The Use of Visual Technologies and Tracking Data to Improve Virtual Reality Perception in Training Simulator

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***Abstract*—The problem of creating the realistic virtual environment for training simalators is receiving considerable attention while requirements for sportsmen grow more and more with the development of modern electronics. The objective of the article is determining the requirements for training simulators with a realistic virtual environment and creating the alpine skiing training system. The quality of visualization, the realistic physics engine, the realistic terrain and the user movement processing are highlighted among all the factors affecting the perception of a virtual 3D scene. The methods of a VR environment system implementation that take these factors into account are also described and implemented.**

I. Introduction

The rapid progress of virtual environment technology and computer vision makes possible to use 3D virtual reality systems in various application areas: engineering, science, medicine, pointing and tactics systems, games and video, telemetry in sport, training and simulation. This became possible thanks to the compactness, high-quality visualization and high precision tracking of the modern equipment. In this work we consider the training system formed by the alpine ski simulator, the optical tracking system and the visualization system. The problem is to use the capabilities of all its components to form a realistic 3D virtual environment.

The problems of human 3D perception have been investigated for a long time starting with the pioneer works of V. Rauschenbusch [1]. The study of the perception is vital for professional sportsmen. Professional athletes and coaches know that visual skills play the key roles in the sport performance. They could be the major factor that prevents a good athlete from becoming an exceptional one and vice versa [2]. The research in the field of the virtual reality perception include the studying a broad range of factors: disparity, accomodation, visual effects, cognitive skills, immersion in induced environment, safety factor [3], [4], [5].

Each practical application area depends very much on proper perception of 3D scene and has its own specifics of such a perception.

In this article we focus on the alpine skiing training systems, define the requirements for such systems, which consider existing training simulators, and describe our implementation of the alpine skiing training systems, which satisfies these requirements. Since virtual reality training systems are important for sportsmen nowadays, there are several known implementations of them. The development of the system is considered to be fundamental because it includes the research of the systems, which have high degree of immersion of the sportsman in a virtual environment and realistic virtual scene creation with the help of tracking data. In the Section II we analyze possible implementations of such systems. The perception of the virtual environment is the most important thing that should be taken into account while creating the training system. In the Section III we describe the main problems of 3D scenes perception and define the requirements for the alpine skiing training system. The analysis of available hardware equipment and development tools is the essential part of the application development. In the Section IV we give an overview of hardware equipment used to create the virtual environment and justification of the software and development tools. In the Section V we describe how all virtual objects in the scene are constructed. The real-life slopes are also very important part of ski training systems, which help sportsmen achieve better results. In the Section VI we explain how the terrains in the scene are created. The optical tracking system in our project became the main tool for creating a realistic skiing virtual environment, and it is the usage of tracking system that became the essential feature in our simulator. In the Section VII we describe the optical tracking system used to compensate restrictions of the skiing simulator used.

II. Skiing Training Systems

For the purposes of this work we use the active alpine skiing training system produced by the SkyTec Interactive Russian company, which is available for the MIPT ski sports section students [6]. It is shown in Fig. 1 and has been well described in [3].

The following virtual environment subsystems are used: the passive 3D stereo vision system based on the binocular parallax, the system with active stereo and head mounted displays (HMD), OPTITRACK cameras, markers, and Motive software as head-skis tracking system [5].

Benefits of this system include:

- Advanced platform with skis, equipped with powerful motors hidden inside the simulator.
- Nets on the sides of simulator that take a safety factor into account.

Fig. 1. SkyTech based training system

- Possibility to use SkyTech virtual reality implementation on a wide panorama screen.

But the system has following disadvantages:

- SkyTech implementation doesn't use stereo image. 2D view cannot provide the same VR-immersion quality as 3D systems.
- Absence of API to communicate with trackers in the platform.
- High price of the whole system.

Another notable system is the 3D-Live project [7]. It allows to use the PROSKI-SIMULATOR (see Fig. 2) with head mounted displays or screens in front of the skier like SkyTech simulator. This system was used in a race, where two people wearing Oculus Rift [8] headsets on the 3D-Live simulator raced a real skier on the slope [9].

Fig. 2. PROSKI-SIMULATOR

The advantages include:

- Compactness of the whole construction. It requires 4-5 times less space compared to the SkyTech simulator.
- The ability of head-mounted displays to build a realistic 3D virtual world around the skier.

The main problem with such a system is that it requires some preliminary training in order to compensate the loss of orientation in real space.

The last system to mention is the RideOn augment reality system [10]. Due to the type of the system, it can not be used in laboratory for studies, but it is noteworthy that is has the degree of immersion hardly reachable in virtual reality systems. RideOn could also be used as training and advising system.

As may be seen, all the above systems have disadvantages that cause problems of the virtual space perception. Realistic three-dimensional scene is important for the quality of training systems. We use the SkyTec alpine skiing training system, because it has the most advanced platform among the training system we have analyzed. In this article we propose ways to improve the experience quality and overcome the disadvantages (low visualization quality and absence of tracking API) of the SkyTec training system using modern visualization and physics simulation technologies and the user movements tracking data.

III. Perception of 3D scenes

The perception of a 3D virtual scene is a highly complicated process. It is the reason why there could be a lot of realizations of virtual environment systems. The requirements for virtual environment systems have been described in [11]. The effectiveness of virtual worlds is determined not only by the system itself, but also by capabilities and limitations of a user of the system (skier in our particular case). Fig. 3 shows the key human factors affecting the user perception of a virtual environment system.

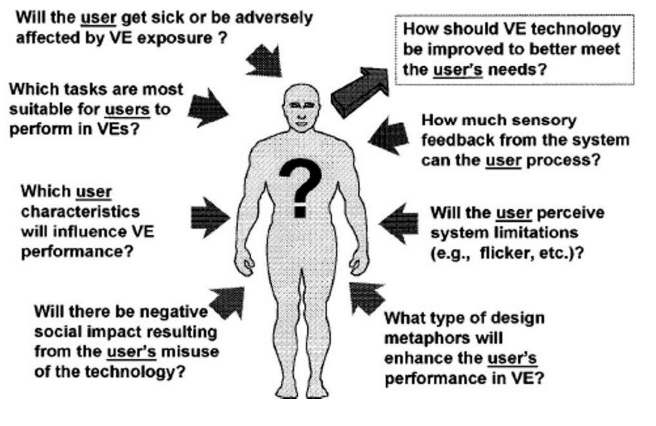

Fig. 3. The human factors in virtual environments

The role of disparity, vergence, and accomodation in the visualization of ski slope have been described in [3]. These factors are important because they form a "main triad" of stereoscopic vision. This work also studies visual effects, like fog, snow, and rain, experimentally as they have a great impact on the time of the turn. Perceptual-cognitive skills of sportsmen are studied in [2]. The results of the work are used for training by teams in the English Premier League, the National Hockey League (Hockey), the Top 14 French Rugby League (Rugby) and US NCAA varsity teams. The work [4] focuses on the concept of immersion and identifies it as the fundamental property of virtual reality. The author opposes opportunities of the virtual reality to viewing the world as a spectator, as if through a window. The work [12] contains the review of unwanted physical, physiological, and psychological side-effects that VR equipment may have.

Having analysed factors that affect the perception of a virtual environment system, we can now formulate the requirements for the alpine skiing training system:

1) Degrees of freedom requirement. In the most cases such training systems have less than six degrees of freedom, but the user avatar (virtual incarnation) in generated 3D virtual scene should have all possible degrees of freedom. For example, one-directional movements on the SkyTec Interactive training system should be transformed into realistic movements of the skier on the hillside with six degrees of freedom: three position components and three vector of inertia components.
2) Presence in the scene requirement. The skier should "feel" his presence in the scene, and the virtual environment system should be able to generate approximate optical flow patterns. Otherwise the skier will be aware that the experience is not natural. For example, the skier perceives other moving objects like fans, falling snow and so on during his movement.
3) Physics engine requirement. At the same time not only optical effects affect the realism of the virtual space. This is very important to implement the behaviour of virtual objects, according to the physics laws. In other words, the software that processes the virtual space needs to have not only a good graphics engine, but also a realistic physical one.
4) The stability of perception requirement. The stability of perception should be guaranteed. It means that static virtual objects should remain motionless while the skier moves.
5) Performance requirement. All subsystems that are used to construct the 3D virtual scene, like tracking systems, should show enough performance to process all the required data in a short time.
6) Negative effects alleviation requirement. All possible negative effects of subsystems that are used to construct the 3D virtual scene should be minimized.

The current implementations of the known training systems don't fully satisfy requirements above. The common key factors for the skiing virtual environment systems that affect the perception of a virtual 3D scene are the quality of visualization (the 3D scene should be correctly perceived by the binocular vision taking the view stability in account), the realistic physics engine (the software should properly handle the movement of objects in the virtual space), the realistic terrain (the simulated track should be close to the actually existing) and the user movements processing (the user natural movements should be used for workaround of the equipment freedom degrees limitations). Below we describe the technologies and approaches that are aimed at improving the realism of the virtual environment system taking such factors into account.

IV. VISUALIZATION TECHNOLOGIES

Visual perception of 3D space is a major source of information for people. Therefore, it is very important to choose the right hardware equipment and software tools for the visualization.

A. *Hardware equipment*

Nowadays there are two types of the 3D scene visualization systems applicable for a simulator: an external display or a head-mounted display (a virtual reality helmet). The external display was used with the old version of the ski simulator. This approach has a number of disadvantages associated with the distortion type:

- Distortion occurring due to the horizontal parallax.
- Very low degree of immersion in the virtual environment.
- Extra space required for the wide screen.

The modern history of virtual reality helmets started in 2012 when id Software showed its early prototype of Oculus Rift at Electronic Entertainment Expo [8]. It was based on a 5.6-inch LCD-screen and a pair of lenses. This system allowed you to receive a stereo image with the field of view of 90° horizontally and 110° vertically. The new version of this device was developed in 2013. It utilizes a high-resolution Samsung screen with a refresh rate of 75 Hz and a variety of new sensors to improve the tracking system.

Oculus Rift requires a wire connection to a PC which renders the virtual scene view on the basis of the tracking data. The ski simulator user moves very rapidly, so such a connection is not allowed. However, mobile devices have become quite productive not only to perform the processing and visualization of the virtual scene, but also fully reproduce the job tracking system using built-in sensors: accelerometer and magnetometer. Therefore, new VR-helmets projects based on mobile devices appeared in 2014.

The pioneer in this direction was the company Samsung, which developed the GearVR helmet in cooperation with Oculus [13]. The basis of the helmet is the Samsung Galaxy Note 4 smartphone, which activates a special operating mode when connected to GearVR. In this mode the performance of the smartphone is forwarded for the 3D graphics processing, and the Oculus software environment started repeating the principles of interaction with the Oculus Rift. So a bunch of GearVR and Note 4 works as a union VR-helmet with hardware optimized for the Oculus technologies. Samsung has released several similar devices compatible with some other smartphones. We use Samsung GearVR for Samsung Galaxy S6 and S6 Edge [14].

Other manufacturers selected the way of universal holder development. The idea is to fix a mobile phone at the user head with a helmet. One of the most well-known products of such type is Fibrum which we use in our research [15].

The principle of these devices is based on the use of mobile applications which process data from sensors implementing the tracking system and displaying two adjacent images which provide a stereo effect. Important differences from GearVR are the compatibility with a variety of mobile devices and the multiple operating system support.

The physical design of all the VR-helmets using mobile devices is similar to and based on the principles used in the Oculus Rift prototype. It is shown in Fig. 4. Two images that form a stereo pair are shown at the mobile device screen. Each image passes through a lens that is used to increase the field of view. In some helmets, for example, Samsung GearVR, the distance from the screen to the lens can be adjusted to compensate for the operator impairment, in others it is fixed.

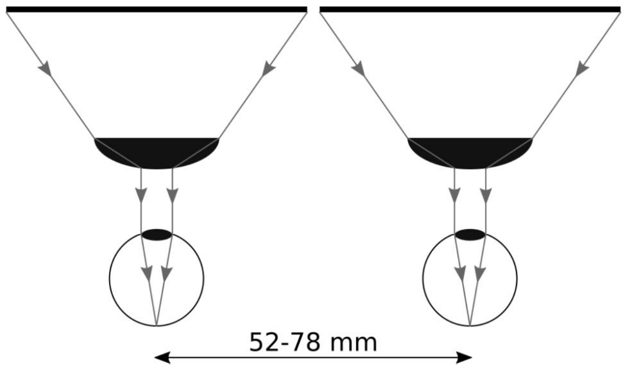

Fig. 4. Principal VR-helmets design

B. *Software and development tools*

The analysis of available tools is the essential part of the application development. The quality of the virtual scene induced depends significantly on the technologies used. We have analysed a number of tools used for virtual reality application development and have chosen Unity [18]. We have compared Unity, Android Sudio with OpenGL ES [19], WorldViz [20], Unreal Engine [23], OpenSceneGraph [24] and MiddleVr [25]. The main criteria were the following:

1) The number of supported devices, including head-mounted displays and PCs.
2) The possibility to import 3D models, created in other applications.
3) The support of one of the languages from the list: C, C++, C# or Python, because Motive software supports a number of data streaming protocols, which have bindings to these languages.
4) Built-in physics engine for acceleration of application development.
5) Free licensing.

These criteria are justified by the design of other subsystems of the alpine ski simulator. The results of comparison of examined virtual reality development tools is presented in Tab. I.

In the case of head mounted displays, device manufacturers offer their own products. Oculus Mobile SDK (OVR) and Fibrum SDK are the SDKs for Samsung GearVR and Fibrum, respectively [16], [17]. They both provide plug-ins for Unity 3D as many other SDKs.

Unity is a cross-platform engine used for the development of 2D and 3D applications: video games, virtual reality applications, training systems, etc. It includes the visual editor and supports scripting languages (JavaScript, C# and other .NET languages that compile to compatible .dll), which can be used to control objects and their properties, perform calculations, implement networking, etc.

Thus, the virtual reality application development model is suggested to be the following:

TABLE I. COMPARISON OF VIRTUAL REALITY DEVELOPMENT TOOLS

	Unity (free)	**Android Studio with OpenGL ES**	**WorldViz (Free)**	**Unreal Engine**	**Open Scene Graph**	**MiddleVr (Free)**
Supported HMDs	Oculus, Samsung Gear VR, Fibrum, Google Cardboard	Oculus, Samsung Gear VR...	Oculus	Oculus, Samsung Gear VR, Steam VR	-	Oculus
3D models import	obj, fbx, dae, 3DS, dxf	obj	fbx, dae	fbx	-	-
Languages	JavaScript, C#, Python	C++	Python	C++	C++	C++
Built-in physics engine	yes	no	yes	yes	no	yes
Licensing	free with minor restrictions	free	free with minor restrictions	free	free	non-commercial use
Text-based / graphical programming	both	text	both	both	text	both

1) Create or import 3D scenes and all the objects to the Unity visual editor.
2) Implement the application logic in C# or JavaScript using the built-in physics and visualization engines.
3) Integrate the virtual reality systems plug-in in the application.
4) If necessary, change the cameras and the camera control script object.

This model provides the following advantages to researchers:

- The opportunity to reuse a well-tested code.
- The freedom for the user to choose among platforms. For example, the skier can choose between the training complex with the passive 3D stereo vision system (see Fig. 1) or the PROSKI-SIMULATOR equipped with any binocular head mounted display (see Fig. 2).
- The flexible set-up of the physics and visualization through scripts.

On the one hand, the choice of Unity as the main part of visualization subsystems gives the opportunity to reuse well-tested graphycs optimizations, which Unity provides, and remain in full control of models and scripts used in the project on the other hand. This is important to satisfy the performance requirement mentioned in Section III.

V. PHYSICS AND OBJECT INTERACTIONS

Since we have chosen Unity 3D for the visualization, we can use all the features of this framework for the physics processing.

A. Basics

A 3D skiing track scene consists of the terrain surface, the skiing track attributes like flags, nets, ski lifts, other objects like trees, houses, spectators, the landscape in the background and light.

In terms of Unity, we have a scene, filled with the objects of the simulator. All objects that are listed above become `GameObjects` in Unity. `GameObjects` are fundamental in Unity and represent characters, properties and scenery. The real functionality is implemented in `Components`, which are parts of `GameObjects`.

Every `GameObject` contains a `Transform` component. This component encapsulates a 3×3 matrix defining position, rotation and scale in the virtual 3D scene as the corresponding three-dimensional vectors. It is the only component that is presented in every Unity `GameObject`. Other components provide additional functionality to the `GameObject`. For example, it is possible to add a `Light` component to an empty `GameObject` to create light source.

B. Skier object

The skier in our 3D environment is represented as an object, consisting of a 3D ski model, virtual camera object (see Fig. 5), and `Rigidbody`, `Trail Renderer` and `Script` components.

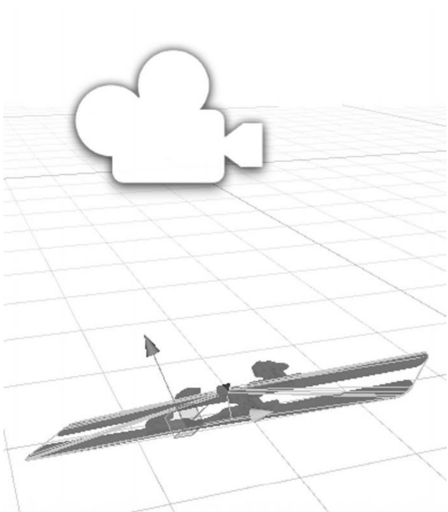

Fig. 5. The skier object view

We control the behavior of these components using the following settings:

`Transform Component` parameters:

- Position (X, Y, Z axis) of the object.
- Rotation (X, Y, Z axis) of the object.
- Scale (X, Y, Z axis) of the object.

A `Rigidbody` component is the main component that enables physical behaviour for an object. With a Rigidbody attached, the object immediately responds to gravity. If one or more Collider components are also added, the object will be moved by incoming collisions. Since a `Rigidbody` component takes over the movement of the object it is attached to, one shouldn't try to move it from a script by changing the `Transform` properties such as position and rotation. Instead, one should apply forces to push the object and let the physics engine calculate the results.

`Rigidbody Component` parameters:

- The mass of the object (in kilograms by default).
- Angular drag defines how much air resistance affects the object when rotating from torque.
- Gravity. This parameter is always set to true, which means the object is affected by gravity.
- Collision Detection. This parameter is always set to true and prevents other objects from passing through the virtual skier.

The `Trail Renderer` component is used to make trails behind objects in the scene as they move about.

`Trail Renderer Component` parameters:

- Receive Shadows.
- Material. It is used for rendering the trail.
- Light Probes
- Time parameter determines how long the trail will be.
- Start Width parameter determines width of the trail at skier position.
- End Width parameter determines width of the trail at the end. It is equal to the Start Width in our case.

The `Script Component` extends the built-in Unity physics engine and defines the forces applied to the skier in order to move him.

`Script Component` parameters:

- Horizontal Speed.
- Rotate Coefficient.

An important component for building 3D objects in Unity is `Collider`. `Collider` components define the shape of an object for the purposes of physical collisions. A collider, which is invisible, need not be the exact same shape as the object's mesh, and a rough approximation is often used. In our case, we also don't use the whole ski mesh, but a simple pyramid-like collider for performance reasons. It approximates the shape of the ski quite well while keeping a low processor overhead.

The virtual camera objects are quite similar in different SDKs [21]. `OVRCameraRig` with the following structure is used in OVR:

- `TrackingSpace`
  - `LeftEyeAnchor`
  - `CenterEyeAnchor`
  - `RightEyeAnchor`
  - `TrackerAnchor`

Fibrum SDK uses `VR_Camera`:

- `VRCamera`
  - `RCamera`
  - `LCamera`
  - `VR_UI_dummyCamera`

Tracking data is received from `TrackingSpace` in OVR and from `VRCamera` in Fibrum SDK.

Before rendering the next frame, the training systems receives data from the tracking system, which describes the sportsman's position, his/her shift relative to the previous position. Then this shift is used to move the skier object by applying forces to the `Rigidbody` component as described earlier.

```
void FixedUpdate () {
    float horizontalMovement = this.getShift();
    _rigidbody.AddTorque (_transform.up *
        RotateCoeff * horizontalMovement);
    Vector3 movement =
        new Vector3(horizontalMovement, 0.0f, 0.0f);
    _rigidbody.AddForce(movement * HorizontalSpeed);
}
```

In this way, we compensate the missing degrees of freedom and improve Unity physics engine to implement the realistic behaviour on the slope. It helps to satisfy two requirements listed in Section III. It helps the sportsman experience the turn as if he was making it on the real ski slope.

VI. Realistic terrain

It is useful to simulate the real-world tracks to get the best experience from the training simulator. Unity `Terrain` system allows developers to add vast landscapes to their applications. At runtime, terrain rendering is highly optimized for rendering efficiency. This section explains how the surfaces for the ski training system have been created.

The first slope was created from the standard 3D object `Terrain`, which is provided by Unity. Initially, added terrain is nothing more than a large, flat plane. With the use of `Raise / Lower Terrain` (see Fig. 6), `Paint Height` and `Smooth Height` tools it is possible to create any surface needed [18]. All of them use brushes like the ones used in paint editors to "paint" height on initially flat plane.

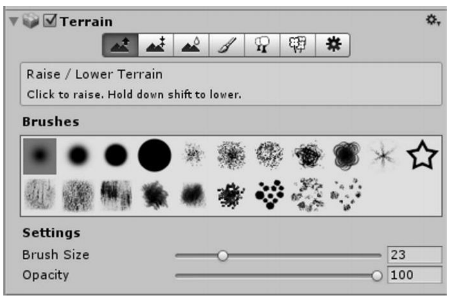

Fig. 6. Raise / Lower Terrain tool

As it was mentioned above, there is a number of objects on the slope, which the skier can observe, like trees or spectators. All of them can be implemented using `Trees`. `Trees` are solid 3D objects that grow on a surface. Unity uses various optimizations to maintain rendering performance, e. g. billboarding for distant trees. Billboarding is a technique that adjusts an object's orientation, so that it "faces" some target, usually the camera [22]. Tree also can have `Colliders`, so that skier can run into them in the virtual environment, too. The presence of trees and spactators is one of the requirements for training system (see Section III). Unity `Trees` also provide the stability of perception, which is also a requirement.

The created terrain is presented in Fig. 7.

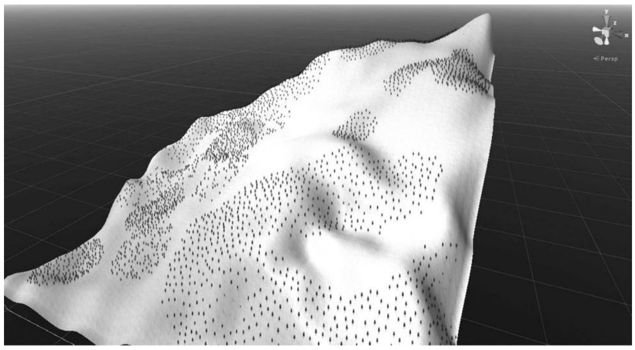

Fig. 7. Manually created terrain

In fact, Unity `Terrain` is implemented using a *heightmap*. The heightmap is grayscale image, which represents a special array. This array contains the height of each point on the terrain. So, the second way to make a slope for the simulator is to make or obtain a heightmap, representing the area of interest. There is a number of ways to achieve that: internet services [26], Google earth [27] plug-ins, and special applications. The second terrain for the simulator is presented in Fig. 8 and is a part of the Rosa Khutor Alpine Resort.

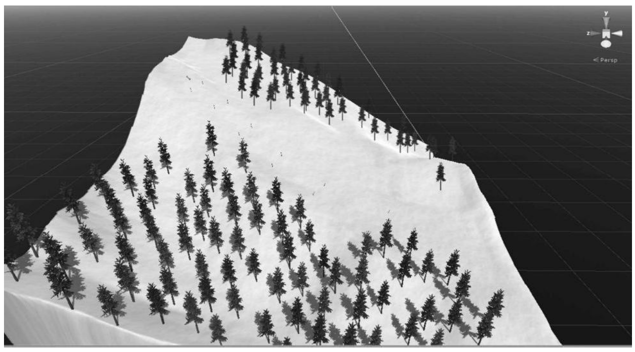

Fig. 8. Rosa Khutor Terrain

So, we have proposed the ways of implementation of the real ski slope in the virtual environment. This is important not only because it noticeably increases the degree of immersion in the virtual environment and gives the skier the feeling of his presence in the virtual scene, but also gives the researcher an opportunity to compare the experience, obtained on the real-world and virtual tracks.

VII. Using of optical tracker

The simulator that we use allows you to control only the speed and the direction of the offset relative to the skier virtual trajectory baseline. It is quite insufficient for the realistic skiing modelling. Therefore, the use of an external tracking system is deemed necessary.

The tracking system consists of OPTITRACK cameras, markers and Motive software [28]. Two groups of markers are used, both consisting of three markers forming a triangle: one group is placed between skis and the other is placed on the helmet. In front of the sportsman a wide screen is located. The induced virtual environment is displayed either on this screen or in the head mounted display. Three OPTITRACK cameras are placed around the screen as shown in Fig. 9.

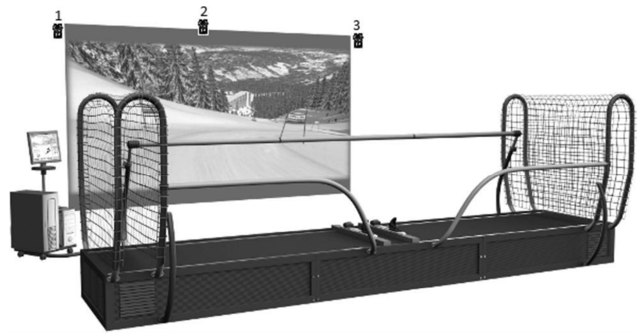

Fig. 9. Tracking system scheme

A collection of markers with a unique identifier, position and orientation data is called *rigidbody*. For the purposes of the project, two rigidbodies are required: the ski rigidbody and the helmet rigidbody. After the setup, calibration of the system and creating rigidbodies one can start receiving data. The sportsman motion modelling subsystem receives coordinates of both rigidbodies, so that before rendering the next frame, the sportsman shift on the training platform and his head position are known.

The future work includes adding more markers to track. With them, it will be possible not only to get data, describing the sportsman shift on the training platform, but fully represent his body position and force our physics engine to take it as a parameter.

All the information obtained from the system of markers could be used not only to improve the physics engine, compensate the missing degrees of freedom and create the realistic virtual environment, but also to analyze different parameters, like skill level, of the sportsman himself.

Our previous research shows that this data is enough for the determining of the skier's skill level [29]. In that work it was shown that the virtual trajectory of a simulator user can be constructed based on the tracking data. The trajectories set of skiers with known skill level forms the training set. And machine learning methods can be used to generate an algorithm determining the skills of a new athlete.

The future work in this area includes the research and development of the help system, which will analyze tracking data and give some suggestions to the sportsman on his technique, speed, decision making ability and so on.

Constructing the feature space used for this problem solution, we found that many of the skier motion parameters are interrelated. The hypothesis is that the direction and the angle speed when skiing on a slope are determined by the relative position of the sportsman body and the ski base. Thus, the analysis of the optical tracker data will enable the training simulator user to control not only his avatar offsets relative to the trajectory baseline path, but the direction of this line in the virtual space. This will allow the full usage of the simulator for the track models with complex structures preserving the high quality of realistic movement.

VIII. Conclusion

In this work we have studied factors affecting the virtual environment perception of the alpine skiing simulator user. Factors that describe common shortcomings of the existing virtual reality systems were identified. Based on the factors described, the requirements for the alpine skiing training system were defined. The whole alpine skiing training system was developed to meet the established requirements. It includes the following components:

- Head mounted displays are suggested to be used for improving the virtual reality perception.
- Unity 3D components and appropriate import tools are suggested to be used for the realistic physical processes and track modelling.
- Optical tracking system is suggested to be used for the implementation of additional degrees of freedom while controlling the movements of a skier.

The next generation of the alpine skiing training system for research of visual 3D perception was developed and implemented. The integrated physical model of Unity 3D was improved to reconstruct the motion of a skier on a slope.

The main result of the works is the research and development of the alpine training system, created with respect to all defined factors at the same time, which is crucial for the developing of the virtual environment with the best perception level.

The designed training system allows to study the virtual reality perception in the laboratory. It also allows to continue the work started in [29] with the use of more criteria for the machine learning approach.

Acknowledgment

The authors are deeply indebted to Prof. Stanislav Klimenko, Asst. Prof. Vladimir Aleshin, Asst. Prof. Valery Afanasiev (all from Moscow Institute of Physics and Technology) for assistance with the used technologies. We are also immensely grateful to Tatiana Alenkina (Moscow Institute of Physics and Technology) for the comments on the manuscript. We are also grateful to the Moscow Institute of Physics and Technology ski section for the comments on the training simulator.

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