characteristics of a real dust devil best. A possible explanation for this result could be the different materials of the dust devils. Both, the second and the third dust devil use a kind of smoke or fog material which can also be used to imitate dust. As described in section 3.1.1.3.3, the second dust devil has a volume material applied to its particle system, which causes the particles to look like little dust spheres. This results in blurred transitions between the single particles, so the particle system looks like one big dust cloud moving inside the vector fields' structure. The look of the third dust devil is based on fluid simulation. Instead of particles, the dust devil consists of smoke spheres that are generated according to the particle system that works as a base structure. The result looks like a homogenous mass of dust formed like a dust devil. Its implementation is described in detail in section 3.1.2. The first dust devil has a surface material applied to it, which causes the particles to have a semi-solid look. This doesn't create the look of one dust cloud, but a mass of single dust particles. As it can be seen in figure A.13, the sand particles of the real dust devil don't look like many single particles. Instead, they lose their outlines and become one big cloud that moves together. Therefore, the second and third dust devil fulfill this feature better than the third dust devil. The fact that the second dust devil has more votes than the third dust devil can be explained with the results of the previous questions regarding the fulfilling of the characteristics of a real dust devil. Even if the third dust devil maybe matches the look of a dust cloud, the second dust devil got higher ratings for most of the characteristics. This means, the second dust devil fulfills the characteristics of a real dust devil better than the third dust devil and furthermore looks like one dust cloud instead of single particles. It can be concluded, that in a direct comparison to a real dust devil, the material gets weighted more than other characteristics.

4.3.3 Second Part

In the 'Second part' of the study, the focus is on the three dust devils integrated into the virtual Mars environment of the VaMEx-VTB. Just like in the previous content question set, the first three questions of the 'Second part' have an identical structure to provide the best possible comparison. Each of the three dust devils is rated regarding the characteristics 'Color scheme', 'Proportions' and 'Material'. The aim is to rate if the implementation of the characteristic regarding the dust devil, matches the implementation of these characteristic of the virtual environment. For example, if the material that is used for the dust devil matches the material that is used for the virtual Mars environment. The order of the dust devils is the same as in the 'First part', to keep the structure of the study clear.

Again, as in the 'First part', the first dust devil has the highest total arithmetic mean of the ratings of the three characteristics summarized, with 3.9. In detail, the first dust devil shows the highest rating regarding 'Color scheme' and 'Material'. Because the standard deviations of all three characteristics is lower than 1 their arithmetic means are considered as representative. The high rating of the 'Color scheme' can be explained by the fact that the first dust devil is also built with Unreal Engine 4 and even in the project of the VaMEx-VTB (2.5). Therefore, the color of the material, used for the particle system of the first dust devil, is picked directly out of the virtual environment to match its color scheme. The fact that the rating doesn't reach 'agree' is probably because the small particles react different to the lighting. Also, as it is not a big solid surface, but rather many tiny solid surfaces, the color of the particles appears differently than the one of the landscape. The 'Material' characteristic of the first dust devil also shows the highest rating compared to the other two dust devils regarding the matching effect towards the virtual environment. Even though, the first dust devil has the fewest votes being compared to a real dust devil in the previous content question set and the influence of the material is mentioned as a possible reason for this result. But, the whole virtual environment of the VaMEx-VTB consists of solid surfaces and therefore has kind of its own style. Therefore, the first dust devil, with its semi-solid particles, matches the style of the environment better than the fog and smoke particles of the other two dust devils.

In comparison, the second dust devil shows a lower arithmetic mean for the 'Material', even if it is just a difference of 0.21. This value causes the 'Material' of the second dust devil to be rated as 'neither agree nor disagree' instead of 'rather agree' like the first dust devil. The standard deviation of the characteristic shows a value of 1. Even if this value is relatively high, the distribution of the ratings regarding the 'Material' shows a clear positive tendency. Almost 60% of the ratings for this characteristic are 'rather agree' or 'agree', which is not clearly noticeable in the arithmetic mean of 3.43. A reason for the eighteen participants that voted lower than 'rather agree' and therefore caused the final arithmetic mean, could be the volume material of the second dust devil. This volume material results in the blurred look of the dust devil. A blurry style like this can't be seen anywhere else in the virtual Mars environment of the VaMEx-VTB. Therefore, the dust devil kind of stands out, which could be the reason why the first dust devil, with its surface material that integrates smoother into the environment, has a better rating. Even though, the second dust devil was also built inside Unreal Engine 4 and the color for the material is likewise picked directly from the virtual environment, the arithmetic mean of the 'Color scheme' of the second dust devil is 0.55 lower than the one of the first dust devil. The standard deviation of the characteristic is 1.02. Despite the relatively high value, the distribution of the ratings shows a clear tendency, which is represented by the arithmetic mean of 3.67. A reason for the low arithmetic mean could be, again, the volume material, because it reacts differently to the lighting than the rest of the virtual landscape. Put inside the landscape the color of the dust looks way darker than in the material editor. For example, if another light is put inside the virtual environment, shining directly at the dust devil, it would probably look brighter and therefore match the color scheme better. This adjustment isn't made because of the movement of the dust devil in the simulation, when it moves randomly inside the landscape it would be hard to keep the lighting conditions. The characteristic 'Proportions' shows a high arithmetic mean of 3.98. This value is supported by a low standard deviation. Therefore, the participants 'rather agree' that the proportions of the second dust devil match the proportions of the virtual environment.

The third dust devil shows the lowest arithmetic mean for all three characteristics. Also, each characteristic has a standard deviation higher than 1 and, which is higher than the standard deviations of every characteristics of the other two dust devils. In general, this shows that the distribution of the ratings is higher. Having a closer look at the tables of the gathered data of the characteristic ratings in section A.6.3.3, each characteristic still shows a clear positive or negative tendency. The arithmetic means of 'Proportions' and 'Material' support this tendency, which makes the arithmetic mean representative for the distribution of the ratings. Whereas, the arithmetic mean 2.57 of 'Color scheme' should be considered closer to 'rather disagree' than to 'neither disagree nor agree'. Almost 60% of the participants rate this characteristic with a '1' or '2'. Compared to the other dust devils, the arithmetic mean of 'Color scheme' is 1.1 lower than the one of the second dust devil and even 1.72 lower than the one of the first dust devil. This is the highest difference in ratings regarding all characteristics in the whole study. A reason for this significant difference can be the fact that the third dust devil isn't built inside Unreal Engine 4, but with the 3D creation software Blender. The integration of the third dust devil into the virtual environment is made with the raster graphics editor Photoshop, as there is no way to integrate an animated smoke simulation from Blender into Unreal Engine 4. Even if the color of the third dust devil is picked from the color scheme of the virtual environment of the VaMEx-VTB, it looks way to bright when integrated. Build in Blender, the third dust devil has its own lighting, which makes it difficult to match it with the lighting of the virtual Mars environment. Also, the animation of the third dust devil has a white background. As the smoke of the dust devil isn't solid the white background shines through the smoke. It is impossible to separate the whole white background color from the smoke of the dust devil without a high workload that exceeds the requirements of this thesis. That's the reason why the third dust devil looks brighter and even a bit shiny on the outlines and therefore that the color scheme of the third dust devil doesn't fit as well into the virtual environment as the color scheme of the first and second dust devil. The lower rating regarding the material of the third dust devil in comparison to the material of the virtual environment can also partly be reasoned by the mismatch of the brightness as a result of the Photoshop-integration. Also, the reason why the second dust devil is rated lower regarding the material than the first one, can be applied for the third dust devil. Because the smoke material of the smoke simulation of Blender isn't available for Unreal Engine 4, it can't exactly match any kind of material that is used for the implementation of the landscape and therefore the material of the third dust devil stands out inside the virtual environment. The lower rating of the proportions of the third dust devil could also be led back to the integration with Photoshop and the implementation inside another software.

Again, the question ' 'Which of these three scenes conveys the most harmonic overall impression in your opinion?" is used a control question to check whether the dust devil, that matches the characteristics of the virtual environment best is the same that conveys with the most harmonic overall impression. The ranking of the rating regarding the characteristics shows the first dust devil in first place, the second dust devil in second place, and the third dust devil in third place. Compared to this, the ranking of the control question about the most harmonic overall impression shows that the scene with the second dust devil has the most votes, while the scene with the first dust devil has the second highest number, and the scene with the third dust devil has the fewest votes. With exactly 50% of the votes, the second dust devil's scene convinces the most participants again, as it already does in the control question of the 'First part'. The first dust devil reaches 40% of the votes. This doesn't match the expectations of the ratings of the characteristics, where it gathers the best results. Whereas, the scene with the third dust devil has the same rank for both, the characteristic rating and the harmonic overall impression. The reasons, which caused the low arithmetic means for the ratings, can also be applied to the overall impression. If the participants 'neither disagree nor agree' that the 'Color scheme', 'Proportions', and 'Material' of the third dust devil match the one of the virtual environment it's no surprise that the overall impression doesn't seem harmonic either. The shift of the first and second dust devil regarding their ranks for the control question could be a consequence of the result of the control question from the 'First part' 'Which of the three animated dust devils seems the most realistic implementation in comparison to the picture of a real dust devil on the left?'. For this question, the second dust devil also gains about 50% of the votes. It's a likely assumption that the participants, which vote for the second dust devil as the one that is closest to a real dust devil would also vote for the second dust devil as the most harmonic overall impression. Again, the reason why both, the first and second dust devil, are rated much higher regarding the harmonic overall impression than the third dust devil, can be the use of the same engine for the implementation of the dust devils and the virtual environment.

The last question of the 'Second part' and at the same time the last content question, is used as an additional information gathering regarding the use of exponential height fog. This question refers a bit to the knowledge of the participants. It can show if they have watched the videos from the information page of the study or even got previous knowledge about dust devils before. Having a look at the videos from the dust devils on Mars, one can see that the air around the dust devils does mostly seem to be quite clear, without any fog evolving. The first scene of the question 'Which of the two scenes, shown in this picture, is closer to reality in your opinion?' shows again the scene of the first dust devil integrated into the virtual Mars environment of the VaMEx-VTB. This scene has no fog effects enabled and is used to represent the realistic circumstances of the environment. The second picture shows the same scene, but with the exponential height fog of Unreal Engine 4 enabled. This exponential height fog causes the foggy atmosphere in the landscape. The fog has a similar color as the dust devil, so the participant could be led to the impression, that the dust devil caused the fog. 54.76% of the participants believe that the fog around the dust devil seems more realistic than the scene without fog. This shows that the participants doesn't always choose the scene that is objectively the more realistic one, but that scene that seems more realistic to them. A similar behavior can also be seen in the previous parts of the study. For example, the first dust devil is rated as the one that fulfills the characteristics of a real dust devil best, but isn't chosen as the most realistic one in comparison to a real dust devil.

4.3.4 Third Part

In the third and last part of the study the question 'Did you like the study?' is provided to the participants. It is used as a filter question, as already explained in the structure section of the user study chapter. Furthermore, the question should tell if the concept of the study is approved by the participants. As only two of forty-two participants answered with 'No', the study can be rated positive.

5 Results

The previous chapter 4 is about the conducted user study. Its structure, the collected data and their analysis are described. This chapter summarizes the results of this thesis. First, the results of the implementation chapter 3 are provided. This includes the three different animated dust devils described in section 3.1, the two dust storm simulations from section 3.2, and the simulation of the Martian atmosphere with the use of an atmospheric dust particle system in section 3.3. Also, the result of the integration of the implementations of the natural phenomena into the virtual Mars environment of the VaMEx-VTB is provided. Second, the summary of the results of the user study from chapter 4 is presented in section 5.2.
In the last chapter of this thesis, 6, the conclusion and future work are outlined.

5.1 Implementation Results

In this section the results of the implementation chapter 3 are presented. This includes the three animated dust devils, a summary of their implementation methods, and their possible effects on the VaMEx-VTB in section 3.1. A short overview of the VaMEx-VTB can be found in section 2.5. Furthermore, the two simulated dust storm versions and their influence on the VaMEx-VTB are described in section 3.2. Last, comes the implementation result of the Martian atmosphere in section 3.3.
Section 5.2 of the results chapter summarizes the findings of the user study.

5.1.1 Dust Devils

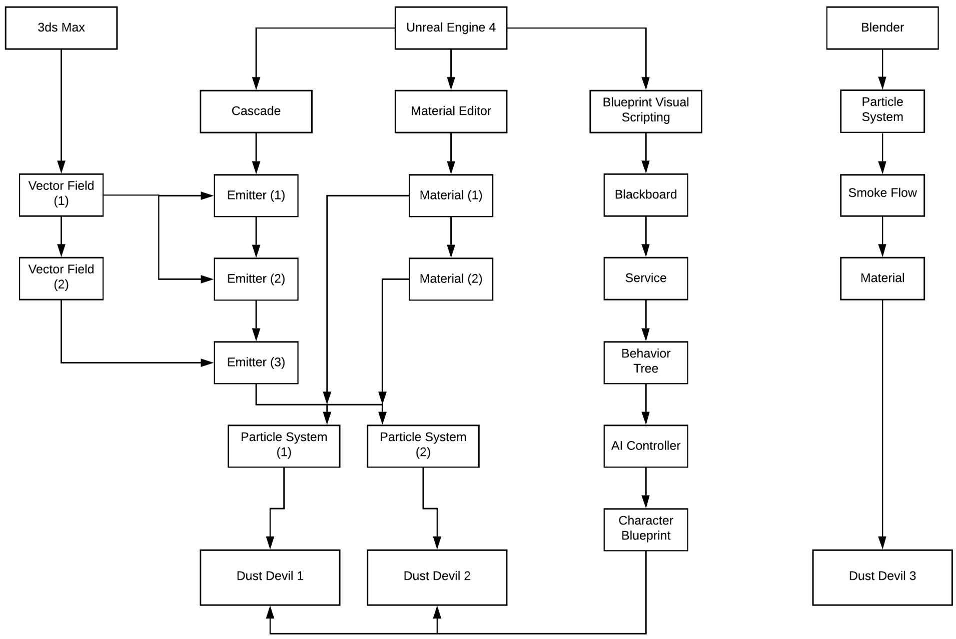


Figure 5.1 Flow chart of the implementation of the three dust devils

The implementation of the natural phenomena of planet Mars provided three different animated dust devils in section 3.1. Their implementation process can be retraced in the diagram in figure 5.1. The first and second dust devil share the same basic implementation method and are both animated in Unreal Engine 4. Each implementation is based on two vector fields generated with 3ds Max, a material created with Unreal Engine 4's material editor, one particle system built with Cascade, and an AI movement that utilizes blueprints. Both dust devils use the first vector field to provide the helical shape of the dust devils rotating column of dust and the second to form the circular moving dust at the bottom of the dust devil. Each particle system consists of three particle emitters. Two emitters have the first vector field applied to them, to form the dust devils' torso and the third emitter uses the second vector field to create the moving dust cloud at ground level. The difference between these two dust devils is the material. While a surface material is applied to the first dust devil, the second dust devil uses a volume material. A detailed description of the implementation of these two dust devils is provided in section 3.1.1. The results of the implementations of the first and second animated dust devil are shown in figure 5.2.

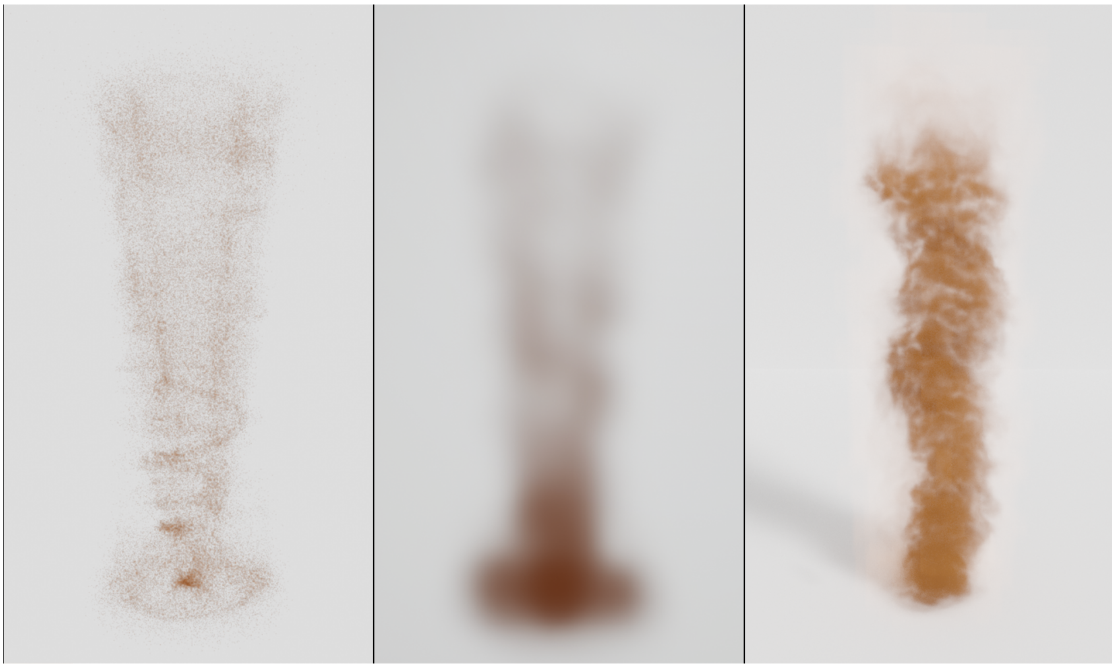


Figure 5.2 All three dust devil. From left to right: the first dust devil made with Unreal Engine 4 and a surface material, the second dust devil, which was also build with Unreal Engine 4 and a volume material, the third dust devil animated in Blender

The third dust devil, which is implemented inside Blender, also uses a particle system. Different to the other two dust devils, the particle system defines the shape of the rotating dust column. It is influenced by force fields, which cause, among others, the rotating movement. The smoke of the smoke simulation forms according to the particles. Smoke simulation is part of the build in fluid simulation of blender. Also, a material is applied to the smoke, to give it the right color and look of dust. The result of the implementation section 3.1.2 of the third dust devil is also presented in figure 5.2.

Figure 5.3 shows all three dust devils integrated into the virtual Mars environment of the VaMEx-VTB, which is built with Unreal Engine 4. As the first and second dust devil use the same engine they are easily imported into the scene. The third dust devil, which is created with Blender, is integrated into a screenshot of the virtual environment with Photoshop, to show how it would look like. A real integration of the smoke simulation from Blender into Unreal Engine 4 is not supported yet.

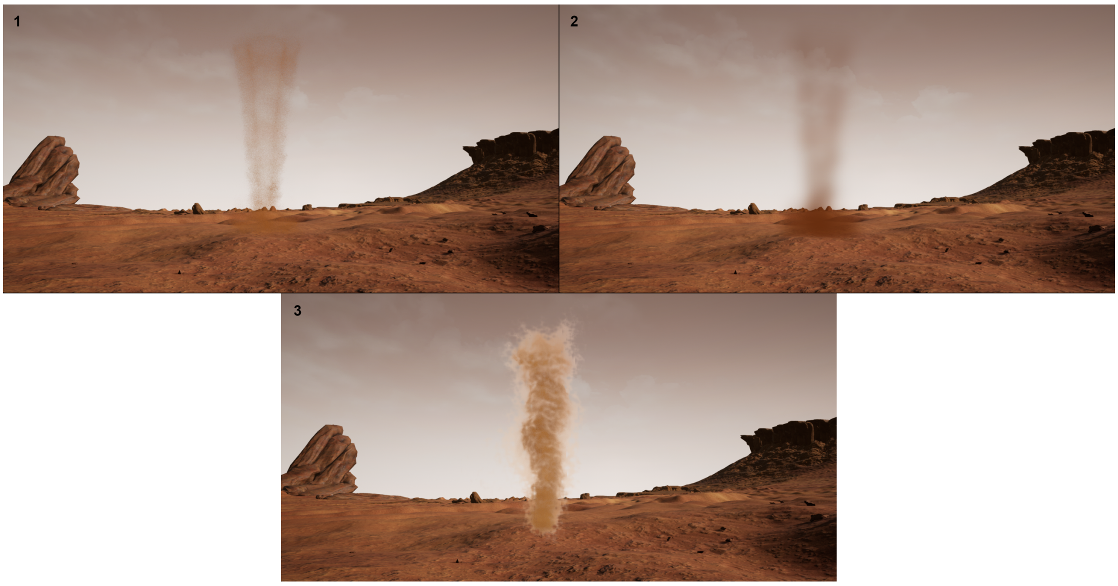


Figure 5.3 All three dust devil integrated into the virtual Mars environment of the VaMEx-VTB - Unreal Engine 4.23.1

These dust devils have been implemented to extend the virtual testbed of virtual Mars environment of the VaMEx-VTB. The devices of the robotic swarm exploration use landmarks and the horizon to create a map of their surroundings and keep the orientation while moving. These skills are based on the visual sensors of the devices and the use of the VSLAM algorithm. The scenes in figure 5.3 show that an integrated dust devil adds a new kind of object to the landscape. Different to the other objects in the scene the dust devil moves. If a dust devil is captures by the visual sensors of a device, it may simply covers a landmark in the scene or it is registered as a landmark itself. As the dust devil doesn't stay in one place, the next time this scenery is captured it differs from the existing data. The device can't recognize the same features of the landscape, which could lead to problems in the orientation and misinformation for the creation of the navigation map. Furthermore, the robotic devices share the information they gather about their surroundings to create an overlapping map with the information of all devices. Such misinformation can lead to a incorrect navigation of all devices of the autonomous, heterogeneous, robotic swarm exploration.

5.1.2 Dust Storms

In chapter 3.2 two different dust storm simulations for the virtual Mars environment of the VaMEx-VTB are provided. The first one uses exponential height fog and volumetric fog to create a scene inside a large regional or global dust storm. The result of the simulation is presented in figure 5.4.

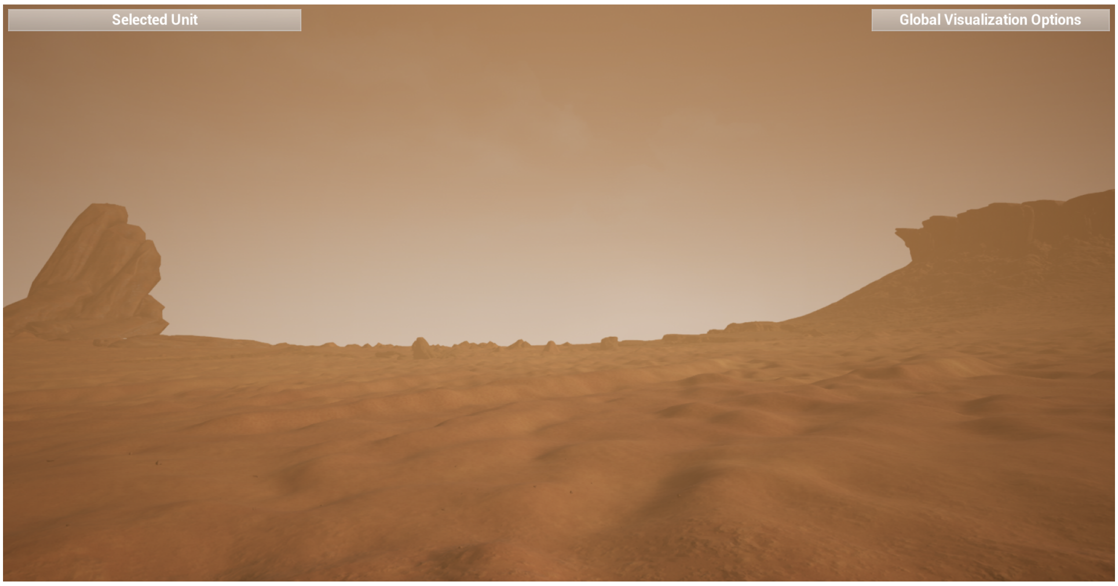


Figure 5.4 Example scene of the VaMEx-VTB with a dust storm simulated by the use of exponential height fog with an extinction scale of 10 - Unreal Engine 4.23.1

By adding a particle system to a scene with volumetric fog enabled, the second dust storm simulation is built. It controls the fog locally and produces a dust cloud. The AI movement applied to it makes the dust cloud move independently through the landscape like a local or small regional dust storm. Figure 5.5 shows the result of the simulation of the second dust storm.

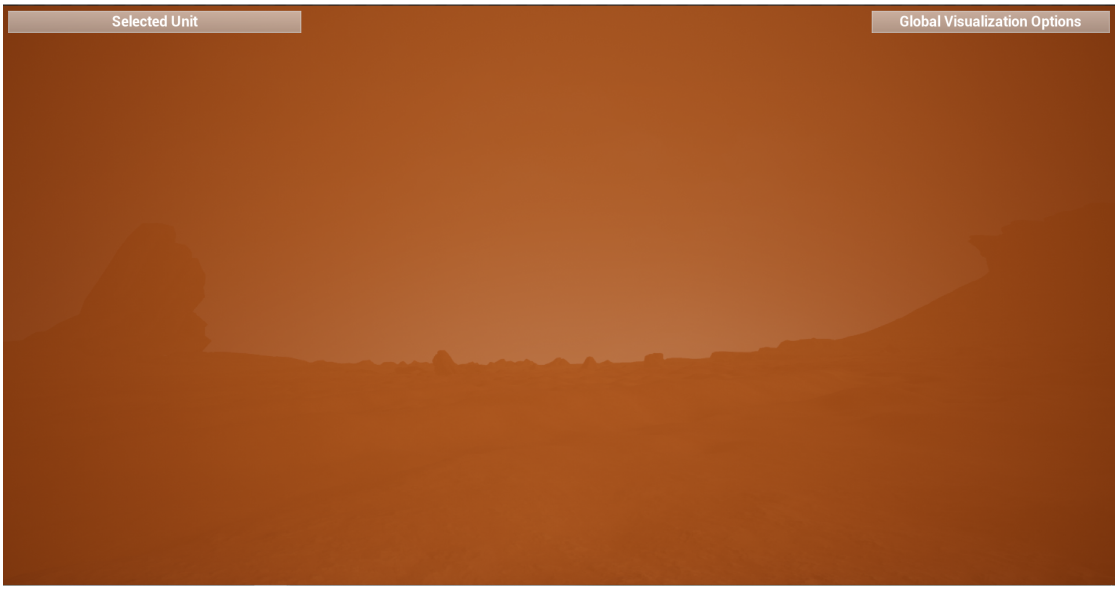


Figure 5.5 Example scene of the VaMEx-VTB with a dust storm simulated by the use of a particle system - Unreal Engine 4.23.1

The scenes show that the integration of dust storms into the VaMEx-VTB can limit the view inside the scene. For example, the horizon becomes hard to recognize. This can also influence the behavior of the VSLAM algorithm, just like the integration of the dust devils in the previous section 5.1.1. A dust storm changes the view of the scene that is captured by the visual sensors of the devices compared to the scene without fog. Possible results could be disorientation and mistakes in information processing. When the horizon isn't visible, it won't be recognized as a orientation point anymore. This also holds true for other landmarks, which can be important for the creation of the navigation map and the orientation of the devices. Additionally, the effect that an occurring dust storm could possibly darken the sun in the virtual Mars environment is shown in the figures 5.7 and 5.6. The darkening of the sun can influence the solar power, which is used to charge the batteries of the devices of the robotic swarm.

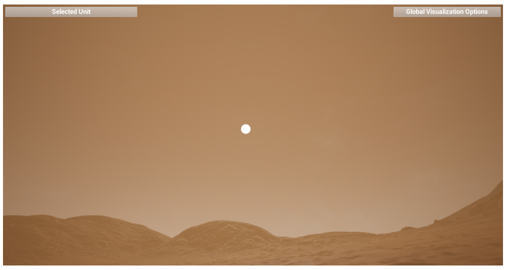


Figure 5.6 Example scene of the VaMEx-VTB with a dust storm simulated by the use of exponential height fog with an extinction scale of 10 showing the view of the sun - Unreal Engine 4.23.1

Figure 5.7 Example scene of the VaMEx-VTB shows the view of the sun with no fog enabled - Unreal Engine 4.23.1

5.1.3 Atmosphere

The last natural phenomenon that is implemented in chapter 3 is the Martian atmosphere. In section 3.3, a particle system is created, which is used to generate dust particles that float through the air. These dust particles should simulate the presence of a dusty atmosphere in the virtual Mars environment in VaMEx-VTB. The result can be seen in figure 5.8.

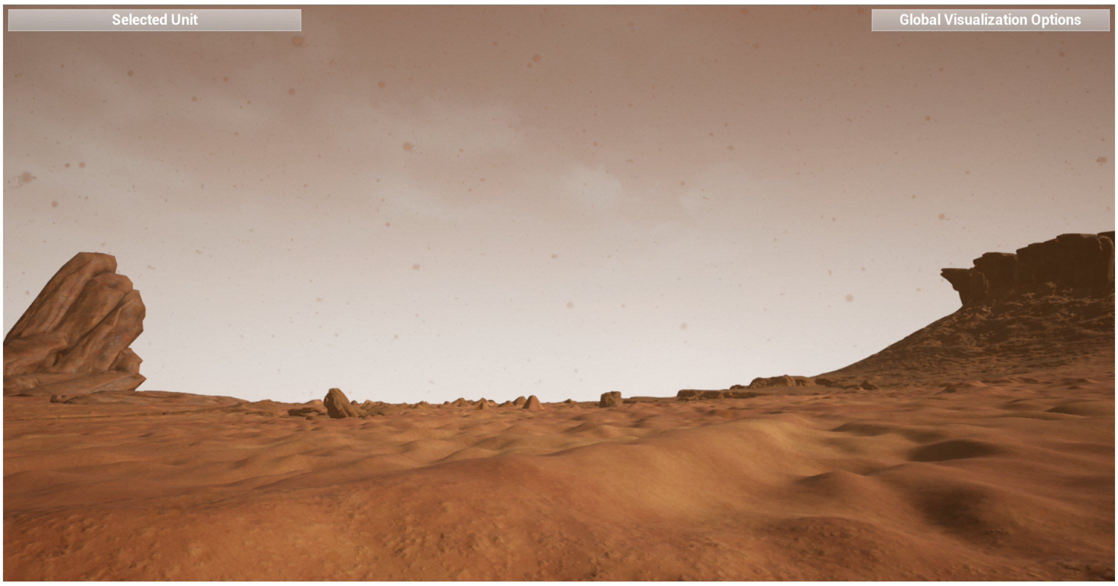


Figure 5.8 Example scene of the VaMEx-VTB with the dust particle system integrated- Unreal Engine 4.23.1

5.2 User Study Results

After the presentation of the results of the implementation chapter in the previous section 5.1, this section summarizes the results of the user study. The structure of the user study, the collected data and the analysis of these data can be found in chapter 4. Main topic of the user study is the evaluation of the three dust devils implemented in section 3.1. Additionally, the use of exponential height fog in the virtual Mars environment of the VaMEx-VTB is considered. Exponential height fog is used for the implementation of a dust storm in section 3.2. More information about the VaMEx-VTB can be found in section 2.5.
In the last chapter of this thesis, 6, the sections about conclusion and future work are provided.

The first dust devil, which is built with Unreal Engine 4 and uses the surface material, receives the best average rating regarding the questions 'Does this animated dust devil fulfill the following characteristics of a real dust devil?' and 'Does this dust devil match the following characteristics of the virtual environment?'. Both questions include a list of characteristics that is based on the list of characteristics of a real dust devil provided in section 2.1.1.1. Each characteristic has its own five-step rating scale. The second dust devil, which is also implemented in Unreal Engine 4 and uses the volume material, has the second highest arithmetic mean of all characteristics summarized for both questions. Whereas, the third dust devil, created with Blender, reaches the lowest average in both questions.

In comparison, the control questions of each content question set show different outcomes regarding the dust devil ratings. Regarding the question 'Which of the three animated dust devils seems the most realistic implementation in comparison to the picture of a real dust devil on the left?', the second dust devil receives the most votes. The third dust devil follows with the second highest number of votes and the first has the fewest votes. For the second control question, 'Which of these three scenes conveys the most harmonic overall impression in your opinion?', the second dust devil reaches the highest number of votes, followed by the first dust devil in second place, and the third dust devil in third place.

Summarized for all questions, the first dust devil reaches first place two times, second place one time and third place one time. The second dust devil also reaches first place two times, but also second place two times. Whereas, the third dust devil only reaches second place one time and third place three times. Compared to each other in total, the second dust devil shows the best results, followed closely by the first dust devil. Furthermore, the user study shows, that according to the votes of the participants, the virtual environment with a dust devil integrated seems more realistic with exponential height fog enabled.

6 Conclusion and Future Work

Chapter 5 summarizes the results of this thesis. This includes the outcomes of the implementation chapter 3 and the user study in chapter 4.
In this last chapter of the thesis, the conclusion is presented in section 6.1, followed by the ideas for future work in section 6.2.

6.1 Conclusion

This section presents the conclusion of this bachelor's thesis. It includes a summary of the results and findings of this work.
The following section 6.2 is about the future work regarding the topic of this thesis.

The results of the user study in section 5.2 in combination with the experiences of the implementation chapter 3 show that the easiest and best way to include a dust devil into the virtual Mars environment of the VaMEx-VTB, which is built with Unreal Engine 4, is the implementation method of the second dust devil. It offers a simple integration, because it also uses Unreal Engine 4 and the ratings that the second dust devil gathers during the user study show that the implementation offers the best combination of realistic animation and harmony between the dust devil and the virtual environment of the VaMEx-VTB. The implementation method includes the creation of two different vector fields with 3ds Max, which are applied to the three emitters of the particle system generated with Cascade, the use of a volume material to create the impression that the dust devil consists of one dust cloud, and an AI movement created with the blueprint visual scripting language of Unreal Engine 4. This implementation process is described in detail in section 3.1.1. If the dust devil is built with Unreal Engine 4 the whole implementation of the natural phenomena can be done with the same engine, except for the vector field generation, because the dust storm simulations presented in section 3.2 and the atmospheric dust in section 3.3 are also build with Unreal Engine 4.

The user study results shows that the use of different materials, a surface and a volume material, for the first and second dust devil can make a significant difference in the rating of the dust devil, regarding an implementation close to reality and the overall impression. Both implementations are described in section 3.1.1. Also, the results show that the use of the fluid simulation of Blender has some advantages regarding the behavior and movement of the third dust devil, especially the tilting of the dust devils towards the direction of motion. Still, the fluid simulation of Blender loses against the dust devils build with Unreal Engine 4, regarding the easy integration and the overall impression.

All natural phenomena that are implemented in this thesis meet the goals that are described in section 1.2. They extend the virtual testbed of the VaMEx-VTB project and provide a base for a wider range of more realistic test scenarios. The dust devils and dust storms can have an influence on the VSLAM algorithm of the robotic swarm of the VaMEx-VTB, which can cause problems or mistakes in the navigation and orientation of the devices. Test scenarios like dust devils that are recognized as landmarks by the visual sensors of the robotic swarm and the limitation of view through a dust storm are provided through the integration of the natural phenomena as presented in section 5.1 of the results chapter. The integration of the natural phenomena offers the wanted opportunity to expand the VaMEx-VTB, to test the possible impacts of the phenomena on the robotic swarm, to provide a better preparation, and to minimize possible problems through adequate testing.

6.2 Future Work

In the previous section 6.1, the conclusion of this thesis is presented. The last section is about the future work ideas regarding the use of animated and simulated natural phenomena in the virtual Mars environment of the VaMEx-VTB.

The animation and simulation of natural phenomena offers a lot possibilities for future work. Inter alia, the use of dust devils can be expanded in many ways. Dust devils doesn't always look the same in reality (Balme and Greeley 2006). They can have a lot of different shapes and sizes. By using the implementation method of the first and second dust devil many different versions of dust devils can be built inside Unreal Engine 4. Therefore, the size and radii of the vector field, which decides about the basic shape of the dust devil, need to be varied. Also, changes in the particle system could be used to create more variety. For example, by adjusting the spawn rate of the emitters of the particle system. A higher spawn rate results in a denser dust devil. Also, a longer or shorter lifetime of the particles or changes in the rotation rate of the vector field could cause changes in the look of a dust devil. Regarding the implementation method used for the third dust devil, which is built with Blender, even more variances of dust devils are possible. By adjusting the strength of the force fields, the time the smoke needs to fade, or the gravity settings of the particle emitter, many different dust devils can be built. The variety should support the realistic impression of the virtual Mars environment of the VaMEx-VTB. Next to the shape and look of a dust devil, the rotation direction can differ, depending on the hemisphere of Mars the dust devil occurs.

Furthermore, another addition to the existing dust devils would be the creation of dust devil tracks. Dust devil tracks form on Mars when a dust devil moves over the ground. These dark paths can be hundreds of meters wide and stretch over a few kilometers (European Space Agency 2019). To provide a simulation that is as close to the reality as possible, these tracks should be integrated, because they could have an influence on the navigation and orientation of the autonomous heterogeneous robotic swarm exploration. The VSLAM algorithm could use the tracks as landmarks for the creation of the navigation map and it should be considered that these tracks aren't static. This means, that if a new dust devil moves through the existing tracks, they will be changed and the scenery will differ from data that may have been gathered earlier by the VSLAM. Also, the tracks of the rovers themselves, could be covered through the tracks of a dust devil.

Another natural phenomenon that should be considered for the virtual Mars environment of the VaMEx-VTB initiative is landslides. Especially in the Valles Marineris, where the virtual environment of the VaMEx-VTB is located, the results of large landslides can be seen (Brunetti et al. 2014). A large landslide could cover hundreds of square kilometers (Lucchitta 1987). This influence on the landscape should be considered in the design of a virtual environment of planet Mars, especially because of the possible influence on the VSLAM algorithm and the navigation of the robotic swarm. These landslides could be realized in Unreal Engine 4, for example, through decals or a mesh emitter, which emits rocks as particles.

The most important part of the future work is the influence of the natural phenomena on the devices of the robotic swarm. Things like the influence on view or navigation, less solar power due to the darkened sun, or dirt on the solar panels, the lens, and the mechanics could be implemented to support the realistic impression of the simulation. The dust devils, dust storm, and the atmospheric dust can influence the view of the cameras of the robotic swarm devices, which could influence the visual sensors and therefore the navigation of the swarm. Also, the dirt evolving from the surrounding dust should be considered in the implementation, because it can influence the mechanic of the devices. For example, the power of the solar panels could be reduced, when they get covered by dust, or the dust on the lens of the visual sensors could influence the view. With the natural phenomena of this thesis integrated, the VaMEx-VTB can be expanded to test these scenarios. The more cases the test bed covers, the less surprises or problems occur when it comes to the real Mars exploration.

A Appendix

A.1 List of Figures

A.2 Bibliography

Ahrens, C.D. (2012). *Meteorology Today: An Introduction to Weather, Climate, and the Environment*. Cengage Learning. ISBN: 9781285400969. URL: *https://books.google.de/books?id=IagKAAAAQBAJ* (visited on 07/27/2020).

Autodesk Inc. (2019). *3ds Max*. URL: *https://www.autodesk.de/products/3ds-max/overview* (visited on 07/27/2020).

Balme, Matt and Ronald Greeley (2006). "Dust devils on Earth and Mars". In: *Reviews of Geophysics* 44: *Issue 3*.

Bernsdorf, J., U. Jaekel, T. Zeiser, S. Doi, T. Takei, H. Matsumoto, and K. Nishizawa (2003). "Numerical Simulation of Reaction-Diffusion and Adsorption Processes in Porous Media using Lattice Boltzmann Methods with Concurrent Visualisation". In: *Parallel Computational Fluid Dynamics 2002*. Ed. by K. Matsuno, A. Ecer, N. Satofuka, J. Periaux, and P. Fox. Amsterdam: North-Holland, pp. 233–240. ISBN: 978-0-444-50680-1. DOI: *https://doi.org/10.1016/B978-044450680-1/50030-9*. URL: *http://www.sciencedirect.com/science/article/pii/B9780444506801500309* (visited on 07/27/2020).

Blender Foundation (2019). *Blender*. URL: *https://www.blender.org/* (visited on 07/27/2020).

– (2020). *Gas Simulations*. URL: *https://docs.blender.org/manual/en/latest/physics/fluid/introduction.html%5C#liquid-simulations* (visited on 07/21/2020).

Brosius, H.B., F. Koschel, and A. Haas (2008). *Methoden der empirischen Kommunikationsforschung: Eine Einführung*. Studienbücher zur Kommunikations- und Medienwissenschaft. VS Verlag für Sozialwissenschaften. ISBN: 9783531907628. URL: *https://books.google.de/books?id=FwcI8VzyA-UC*.

Brunetti, Maria Teresa, Fausto Guzzetti, Mauro Cardinali, Federica Fiorucci, Michele Santangelo, Paolo Mancinelli, Goro Komatsu, and Lorenzo Borselli (2014). "Analysis of a new geomorphological inventory of landslides in Valles Marineris, Mars". In: *Earth and Planetary Science Letters* 405, pp. 156–168. ISSN: 0012-821X. DOI: *https://doi.org/10.1016/j.epsl.2014.08.025*. URL: *http://www.sciencedirect.com/science/article/pii/S0012821X14005317* (visited on 07/27/2020).

Bundesministerium für Wirtschaft und Energie (2020). *BMWi*. URL: *https://www.bmwi.de* (visited on 07/27/2020).

Burg, John van der (2000). "Building an Advanced Particle System". In: *Gamasutra*.

Cantor, Bruce A. (2007). "MOC observations of the 2001 Mars planet-encircling dust storm". In: *Icarus* 186.1, pp. 60–96. ISSN: 0019-1035. DOI: *https://doi.org/10.1016/j.icarus.2006.08.019*. URL: *http://www.sciencedirect.com/science/article/pii/S0019103506002855* (visited on 07/27/2020).

Cantor, Bruce A., Philip B. James, Michael Caplinger, and Michael J. Wolff (2001). "Martian dust storms: 1999 Mars Orbiter Camera observations". In: *Journal of Geophysical Research: Planets* 106.E10, pp. 23653–23687. DOI: *10.1029/2000JE001310*. eprint: *https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2000JE001310*. URL: *https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2000JE001310* (visited on 07/27/2020).

Cantor, Bruce A., Nicholas B. Pickett, Michael C. Malin, Steven W. Lee, Michael J. Wolff, and Michael A. Caplinger (2018). "Martian dust storm activity near the Mars 2020 candidate landing sites: MRO-MARCI observations from Mars year 28-34". In: *Icarus* 321, pp. 161–170.

Carr, Michael H. (2007). *The Surface of Mars*. Cambridge Planetary Science. Cambridge University Press. DOI: *10.1017/CBO9780511536007*.

Chen, Shiyi and Gary Doolen (Nov. 2003). "Lattice Boltzmann Method for Fluid Flows". In: *Annual Review of Fluid Mechanics* 30, pp. 329–364. DOI: *10.1146/annurev.fluid.30.1.329*.

Deutsches Zentrum für Luft- und Raumfahrt e.V. (2020). *DLR*. URL: *https://www.dlr.de* (visited on 07/27/2020).

Döring, N., J. Bortz, S. Pöschl, C.S. Werner, K. Schermelleh-Engel, C. Gerhard, and J.C. Gäde (2015). *Forschungsmethoden und Evaluation in den Sozial- und Humanwissenschaften*. Springer-Lehrbuch. Springer Berlin Heidelberg. ISBN: 9783642410895. URL: *https://books.google.de/books?id=EvfNCgAAQBAJ*.

Epic Games (2019). *Unreal Engine 4*. URL: *https://www.unrealengine.com/* (visited on 07/27/2020).

Epic Games Inc. (2020). *Gradient*. URL: *https://docs.unrealengine.com/en-US/Engine/Rendering/Materials/Functions/Reference/Gradient/index.html* (visited on 07/15/2020).

Epic Games, Inc. (2019a). *Documentation of Unreal Engine, Materials*. URL: *https://docs.unrealengine.com/en-US/Engine/Rendering/Materials/index.html* (visited on 07/27/2020).

– (2019b). *Documentation of Unreal Engine, Textures*. URL: *https://docs.unrealengine.com/en-US/Engine/Content/Types/Textures/index.html* (visited on 07/27/2020).

– (2020a). *Blueprints Visual Scripting*. URL: *https://docs.unrealengine.com/en-US/Engine/Blueprints/index.html* (visited on 07/10/2020).

– (2020b). *Datasmith Supported Software and File Types*. URL: *https://docs.unrealengine.com/en-US/Engine/Content/Importing/Datasmith/SupportedSoftwareAndFileTypes/index.html* (visited on 07/10/2020).

– (2020c). *Documentation of Unreal Engine, Exponential Height Fog*. URL: *https://docs.unrealengine.com/en-US/Engine/Actors/FogEffects/HeightFog/index.html* (visited on 07/27/2020).

– (2020d). *Surviving Mars*. URL: *https://www.epicgames.com/store/en-US/product/surviving-mars/home* (visited on 07/13/2020).

European Space Agency (2019). *Dark dust devil tracks on Mars*. URL: *https://www.esa.int/Science_Exploration/Space_Science/Mars_Express/Dark_dust_devil_tracks_on_Mars* (visited on 07/27/2020).

Gamefabrik (2017). *Mars Tomorrow*. URL: *https://www.amazon.de/gamefabrik-GmbH-Mars-Tomorrow/dp/B01CMIQ470* (visited on 07/27/2020).

Ghosh, Tuhin and Indrajit Pal (Jan. 2014). "Dust Storm and its Environmental Implications". In: *Journal of Engineering Computers & Applied Sciences (JECAS)* 3, pp. 30–37.

Haemimont Games (2018). *Surviving Mars - First Colony Edition*. URL: *https://www.microsoft.com/de-de/p/surviving-mars-first-colony-edition/bq8jvhsg2j3p?activetab=pivot:overviewtab%5C#* (visited on 07/27/2020).

Haemimont Games AD (2020). *Haemimont Games*. URL: *https://www.haemimontgames.com/* (visited on 07/13/2020).

He, Xiaoyi and Li-Shi Luo (Dec. 1997). "Theory of the lattice Boltzmann method: From the Boltzmann equation to the lattice Boltzmann equation". In: *PHYSICAL REVIEW E* 56, pp. 6811–6817. DOI: *10.1103/PhysRevE.56.6811*.

Horton, W., H. Mlura, O. Onishchenko, L. Couedel, C. Arnas, A. Escarguel, S. Benkadda, and V. Fedun (2016). “Dust devil dynamics”. In: *Journal of Geophysical Research: Atmospheres*.

Ilic, Slobodan and Pascal Fua (2003). “From Explicit to Implicit Surfaces for Visualization, Animation and Modeling”. In: *ISPRS workshop on Visualization and Animation of Reality-based 3D Models, Vulpera, Switzerland*. URL: *http://infoscience.epfl.ch/record/64644* (visited on 07/27/2020).

Königsberger, Prof. Dr. Konrad (2004). *Analysis 2 - 2004*. Springer. ISBN: 9783540350774.

Lachner, Christoph and Andreas Vorderleitner (2017). “Partikelsysteme. Anwendung in 3D-Systemen”. URL: *http://www.cosy.sbg.ac.at/~held/teaching/wiss_arbeiten/slides_17-18/Partikelsysteme.pdf* (visited on 07/27/2020).

Lander, Jeff (1998). “The Ocean Spray in Your Face”. In: *Graphic Content*.

Lucchitta, Baerbel K. (1987). “Valles Marineris, Mars: Wet debris flows and ground ice”. In: *Icarus* 72.2, pp. 411–429. ISSN: 0019-1035. DOI: *https://doi.org/10.1016/0019-1035(87)90183-7*. URL: *http://www.sciencedirect.com/science/article/pii/0019103587901837* (visited on 07/27/2020).

Martin, Leonard J. and Richard W. Zurek (1993). “An Analysis of the History of Dust Activity on Mars”. In: *Journal of Geophysical Research* 98, pp. 3221–3246.

Martin, Terry Z. (1994). *Mass of Dust in the Martian Atmosphere*.

Mur-Artal, Ra´ul, J. M. M. Montiel, and Juan D. Tard´os (2015). “ORB-SLAM: A Versatile and Accurate MonocularSLAM System”. In: *IEEE TRANSACTIONS ON ROBOTICS* 31. URL: *https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7219438* (visited on 07/27/2020).

NASA (2005). *Phantoms From the Sand: Tracking Dust Devils Across Earth and Mars*. URL: *https://www.nasa.gov/vision/universe/solarsystem/2005_dust_devil.html* (visited on 07/08/2020).

NASA/JPL-Caltech/MSSS (2018). *The 2001 Great Dust Storms - Hellas/Syrtis Major*. URL: *https://mars.nasa.gov/resources/21448/global-dust-storm/* (visited on 07/27/2020).

– (2019). *Curiosity's Selfie at ”Rock Hall”*. URL: *https://mars.nasa.gov/resources/22273/curiositys-selfie-at-rock-hall/* (visited on 07/27/2020).

NASA/JPL-Caltech/TAMU (2018). *Shades of Martian Darkness*. URL: *https://www.jpl.nasa.gov/spaceimages/details.php?id=PIA22521* (visited on 07/27/2020).

Open Robotics (2020). *ROS*. URL: *https://www.ros.org/* (visited on 07/31/2020).

Peng, Xinlai, David Roueche, David Prevatt, and Kurtis Gurley (June 2016). “An Engineering-Based Approach to Predict Tornado-Induced Damage”. In: *Multi-hazard Approaches to Civil Infrastructure Engineering*, pp. 311–335. ISBN: 978-3-319-29711-8. DOI: *10.1007/978-3-319-29713-2_15*.

Reeves, William T. (1983). “Particle Systems - A Technique for Modeling a Class of Fuzzy Objects”. In: *ACM Trans. Graph.* 2, pp. 91–108.

Ruben Henares (2014). *VFShapes*. URL: *https://luos.stackstorage.com/s/U3PHOF4ssOBXDQp* (visited on 07/14/2020).

Singh, Ramdayal, ed. (Jan. 2019). *Martian Dust Devils Observed by Mars Colour Camera Onboard Mars Orbiter Mission*.

Tavakkoli, Alireza (2015). *Game Development and Simulation with Unreal Technology*. ISBN: 9781498706254.

Tomasko, M. G., L. R. Doose, M. Lemmon, P. H. Smith, and E. Wegryn (1999). "Properties of dust in the Martian atmosphere from the Imager on Mars Pathfinder". In: *Journal of Geophysical Research: Planets* 104.E4, pp. 8987–9007. DOI: *10.1029/1998JE900016*. eprint: *https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/1998JE900016*. URL: *https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/1998JE900016* (visited on 07/27/2020).

TU Braunschweig (2020). *Institut für Fahrzeugtechnik*. URL: *http://www.iff.tu-bs.de/index.php?id=4* (visited on 07/31/2020).

TU München (2020). *Institut für Fahrzeugtechnik*. URL: *https://www.ei.tum.de/startseite/* (visited on 07/31/2020).

Universität der Bundeswehr München (2020). *Institut für Fahrzeugtechnik*. URL: *https://www.unibw.de/lrt9* (visited on 07/31/2020).

Universität Würzburg (2020). *Institut für Fahrzeugtechnik*. URL: *https://www.uni-wuerzburg.de/studium/angebot/faecher/luri* (visited on 07/31/2020).

University of Bremen - Institute for Computer Graphics and Virtual Reality (2020). *VaMEx-VTB*. URL: *https://cgvr.cs.uni-bremen.de/research/vamex-vtb/* (visited on 07/27/2020).

Wang, Huiqun and Mark I. Richardson (2015). "The origin, evolution, and trajectory of large dust storms on Mars during Mars years 24–30 (1999–2011)". In: *Icarus* 251. Dynamic Mars, pp. 112–127. ISSN: 0019-1035. DOI: *https://doi.org/10.1016/j.icarus.2013.10.033*. URL: *http://www.sciencedirect.com/science/article/pii/S0019103513004624* (visited on 07/27/2020).

Yousif, K., A. Bab-Hadiashar, and R. Hoseinnezhad (2015). "An Overview to Visual Odometry and Visual SLAM: Applications to Mobile Robotics". In: *Intelligent Industrial Systems*. URL: *https://link.springer.com/article/10.1007%5C%2Fs40903-015-0032-7* (visited on 07/27/2020).

Zachmann, Gabriel (2007). *Computergraphik 2*. Universität Bremen. URL: *https://cgvr.cs.uni-bremen.de/teaching/cg2_07/* (visited on 07/27/2020).

Zurek, Richard W. and Leonard J. Martin (1993). "Interannual Variability of Planet-Encircling Dust Storms on Mars". In: *Journal of Geophysical Research* 98, pp. 3247–3259.

A.3 List of Abbreviations

3D three-dimensional, S. 3, 11–13, 18, 20, 21, 23, 26–28, 35, 37–39, 50

AI artificial intelligence, S. 15, 36, 43, 50, 58, 60, 92, 95

AR augmented reality, S. 15

BMWi Federal Ministry of Economic Affairs and Energy, S. 1, 29

DLR German Aerospace Center, S. 1, 29

ESA European Space Agency, S. 6

HDR high dynamic range, S. 13

LBM Lattice Boltzmann method, S. 19

MR mixed reality, S. 15

UVAs unmanned aerial vehicles, S. 30

VaMEx Valles Marineris Explorer, S. 29
VaMEx-VTB Valles Marineris Exploration - Virtual TestBed, S. 1–4, 23, 27–31, 35, 41, 42, 44, 51, 52, 55–61, 65, 66, 69, 77, 80, 86–88, 90, 91, 93–102, 105
VFX visual effects, S. 13
VR virtual reality, S. 13, 15
VSLAM Visual Simultaneous Localization and Mapping, S. 28, 94, 96, 100, 101

A.4 Glossary

Fe2-O3
stands for ferric oxide. It is a stable oxid of iron. Ferric oxide is a component of rust and causes its color.
S. 9

Martian global dust storm
This planet-encircling dust storm developed on Mars in June and July of 2001 through a set of storms that occurred at the same time. In July the planet was almost completely enveloped and the dust extended to altitudes of more than sixty kilometers. The storm was observed by the MGS Mars Orbiter Camera. (NASA/JPL-Caltech/MSSS 2018)
S. 8

Photoshop
is a raster graphics editor. It is developed and published by Adobe Inc. Photoshop is mainly used to edit and compose raster images in multiple layers.
S. 88

prefabs
are similar to object classes. Instances of a prefab can be added to a scene like a normal game object. If a prefab is changed all instances of the prefab are changed simultaneously.
S. 16

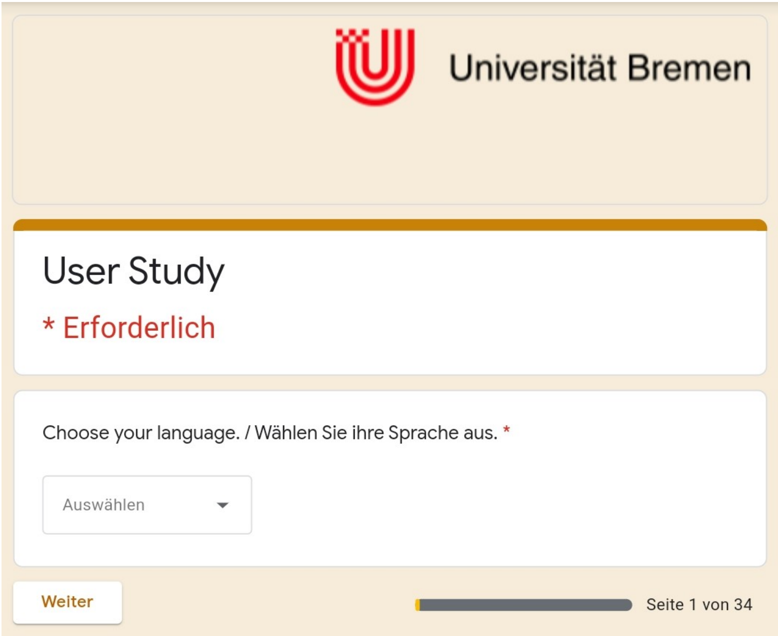
ROS
stands for Robot Operating System. This is a flexible framework, which is used to create complex and robust robot behavior. It consists of a collection of tools, libraries, and conventions. The idea behind this framework is collaborative robotic software that benefits from more than one laboratory. (Open Robotics 2020)
S. 30

sol is the name of one rotation period of the Mars in relation to the sun. In other words, a sol is one day on Mars. One day-night-cycle on Mars has twenty-four hours, thirty-nine minutes, and thirty-five seconds. (Carr 2007)
S. 5, 8, 10, 103

Valles Marineris
is a canyon system on Mars that is located along the Martian equator. It is over four-thousand kilometers long, seven-hundred kilometers wide and up to seven kilometers deep. The Valles Marineris is the largest canyon system in our solar system. (Brunetti et al. 2014)
S. 29, 101

A.5 Screenshots of the User Study

A.5.1 Screenshots of the questions of the Introduction


Universität Bremen

User Study

* Erforderlich

Choose your language. / Wählen Sie ihre Sprache aus. *

Auswählen

Weiter

Seite 1 von 34

Figure A.1 User study, page one

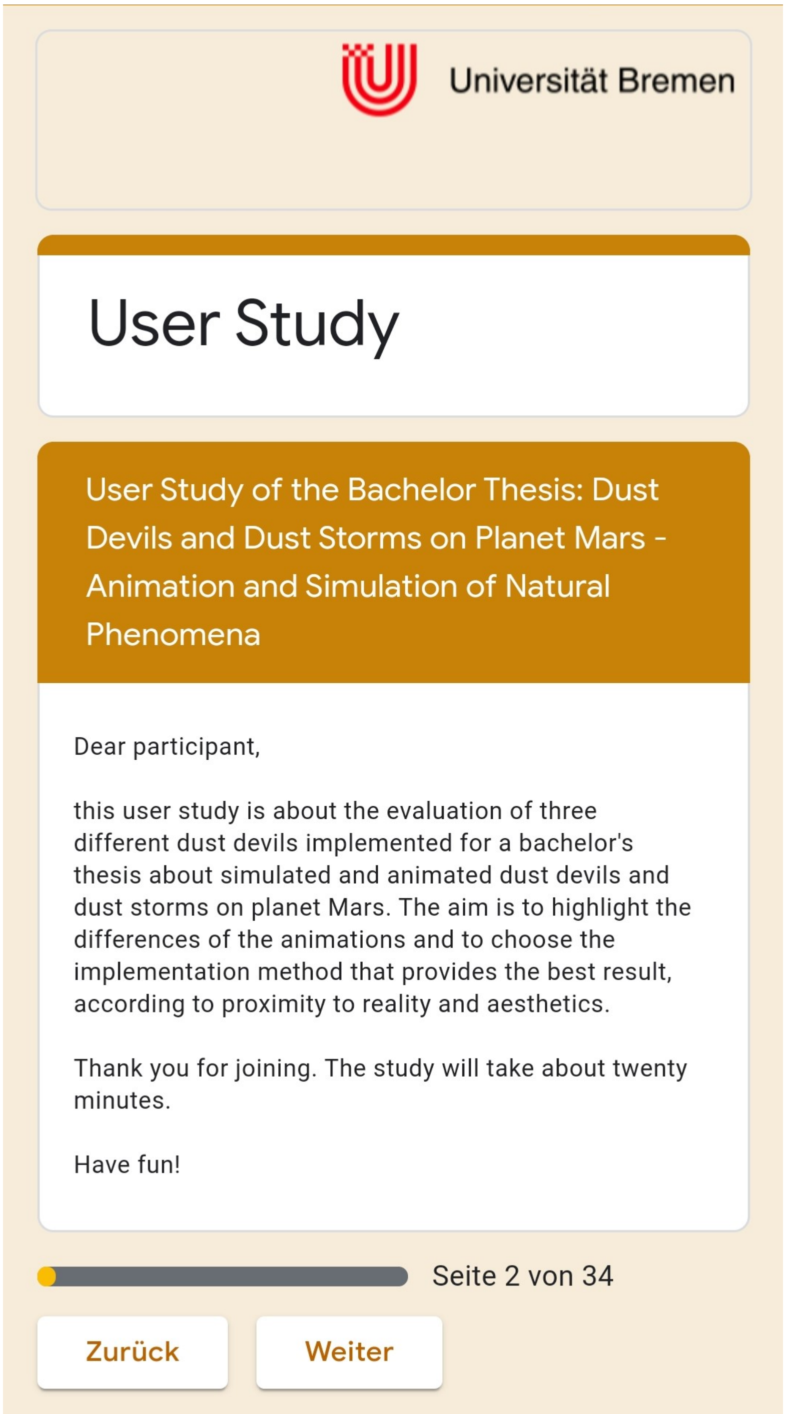


Figure A.2 User study, page two

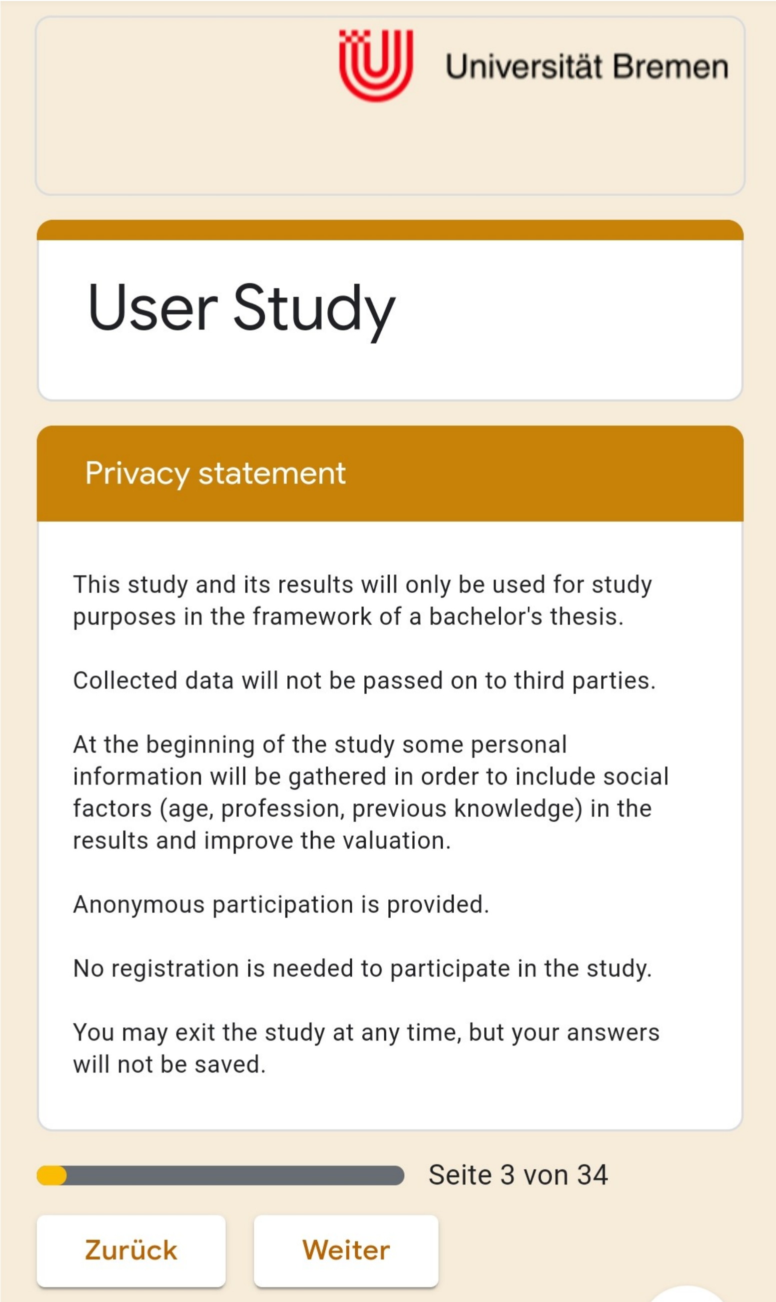


Figure A.3 User study, page three

User Study

* Erforderlich

1. How old are you? *

Auswählen

2. In which professional field do you work? *

Auswählen

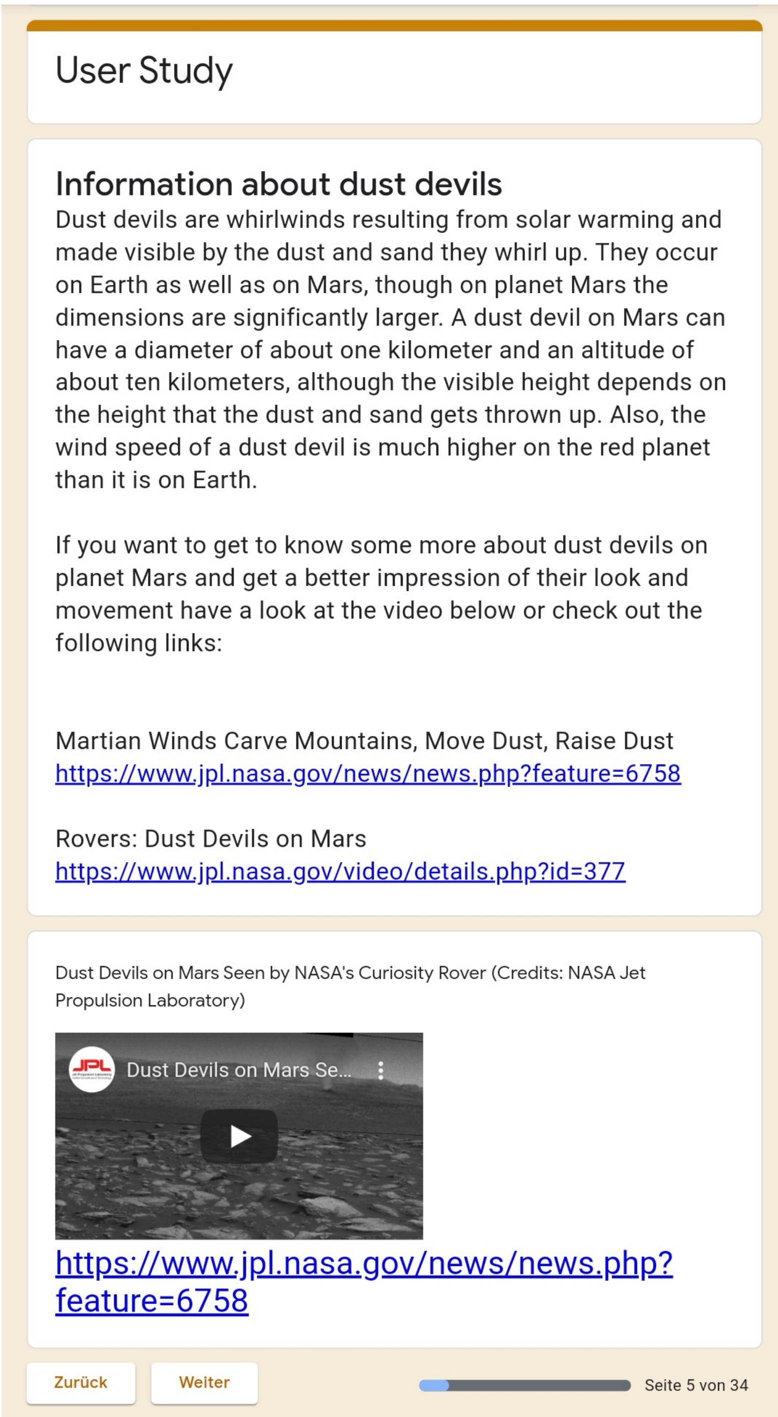
3. Have you ever heard about dust devils on planet Mars before? *

A Martian dust devil can be seen in the background of this picture taken by NASA's Mars Exploration Rover "Opportunity". (Image Credit: NASA/JPL-Caltech)

Auswählen

Zurück Weiter Seite 4 von 34

Figure A.4 User study, page four (1)



User Study

Information about dust devils

Dust devils are whirlwinds resulting from solar warming and made visible by the dust and sand they whirl up. They occur on Earth as well as on Mars, though on planet Mars the dimensions are significantly larger. A dust devil on Mars can have a diameter of about one kilometer and an altitude of about ten kilometers, although the visible height depends on the height that the dust and sand gets thrown up. Also, the wind speed of a dust devil is much higher on the red planet than it is on Earth.

If you want to get to know some more about dust devils on planet Mars and get a better impression of their look and movement have a look at the video below or check out the following links:

Martian Winds Carve Mountains, Move Dust, Raise Dust
https://www.jpl.nasa.gov/news/news.php?feature=6758

Rovers: Dust Devils on Mars
https://www.jpl.nasa.gov/video/details.php?id=377

Dust Devils on Mars Seen by NASA's Curiosity Rover (Credits: NASA Jet Propulsion Laboratory)

Dust Devils on Mars Se...

https://www.jpl.nasa.gov/news/news.php?feature=6758

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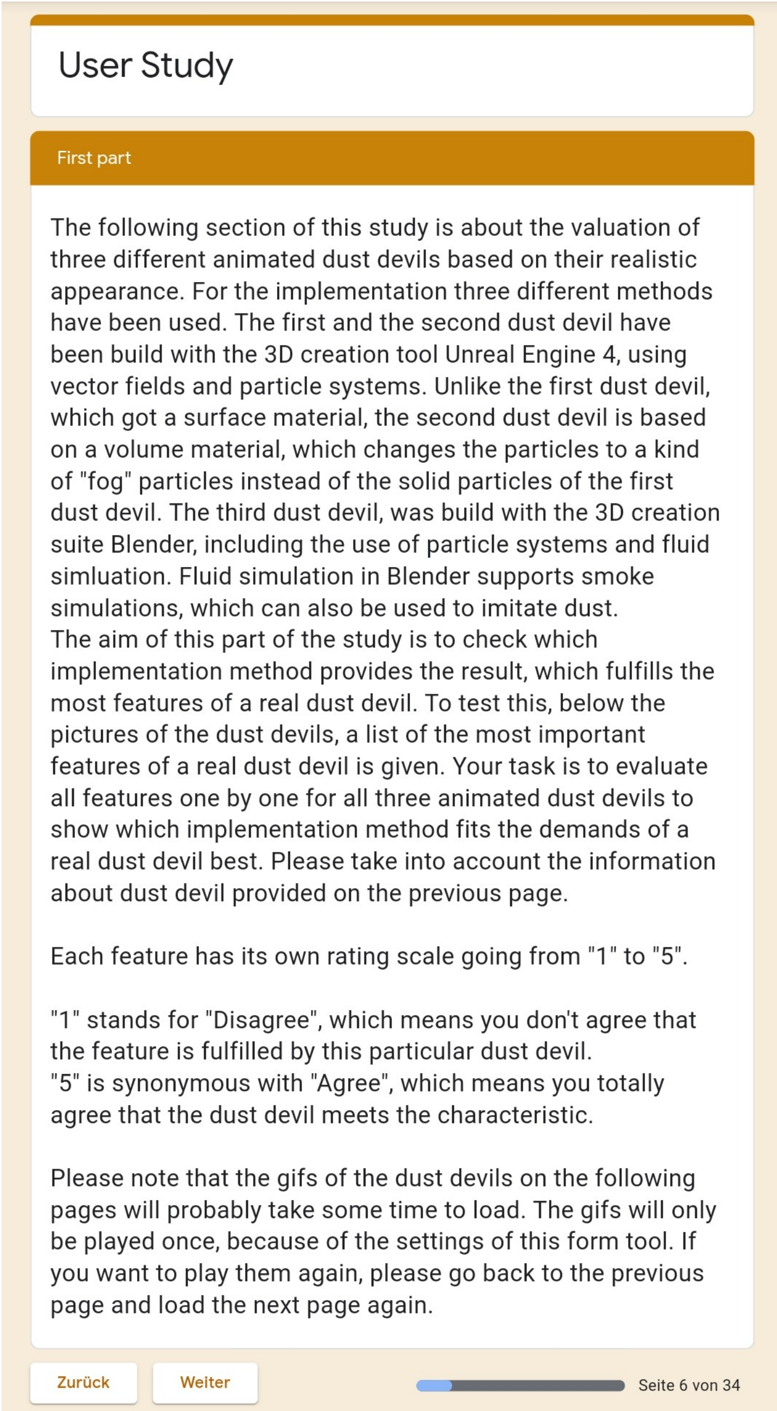
Figure A.5 User study, page five

A.5.2 Screenshots of the questions of the First Part


User Study

First part

The following section of this study is about the valuation of three different animated dust devils based on their realistic appearance. For the implementation three different methods have been used. The first and the second dust devil have been build with the 3D creation tool Unreal Engine 4, using vector fields and particle systems. Unlike the first dust devil, which got a surface material, the second dust devil is based on a volume material, which changes the particles to a kind of "fog" particles instead of the solid particles of the first dust devil. The third dust devil, was build with the 3D creation suite Blender, including the use of particle systems and fluid simluation. Fluid simulation in Blender supports smoke simulations, which can also be used to imitate dust.
The aim of this part of the study is to check which implementation method provides the result, which fulfills the most features of a real dust devil. To test this, below the pictures of the dust devils, a list of the most important features of a real dust devil is given. Your task is to evaluate all features one by one for all three animated dust devils to show which implementation method fits the demands of a real dust devil best. Please take into account the information about dust devil provided on the previous page.

Each feature has its own rating scale going from "1" to "5".

"1" stands for "Disagree", which means you don't agree that the feature is fulfilled by this particular dust devil.
"5" is synonymous with "Agree", which means you totally agree that the dust devil meets the characteristic.

Please note that the gifs of the dust devils on the following pages will probably take some time to load. The gifs will only be played once, because of the settings of this form tool. If you want to play them again, please go back to the previous page and load the next page again.

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Figure A.6 User study, page six

User Study

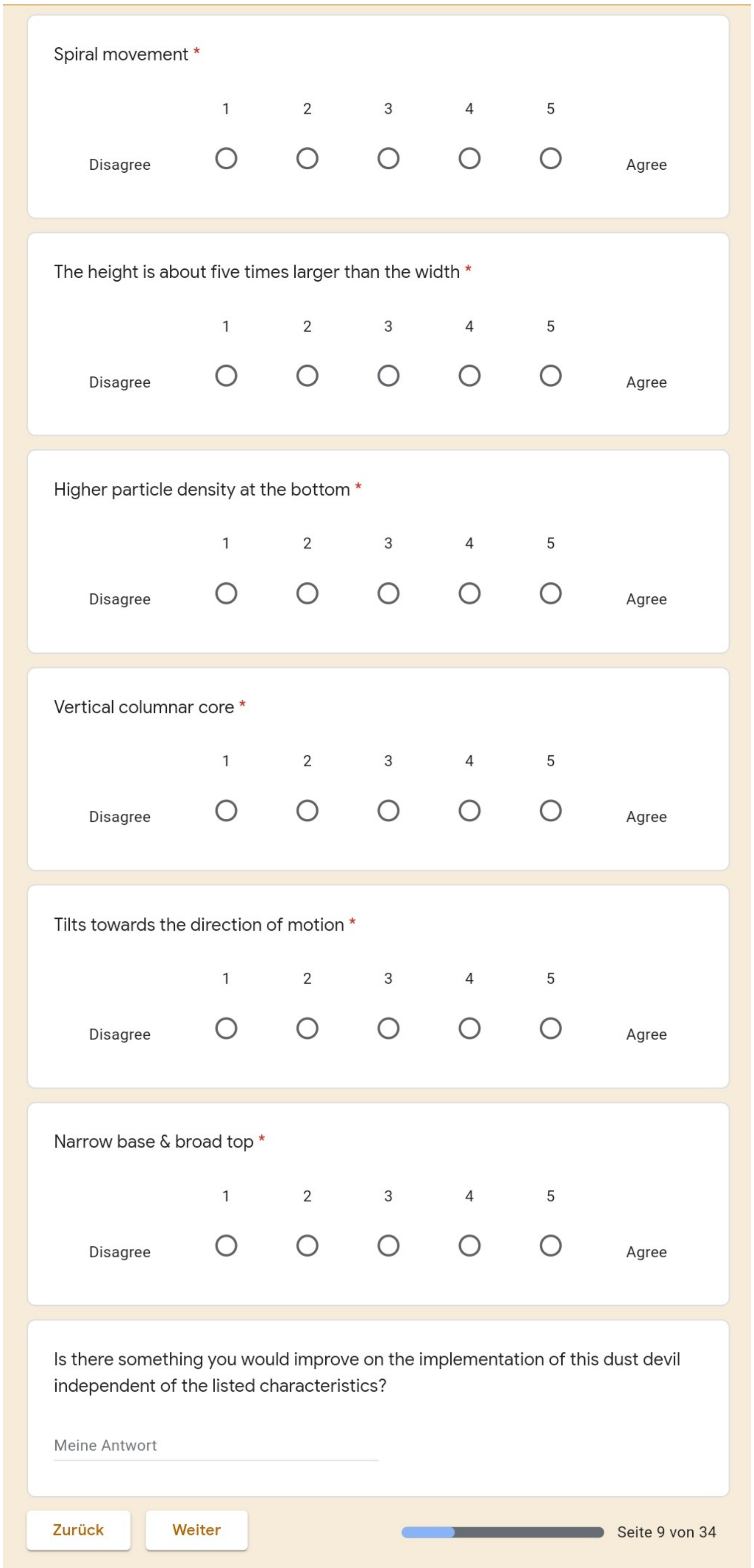
* Erforderlich

4. Does this animated dust devil fulfill the following characteristics of a real dust devil?

Upward movement *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Figure A.7 User study, page seven



Spiral movement *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

The height is about five times larger than the width *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Higher particle density at the bottom *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Vertical columnar core *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Tilts towards the direction of motion *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Narrow base & broad top *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Is there something you would improve on the implementation of this dust devil independent of the listed characteristics?

Meine Antwort

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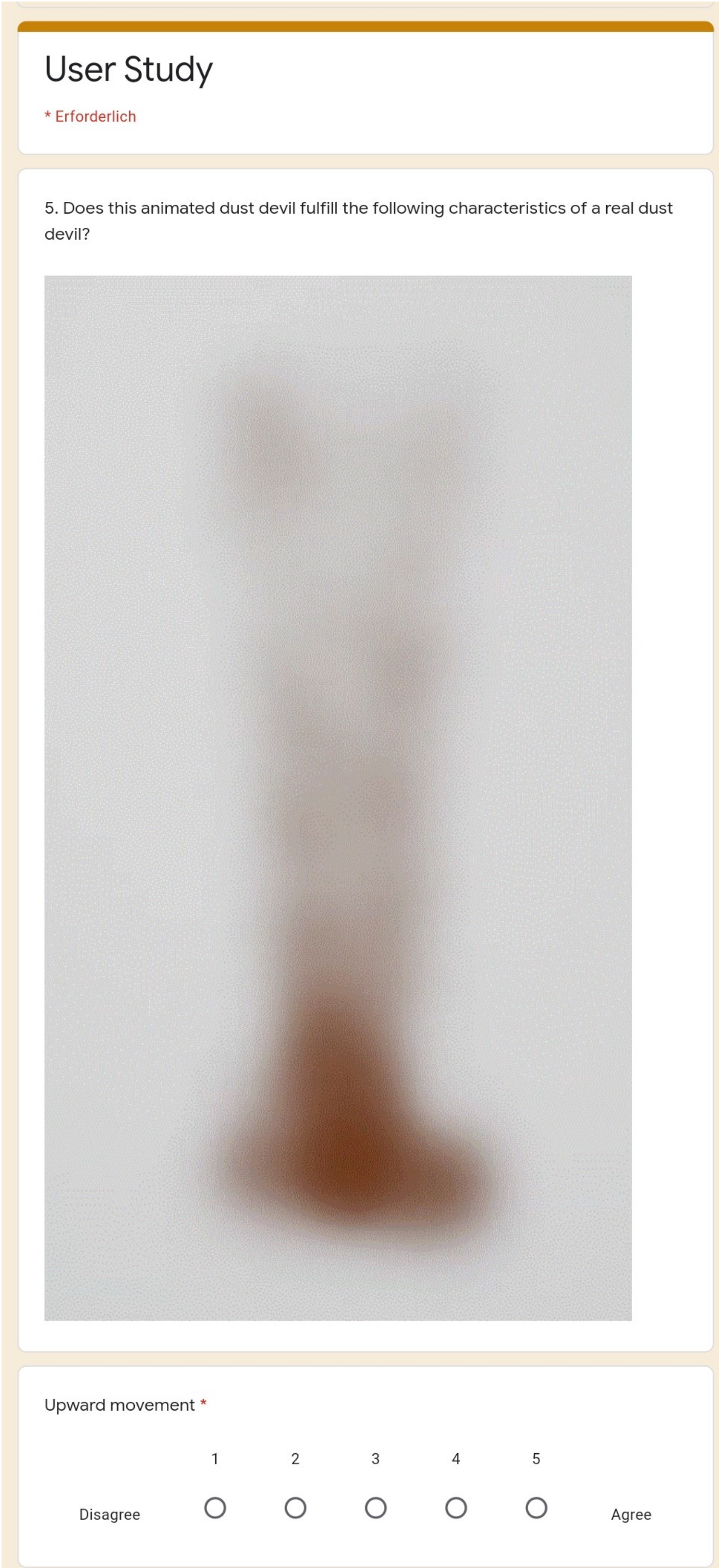
Figure A.8 User study, page seven (2)



User Study

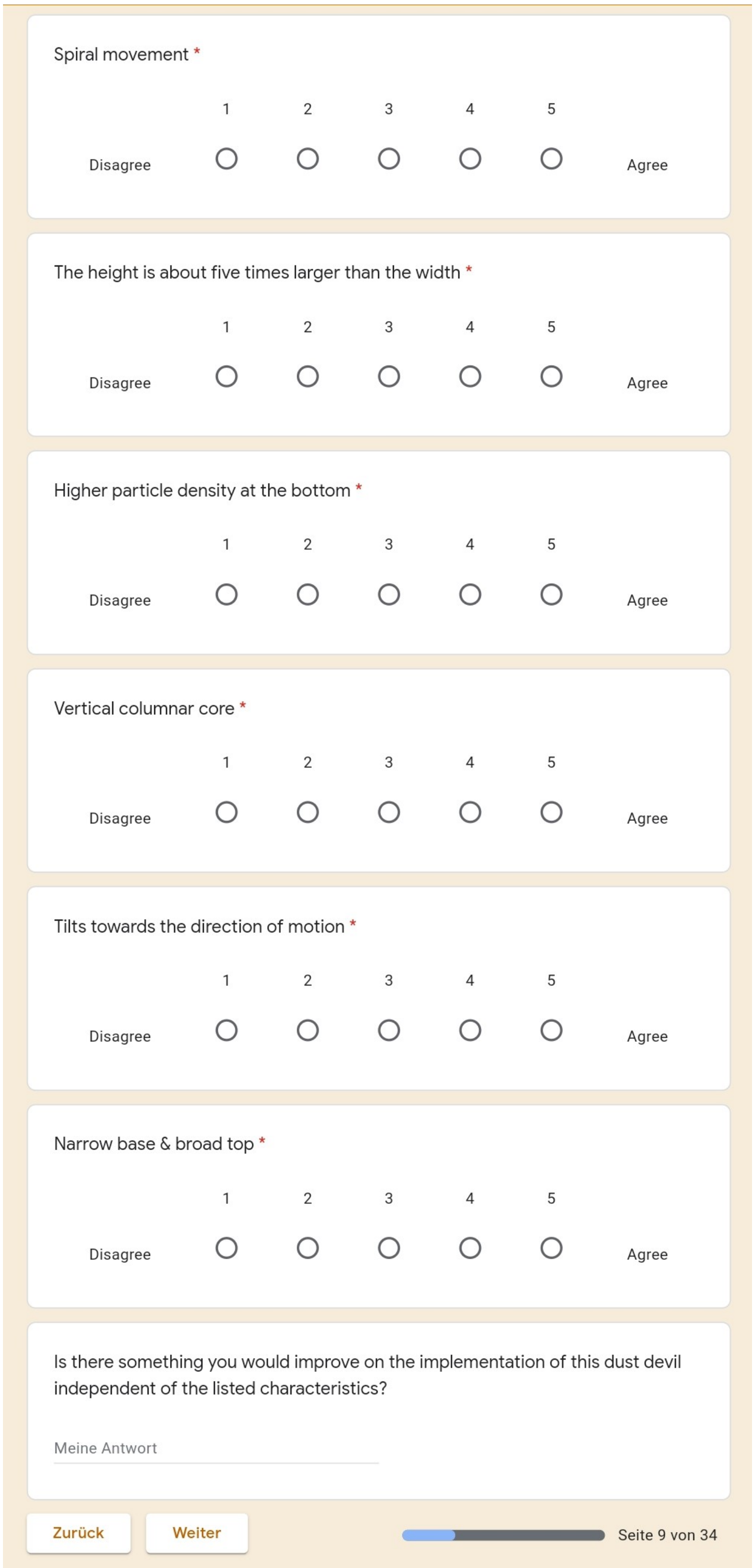
* Erforderlich

5. Does this animated dust devil fulfill the following characteristics of a real dust devil?

Upward movement *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Figure A.9 User study, page eight



Spiral movement *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

The height is about five times larger than the width *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Higher particle density at the bottom *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Vertical columnar core *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Tilts towards the direction of motion *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Narrow base & broad top *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Is there something you would improve on the implementation of this dust devil independent of the listed characteristics?

Meine Antwort

Zurück Weiter Seite 9 von 34

Figure A.10 User study, page eight (2)


User Study

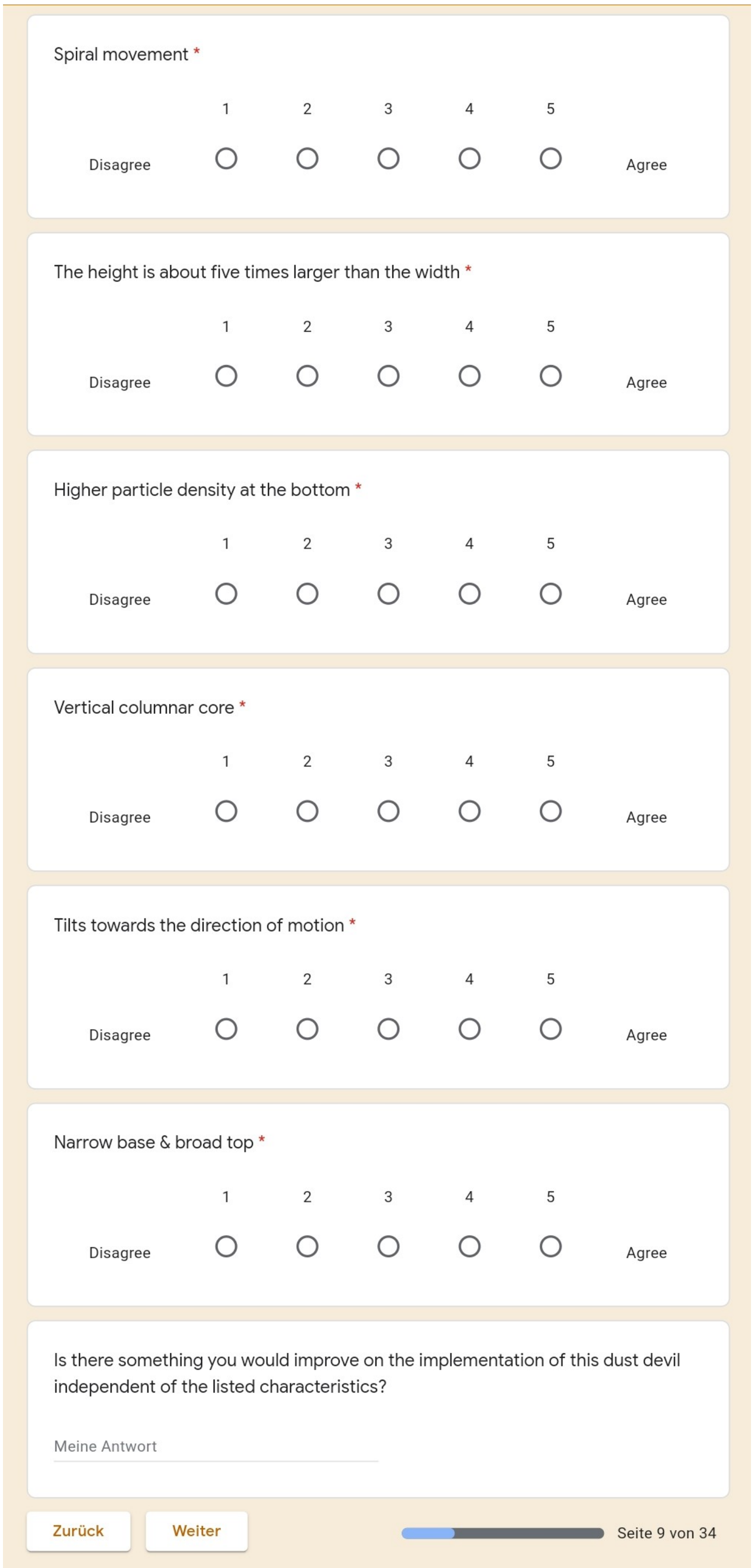
* Erforderlich

6. Does this animated dust devil fulfill the following characteristics of a real dust devil?

Upward movement *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Figure A.11 User study, page nine



Spiral movement *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

The height is about five times larger than the width *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Higher particle density at the bottom *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Vertical columnar core *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Tilts towards the direction of motion *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Narrow base & broad top *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Is there something you would improve on the implementation of this dust devil independent of the listed characteristics?

Meine Antwort

Zurück Weiter Seite 9 von 34

Figure A.12 User study, page nine (2)

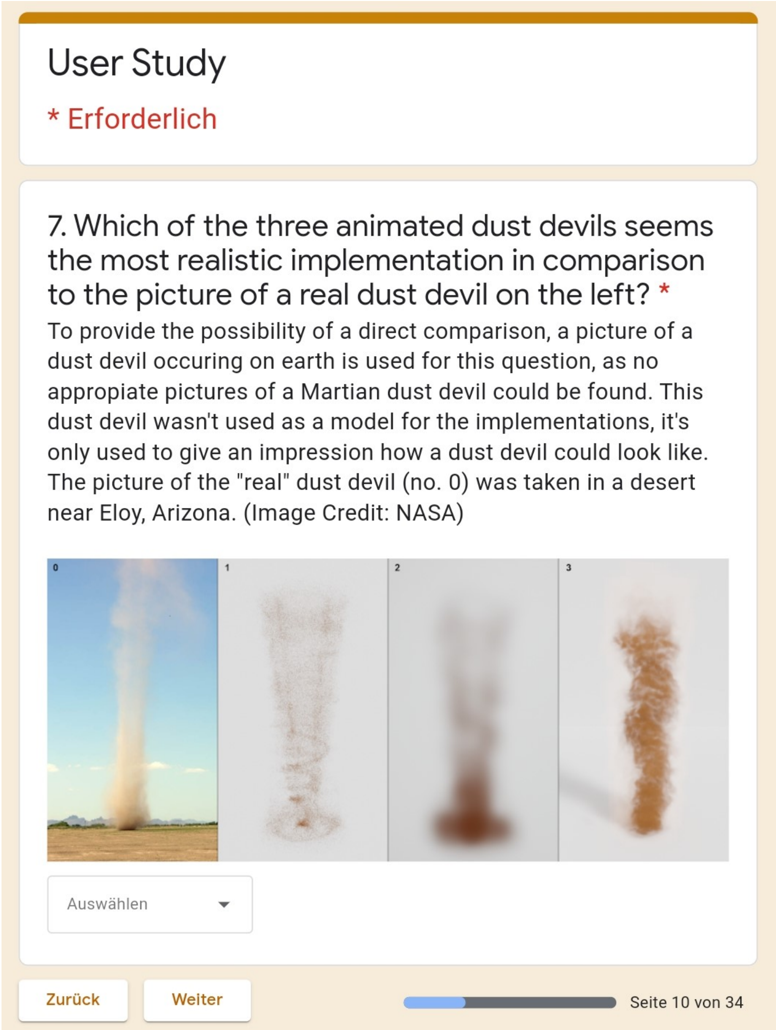
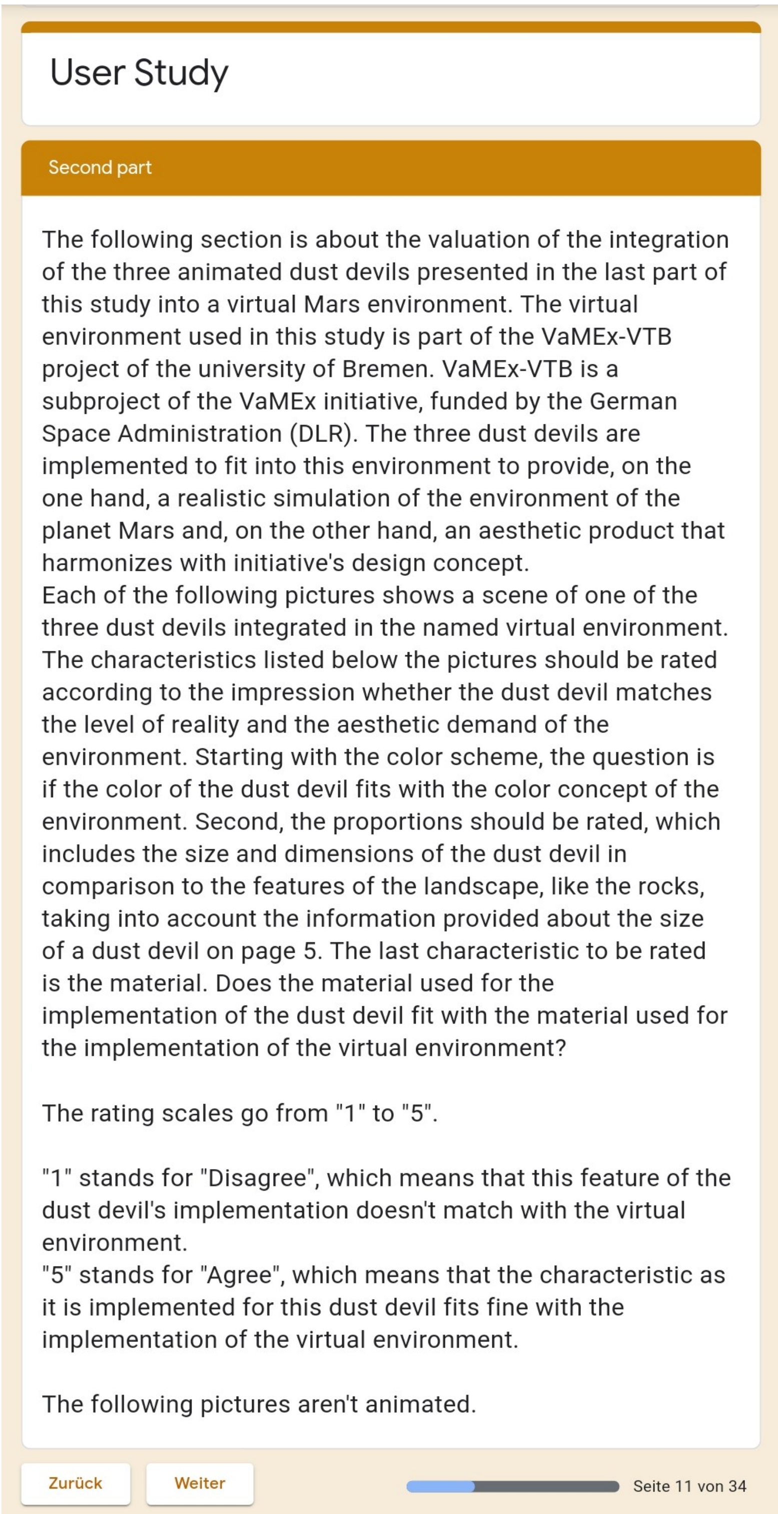


Figure A.13 User study, page ten

A.5.3 Screenshots of the questions of the Second Part



User Study

Second part

The following section is about the valuation of the integration of the three animated dust devils presented in the last part of this study into a virtual Mars environment. The virtual environment used in this study is part of the VaMEx-VTB project of the university of Bremen. VaMEx-VTB is a subproject of the VaMEx initiative, funded by the German Space Administration (DLR). The three dust devils are implemented to fit into this environment to provide, on the one hand, a realistic simulation of the environment of the planet Mars and, on the other hand, an aesthetic product that harmonizes with initiative's design concept.
Each of the following pictures shows a scene of one of the three dust devils integrated in the named virtual environment. The characteristics listed below the pictures should be rated according to the impression whether the dust devil matches the level of reality and the aesthetic demand of the environment. Starting with the color scheme, the question is if the color of the dust devil fits with the color concept of the environment. Second, the proportions should be rated, which includes the size and dimensions of the dust devil in comparison to the features of the landscape, like the rocks, taking into account the information provided about the size of a dust devil on page 5. The last characteristic to be rated is the material. Does the material used for the implementation of the dust devil fit with the material used for the implementation of the virtual environment?

The rating scales go from "1" to "5".

"1" stands for "Disagree", which means that this feature of the dust devil's implementation doesn't match with the virtual environment.
"5" stands for "Agree", which means that the characteristic as it is implemented for this dust devil fits fine with the implementation of the virtual environment.

The following pictures aren't animated.

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Figure A.14 User study, page eleven

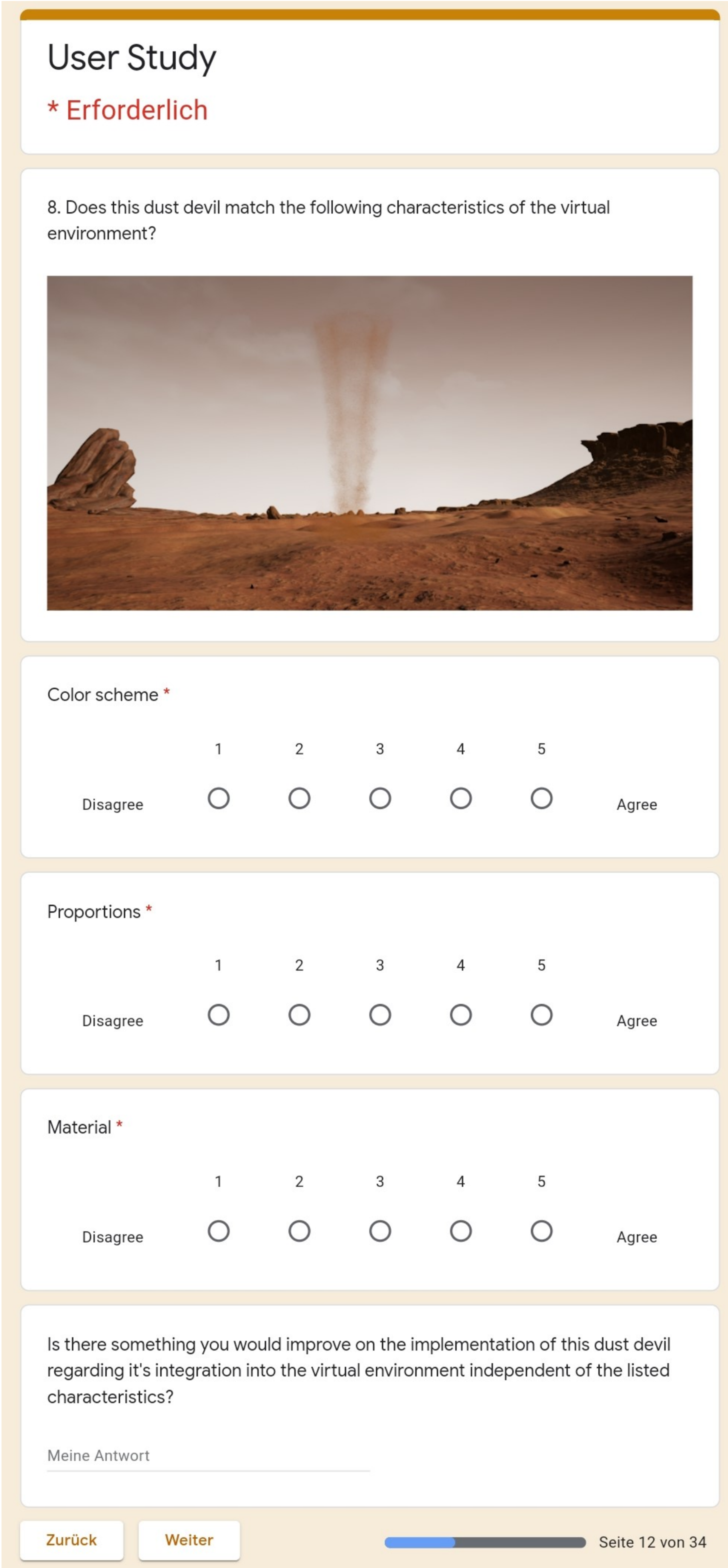
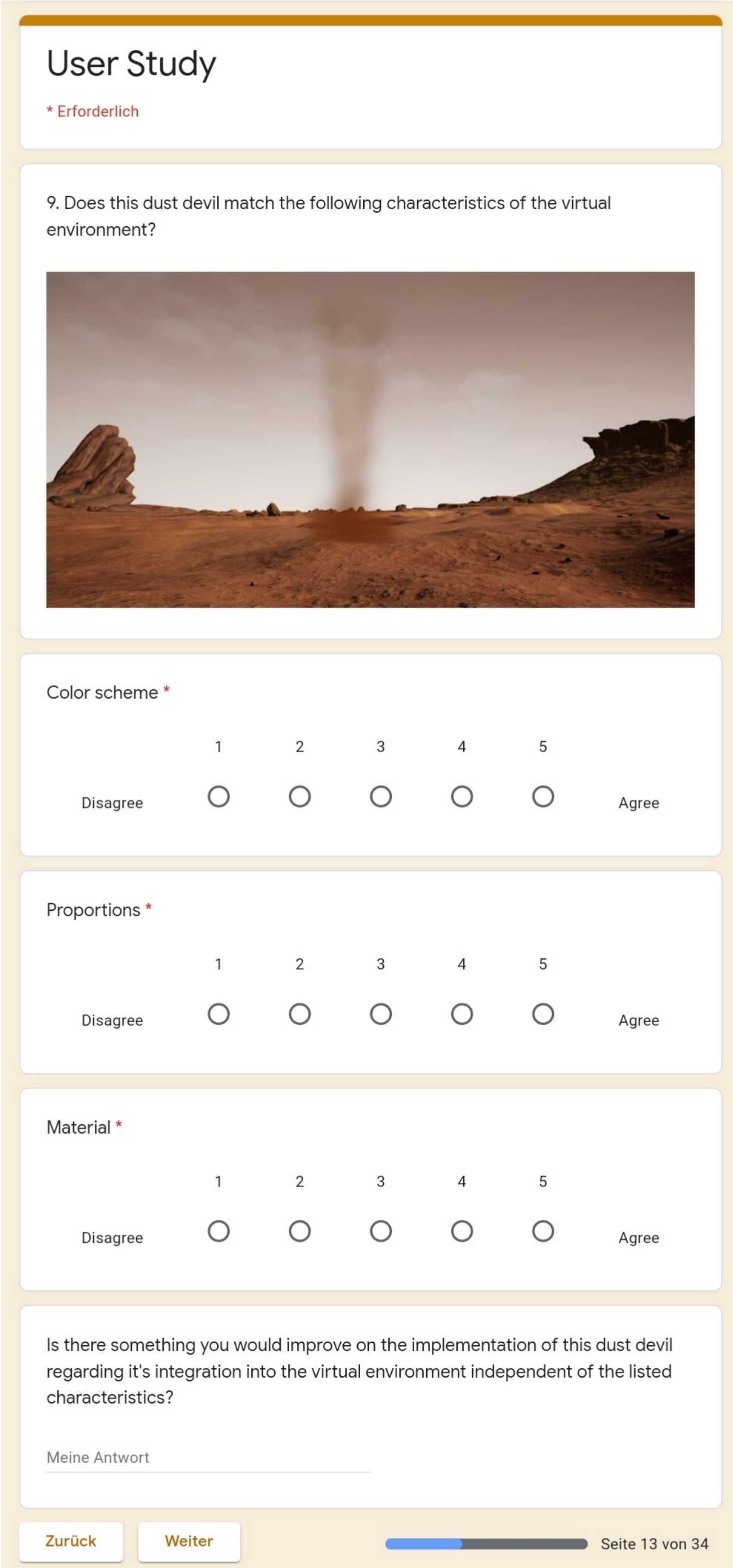


Figure A.15 User study, page twelve



User Study

* Erforderlich

9. Does this dust devil match the following characteristics of the virtual environment?

Color scheme *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Proportions *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Material *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Is there something you would improve on the implementation of this dust devil regarding it's integration into the virtual environment independent of the listed characteristics?

Meine Antwort

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Figure A.16 User study, page thirteen

User Study

* Erforderlich

10. Does this dust devil match the following characteristics of the virtual environment?

Color scheme *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Proportions *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Material *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Is there something you would improve on the implementation of this dust devil regarding it's integration into the virtual environment independent of the listed characteristics?

Meine Antwort

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Figure A.17 User study, page fourteen

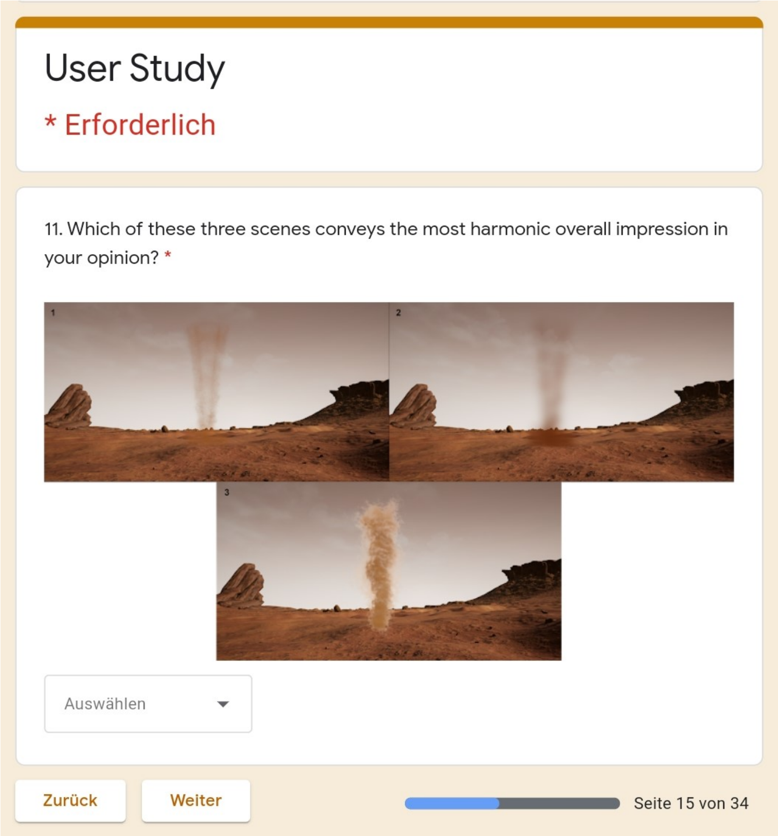
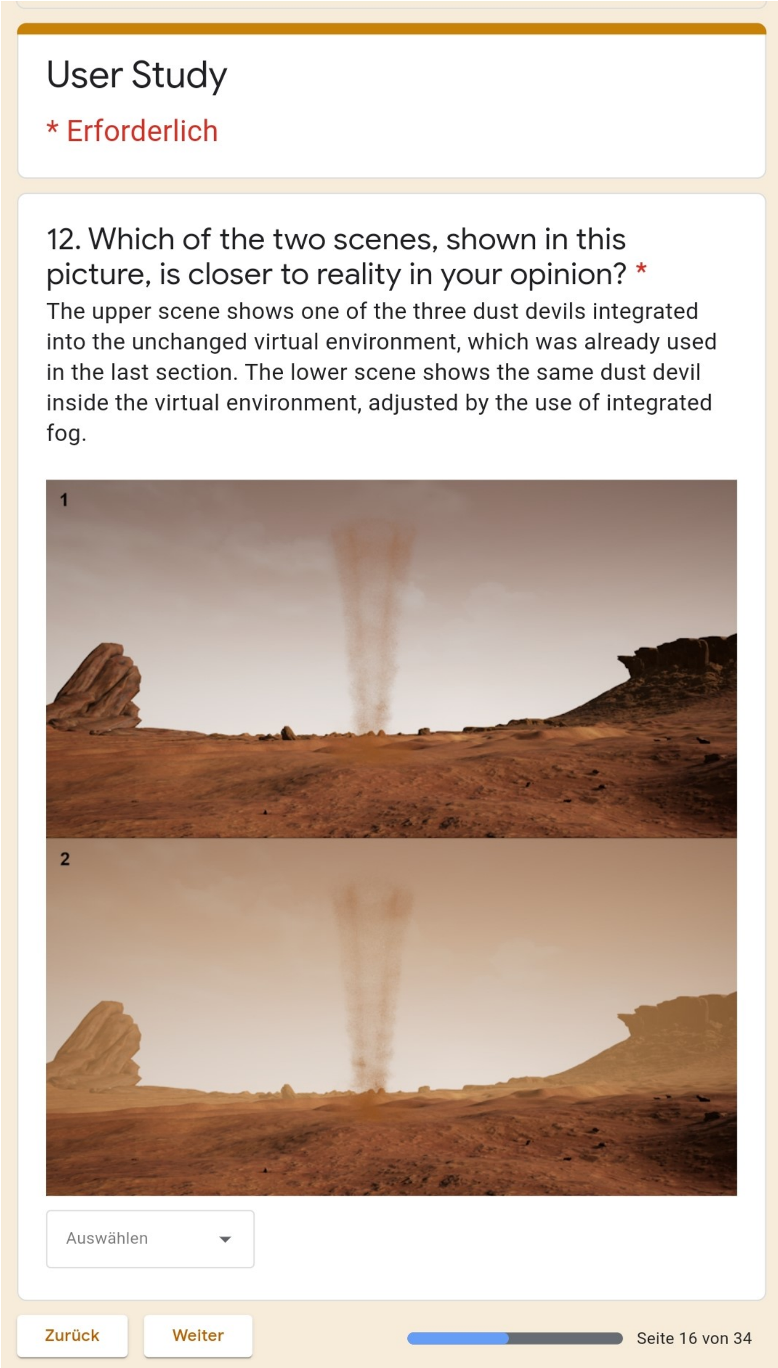


Figure A.18 User study, page fifthteen



User Study

* Erforderlich

12. Which of the two scenes, shown in this picture, is closer to reality in your opinion? *

The upper scene shows one of the three dust devils integrated into the unchanged virtual environment, which was already used in the last section. The lower scene shows the same dust devil inside the virtual environment, adjusted by the use of integrated fog.

1

2

Auswählen

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Figure A.19 User study, page sixteen

A.5.4 Screenshot of the question of the Third Part

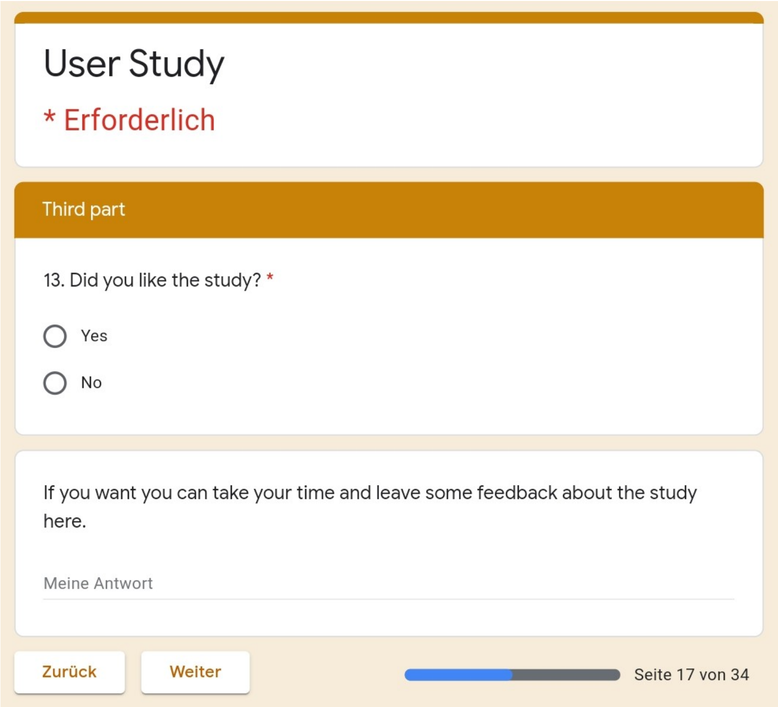

Figure A.20 User study, page seventeen

A.5.5 Screenshot of the question of the Farewell

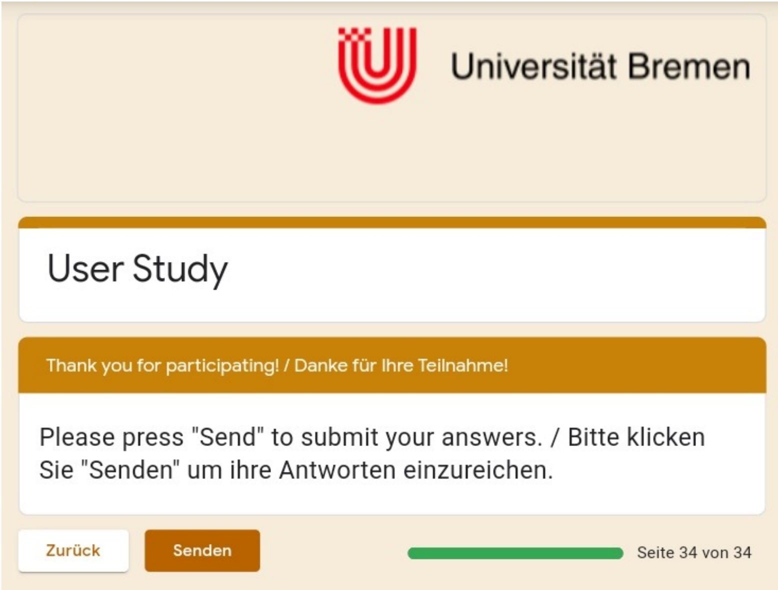

Figure A.21 User study, page thirty-four

A.6 Tables of the Collected Data of the User Study

A.6.1 Tables of the Introduction

Language	Participants	Percentage
English	1	2,38%
German	41	97,62%
Total	42	100,00%

Figure A.22 Choose your language.

Age	Participants	Percentage
under 18	0	0,00%
18 - 30	30	71,43%
30 - 40	4	9,52%
older than 40	8	19,05%
Total	42	100,00%

Figure A.23 Question: '1. How old are you?'

Professional field	Participants	Percentage
Accounting, Taxes & Law	0	0,00%
Architecture & Building Trade	0	0,00%
Art, Culture & Sports	0	0,00%
Automotive Industry	0	0,00%
Banks & Financial Services	3	7,14%
Computer Science & Information Technologies	8	19,05%
Consulting	1	2,38%
Education & Science	4	9,52%
Energy, Water & Environment	2	4,76%
Engineering	3	7,14%
Health Care & Social Affairs	3	7,14%
Insurance	0	0,00%
Marketing, PR & Design	6	14,29%
Media & Publishing	0	0,00%
Pharmaceutical & Medical Technology	0	0,00%
Public Service, Associations & Institutions	2	4,76%
Real Estate Market	0	0,00%
Staffing Service	0	0,00%
Telecommunication	0	0,00%
Tourism & Gastronomy	1	2,38%
Trading	3	7,14%
Transport & Logistics	3	7,14%
Other	3	7,14%
Total	42	100,00%

Figure A.24 Question: '2. In which professional field do you work?'

Rating	Participants	Percentage
Yes	12	28,57%
No	30	71,43%
Total	42	100,00%

Figure A.25 Question: '3. Have you ever heard about dust devils on planet Mars before?'

A.6.2 Tables of the First Part

A.6.2.1 Tables regarding the Question '4. Does this animated dust devil fulfill the following characteristics of a real dust devil?' - First Dust Devil

Rating	Participants	Percentage
1	0	0,00%
2	6	14,29%
3	3	7,14%
4	16	38,10%
5	17	40,48%
Total	42	100,00%
Arithmetic mean	4,05	
Standard deviation	1,02	

Figure A.26 Question 4: First dust devil - Upward movement

Rating	Participants	Percentage
1	0	0,00%
2	0	0,00%
3	7	16,67%
4	19	45,24%
5	16	38,10%
Total	42	100,00%
Arithmetic mean	4,21	
Standard deviation	0,71	

Figure A.27 Question 4: First dust devil - Spiral movement

Rating	Participants	Percentage
1	2	4,76%
2	3	7,14%
3	3	7,14%
4	17	40,48%
5	17	40,48%
Total	42	100,00%
Arithmetic mean	4,05	
Standard deviation	1,09	

Figure A.28 Question 4: First dust devil - The height is about five times larger than the width

Rating	Participants	Percentage
1	0	0,00%
2	0	0,00%
3	3	7,14%
4	16	38,10%
5	23	54,76%
Total	42	100,00%
Arithmetic mean	4,48	
Standard deviation	0,63	

Figure A.29 Question 4: First dust devil - Higher particle density at the bottom

Rating	Participants	Percentage
1	0	0,00%
2	4	9,52%
3	8	19,05%
4	16	38,10%
5	14	33,33%
Total	42	100,00%
Arithmetic mean	3,95	
Standard deviation	0,95	

Figure A.30 Question 4: First dust devil - Vertical columnar core

Rating	Participants	Percentage
1	2	4,76%
2	15	35,71%
3	18	42,86%
4	5	11,90%
5	2	4,76%
Total	42	100,00%
Arithmetic mean	2,76	
Standard deviation	0,89	

Figure A.31 Question 4: First dust devil - Tilts towards the direction of motion

Rating	Participants	Percentage
1	0	0,00%
2	3	7,14%
3	2	4,76%
4	11	26,19%
5	26	61,90%
Total	42	100,00%
Arithmetic mean	4,43	
Standard deviation	0,88	

Figure A.32 Question 4: First dust devil - Narrow base & broad top

A.6.2.2 Tables regarding the Question '5. Does this animated dust devil fulfill the following characteristics of a real dust devil?'- Second Dust Devil

Rating	Participants	Percentage
1	1	2,38%
2	6	14,29%
3	10	23,81%
4	14	33,33%
5	11	26,19%
Total	42	100,00%
Arithmetic mean	3,67	
Standard deviation	1,08	

Figure A.33 Question 5: Second dust devil - Upward Movement

Rating	Participants	Percentage
1	4	9,52%
2	10	23,81%
3	11	26,19%
4	11	26,19%
5	6	14,29%
Total	42	100,00%
Arithmetic mean	3,12	
Standard deviation	1,2	

Figure A.34 Question 5: Second dust devil - Spiral movement

Rating	Participants	Percentage
1	0	0,00%
2	1	2,38%
3	9	21,43%
4	13	30,95%
5	19	45,24%
Total	42	100,00%
Arithmetic mean	4,19	
Standard deviation	0,85	

Figure A.35 Question 5: Second dust devil - The height is about five times larger than the width

Rating	Participants	Percentage
1	0	0,00%
2	0	0,00%
3	2	4,76%
4	8	19,05%
5	32	76,19%
Total	42	100,00%
Arithmetic mean	4,71	
Standard deviation	0,55	

Figure A.36 Question 5: Second dust devil - Higher particle density at the bottom

Rating	Participants	Percentage
1	1	2,38%
2	10	23,81%
3	6	14,29%
4	20	47,62%
5	5	11,90%
Total	42	100,00%
Arithmetic mean	3,43	
Standard deviation	1,05	

Figure A.37 Question 5: Second dust devil - Vertical columnar core

Rating	Participants	Percentage
1	4	9,52%
2	16	38,10%
3	15	35,71%
4	6	14,29%
5	1	2,38%
Total	42	100,00%
Arithmetic mean	2,62	
Standard deviation	0,92	

Figure A.38 Question 5: Second dust devil - Tilts towards the direction of motion

Rating	Participants	Percentage
1	0	0,00%
2	4	9,52%
3	4	9,52%
4	17	40,48%
5	17	40,48%
Total	42	100,00%
Arithmetic mean	4,12	
Standard deviation	0,93	

Figure A.39 Question 5: Second dust devil - Narrow base & broad top

A.6.2.3 Tables regarding the Question '6. Does this animated dust devil fulfill the following characteristics of a real dust devil?' - Third Dust Devil

Rating	Participants	Percentage
1	2	4,76%
2	10	23,81%
3	9	21,43%
4	13	30,95%
5	8	19,05%
Total	42	100,00%
Arithmetic mean	3,36	
Standard deviation	1,17	

Figure A.40 Question 6: Third dust devil - Upward Movement

Rating	Participants	Percentage
1	2	4,76%
2	5	11,90%
3	7	16,67%
4	11	26,19%
5	17	40,48%
Total	42	100,00%
Arithmetic mean	3,86	
Standard deviation	1,21	

Figure A.41 Question 6: Third dust devil - Spiral movement

Rating	Participants	Percentage
1	1	2,38%
2	3	7,14%
3	5	11,90%
4	12	28,57%
5	21	50,00%
Total	42	100,00%
Arithmetic mean	4,17	
Standard deviation	1,04	

Figure A.42 Question 6: Third dust devil - The height is about five times larger than the width

Rating	Participants	Percentage
1	7	16,67%
2	20	47,62%
3	7	16,67%
4	2	4,76%
5	6	14,29%
Total	42	100,00%
Arithmetic mean	2,52	
Standard deviation	1,24	

Figure A.43 Question 6: Third dust devil - Higher particle density at the bottom

Rating	Participants	Percentage
1	2	4,76%
2	10	23,81%
3	11	26,19%
4	11	26,19%
5	8	19,05%
Total	42	100,00%
Arithmetic mean	3,31	
Standard deviation	1,16	

Figure A.44 Question 6: Third dust devil - Vertical columnar core

Rating	Participants	Percentage
1	1	2,38%
2	10	23,81%
3	10	23,81%
4	9	21,43%
5	12	28,57%
Total	42	100,00%
Arithmetic mean	3,50	
Standard deviation	1,2	

Figure A.45 Question 6: Third dust devil - Tilts towards the direction of motion

Rating	Participants	Percentage
1	3	7,14%
2	19	45,24%
3	8	19,05%
4	7	16,67%
5	5	11,90%
Total	42	100,00%
Arithmetic mean	2,81	
Standard deviation	1,16	

Figure A.46 Question 6: Third dust devil - Narrow base & broad top

A.6.2.4 Table regarding the question '7. Which of the three animated dust devils seems the most realistic implementation in comparison to the picture of a real dust devil on the left?'

Dust devil	Participants	Percentage
No. 1	5	11,90%
No. 2	22	52,38%
No. 3	15	35,71%
Total	42	100,00%

Figure A.47 Question 7

A.6.3 Second Part

A.6.3.1 Tables regarding the Question '8. Does this dust devil match the following characteristics of the virtual environment?' - First Dust Devil

Rating	Participants	Percentage
1	0	0,00%
2	1	2,38%
3	3	7,14%
4	21	50,00%
5	17	40,48%
Total	42	100,00%
Arithmetic mean	4,29	
Standard deviation	0,7	

Figure A.48 Question 8: First dust devil - Color

Rating	Participants	Percentage
1	1	2,38%
2	4	9,52%
3	7	16,67%
4	21	50,00%
5	9	21,43%
Total	42	100,00%
Arithmetic mean	3,79	
Standard deviation	0,96	

Figure A.49 Question 8: First dust devil - Proportions

Rating	Participants	Percentage
1	0	0,00%
2	2	4,76%
3	16	38,10%
4	19	45,24%
5	5	11,90%
Total	42	100,00%
Arithmetic mean	3,64	
Standard deviation	0,75	

Figure A.50 Question 8: First dust devil - Material

A.6.3.2 Tables regarding the Question '9. Does this dust devil match the following characteristics of the virtual environment?' - Second Dust Devil

Rating	Participants	Percentage
1	1	2,38%
2	6	14,29%
3	7	16,67%
4	20	47,62%
5	8	19,05%
Total	42	100,00%
Arithmetic mean	3,67	
Standard deviation	1,02	

Figure A.51 Question 9: Second Dust Devil - Color

Rating	Participants	Percentage
1	0	0,00%
2	1	2,38%
3	9	21,43%
4	22	52,38%
5	10	23,81%
Total	42	100,00%
Arithmetic mean	3,98	
Standard deviation	0,74	

Figure A.52 Question 9: Second Dust Devil - Proportions

Rating	Participants	Percentage
1	2	4,76%
2	6	14,29%
3	10	23,81%
4	20	47,62%
5	4	9,52%
Total	42	100,00%
Arithmetic mean	3,43	
Standard deviation	1	

Figure A.53 Question 9: Second Dust Devil - Material

A.6.3.3 Tables regarding the Question '10. Does this dust devil match the following characteristics of the virtual environment?' - Third Dust Devil

Rating	Participants	Percentage
1	6	14,29%
2	18	42,86%
3	8	19,05%
4	8	19,05%
5	2	4,76%
Total	42	100,00%
Arithmetic mean	2,57	
Standard deviation	1,09	

Figure A.54 Question 10: Third dust devil - Color

Rating	Participants	Percentage
1	2	4,76%
2	7	16,67%
3	12	28,57%
4	11	26,19%
5	10	23,81%
Total	42	100,00%
Arithmetic mean	3,48	
Standard deviation	1,16	

Figure A.55 Question 10: Third dust devil - Proportions

Rating	Participants	Percentage
1	7	16,67%
2	10	23,81%
3	14	33,33%
4	7	16,67%
5	4	9,52%
Total	42	100,00%
Arithmetic mean	2,79	
Standard deviation	1,19	

Figure A.56 Question 10: Third dust devil - Material

A.6.3.4 Table regarding the question '11. Which of these three scenes conveys the most harmonic overall impression in your opinion?'

Scene	Participants	Percentage
Scene 1	17	40,48%
Scene 2	21	50,00%
Scene 3	4	9,52%
Total	42	100,00%

Figure A.57 Question 11

A.6.3.5 Table regarding the question '12. Which of the two scenes, shown in this picture, is closer to reality in your opinion?'

Scene	Participants	Percentage
Scene 1	19	45,24%
Scene 2	23	54,76%
Total	42	100,00%

Figure A.58 Question 12

A.6.4 Third Part

	Participants	Percentage
Yes	40	95,24%
No	2	4,76%
Total	42	100,00%

Figure A.59 Question: '13. Did you like the study?'