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Towards Dynamic Modeling in Immersive Environments with Assessment of User Experiences

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology, has not been submitted for any academic degree elsewhere.

Ahmet Köse ______________________________
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Dünaamilised mudelid virtuaalsetes keskkondades ja kasutajakogemuste hindamine

AHMET KÖSE

TALTECH KIRJASTUS

Contents

List of Publications

The present Ph.D. thesis is based on the following publications that are referred to in the text by Roman numbers.

I: A. Köse, A. Tepljakov, E. Petlenkov, K. Vassiljeva. Virtual Reality Meets Intelligence in Large Scale Architecture. *in 4th International Conference on Augmented and Virtual Reality*, pages 297—309, Lecce, Italy, Jun. 2017.

II: A. Köse, A. Tepljakov, S. Astapov. Real-time Localization and Visualization of a Sound Source for Virtual Reality Applications. *in 25th International Conference on Software, Telecommunications and Computer Networks.* pages. 1–6, Split, Croatia, Sep. 2017.

III: A. Köse, A. Tepljakov, S. Astapov, D. Draheim, E. Petlenkov, K. Vassiljeva. Towards a synesthesia laboratory: Real-time Localization and Visualization of a Sound Source for Virtual Reality Applications. *Journal of Communications Software and Systems*, vol 14, pages 112—120, 2018.

IV: A. Köse, A. Tepljakov, E. Petlenkov. Towards Assisting Interactive Reality: Interactive Reality for Education, Data Analysis and Industry. *in 5th International Conference on Augmented and Virtual Reality*, pages 569—588, Lecce, Italy, Jun. 2018.

V: A. Köse, A. Tepljakov, M. Abel, E. Petlenkov. Towards Assessment of Behavioral Patterns in a Virtual Reality Environment. *in 6th International Conference on Augmented and Virtual Reality*, pages 237—253, Lecce, Italy, Jun. 2019.

VI: A. Köse, A. Tepljakov, E. Petlenkov. Dynamic Predictive Modeling Approach of User Behavior in Virtual Reality Based Application. *in 27th Mediterranean Conference on Control and Automation*, pages 57—62, Akko, Israel, Jul. 2019.

VII: A. Köse, A. Tepljakov, E. Petlenkov. Real Time Data Communication for Intelligent Extended Reality Applications. *in IEEE International Conference on Computational Intelligence and Virtual Environments for Measurement Systems and Applications*, Tunis, Tunisia, Jun. 2020.

Other publications

1. A. Köse, E. Petlenkov. System identification models and using neural networks for Ground Source Heat Pump with Ground Temperature Modeling. *in 2016 International Joint Conference on Neural Networks (IJCNN)*, pages 2850–2855, Vancouver, BC, Canada, Jul 2016.

2. A. Köse, E. Petlenkov. Identification, implementation and simulation of Ground Source Heat Pump with ground temperature modeling. *in 2016 15th Biennial Baltic Electronics Conference (BEC),* pages 163–166, Tallinn, Estonia, Oct 2016.

Author's Contribution to the Publication

I In Publication I, investigated available software products to design, hardware devices to use and platforms to deploy for building VR applications. Custom 3D models were created completely based on physical objects by the author. Planned and created the immersive environment including animations, lighting as well as visual effects. Prepared and conducted the questionnaire to compile user feedback for the importance of digital twin design with data collection in mind for next applications during doctoral studies. Wrote the article as the main author and presented in the conference.

II In Publication II, created all of realistic 3D models and designed the immersive environment by following the pipeline that is introduced in the thesis. Contributed in the experimental design and configuration, conducted part of the experiments and performance testing. Contributed to writing the paper. Additionally, the publication received "the Best Student Paper Award". In Publication III, further contribution has placed.

III In Publication III, designed realistic immersive environment–*replica of Augmented and Virtual Laboratory* and created all of 3D interactive objects. Improved the configuration of an experiment. Contributed to resolve appeared issues in previous work. Participated in the writing and the publication process.

IV In Publication IV, participated defining the research problem. Contributed designing 3D control objects, modeling of the dynamics of those objects and in the implementation process by Matlab. Participated in optimization of the immersive environment for control objects, and the integration of laboratory objects. Planned and designed implementation of Digital Twins for vehicle controlled by hand tracking technology. Wrote the paper that received "Best Young Researcher Paper Award" after the author's presentation and presented in the conference.

V In Publication V, defined the goals of the application by cooperating with the company representatives including designers, IT developers and human resource managers. The author was the team leader for developments and contributed in multi–steps including design, game mechanics, user interface development and performance testing. Defined the research problem and created the architecture that consists of data preprocessing, storage and transmission in real–time. Analysed collected data and created figures for publication. Wrote the article.

VI In Publication VI, designed the experiment, conducted it and applied performance testing to address dynamic modeling of user behavior approach in state of the art level. Improved previously created architecture to use nonlinear auto–regressive artificial neural networks models. Assembled implementations to perform neural network models. Wrote the article.

VII In Publication VII, defined the research problem and proposed the architecture to obtain a feedback mechanism Created the drawings and wrote the article.

All results in Publications were obtained by the author of the thesis under the supervision of Prof. Eduard Petlenkov and Dr. Aleksei Tepljakov.

Abbreviations

CS	Computer Simulation
VR	Virtual Reality
AI	Artificial Intelligence
VE	Virtual Environment
IEs	Immersive Environments
DT	Digital Twin
HMD	Head-mounted Display
DOF	Degrees of Freedom
RE	Realistic Environments
IE	Imaginary Environments
NAR	Nonlinear Autoregressive
NARX	Nonlinear Autoregressive exogenous
UI	User Interfaces
MLS	Magnetic Levitation System
UE4	Unreal Engine 4
FBX	Film Box
LOD	Level of Detail
HMI	Human Machine Interaction
OSI	Open Systems Interconnection
ISO	International Organization for Standardization
TLP	Transport Layer Protocols
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
Blueprint	Blueprint Visual Scripting System
KF	Kalman Filter
VLEs	virtual learning environments
RLs	Remote Labs
VLs	Virtual Labs
HMI	Human Machine interface
UX	User Experience
CI	Confidence Interval
ANN	Artificial Neural Networks
NL	Nonlinear
MAE	Mean Absolute Error
MSE	Mean Square Error
DCDA	Real time Data Communication Tool and Designed Architecture

Introduction

Computer simulation (CS) can be defined as a hybrid technology of using computer science and available technology to build simulation models and then performing experimentation on the models under various conditions [101]. Essentially, CS provides the dynamic nature of the system process and the underlying mathematical structure therein. This technology offers the potential to transform research and practice by allowing us to understand human behavior in detail, hence potentially to provide training or therapeutic applications at scale [127]. Virtual Reality (VR) is the fruition of CS complemented with immersive technologies that is enabled by leveraging recent advances in communication, connectivity, computing, analytical aspects of Big Data, artificial intelligence (AI), and other adjacent areas [12]. Virtual environments (VE) formed by VR technology have proven effective in many scientific [35, 79, 166], industrial [8, 171] and medical applications [14, 173, 184] and are applied in, including but not limited to: computer-simulated environments, visualizations of complex data, joyful learning tools, etc. Human experience with computers, namely multimodal interaction to some degree: mouse clicks, buttons, visual and auditory signals etc. are transformed to head rotation, hand movement, speech and eye gaze in VE [58, 169]. Furthermore, VR has been growing rapidly. It is estimated that this technology will reach over 300 million users worldwide by 2020 [76]. On the other hand, VR technology also faces challenges to become a modern medium at present such as feedback mechanism related the user's behavior that includes user motion, emotional states and interactions. Furthermore, convenient methods and robust infrastructures are not available yet to analyze interaction and behavior in immersive environments (IEs), however a number of studies have proposed solutions [153, 161], also with emphasizing interactions [20, 49]. The present thesis is devoted to study the potential of VR in the context of IEs and multimodal interactions. In particular, developments for real–time monitoring and analyzing user's activities in VR based applications are proposed and discussed. These developments largely form the basis for creating VR based applications towards assessment of behavioral patterns in IEs. During this work, a number of VE mostly devoted to concept of Digital Twins (DT) are created to perform interactions. In following, real–time communication system is created to collect data of motion, interaction, emotional states. The developed applications are served with head–mounted display (HMD) devices, where real–time data communication tool is employed by considering the latency related issues. Next, the architecture to obtain the feedback mechanism is also investigated, as it is especially important for communication with different sampling rates. All the developments discussed are then presented in the state of art level for behavioral modeling. Finally, the developed framework is presented in the thesis on the basis of several IEs endowed with real–time communication capabilities. The thesis results in a methodology for automated analysis of human behavior making possible significant improvements of VR based applications and immersive experiences.

State of the Art

VR is a high–end human computer interface that strives to immerse the users completely in a virtual interactive environment for a simulation of real world [57]. VR technology emerged in the 1960s [162], with the development and marketing of systems consisting of HMD and data–suit or data–glove attached to a computer [23]. The term virtual reality was coined in 1988 by Jaron Lanier [89]. However, the same concept was developed under the name of artificial reality, coined by Myron Kruger in 1977 [86], who claimed the paternity of the concept. Indeed, in all these expressions, the term virtual relates to the same concept: "computed by numbers, as opposed to created by physical matter". Virtual reality, virtual environment, virtual words, etc. Mutual requirements are computer simulation processes and transducers that transform the digital representations into a perceptible experience (visual, acoustical, mechanical) [104]. Sherman and Craig [151] defines VR technology with four essential elements: a virtual world, immersion, sensory feedback, and interactivity. A virtual world is a description of a collection of computer generated objects in a space and rules and relationships governing these objects. Immersion is the sensation of being present in an environment, rather than just observing an environment from the outside. Sensory feedback is the selective provision of sensory data about the environment based on user input. The actions and position of the user provide a perspective on reality and determine what sensory feedback is given. Interactivity, finally, is the responsiveness of the virtual world to user actions. Interactivity includes the ability to navigate virtual worlds and to interact with objects, characters, and places [30]. VR is also a favored tool to utilize interactions in various fields. The interactivity usually encourages users to be more operative, complements their learning processes and assists them in exploring VE and complex data visualizations [43]. Furthermore, researchers compared a HMD to a desktop for interactive navigating large–scale VEs and found that the increased display and interaction fidelity of the HMD allows users to navigate in VEs significantly faster [26, 143]. A teleportation is a type of locomotion and ubiquitous interaction feature for most of VR based applications [33]. The feature is used mainly for navigating in VEs, usually delivered by HMD devices, also and supporting collaborative tasks in IEs. [41, 111].

Recent exponential growth towards computational power gave rise to expand researches towards VR technology. Furthermore, the advent of low–cost HMD devices such as Oculus Rift [123] and HTC Vive [62] has stimulated VR for a broader audience in recent years [163]. Since the research part of the thesis was performed in 2015–2019 in parallel with the state–of–the advances in the field, the novelty contribution is introduced under three main directions:

1. Interactive IEs as Digital Twins: In Publication I, In Publication IV
2. Real–Time Multimodal Sensor Tracking: In Publication II, In Publication III, In Publication VII
3. Dynamic Predictive Behavior Modeling Approach: In Publication V, In Publication VI

Interactive Immersive Environments as Digital Twins

IEs created based on VR technology allow users experience realistic conditions to enhance their understanding, even for non–existent objects. Although the digital twin concept spans many disciplines, one way to define the concept in focus of this research; creation of high–fidelity virtual models for physical objects and providing significant simulations of those models [135]. Therefore, the VR term in the scope of research is also referred to a computer–generated world delivered by HMD devices. Accordingly, developed VR based applications may relief difficulties of mapping between an action in the physical world and the resulting action in the virtual world. That also implies potential benefits of human behavior research for real world challenges.

Real–Time Multimodal Sensor Tracking

One of the aspects that makes VEs unique from other interactive technologies is their ability to present the user with multimodal interactions. These multimodal interactions may be a primary factor that leads to enhanced human performance for certain tasks presented in virtual worlds. Efficient integration of multimodal interactions are as important as generated data by synthesis of visual, auditory, and haptic representations in visual worlds [158].

Recent advances in VR technology allow to induce a persistent effect of presence in a visual world created using advanced user's real–world position and orientation tracking through HMD devices. Behavioral investigation in VR based applications requires to trace the location and the orientation in the movement path for one or many skeletal joints. [60].

A deep knowledge of human senses and a development of new user interfaces (e.g. brain–computer interfaces) would help contribute to develop more effective immersive experiences and VEs [142]. One of the remarkable factors to advance knowledge of human senses for immersive experience is considered to be positional tracking technology [9]. The former solutions for tracking sensors within VR technology are often costly, yet researchers have brought low–cost solutions to the literature [120]. Besides providing hardware solutions, collecting of sensor data while user performs in VR based application with minimum latency is also crucial. VR based applications delivered by recent HMD devices allow to track any objects in immersive environment. Ideally trackers consist of six degrees of freedom (DOF) sensors for position (X, Y and Z coordinates) and orientation (pitch, roll and yaw). Consequently, presented work in the thesis implies possibilities and describes verified method to transmit data that is available via sensor and related to IEs.

Dynamic Predictive Behavior Modeling Approach

IEs can interact with various senses such as visual, auditory, gesture, haptic, etc. including any combination of these senses while allowing users to interact and move within [18]. Accordingly, VR can be used for developing novel interaction means, such as those based on interchange of senses [83] and these novel developments may advance research and applications, refine the ways of understanding the data that is visualized. IEs can be divided into two main directions in the point of view of this research: Realistic Environments (RE) and Imaginary Environments (IE). RE such as digital twins are often designed to study, train and educate towards real life scenarios. If users are immersed and believe that they are really acting out the experience, they will react as they would in a real situation (i.e., behaviors could emerge). So, the user would be actively and cognitively engaged with the virtual environment [76]. IEs enable interactions for situations and manipulations that would be impossible in real life to be created. Variables in IE which are impossible real life that interact with each other and advance our theoretical understanding of human cognition and behavior [21], for instance, one form known as the

Proteus effect [183].

There are several researches that conducted with performing prediction related to users' behavior in IEs. The research conducts a short term path prediction of human locomotion is presented by using tracking data in [119]. However, difficulties to finding a robust generic predictor is also reported; because of the dynamics of human locomotion are different for different persons, e.g. because of different step lengths. Another method is proposed for human identification in VR to provide oriented information and treatment by deploying neural network–based classification in [131]. Additionally, it is claimed in [152] that head orientation is recorded by inertial sensors may be sufficient for prediction purposes with reasonable accuracy. However, due to lack of real–time data transmission at present, it is still a challenge to obtain a feedback mechanism related the user's behavior. Thus, the level of behavioral understanding of users is not sufficient and statistical models are not available to apply predictions. Moreover, with unprecedented capabilities for creating synthetic IEs, many important questions arise to evaluate designed applications in many directions, assess the efficiency of delivered content. Therefore, it is crucial to understand how users explore virtual environments [152]. Consequently, a novel architecture consists of a data communication tool, a relevant immersive environment and third party software is designed to implement a feedback mechanism, in addition to the three defined research directions.

The idea of creating a real–time feedback mechanism is a recurrent interest to facilitate the broad adoption of VR technology. Novel solutions to obtain a feedback mechanism for this technology began almost a decade ago, based on conducted state of the art overview. One of early tailor–made solutions was employed to accomplish a real–time motion tracking system. Real–time VR feedback is achieved by using a point light display while placing retroreflective markers on the novice participants' joint centers. Besides that, The novel technique employs projectors to display sensory feedback [45]. A software system—D–Flow— is also introduced in the same years that designed for the development of interactive and immersive VR based applications. Although the key concept of this software architecture enables real–time feedback from several multi–sensory input devices, the system is used for the purpose of clinical research and rehabilitation (e.g. balance training, gait training). The system also requires a customizable and extensible API to allow the communication with dedicated host machines and software is used to design VR based applications [51]. Few years later, an online VR based application that is introduced [74]. The application is able to monitor and collect the user‘s behavior by built–in feedback mechanism. Furthermore, the mechanism enables to assess the actions and limited movements to change the difficulty level in gaming environment. The architecture supports to perform predictions in order to assist the user based on domain knowledge. However, the built–in mechanism is designed for a first–person perspective that is not applicable for HMD devices.

A feedback mechanism is described through a gaming oriented VR based application in [71], while the research part of the thesis was performed. The introduced mechanism consists of additional hardware components including a microcontroller, vibration motor, Bluetooth transmitter, and Open–Source HMD device to provide a highly immersed experience by obtaining a real–time haptic feedback. Furthermore, microcontrollers are connected through an outdated middleware to synchronize with VR application, meaning that the middleware is compatible with 32 bits applications and can not communicate with third party software.

VR technology has already been utilized for many medical applications with risk–free and repeatable advantages. Automated real–time feedback mechanism is accomplished for one of those medical applications, VR based surgical training [180]. A virtual drill as controller reflects the movements of a haptic device that provides tactile feedback to the user. The application is displayed to the user only by stereoscopic 3D glasses.

The feedback mechanism has accomplished for a mobile VR based application recently. The firm motivation to obtain a feedback mechanism in [150] is derived from a big jump real life to VR may cause an overload of drastic changes for the user. The framework is presented with a simple game that allows to use of the gaze modality as a primary source of input but the game does not include any other interactions. The mechanism is able to monitor and collect data towards the user‘s behavior and gaze patterns. The framework can adapt in two different ways; rule–based and dynamic. The performance measures for rule–based method are set of static rules such as expected completion time and required hints. Dynamic method has high dependency to the user‘s patterns that are clustered into different groups in preprocessing stage as diversified disorders, age groups etc.

A recent research towards comparative study of several input technologies for VR based applications also present an architecture that is able to collect the interactions and location of user only in IEs. The solution provides only one way communication and it is not possible to alter the time stamp for collecting data [138]. Overall, the methodology in this research provides the framework to enable dynamic modeling of user behavior in an interactive VR based application, particularly delivered by HMD devices. Data is captured by employing real–time data communication tool to track accurate location and orientation through HMD devices worn by the user. In following conducted experiments, collected data is used and provide a methodology to predict next movements of the user by using nonlinear auto–regressive (NAR) and location/area in the application by the nonlinear auto–regressive neural network with exogenous inputs (NARX). Results suggest both neural networks are suitable for performing prediction which can be used to achieve an improved feeling of presence while reducing required high computational power.

Motivation and Problem Statement

Based on the state of the art and relevant discussion, the following problems may be formulated and constitute the motivation for the work presented in this thesis.

Analysis of large datasets has been attracting the attention from various fields including, educational facilities, public sector, commercial companies [72]. Investigation of those large data–sets is typically referred to as *Big Data*. In scientific perspective, the key point is beyond Big Data about discovery and understanding of meaningful patterns hidden in the data. In other words, utilizing data sets by discovering relevant patterns among them values more than complexity and size of data sets. This applies to measured and simulated data–sets that should be compared and interpreted [41]. VR has been shown to lead to better discovery in domains that whose primary dimensions are spatial in a number of fields such as paleontology [88], underground cave analysis [136] etc. Investigation of Big Data usually requires visual analysis and naturally high computational power, especially in immersive environment. Presented dynamic modeling approach in the thesis may alleviate difficulties conceptually, linked to data visualization applications that is established through HMD device, particularly in VR domain. The dynamic modeling can ensure to make short time predictions and proactively start downloading the part of the data generated by a system or process that have to be visualized next. Moreover, analysis of user's behavior may provide relevant insight for big data visualization by designated areas considering user's location and interest within IEs. Consequently, Big Data related systems and processes will remain realistic and immersive while required computational power and network bandwidth are diminished.

Utilizing VR for complex applications such as product design, Big Data exploration and visualization etc. requires natural and transparent user interfaces (UI). The simplified UI can attract non–expert users to engage with VR widgets, by exploiting human modalities. Moreover, these modalities must be simultaneously perceived and interpreted, to compensate the need for multimodal interfaces in VEs. Martin et. Al. [109] underlines a number of critical remarks regarding multimodal interaction in carried studies: disambiguation (comparing user's inputs), decision (generating actions desired by a user) and dialog (decision management, identifying additional treatments to be applied on incoming actions). Furthermore, outcome of research in [69] suggests the multimodal interaction methods to be natural and immersive, thereby offering unique gaming experiences that are attractive and accessible to people of all ages. Overall, the studies on gesture–based control of computers and software applications have been ongoing since the sixties [118]. Another research in [30] results crucial points toward VR applications that should be easy and simple to learn and use, at the same time, they should have a multitude of communication metaphors implemented for the interaction. More precisely, the users should be able understand given tasks to perform easily and naturally while executing those tasks by using the specific input devices. Therefore, applications should handle all user inputs gracefully even the wrong ones and give feedback to the users about their mistake while immersion is ensured in IEs. A number of studies also focus on multimodal or collaborative interactions in VEs [91, 92, 110, 177], but to our knowledge, none covers these topics in real–time behavior learning towards diversified VR based applications.

One of the most important criteria to obtain efficiency in VR based applications is to grant the user by interactions with the components of immersive environment and with other users [140]. Although some applications are more realistic, offering higher levels of visual fidelity, it is not solely clear how the increased display and interaction aspects of fidelity impact to the user experience [112]. The results of conducted studies in the thesis indicate that both display and interaction fidelity significantly affect strategy to solve tasks and performance, as well as subjective judgments of presence, engagement, and usability. Nevertheless, the provided framework may give better understanding to investigate the impact on the user experience. It is claimed in [141], using the VR technology it is possible to simulate any process and situation to evoke a feel of reality which can be efficiently used for learning. Learner profile which is based on the characteristics of learners that can be compared with the different results obtained in learning effectiveness and satisfaction to see if some groups are more inclined to use or learn with specific features. Therefore, the framework may alleviate the difficulties to determine learning efficiency and learner satisfaction. Consequently, an initial research question—How can VR based applications be developed to enable real–time data acquisition of the user's movements and actions on different levels to compose a feedback mechanism suitable for the development of intelligent immersive environments based on said user behavior research?— is formed in the scope of presented thesis to merge interests discussed above.

The research interest towards social sciences for VR technology emerged in the 1990s [16,103]. The advent of low–cost HMD devices has expanded the interest also among social scientists in recent years. The technology has great potential for social scientists with an interest in the objective measured data towards users' the presence feeling, preferences and behavioral responses in IEs. Most experiments in applied and social psychology research as well as other domain areas across a range of psychological topics face challenges to find the balance between control and ecological validity, and only few of them allow multimodal interaction in realistic conditions [64]. However, IEs that are designed to study the behavior can allow users to respond in a manner that is more natural. Greater control over stimulus presentation in three dimensions with multimodal sensory input allows also creation of complex scenarios in IEs. This ability makes it possible to examine even sophisticated complex behaviors, such as avoidance; the situations can be impractical or dangerous to study in real life [181].

VR technology enables to collect a variety of user responses that vary in ontological complexity. For instance, measured head movement data through accessible HMD devices may compose complex responses for interactions [154]. Furthermore, VR can complement qualitative methods into research designs to generate more detailed and insightful findings to explain engagement of users in a particular behavior, which is a one of major limitations of field–based research. Thus, social and behavioral phenomenon observed in the research can be confirmed and refined through VR technology that allows researchers to evaluate the extent to which different physical characteristics elicit variations in behavioral responses to artificial and natural settings. Nevertheless, one of limitations to come over is a feedback mechanism that enables the observation of behavior including collection of user data capabilities with variations including preference, perception and behavioral response in IEs. At the same time, the mechanism should not require advance programming skills to obtain to experiments for social scientists [155]. Moreover, the research in novel VR technology still requires unique considerations such as the availability of sophisticated tools and protocols to measure VR outcomes with examples and data sets. Social scientists can uncover pervasive unknowns and unanswered questions at present surrounding effects of the technology as a medium thereof [90].

Overall, the aim of this research is to enable studying and understanding of behavior patterns. This aim is accomplished through these three objectives:

- To develop a number of IEs to let users perform interactions and motions, conduct survey towards VR experience.
- To develop a system that enables real–time transmission and collection of motion data generated by the user.

- To analyze collected data and emphasize the potential of feedback mechanism with the purpose of deriving behavioral models.

The developed VR based applications are employed particularly to allow investigation into several aspects: an efficiency of VR based applications to let users feel immersion and interact, an applicability of adaptive immersive environment by user's feedback and performance analysis to determine learning efficiency and learner satisfaction.

Author's Contributions

The main contribution of the author of the thesis is the development of a framework for automated analysis of human behavior. The present thesis is devoted to study the potential of VR in the context of interactions and behaviors towards IEs in which HMD devices are employed. In particular, a number of unique IEs are created and formed with third party applications to complete system configuration including hardware and software aspects. The created system in the framework has potential to increase the intelligence of served VR based applications. This contribution comprises several consecutive parts:

- Design several IEs to let users perform interactions and motions.
- Investigation and analysis of existing VR based applications and solutions that are connected to third party software.
- Development a system and its architecture that enables real–time collection of motion data–sets.
- Analysis of collected data–sets with the purpose of deriving behavioral models.
- Implementation of computational intelligence methods to process collected data.

Thesis Outline

Each chapter presents a summary of the research problems discussed therein. Relevant examples are provided where appropriate, including those that span across multiple chapters to illustrate developing ideas. Each chapter of the thesis ends with a section containing concluding remarks pertaining to theoretical and practical results reported in the corresponding chapter. The thesis begins with the promising state of VR technology at present and its remained challenges to be resolved. Brief conclusions on key aspects are drawn in each chapter. Finally, the last chapter comprises general concluding comments, as well as items for prospective research.

In what follows, a summary of each chapter is provided.

Chapter 1

This chapter presents the development process of created environments and digital twin concept from VR perspective in the scope of presented work. Investigation of utilized hardware devices and software tools are also introduced therein.

Chapter 2

In this chapter, the reader is introduced to real–time data communication tool and designed architecture. The introduction is placed with detailed presentation of a number of developed applications. Firstly, achievement of providing real–time sound visualization of physical sound source in immersive environment is presented. Secondly, virtual laboratory contains several replicated control objects with corresponding mathematical models provides accurate feedback in real–time is described. Thirdly, gaming oriented application is introduced as a demonstration of the designed architecture that enables possibilities to analyze and model human behavior in real–time.

Chapter 3

The chapter is devoted to give an overview of the framework consists of preprocessing and analysis of collected data–sets with the motivation of deriving behavioral models. The overview begins with an understanding of observation of user's behavior related to immersive environments. Afterwards, particular implementation is presented to complement the designed architecture with description of data processing and its game play. In following sections, necessity of intelligence towards immersive environments and the approach to derive with the designed architecture is introduced with two major cases. Finally, applied dynamic models to perform predictions are described to illustrate.

Chapter 1

Development of Immersive Environments

In this chapter, the process of creation of VR based applications and achieved objectives are presented and discussed. The chapter is organized as follows. First, the process description is presented in Section 1.1. Utilized software tools to design VR applications and employed hardware devices are introduced in Section 1.2. In Section 1.3, the followed steps to complete IEs are described. Then, system design and optimization steps to enable real–time data communication are addressed in Section 1.4. Finally, conclusions are drawn in Section 1.5.

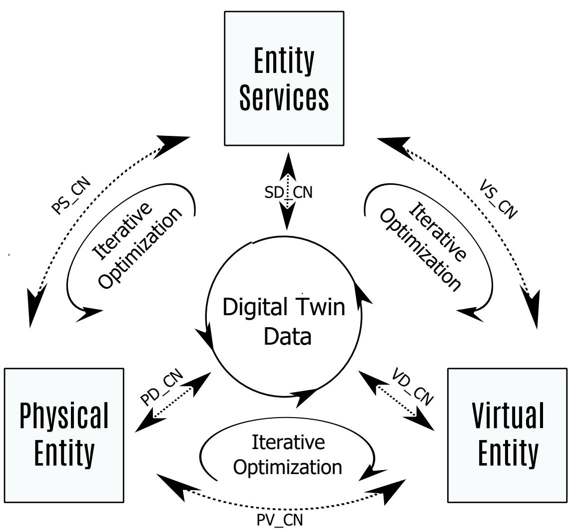


Figure 1.1: Five–dimension model for the DT [165]

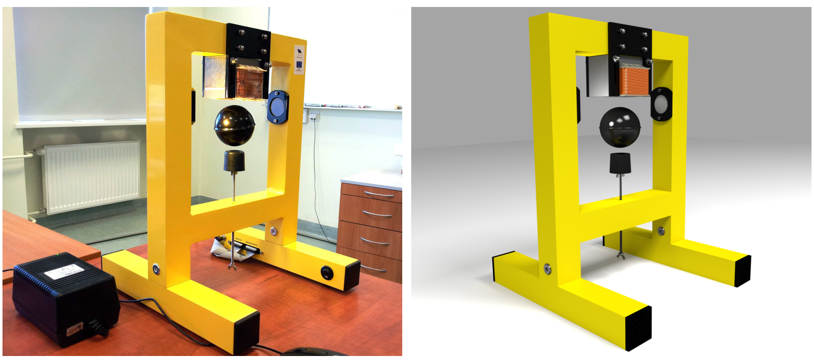
1.1 System Design

In this work, a number of applications are developed with an initiative that the possibility to investigate multimodal interactions in the context of IEs. IEs can be considered one of efficient methods to display the physical world and its complexity by utilizing the sense of presence. For instance, existing capabilities of HMD devices at present such as hand tracking and gesture recognition are employed to map real user action to a resulting action in the virtual world [159]. Those capabilities enable to track and recognize necessary movements and also allows the computer to understand the true intention expressed by gestures. At the same time, relevant user feedback is obligatory to let the user have a natural interactive experience in VR based applications [97]. Furthermore, generated feedback with interactions in the physical world can be interactively visualized in IEs. Accordingly, presented IEs in the thesis are mainly developed based on the Digital Twins (DT) paradigm to maximize experience with interactivity. The concept of DT is creating and interacting a digital representation of the real world objects by the means of optimization and simulation tools, which are fed with real and updated data [87]. Besides that, Tao et al. proposed in [165] that a complete DT should include equally important five dimensions: physical part, virtual part, connection, data and service. The proposed complete model of DT that is on the basis of three–dimension model for the DT [134] is depicted in Fig. 1.1. In addition, the concept of DT from the VR perspective for presented work is referred to realistic replications of corresponding original objects by identifying mathematical models of the system to maximize the feeling of meaningful physical interaction in immersive environment. Although complete design of VR application can be the most time consuming part of the process, appropriate systematic workflow would avoid harder rework thereafter [133]. As a result, the design should grant users with immersive feeling to perceive. Consequently, the developed applications allow to investigate the efficiency of VR based applications to let users feel immersion, so as to evaluate the applicability of adaptive immersive environment by user's feedback.

The first developed VR based application is the virtual replica of the physical building—Innovation and Business Center of TalTech [82]. The center meets numerous number of intercontinental visitors daily with the purpose of demonstrating the current work including prototypes, futuristic applications, start–up ideas etc. Therefore, it seemed relevant to create virtual replica as "World-in-Miniature" [168] to assess interactions with heterogeneous profiles. The main motivation of developed immersive environment to discover the user feedback with performed activities and the data collection in mind. Designed exterior architecture of the building is shown from the front facade in Fig. 1.2. Besides that, design rooms and

Figure 1.2: Exterior view that designed based on physical facility

areas in the building, the replication of the VR laboratory is complemented in terms of interactions which is also used for representing the sound source in immersive environment [84]. Additionally, a number of objects which are used for teaching control systems are modeled [85]. Those models are supported by corresponding mathematical models of their dynamic systems. Because, an ultimate goal was to provide accurate interactions between the user and the objects in IEs. One of those control systems is the Magnetic Levitation System (MLS) [167] and its replication in VR based application is depicted Fig. 1.3.



(a) Real–life MLS control object (b) 3D modeled representation of MLS

Figure 1.3: MLS control object and digital twin for teaching control systems

Finally, an imaginary immersive environment is created as the last developed application which is considered to be final part of the presented work. The last application is utilized to compare the efficiency between realistic and imaginary virtual environments. The game level of the immersive environment is drawn in Fig. 1.4. Furthermore, adaptation of users for non-existing world is observed and presented in the last chapter of the thesis.

Figure 1.4: The game level of the imaginary environment

1.2 Toolset for Development of IEs

Although the work consists of unique VR based applications, principles of the development process remains generic as other VR applications. Overall, the process is as follows: Modeling and Texturing, Environmental Creation and System Design, Hardware and Software Integration, Interactions, Optimization. It is relevant to describe used hardware and software tools before going through the development process. Toolset for designing VR based applications is depicted in Fig. 1.5.

Fundamental Toolset

Autodesk Maya Autodesk Maya is a 3D modeling software delivered by Autodesk [7]. It is regarded as an industry standard for creating quality 3D models. Autodesk Maya was employed for creating 3D models, texturing and rendering purposes. 3D objects were developed using polygon shapes and modified with functions such as extrude and append.

Unreal Engine 4 Unreal Engine 4 (UE4) is chosen to create the virtual environment as the engine is the one of most known and used physics engine [47]. High efficiency for VR applications, compatibility and does not require high maintenance cost are several of prior advantages to prefer. The concept of object oriented programming, process of computer generated graphics, reusable code with libraries are some of main benefits of using primary game engines [25, 122]. Those benefits are also used to create communication tool between software linked to the project.

Head–Mounted Display Devices HMD devices are deployed for various purposes that eventually project VR based applications just in front of the eyes and allow users to focus on display without distraction [50, 106]. The first presented application with the main VR devices provides physical mobility in actual room scale, real–time positioning and tracking with advanced display resolution [94]. Oculus Rift DK2 [78] is used in the early stage of first designed application. Although the development started with Oculus Rift DK2, the work has been accomplished by employing HTC Vive as HMD device. Independent navigational benefits, two sets of convenient hand-held controllers, high resolution display are some facts to prefer HTC Vive. The HMD provides 1080x1200 resolution per eye, and the 9-DOF with 2 lighthouse base stations for tracking. The controller features 24 sensors, dual-stage trigger and multifunction trackpad [38]. HMD devices may also provide a comparable experience for collaborative abstract data analysis to more expensive purpose-built facilities such as CAVE [35].

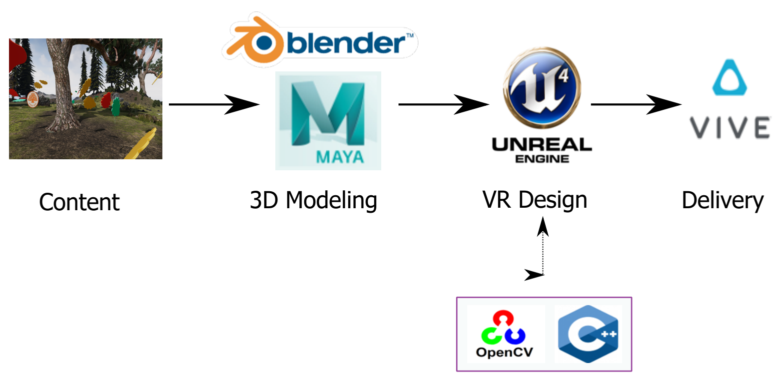


Figure 1.5: Utilized toolset for designing VR based application of the physical building

1.3 Recreation Process

Visualization is applied in various fields related to such as education, product visualization, interactive multimedia and in architecture. Successful IEs should include accurate design to give presence feeling for users. Creating replication of components for VE is a remarkable part of the process. The whole concept is accomplished to create a framework to enable collection of data. In this phase, the 3D model, texturing and rendering of the building including internal and external architecture are presented. The floor plan of facility is used for accurate virtual environment based on physical assets. 3D models of physical objects were developed using polygon shape and modified using functions such as extrudes, append etc. Reactions of those models to the lighting depend on information from the materials. The physics engine can respectfully identify the material components and map file (Textures) with film-box (FBX) file format. Texture map is directly related to the quality of the model for the physics engine. In addition, Using Level of Detail (LOD) feature is utilized to simplify the 3D models. LOD is useful to reduce the number of polygons for rendering. It is important to receive better vision on VR devices with better performance. Overall, the design should ensure the virtual quality to maximize impact of presence feeling during the experience [73]. All of presented VR applications are developed by employing UE4 that allowed to create realistic environments and simulate realistic affects. Hence, users can feel lifelike interaction. Fundamental parts such as walls, columns etc. are inserted in physics engine according to suggested scale compatibility of physics engine (1 unreal unit is equal to 1 cm) [46]. Once modeling and texturing are processed, all the content is created in the physics engine. In other words, 3D models are assembled based on physical world in the immersive environment. The principle logic of the application is referred to predefined VR class of the engine: Motion Controller Pawn, Heads–Up Display, VR Game–Mode, Player Controller. Developing with the engine and running the serious game require specific hardware and software requirements. Developed applications run on a PC equipped with a 4.00 GHz Intel i7-6700 processor, 32 GB RAM, an NVidia GTX 980 graphic card and HTC Vive as a HMD.

1.4 Creating Interactive Environments

Human–Machine Interaction (HMI) is one of notable research topics. The efficiency of learning process is directly connected to hands-on experience. As a matter of fact, merging interactions in VR, brings different perspective to HMI. In other words, HMI can be obtained to maximize in artificial reality conditions [32]. In addition, accurate simulated replications can complement important aspects of learning different types of systems dynamics. Students likewise can understand dynamics of systems and validate their theoretical knowledge with prototypes [15].

First created VR application grants users to interact with objects such as doors (open-close), lights and displays (turn on-off) are implemented in two different approaches; self-controlled systems and automated systems. The main motivation is to introduce capabilities of DT in immersive environment and users may also sense experience of an interesting approach called *"experimentable digital twin"* [148]. Additionally the presented VR based application allows users to interact by handles are provided with VR device and to grant with sense self–learning activities in VE [141]. Further details are also inserted in the architecture like sounds, lights. The editor of the engine allows to implement three kind of lights: Stationary, Movable and Static. Besides atmospheric light source, particular point lights and spot lights are set up stationary in immersive environment to understand evolution of user experience. One of the reasons to select UE4 to develop IEs is UE4's blueprint visual scripting system (Blueprint) that allows for rapid prototyping [156]. Blueprint is a complete game–play scripting system based on the concept of using a node-based interface to create game–play elements from within Editor View [48]. In other words, blueprints are interconnected blocks which have predefined C++ code inside them. As an example of Blueprint implementation is depicted in Fig. 1.6. Further details of Blueprint implementation with real–time data communication tool can be also found in Section 2.3. Optimization of game level as well as existing assets within IEs is processed in the last stage synchronously with the testing period.

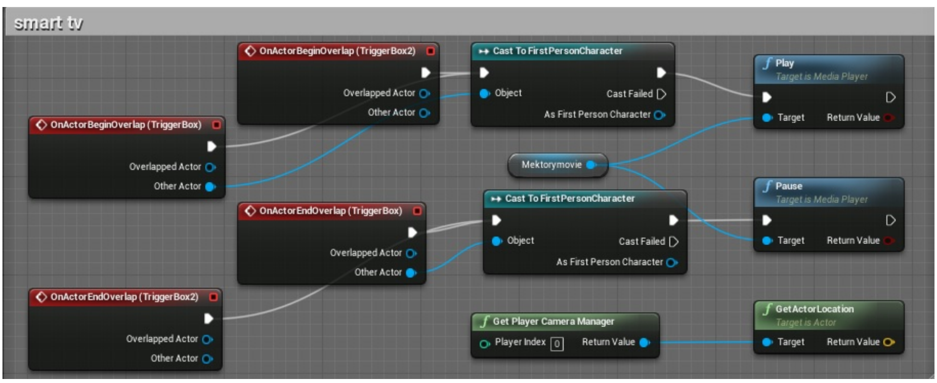


Figure 1.6: Blueprint scripting for display located in immersive environment

Thereafter, an questionnaire was provided to participants who had experienced the replication of the architecture [82]. The questionnaire results reveals that there was no noticeable differences between real building and the presented virtual replica. Basic interactions in the application also engaged their attention. The test period was conducted to determine usability scale of the application by the collected feedback. However, we also observed that granted functionalities of virtual environment might be expanded. Therefore, following developed VR based applications also concentrate to grant users with more efficient experience while minimizing limitations. In order to let users experience with real-time applications, we provide an experiment with visual representation of sound source comes through reality referred to as *Synesthesia.* Other designed VR applications are obtained with the same process; creating 3D models, designing immersive environment and optimizing the application. Moreover, all of designed applications have a teleportation feature that allows users to move independently and effortless. For instance, the user can still ascertain sound source localization during continuous movements in computer simulated realistic laboratory during experiencing synesthesia effect. Detailed description about this development can be found in Section 2.3.

1.5 Conclusion

The developed applications are divided into two main directions in the point of view of this research; Realistic Environments (RE) and Imaginary Environments (IE). The development process remained generic to create VR applications but fundamental tool–set and recreation process including insights during the development period are explained sufficiently to provide researchers with direction and guidance on how to create similar VR based applications. The concept of DT in terms of creating and interacting a digital representation of the real world objects is demonstrated at first by designed application as "World–in–Miniature". The developed replica contains interactive graphical presentation of the physical area including rooms and facilities to comprehend user's behavior.

Recent technological advances in VR technology allow to trace multimodal interactions. However, collecting all aspects of behavioral data at once remains a challenging problem which is also valuable for social interaction research [127]. In other words, appropriate access to behavioral data is a crucial requirement for developing an understanding of user behavior in VR. Therefore, further research efforts were devoted towards enabling collecting data and making automatic and semi–automatic analysis of the collected data to develop a framework of the thesis. The real–time data transmission allowed to provide the meaningful interactions with the support of mathematical models and computational intelligence methods via third party software for next developed RE.

Recording a cross–sensory interaction in perception with the inducing synesthesia experience can support computerized analysis of the perceptual relevance of an environment [59]. As an example, the results also implicit social behavior analysis which may be more revealing than traditional key-hit measures. More precisely, the accurate recording enables to study interactions is that situations and manipulations that would be impossible in real life can be created. Finally, following developed applications provide realistic interactions between the participant and other objects addition to capturing capabilities for human actions in real–time. An application of IE was created to demonstrate a technical readiness of the feedback mechanism and next, examples of data–sets were provided with dynamic modeling approach. For instance, knowing the participant's head location means that a virtual representation of the user can be predicted in immersive environment.

Chapter 2

Real–Time Data Communication and Designed Architecture

In this chapter, real–time data communication tool and designed architecture (DCDA) are presented towards the ultimate goal; to collect and preproces motion data.. The use cases (instances) of DCDA are described within created IEs in Section 2.1. Utilized network protocol is explained in Section 2.2. Primary use case of the communication tool for representing sound source is introduced in Section 2.3. The improved version of the tool to accomplish real–time visualization based on mathematical models is described in Section 2.4. Finally, unified proposed method to enable real–time communication among VR based applications and third party software is given Section 2.5. Conclusions are drawn in Section 2.6.

2.1 Case Studies Towards Designed Architecture

Real–time feedback mechanism from third party software and also from the user what might include user motion, emotional states and interactions is still a challenge for VR based applications. Convenient methods and robust infrastructures must be considered subsequently when tackling the challenge. Novel contribution to the feedback mechanism of designed architecture in the thesis has accomplished with three different case studies to validate real–time communication and following to enable collection of motion data: Synesthesia Experiment, VR Control Systems and Swedbank VR Experience.

Synesthesia—the act of experiencing one sense modality as another—is an interesting phenomenon in which human experience a cross–sensory interaction in perception [182]. The phenomenon that provides many exciting opportunities when applied to VR. For example, some promising results on cross–modal sensory integration in virtual environments were reported in [17]. Novel findings related to audio source localization and sound processing is presented in [166]. Those findings with prerecorded data set an ultimate goal; taking the findings and applying to an immersive environment which reflected the real environment (i.e., represented a digital twin thereof) for the purpose of inducing a synesthetic experience augmented with spatial perception to the listener in real–time.

VR control systems is devoted to provide a visual feedback from the studied control systems coupled with the ability to interact with these in a natural manner brings about a huge improvement in the understanding of the underlying theory. Implementation consists of several recreations of laboratory control system models—which in VR are referred to as digital twins of corresponding original objects. Moreover, modeling of the dynamics of those control objects are employed to provide accurate feedback for users.

Swedbank VR Experience was designed to engage different kinds of user profiles with IE while letting them perform the specific tasks. The primary version of developed application has been used for marketing purposes on various fairs, in their headquarters among Baltic countries to exhibit the innovative and entertainment sides of their business. The application was improved to enable to collect motion data that full details are explained in following Chapter 3.

In what follows, fundamentals of DCDA are described by presenting also technical details of case studies in following sections.

2.2 Utilized Network Protocol

Open Systems Interconnection (OSI) model was developed to demonstrate the architecture of a network communication system that initiated by the International Organization for Standardization (ISO) [36]. The model is a reference to define message transmission between any two points in the system which is the most common networking architecture model at present [22]. The model is composed of seven layers in two main groups: The upper–layer with three layers and the lower–layer with four layers is depicted in Fig. 2.1. The transport layer is particularly substantial in the content of DCDA that locates between the network and session layer. Several different transport layer protocols (TLP) exist to accommodate different application layer needs. Despite the potential diversity in TLP, it can be categorized into connection–oriented and connectionless protocols [179]. While Transmission Control Protocol (TCP) operates in connection–oriented mode, User Datagram Protocol (UDP) is a connectionless protocol that uses datagrams to send messages from one end system to another. UDP does not require any prior connection setup to transmit data [40]. The protocol is essentially designated to support data transfer between the computer network applications such as online video conferencing systems, including a large number of client/server model of network applications. Since UDP is a connectionless protocol, it provides message delivery with minimum effort to upper–layer protocols and applications without setup a permanent connection between two end points [34, 96]. The lightweight procedure to transfer data does not acquire specific requirements when running in numerous platforms. UDP transport protocol provided a straight method to transfer packets over local network among utilized software including Matlab, data management systems in terms of preprocessing and storage and VR based applications. Therefore, UDP based data communication plug–in was developed to transmit data among VR based applications and third party software.

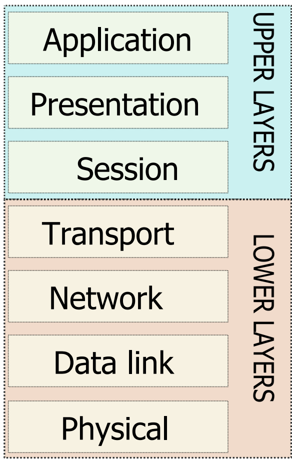


Figure 2.1: The seven layers OSI architecture [188]

UDP based plug–in is implemented by Blueprint visual scripting system to serve for VR based applications. Blueprint allowed to create an interface for UDP [105] to communicate between utilized a number of third party software and the game engine based on a custom C++ class. To avoid problems with Blueprint multi–threading for VR based applications, the implementation uses a custom class variable to transfer data between threads to avoid a racing condition in requesting/getting new data from the UDP socket. With this approach, reliable communication via a UDP socket at sufficiently high sampling rates upwards of $1kHz$ is achieved. However, lower sampling rates are considered for further implementations, even existing high–quality VR systems operate at 2160x1200 resolution and $90Hz$ at present [100].

2.3 Validation of Real–Time Data Communication Tool

Synesthesia Experiment

The proposed prototype comprises several components: a microphone array with four Behringer C2 microphones, an USB audio card—Focusrite Scarlett 18i20 Gen 2—for sound data acquisition, a personal computer running MATLAB/Simulink environment and the VR sound visualizer, the HMD device—HTC Vive, and the emulated sound source represented by a Creative T15 Bluetooth speaker. The user wearing the HMD device and the microphone array are assumed to be stationary. The distance between the user and the conical array is constant and the corresponding VR environment position offset may be computed and applied within the VR room scale. The complete prototype configuration is depicted in Fig. 2.2.

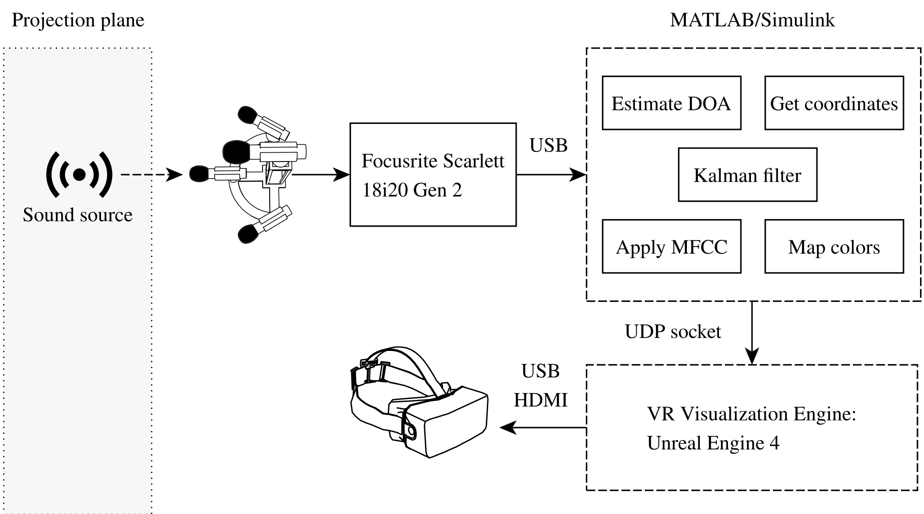


Figure 2.2: Experimental configuration and signal flow

Kalman Filter for Motion Tracking

The discrete time Kalman filter (KF) is a linear quadratic estimator [2], which provides the closed form recursive solution for a linear discrete–time dynamic system of the form:

$$\begin{aligned} \mathbf{x}_k &= \mathbf{A}_{k-1}\mathbf{x}_{k-1} + \mathbf{q}_{k-1} \\ \mathbf{y}_k &= \mathbf{H}_{k-1}\mathbf{x}_k + \mathbf{r}_{k-1} \end{aligned} , \qquad (2.1)$$

where $\mathbf{x}_k$ is the system state vector at time step k, $\mathbf{y}_k$ is the measurement vector at k, $\mathbf{A}_{k-1}$ is the transition matrix of the dynamic model, $\mathbf{H}_{k-1}$ is the measurement matrix, $\mathbf{q}_{k-1} \sim \mathrm{N}(0, \mathbf{Q}_{k-1})$ is the process noise with covariance $\mathbf{Q}_{k-1}$ and $\mathbf{r}_{k-1} \sim \mathrm{N}(0, \mathbf{R}_{k-1})$ is the measurement noise with covariance $\mathbf{R}_{k-1}$. Kalman filtering consists of a prediction step, where the next state of the system is predicted given the previous measurements, and an update step, where the current state is estimated given the measurement at that time instance. The prediction step is characterized by the following equations:

$$\begin{aligned} \hat{\mathbf{x}}_k^- &= \mathbf{A}_{k-1}\hat{\mathbf{x}}_{k-1} \\ \mathbf{P}_k^- &= \mathbf{A}_{k-1}\mathbf{P}_k\mathbf{A}_{k-1}^T + \mathbf{Q}_{k-1} \end{aligned}, \tag{2.2}$$

where $\hat{\mathbf{x}}_k^-$ and $\mathbf{P}_k^-$ are the system *a priori* (i.e., before observing the measurement at time k) state and covariance estimates, and $\hat{\mathbf{x}}_k$, $\mathbf{P}_k$ are *a posteriori* (i.e., after observing the measurement) estimates. The update step is performed as:

$$\begin{aligned} \mathbf{K}_k &= \mathbf{P}_k^-\mathbf{H}_k^T\left(\mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T + \mathbf{R}_k\right)^{-1} \\ \hat{\mathbf{x}}_k &= \hat{\mathbf{x}}_k^- + \mathbf{K}_k\left(\mathbf{y}_k - \mathbf{H}_k\hat{\mathbf{x}}_k^-\right) \\ \mathbf{P}_k &= \left(\mathbf{I} - \mathbf{K}_k\mathbf{H}_k\right)\mathbf{P}_k^- \end{aligned}, \tag{2.3}$$

where $\mathbf{K}_k$ is the Kalman gain of prediction correction at time instance k. KF is optimal for a linear system with Gaussian measurement and process noise [2, 174], which applies to our situation.

Acoustic object movement is described as a discrete Wiener process velocity model [11] with the state vector defined as $\mathbf{x}_k = \begin{bmatrix} x_k & y_k & \dot{x}_k & \dot{y}_k \end{bmatrix}^T$, where (x_k, y_k) denotes object position and $(\dot{x}_k, \dot{y}_k)$ — the velocity in a two-dimensional Cartesian space. The transition and measurement matrices for model (2.1) are then defined as:

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \tag{2.4}$$

where Δt is the time interval between consecutive estimates in seconds. The process and measurement noise variance is specified by matrices

$$\begin{aligned} \mathbf{Q} &= \begin{bmatrix} \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 & 0 \\ 0 & \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 \\ \frac{1}{2}\Delta t^2 & 0 & \Delta t & 0 \\ 0 & \frac{1}{2}\Delta t^2 & 0 & \Delta t \end{bmatrix} q, \\ \mathbf{R} &= diag(r_1, r_2), \end{aligned} \tag{2.5}$$

where q and r_k are the power spectral densities of process and measurement noise, respectively. For our conditions the parameters are set as $\Delta t = 0.1$ s, $q = \begin{bmatrix}0.2 & 0.2 & 0.2 & 0.2\end{bmatrix}^T$, $r_1 = 0.1$, $r_2 = 0.3$.

MATLAB software is used due to the availability of necessary toolboxes for real–time data acquisition and processing. Once the data is processed within Matlab, the necessary information (spatial coordinates of the sphere, its size and color) are sent via a UDP socket connection in real–time to the visualizer application that drives the HMD.

Figure 2.3: Experimental real–time prototype setup. Elements on image: A—Microphone array; B—Emulated sound source (Bluetooth speaker); C—Spherical visualization as it appears in the recreated room VR environment

Experimental Results For initial verification of the designed prototype, two types of experiments are considered. First, the acoustic tracking part is assessed and verification of the real–time VR application is considered to be second part. In both cases, the distance from the sound source to the microphone array is $r = 1.5$m. An audio clip with modern music is used as audio such that has no distinct spectral features. The real-life experimental layout is shown in Fig. 2.3.

In order to validate compatibility of socket connection and the DCDA, another virtual environment was recreated to represent the actual laboratory. To provide a further illustration of the visualization part, the prototype was moved to *Re:creation Virtual and Augmented Reality Laboratory* [164]. Accordingly, the real–time migrated experiment to the laboratory where the application is launched is shown in Fig. 2.4. In this figure, one can observe a snapshot of the visualization resulting in a speaker in the real environment pronouncing the word "hats". It can be noticed that the sound "s" with the *jet* color mapping results in a yellow sphere being produced.

Overall, the experiments to gain deeper insight into the effect generated by introducing sound visualization with source localization in a VR environment. It is also a significant step that expanded the interest to develop the framework to analysis human behavior towards interactive immersive environment by also capturing transmitted data.

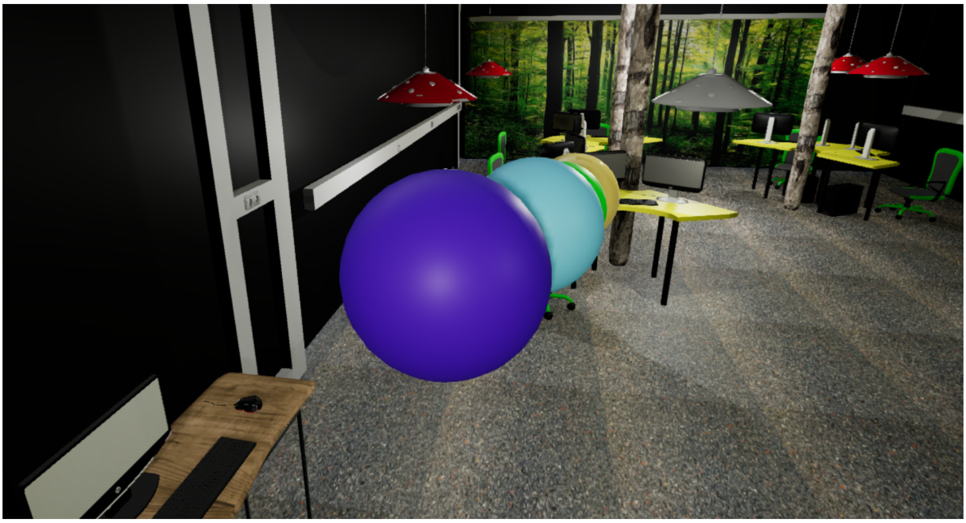


Figure 2.4: Visualization resulting from pronouncing the word "hats"

2.4 Digital Twins Approach Through Laboratory Experiments

Traditional method of teaching is when a teacher directs students to learn through memorization and recitation techniques which might cause inefficiency of developing their critical thinking, problem solving and decision making skills [160]. Moreover, traditional method approaches for engineering instruction such as control and real–time system courses are usually mathematics–intensive and as such remain distant and abstract without developing in the student an intuitive understanding of the problem. Thereby they might fail to enlighten students with the realities of different types of systems [108]. Regardless, it is not reasonable to consider that levels of background among students are equal, not to mention their interests. Those factors may likewise cause less effective experience in classroom [68]. On the other hand, one of the best approaches is to present the theory in a directed fashion with the instructor going through experiments [52]. Unlike education in classroom, laboratory sessions usually makes possible to divide students according to their background, interest and schedule. Students likewise can understand dynamics of systems sufficiently and validate their theoretical knowledge with prototypes in laboratories [15].

As a matter of fact, motivation of students in engineering learning process is also directly correlated with the interactivity of the laboratory. The interactivity in laboratories can encourage students to play a more active role and to get involved in learning process [43]. In addition, laboratory objectives are useful in analyzing what students can likely achieve in a laboratory [137]. Consequently, meeting requirements of particular education such as engineering can be carried out more efficiently by practices such as laboratory sessions from the early stage.

2.4.1 Complementary Solutions for Laboratory Experiments

Laboratory sessions are an essential part of education in engineering that theoretical background should be strengthened by real–life laboratory experiments. Nowadays, however, providing practical experiments is restricted by several major matters such as growing number of students each year, high running cost of necessary laboratory equipment for large student numbers, as well as limited time for laboratory personnel [27]. Researchers have proposed various methods and applications to diminish continuous difficulties and to engage students better with laboratory experiments [1, 121, 144]. Proposed diversified solutions have been observed to meet different criteria such as cost, time efficiency, interactivity and literacy. Despite the variety in this matter, virtual learning environments (VLEs) which become widespread in distance education in the last years but do not usually ensure any possibility of illustrating scientific phenomena [147]. Hence, proposed solutions should be linked to equipment placed in laboratories. Considering the distance education paradigm in scientific and technical areas, in recent years, creation of virtual and/or remote laboratories have become necessary for educational facilities to be universal and successful [6].

Remote Laboratories Remote Labs (RLs) are broad facilities which use physical devices and plants at distance [178]. RLs have an advantage to get feedback in real–time from the controllable objects with realistic perspective. Besides that, the flexibility in control implementations creates novelty to remote laboratories [27]. For instance, a remote laboratory based on networked control system laboratory framework is implemented in [63] where the system is relying only on HTML5 provides full support for control engineering experimentation with MATLAB/Simulink deployment. Another example of RLs is shown in [44] where experiments with a mobile robot are carried out, tested and validated remotely, using a simple graphic interface via web browser where students can control and manipulate the robot. Besides that, several remote laboratories conducted with control engineering are introduced with relevant control approaches, multi–variable systems are covered in [146] and nonlinear and unstable systems in similar direction are illustrated in [56].

Although RLs seem to provide the necessary means to complement physical laboratories, they also have considerable limitations. For instance, RLs usually comprise a scheduling system. The reason for that is to provide a time slot for each student which means that each application can only be used by one student at a time and administrators can create overall reservations [27] a. This allows students to make reservations for a particular setup. In other words, the responsible person for RLs such as professor or laboratory assistant still needs to spend precious amount of time for operating purposes. Additionally, it is confirmed in [68] that the course assistant must be available in the laboratory for any technical supports. Moreover, these experiments in RLs can be made available during the teaching staff's working hours. Overall, experiments in RLs cannot be carried out in parallel, a student who is not conducting an experiment can only observe the individual who is performing an experiment, only if the laboratory has an IP camera or another relevant device to observe remotely. As a result,limitation of active users in a time might also cause the drop of motivation among students.

Virtual Laboratories Facing inconvenient conditions in education have convinced researchers also to employ meaningful replications in IEs. They have accomplished several VR applications relieve if not avoid continuous difficulties to engage students with experiments adequately [10, 42, 77, 98]. VR provides an innovative educational instrument for science that enables students to assess the value of their solutions requiring them to apply relevant knowledge and understanding to a particular real-life complex problem [75]. Specifically, one of extensions of VR based applications—Virtual Labs (VLs)—offers similar vision and methods compared to traditional approaches [55]. VLs can give access to large number of students at once sufficiently thereby providing teaching scalability. Students also gain experiences by interacting with accurate replications of physical objects in VLs. Recently, IEs have been enriched with interactive graphical user interfaces that let students manipulate the experiment parameters and, explore their evolution [147].

The concept of DT in presented work is inferred to a virtual laboratory contains realistic replications of corresponding original objects by identifying mathematical models of control systems. One of similar approaches into DT towards control systems has been introduced in [185]. The work explains real–time application of control systems with mathematical modeling of inverted pendulum that can be employed only through VR toolbox in Matlab. Another control objects related work into DT is presented in [24] which provides control of mechanism system with real-time communication protocol between physical object and human-machine interface (HMI) whereas considerable as an abstract VR aspect with 3D modeling of physical object. The approach also validates to real–time interaction between physical object with its replication.

VLs are also usually considered as a similar approach with the concept of DT. An example of VLs in [28], a human–robot VR experiment shows the transferability of the control approach to a human interaction partner by implementing pendulum in immersive environment. An interesting work in [77] presents a virtual CS laboratory to alleviate difficulties by using a quad-rotor as a plant in Matlab environment. Control approach in experiments [42] successfully evaluated with a robotic manipulator and real pendulum-like objects. In [172], VL and RL are introduced in the same framework by Matlab based software packages. Defined functions in this work allow user to experience video animations of simulated processes. Furthermore, Matlab Web Server allows the implementation of remote laboratories operating in batch mode.

Consequently, according to literature review, similar approaches have been researched and produced relevant implementations within various perspectives. However, existing virtual laboratories do not provide accurate dynamic modeling in immersive environment by using low–cost HMD devices. A specific goal is to mathematically model and implement physically accurate interactions between the user and the virtual objects. By proposed application in this research, multiple tasks and perspectives are merged to fulfill necessary tools and implementations in the same time which will increase the efficiency of education as well as training in industrial context. Furthermore, the application deploys developed UDP socket connection to transfer data between Matlab and VR based applications in real–time. The deployment allows us to obtain highly accurate mathematical models of their dynamic systems thereof. Thus, the educational value of the complete visualization becomes high.

Hereinafter, by respecting to DCDA, the process of the development of several DT is provided. The original real–life control objects that served as reference for the DT were produced by Inteco [67]. Initially, physical objects located in laboratory are modeled by following recreation process described in Section 1.3. So far, three objects have been modeled by following similar steps: The Magnetic Levitation System, the 3D Crane, and the Inverted

Pendulum. The diagram showing the prototyping configuration is depicted in Fig. 2.5.

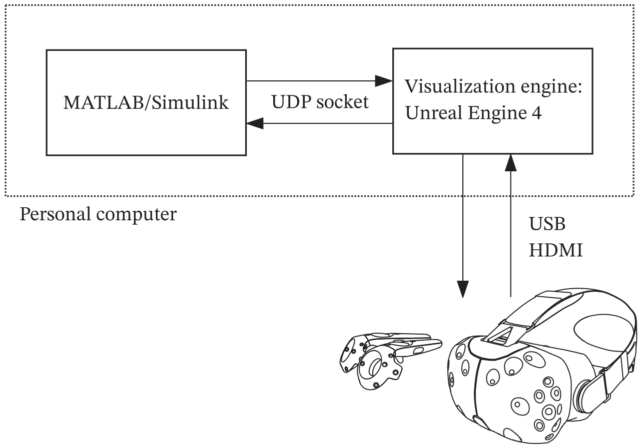


Figure 2.5: Process of the application for real-time platform

The process of the development as follows:

1. Visual and Mathematical Modeling
2. Interaction Implementation
3. Prototyping

2.4.2 3D Modeling and Prototyping in Real Time

3D modeling of those objects are implemented the similar process with the creation of virtual environment which detailed in Section 1.3. It is likewise important to point out that creation of some objects are completed in other modeling software – Blender 3D modeling software [19]. The reason for that to investigate two different 3D modeling software according to initial needs as well as expectations. The cart–pendulum system is one of the most popular laboratory models for practical implementation and demonstration of control systems [129, 170], for example pole balancing models are used in electromechanical systems modeling (robotics) and in missile stabilization problems. Therefore, the study of inverted pendulum dynamics and control methods is an important asset in the control engineer's portfolio. The system discussed in this subsection is the inverted pendulum laboratory model produced by Inteco [67]. It is shown in Fig. 2.6.

The object consists of a rail attached to a rigid frame, and a cart moving along the rail. There are two pendula attached to a shaft on the cart on

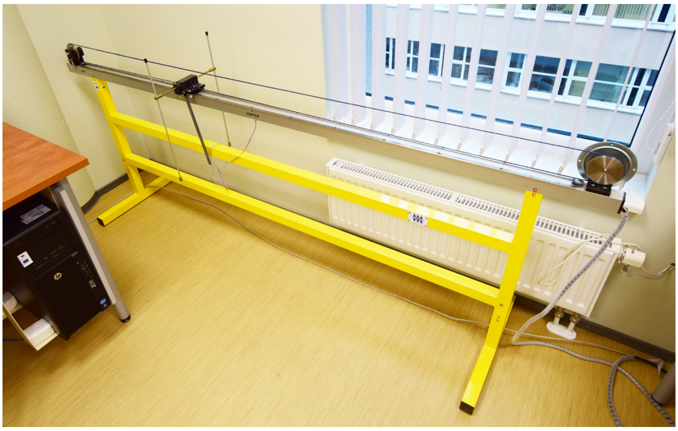


Figure 2.6: Real-life inverted pendulum control object.

two sides. A belt is used to transfer the force generated by a DC motor to the cart. The mathematical model for this object is derived based on first principles modeling. In this work, the control system model consisting of a nonlinear model of the inverted pendulum and corresponding controllers provided by Inteco is used, and is briefly summarized below.

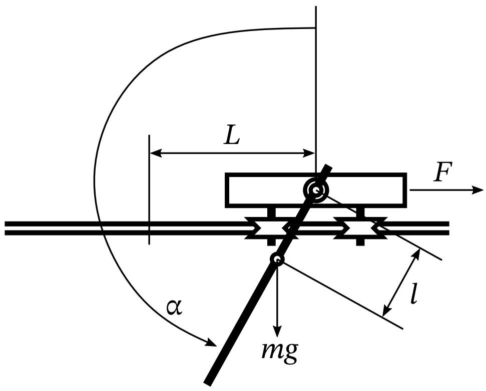


Figure 2.7: Physical model of the inverted pendulum system

The physical model of the inverted pendulum is depicted in Fig. 2.7. The parameter L denotes the distance from the center of the rail to the center of the cart (position), l denotes the distance from the axis of rotation of the pendulum to the center of mass of the system, α denotes the angle between the upward direction and the pendulum, measured counterclockwise, m is the mass of the system, g is gravitational acceleration, and F is the force acting on the cart. The following states are assigned: $x_1 := L$, $x_2 := \alpha$, $x_3 := \dot{x}_1$ (cart velocity), and $x_4 := \dot{x}_2$ (pendulum angular velocity). The dynamic disturbance term ψ to the pendulum angle state computation is also included. Then, the following model is established:

$$\begin{aligned}
\dot{x}_1 &= x_3, \\
\dot{x}_2 &= x_4 + \psi, \\
\dot{x}_3 &= \frac{a_1 w_1(x,u) + w_2(x)\cos x_2}{d(x)}, \\
\dot{x}_4 &= \frac{w_1(x,u)\cos x_2 + a_2 w_2(x)}{d(x)},
\end{aligned} \tag{2.6}$$

where

$$w_1(x,u) = \frac{p_1}{ml}u - x_4^2 \sin x_2 - \frac{f_c - p_2}{ml}x_3, \tag{2.7}$$

$$w_2(x) = g\sin x_2 - \frac{f_p}{ml}x_4, \tag{2.8}$$

$$d(x) = b - \cos^2 x_2 \tag{2.9}$$

and

$$a_1 = \frac{J_p}{ml}, \quad a_2 = \frac{1}{l}, \quad b = a_1 a_2. \tag{2.10}$$

The computation of moment of inertia J_p, associated values, and system parameters can be found in [67] and are not provided here in the interest of space.

The 3D asset that represents the real life system was prepared in Blender. It is important to note that in this case one in terms of asset animation one must consider not only translation, but also rotational motion. For this reason one must ensure that for each piece comprising the 3D model the pivot points are set and exported properly. Once the asset is transferred to UE4, the asset is reconstructed from all elements in a hierarchy that follows the transformation order. That is, since the pendula are attached to the caret, they will inherit the position of the caret. Finally, the dynamic elements are programmed to take input data coming from a UDP socket and move in the following ways according to the model in (2.6)

- the caret with the pendula attached moves across the static rail according to the model state x_1;
- the pendula rotate on the axis according the the angle in the model state x_2.

Previously mentioned UDP communication plugin for UE4 that makes real–time simulation possible with Matlab. In order to progress the prototyping in real time, validated mathematical models are exported to the game engine as C++ code and/or featured visual scripting method discussed in Section 2.2. The platform includes modeled objects (The

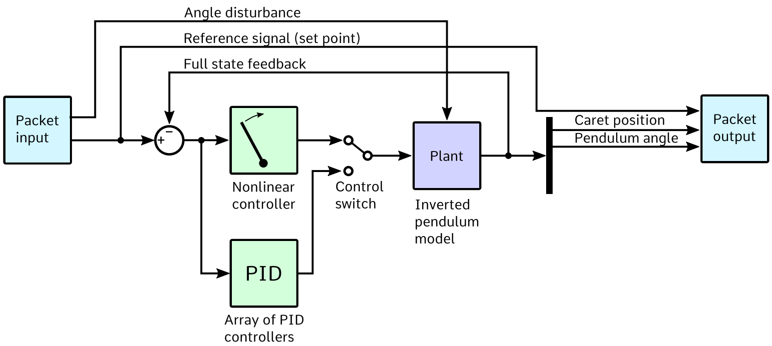


Figure 2.8: The schematic diagram for the inverted pendulum control experiment.

Magnetic Levitation System, the 3D Crane, and the Inverted Pendulum) described enables to work as a group or as a single user. For instance, the application can run simultaneously if Matlab is set up another computer. Besides that, meanwhile a student is experiencing the virtual object, another student can modify the mathematical model if it is desired. Fig. 2.9 presents the replication of inverted pendulum while the user experiences interactivity in VR based application.

The educational objective can be stated as follows. The schematic diagram for the corresponding control experiment is shown in Fig. 2.8. The control loop has two modes of operation. One is the so called *swing up* mode, and the other is *swing down*. The difference between these modes is such that in the former case the controller with a linear one, both encapsulated in the *Nonlinear controller* block, while in the latter an array of PID controllers is used to stabilize a stable system in the downright position. There is a fundamental difference between these two objectives in terms of what is learned by observing both types of control.

2.4.3 Interaction Implementation

Interaction is the primary component of IE. In the development of DT of control systems, the design of meaningful interactions is the main goal of the training aspect of the application [140]. Hence, development of coherent interactions is seen as top priority for ensuring efficient laboratory instruction.

In what follows, the focus is on key aspects of implementation of these interactions. There are several options available when designing interactions. First, one can implement those using the physics engine available in the target platform. In this case, the mathematical description of the process is largely unclear. The task is, however, to obtain a valid mathematical model of the whole system, including interactions. Two methods are used for developing interaction mechanisms:

- Interactions are coupled with the object dynamics, that is, the corresponding (non)linear mathematical model is augmented with corresponding inputs and states;

- Interactions are decoupled from the object dynamics, that is, a separate mathematical model is designed for the interaction. This approach is feasible only if the interaction does not affect control system performance, so its use is usually limited.

Interaction mechanics are first evaluated by comparing the performance of the model with that of the original control object. Then, the subject-based evaluation is performed in VR internally by developers. If results are not satisfactory, the mechanic is revised.

The chart for this experiment shows the desired caret position against the real one on one plot, and the pendula angle on another. This allows to compare the dynamics of both parameters and assess control performance. A screenshot from the actual application is shown in Fig. 2.9. In this case, the application is running in default fallback mode when no HMD is detected. That is, it is still possible to use desktop keyboard and mouse input to navigate the experiment. In this example, the user is pointing the right motion controller towards the rail to select the desired set point which is represented here by a green cylinder. The caret begins to move towards this desired location.

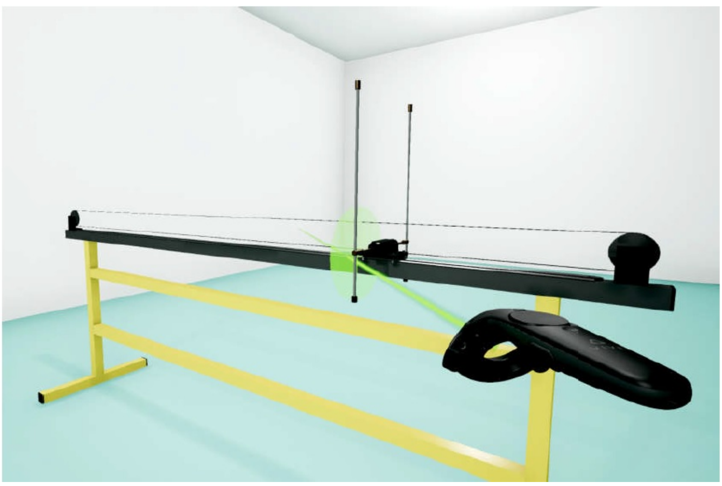


Figure 2.9: Inverted Pendulum in immersive environment

2.5 Designed Architecture for VR based Applications

UDP socket connection is a remarkable part of DCDA since it enables real–time communication between VR based applications and third party software. The socket connection has a dependency to be updated to the same version of the game engine while development process. The protocol allows transferring twenty float and three integer parameters, meaning that only numerical values can be transferred using in a given implementation at present.

Synthesia experiment is a proof of concept implementation to provide feedback from employed third party software with high sampling rates upwards of $1kHz$.

In order to achieve a complete visualization with real–time feedback for such experiments, the following components should be accomplished:

- Available a C++ class / Blueprint based UDP socket implementation must be configured.
- All necessary animations should be scripted and the information should be received via the UDP socket from third party software (e.g. MATLAB).
- Blueprint / C++ class made actors must be available in VR environment.

Since HTC Vive is used as a HMD device in this experiment, the corresponding VR template in the game engine can be employed. The template allows users to navigate in immersive environment directly by adding navigation mesh.

VR Control Systems present both ways communication possibilities that user interaction also can be utilized as an input for third party software in which VR based applications are complemented. By this approach, flexibility is enhanced in terms of amount of inputs and outputs for the system and corresponding mathematical models of dynamics. In this work, there are two types of interactions which arise in the area of control systems which can be applied in various fields such as similar coupled controllable objects:

- Interactive selection of the control system tracking reference (set point).
- Direct physical interaction with the moving parts of the recreated control objects. From control systems perspective, this is generally used to introduce disturbances into the studied systems. From the user perspective, such interactions are of curiosity driven experimental nature.

UDP plugin as well as exported modules can also be reused in any project. In addition, Matlab via Simulink Desktop Real–Time toolbox is set up once and the application via the game engine, created prototypes in the same platform are effectively used to teach conducted system and its design.

2.6 Conclusion

Besides a number of confirmed advantages of VR technology, it also promises interactive visualization that engages users in immersive environments. While HMD devices have been developed significantly in recent years to avoid known issues related user experience, design of VR based applications should solve the remained challenges such as a relevant infrastructure that enables real–time feedback mechanism among third party software, VR based applications and users. The infrastructure must be appropriate technically to employ in different VR based applications delivered with particular goals. At the same time, adaption of the infrastructure should remain simple to utilize in practice.

Accordingly, real–time data communication tool and designed architecture (DCDA) with the ultimate goal to collect motion data is obtained. DCDA consists of developed UDP based data communication tool, HMD devices worn by users, VR based applications and utilized third party software. UDP based data communication tool has been developed particularly to transmit data among VR based applications and third party software by respecting to OSI model. The tool brings a reliable communication via a UDP socket implement by Blueprint with customizable sampling rates upwards of $1kHz$, meanwhile existing high–quality VR systems operate at $90Hz$ at present.

The feedback mechanism of designed architecture is validated through a number of VR based applications and remarkable objectives are accomplished therein. First case study is devoted to provide means for inducing voluntary synesthetic experiences through the VR environment to the listener in real–time by developed UDP communication tool and as a result immersed visualization resulting in a speaker in the real environment is accomplished. The configuration of conducted experiment including followed approach for motion tracking is also explained in details. Laboratory sessions are an essential part of education in engineering, however, existing difficulties have prompted researchers to propose various methods and applications to alter laboratory experiments towards VLEs. Thence, second case study provides an immersive environment contains interactive modeling of the dynamics of several control objects. The physical models of replicated control objects as well as corresponding mathematical models are also described. Those replicated objects are employed to provide accurate feedback for studied control systems coupled with the ability to interact resulting a visual feedback. The last study, particular application is complemented with DCDA to enable collecting motion data while users are performing in immersive environment in order to investigate behavioral modeling approach.

Finally, introduced proof of concept implementations formed proposed DCDA that can be implemented for another VR based applications. DCDA enables realistic interactions between the user and other created objects particularly require accurate and meaningful representation in IEs, in addition to capturing capabilities for human actions in real–time.

Chapter 3

Preprocessing and Analysis of Motion Data

In this chapter, complete designed architecture and utilized feedback mechanism to create behavioral models towards VR based applications are explained in details. The chapter is formalized with a respect to the ultimate goal of the framework; a methodology for automated analysis of human behavior. A firm motivation of feedback mechanism with behavioral modeling approach, understanding of observation of the behavior and the designed prototyping platform to enable automated analysis through designed architecture is described in Section 3.1. The particular implementation of the platform to demonstrate the work flow is also introduced in this section. In Section 3.2, an additional intelligence obtained by feedback mechanism to complement IEs is introduced. Employed computational intelligence methods, system identification models and primary results as an outcome of the novel methodology are addressed in Section 3.3. Conclusions are drawn in Section 3.4.

3.1 Investigation of User Behavior Towards Designed Architecture

VR is a powerful modern medium for immersive data visualization and interaction. Interactive graphical representation can be sufficient approach to obtain efficient and joyful learning experience for diversified users in various fields. Although VR based applications can attract even non–expert users, only a few research efforts targeted the issue of complementing those applications with features derived from real–time human behavior analysis in virtual environments. Furthermore, analysis of performed activities and subjective feedback towards VR based applications are studied typically by post–experience oriented surveys. On the other hand, it has become possible to alter this set of metrics recently by psychophysiological data that requires additional properties and advance techniques in order to obtain fully objective measures [80]. The other family of metrics is related to users' behavior inside the virtual environment [157]. Additionally, precise understanding through ubiquitous interactions in VR may support relevant researches that focus on increasing engagements of immersive scenes with real–world situations. Consequently, understanding the behavior enables to draw conclusions for creating more compelling and efficient applications.

In what follows, the design of the feedback mechanism is presented. Key elements of metrics to investigate user behavior as well as particular VR application that demonstrate the process flow of the designed mechanism are also introduced in following subsections.

3.1.1 Design of Prototyping Platform to Enable Complete Feedback Mechanism

It is apparent that a complete behavioral analysis inside the virtual environment is one of the most recurrent interests for researchers but also requires a significant amount of time and effort. In order to elaborate the framework of this research, prototyping platform to acquire data is necessary to enable assessments towards user's behavior in VR based applications through available main hardware devices to deliver. Therefore, having accurate metrics data to study and model user behaviors such as location, head orientation, interactions, performed actions etc. can give better understanding to study the human behavior besides conducted traditional survey techniques. Accordingly, replicability of experiments in such applications that focus on behavioral studies can be improved. The first phase of the feedback mechanism is accomplished by previously explained *Synthesia Experiment* in Section 2.3. The application provides synthesia experiences through designed VR environments to the user in real–time by employing third party software. In following, the second phase is another presented application—*VR Control Systems* in Section 2.4.2 is an achievement that validates bilateral communication among VR based application and third party software. User interactions play also an important role that provide a visual accurate feedback for the studied systems by designed architecture. The last phase of the feedback mechanism which shapes the framework is collecting motion data in real–time to enable automated analysis of human behavior. After the implementation of this phase, demonstration of the feedback mechanism is carried out by particular implementation—*Swedbank Experience* which is a gaming–oriented VR application that is explained with details in 3.1.4.

3.1.2 Observation of Behavior in Immersive Environment

One of the main attractive features of VR applications is to allow users to interact with the environment and other users. VR based applications are often delivered with the interaction that may also allow an evaluation of the engagement of participants [113]. Paliokas et Al. defines an observation of behavior particularly in immersive environment as follows; "the collection of behavioral data on certain subjects when involved in various activities under particular conditions" [125]. Accordingly, elements of metrics towards VR based applications delivered with HMD devices such as location of user in immersive environment, teleportation, head and controller movement of users, rewarding points in gaming–oriented VR applications should be traced to study users' behaviors.

The teleportation allows the user to navigate and move independently and effortless in immersive environment.However, it is also an artificial feature and somewhat unfamiliar to users in terms of actual experience (with the exception of users having previously used VR). Furthermore, some difficulties while attempting to use teleportation such as lack of presence feeling, cybersickness emotions may also be observed [31]. Thus, the part of study of users' behavior should be devoted for investigating the locomotion which let the user interact with objects during continuous movements.

From the user perspective, interactions linked to the gamification based engagement (e.g. joyful learning, serious games) are of curiosity driven experimental nature [54]. Moreover, the granted interactivity may encourage the user to adapt to the gaming environment and the perceives tasks to be completed [13]. Once the motivation is obtained, an accomplishment of attentional aspects by delivering a VR based application matters of given objects and tasks. Training for real-world scenarios with strict time limitations can be form effectively by following similar methodology [66, 132]. However, applying interactions, teleportation and physical movements at once can be challenging for users even for individuals with previous VR experience. Hence, investigation of behavioral modeling shall include all of these dynamics and researchers should consider to let same users experience delivered applications multiple times to observe the differences, if possible.

3.1.3 Collecting Motion Data in Real Time

In order to collect motion data in real–time and enable automated analysis, additionally layer to UDP Based Structure had to be created. Software architecture of the layer contains data preprocessing and data storage that allows to capture, sort and store received data–sets in this layer. Python

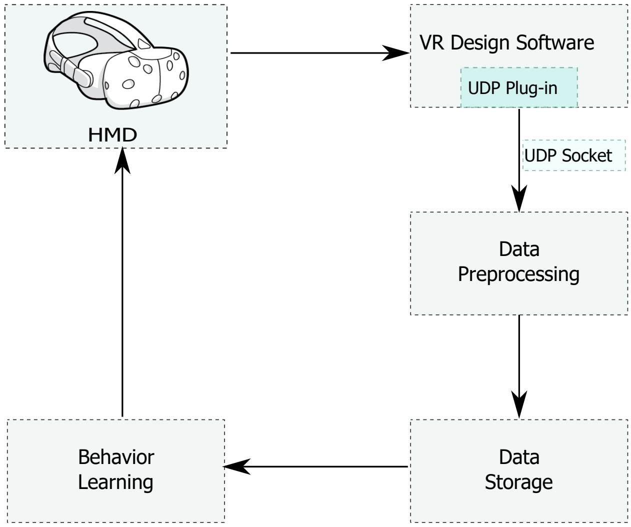


Figure 3.1: Workflow of Complete Feedback Mechanism

made script is in charge of capturing and processing the data before accommodating into data storage. Every four bytes marked as a single input of data that is sent from VR based applications by UDP packet. A script executes the function to send captured information to the designated column of database and added time variables. Relational database management system—SQL is in charge of managing the data for the purpose, facilitate user behavior data–sets to reach.

Collected data mainly contains tracking and measuring human behavior related to IEs and physical movements. Additionally, static information including background information, basic demographic data, about users consists of such information as age, gender, education, previous VR experience etc. can be collected by the mechanism based on research interest but after confirmation of the user. The location of the user in the game level is provided through $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates. Gyro sensor integrated to HMD devices are used to collect information of head rotation (yaw, pitch and roll) while the user experiences IEs. Yaw is considered during looking left and right, positive when turning left. While looking up or down in the application is referred to pitch which is positive when pitching up. Finally, roll can be defined as tilting the head sideways. To proceed with behavioral modeling of the user's, proposed classified data types are listed in Table 3.1. Additionally, timestamp including date and time and unique player id generated by the communication tool are attached in the tail of collected data–sets.

Although UDP plugin can be reused in any project, the plugin may require configuration in the level of Blueprint for communications, meaning

Table 3.1: Classified Types of Collected Real Time Data in Feedback Mechanism

Data Type	Collected Information
1	Static Information: Demographic and Background
2	Interactions: Teleportation, Success indicators
3	User's Location in Immersive Environment
4	Head Movement of User

that the reference to UDP actor in visual level can be given only into a corresponding game level. Thus, it is required to gather all the needed variables that contained desired data with “get” function from game instance in Blueprint. All the form input data was translated into numeric values to be stored in the database if necessary.

The game instance in Blueprint acts as a collection of global variables. The collection can exchange values of global variables between all items of Blueprint within the project via “get” function. Furthermore, new values can be written into global variables by other Blueprint via the “set” function. “get” function is used to get the value of certain variable and “set” function was used to forward new value to the global variable [48]. Data transmission and collection is obtained by this approach in real–time.

Consequently, the basis of the feedback mechanism implementation can be described as follows: The game engine (e.g. UE4) is employed as the visualization platform while the user experiences the virtual facility with interactive equipment. Motion capture is achieved using present HMD technology which provides access to user movement data. UDP serves as a communication plugin between the game engine and software environment that makes real–time data communication and simulation possible. To proceed with modeling of the user's head and controller movement, the data related to the user is sent out to Python and database to store and apply statistical and computational intelligence methods. Behavioral learning is located between HMD device and data preprocessing layer. The workflow to illustrate a complete feedback mechanism is depicted in Fig. 3.1.

3.1.4 Particular Implementation of Prototyping Platform

The first version of the gaming–oriented VR application was completed at the beginning of 2018 in cooperation with a private bank in Estonia. The bank is now using the first version of the application for marketing purposes on various fairs, in their headquarters among Baltic countries to exhibit the

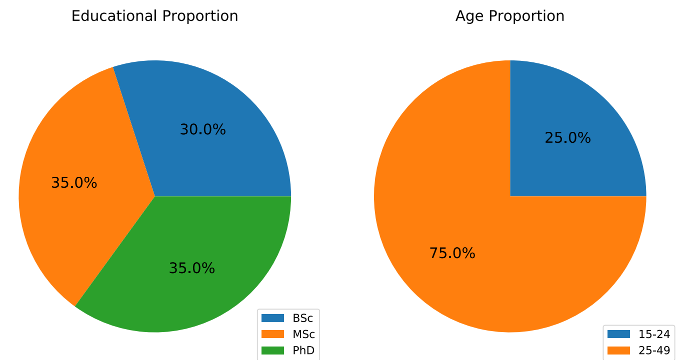
Figure 3.2: The screenshot while experiencing VR application with timer and score

innovative and entertainment sides of their business.

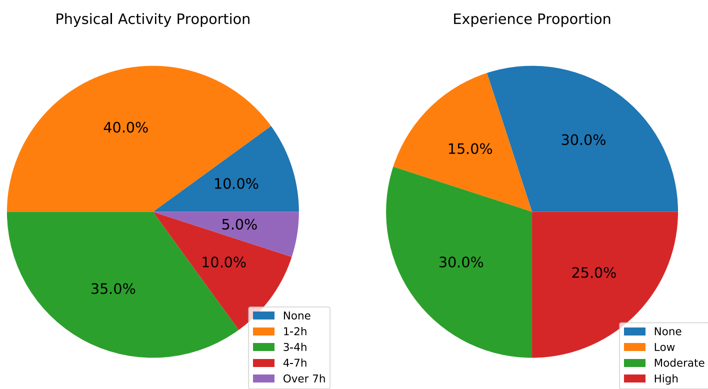
The earlier version consists of three main components: starting screen with a custom UI form, tutorial level and main game level. The main level is situated in the hill–top virtual environment and it was designed to let the users perceive in a borderless environment. The screenshot while the user is playing and all software packages are working is depicted in Fig. 3.2. Secondly, the tutorial level was designed to keep the player in boundaries in order to direct the player to complete the specific tasks. The tutorial environment remained simple in order to assist the player in taking the desired actions leaving only minimal possible distractions. Accordingly, the main motivation of the tutorial is to let users understand existing main functions in the application such as teleportation, interactions etc. Additionally, users benefit from the warm–up session before the main game, especially individuals who do not have previous VR experience.

In game level, the items are randomly generated and scattered but only around the defined play–area. Those items are placed in the level by the algorithm uniquely for each game. Players are motivated to use teleportation feature to move around the play–area in VE since the distance between collectable objects are random and often the objects are far apart from each other. The objects spawn in different locations and at a varying distance from the ground, so the player must still move physically.

The particular implementation was designed to gather data in two different situations: before the players had some experience in VE and after. Therefore, in order to succeed with further analysis, the application is configured to provide a set of data in real–time. Since the goal is devoted to provide the methodology for automated analysis of human behavior, any statistically relevant conclusions is not drawn from collected data through the experiments described herein. In other words, the aim was to design the



(a) *Education and age division*



(b) *Physical activity and experience division*

Figure 3.3: Collected background profiles of participants

Table 3.2: Given Options to Users for Collecting Background Information

Options	Age	Gender	Education	VR Experience	Activity
1	3–7	Female	Primary School	None	None
2	7–14	Male	High School	Low	1–2 h
3	15–24		Bachelor‘s Degree	Moderate	3–4 h
4	25–49		Master‘s Degree	High	4–7 h
5	50+		PhD		7+ h

experiment including the development of technical tools enabling the convenient and robust infrastructure for feedback mechanism. The experiment itself may continue with an interest and the number of participants can be extended constantly with the goal of obtaining statistically relevant data based on a large number of experiments.

Data Processing and Game Play of Particular Implementation

The data set is collected in three parts for particular implementation. In the first part, the customized UI is in charge of handling the collection of the information about the participant's background. The data collection is only activated by filling up the form and accepting to share the data for research and development purposes for each user. The data is categorized based on age, gender, education, previous gaming experience and hours spent weekly on physical activities. Users are asked to choose the best fit option based on multiple choice questions that are listed in Table 3.2. Since the feedback mechanism is designed into numeric values, selected output by users must be transformed. For instance, “Gender” is the part of the required form to fill by the user via UI and selected output is defined as 0 or 1 meaning male or female to employ UDP plug–in and store the data in the database. According to collected experimental data, most diversified information is gathered by physical activity level and VR experience. While experience in VR levels raised in all categories almost equally, activity levels of participants remain coincidental. Participants who selected low VR experience is referred to none of physical experience with HMD devices previously. Further classification is illustrated by means of pie charts presented in Fig. 3.3.

The second part of process is allocated into game sessions, the player's goal in the game is to collect maximum points possible in limited time. There are four different items in the game for the defined goal; yellow leaf, green leaf, orange leaf, and coin. Each item rewards the player with $1, 2, 3, 10$ points respectively. Meanwhile, the head movement of users are also captured.

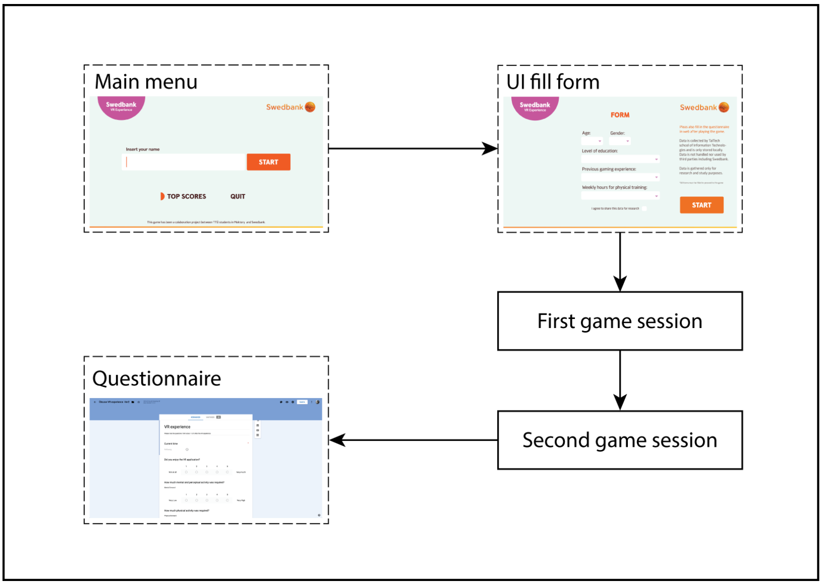


Figure 3.4: Data collection process of the experiment

Finally, the last part is placed after the game sessions; Each player is also asked to fill the survey that consists of seven questions in a five–level Likert scale by rating from 1 (very low) to 5 (very high) [99]. The process of collecting data for the particular implementation is illustrated in Fig. 3.4.

The experiment to deploy the prototyping platform was conducted with twenty volunteers. Each of them played the game two times in row. After the intro session and the UI phase, users were asked to play the game two times in a row and each time frame is restricted to 120 seconds. The motivation for that is to observe the difference from user perspective between first and second attempt for the VR based application. As it is mentioned previously, each object in the application has different color and users are rewarded with corresponding points adequately. Participants are introduced about game logic before the experiment and most of participants perform better during the second attempt. That finding also implies one of remarkable advantages of VR based applications that is usually possible to repeat with low cost even with different configurations. Moreover, another interesting of observation is that participants with low or none VR experience have performed much better in second try that indicates participants were already able to adapt to presented the VR based application during the experiment. Data consists of collected points by participants also supports the observation that is presented in Fig. 3.5.

Participants who claim to have VR experience in high and moderate levels used teleportation feature at most in both times. Furthermore, the

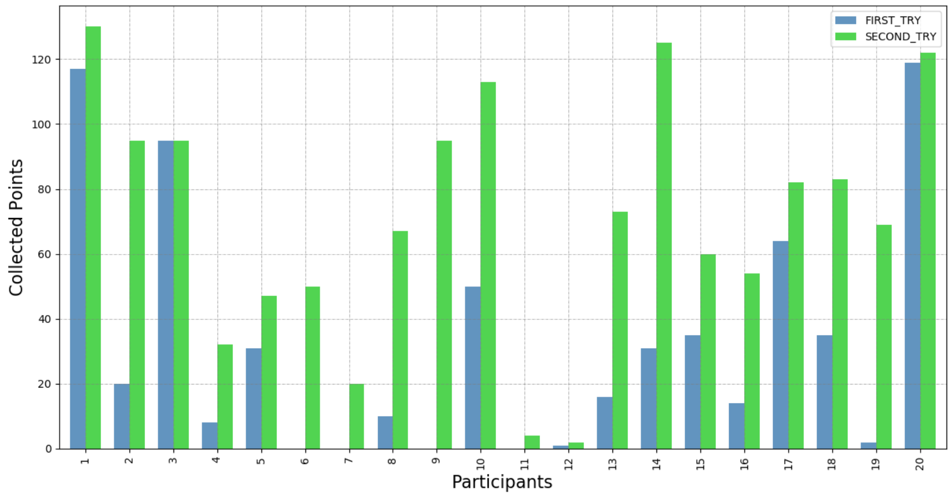


Figure 3.5: Collected points by participants in both times

rest of participants who had less VR experience have used the teleportation feature much more frequently in the second time of the experience. As a conclusion based on collected data, the teleportation feature is easy to adapt and very convenient to employ even for users who might not have previous VR experience with HMD device. The comparison among teleportation usage of participants in is shown in Fig. 3.6.

Further analysis towards the experiment in this work is devoted to investigate the location of participants in immersive environment. Another important fact is that collectable items are spawn height varied randomly as well as their existing location. Thus, players are forced to move physically while interacting and the location information of users in both times is traced to explore dynamic changes of location as $(\mathbf{\Delta x}, \mathbf{\Delta y}, \mathbf{\Delta z})$ coordinates. Collected data of first and second attempts indicates that motions are increased significantly through $(\mathbf{x}, \mathbf{y})$ coordinates in second time. A sample of user behavior related to interaction and location in immersive environment is shown in Fig. 3.7.

Conducted Survey Results and Correlations with Collected Data

Statistical terminology Prior to discussing the findings towards performance analysis of participants, a brief explanation of used statistical terminology is given. The mean $(\bar{x})$ is used to summarize interval data by the sum of the set values divided by the length of set. Standard deviation (σ) : An estimate of the mean variability (spread) of a sample [29].

After the VR experience, participants were asked to fill in the survey and results are presented in Table 3.3. Conducted questions are associated with

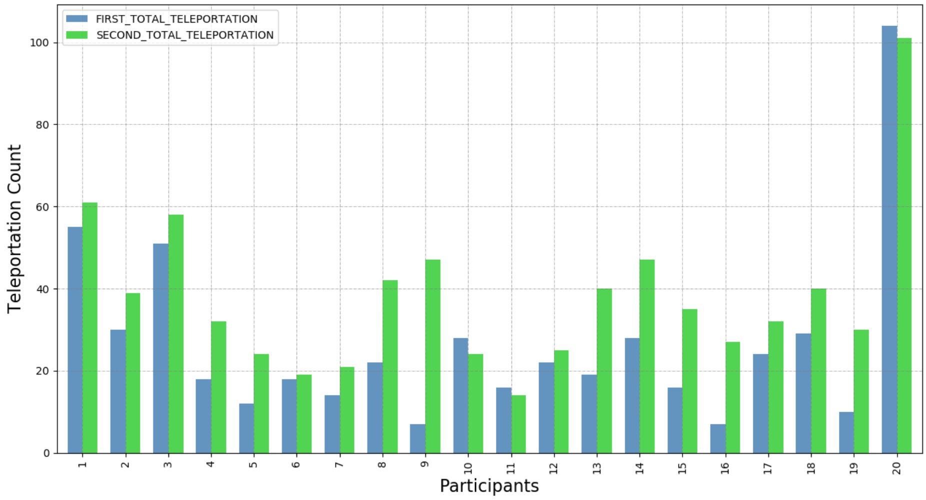


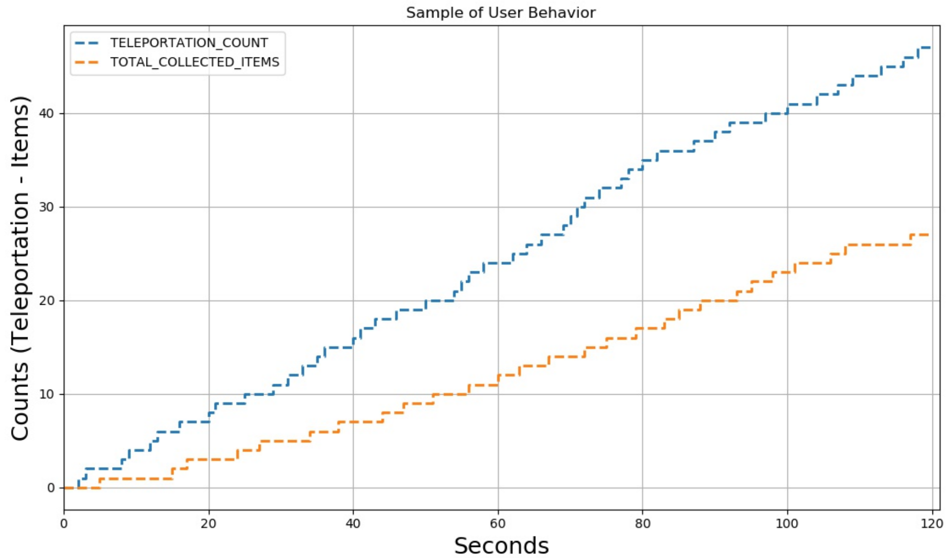
Figure 3.6: Teleportation attempts of participants in both times

the research that is devoted to study subjective evaluation for experimental tasks and its correlation with the performance in National Aeronautics and Space Administration (NASA), that is also adopted in other research areas including VR technology [95, 149]. Additionally, the last two questions are custom–made and are intended for the feelings during the experience.

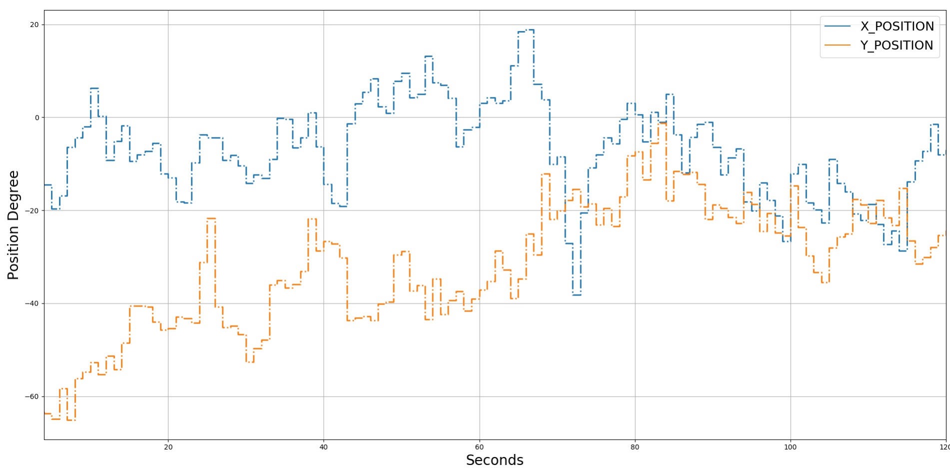
Nevertheless, applying further statistical methods may support the mentioned initial research question—whether the subjective self–evaluation of the presence feeling, motivations and success rate of the player correlates the objective measurement data by measuring of movements and actions in perspective of VR—. One of common statistical methods among researchers to conduct studies is Student's t–distribution [128], particularly in the field of VR to study the behavior while the sample size is small or the population variance is unknown [3, 126, 176]. Accordingly, considering the amount of participants ($n = 20$) for the experiment and most common practices, 95% Confidence Interval (CI) seems relevant.

The survey results reveal that participants performed better in the second time. In addition to measured data, interpretation of T–test for first and second time experience with dependent samples demonstrates the positive correlation with self–evaluation that participants presumably will collect more points in second time experience. However participants who were not satisfied with their performance collect almost the same points as others in average of both times. Thus, the outcome suggests to confirm subjective feedback results with objective measures.

Joyful VR experience is one of important factors to motivate the user. As it is mentioned previously the teleportation feature is available in the



(a) Sample interaction information consists of teleportation and collected items



(b) Captured time based location changes of a user in immersive environement

Figure 3.7: Sample visualization of collected datasets while a user experiencing the application

Table 3.3: Survey results

Questions	**Mean** ($\bar{x}$)	**Std** (σ)
Did you enjoy the VR application?	4.15	0.7
How much mental and perceptual activity was required?	2.75	0.9
How much physical activity was required ?	2.3	1.2
How satisfied were you with your performance ?	3.55	1.1
Did you perform better for the second time ?	4.15	1.1
Did you have the immerse feeling while the experience?	3.85	0.7
Would you like to try the VR application again?	4.3	0.7

nature of the gaming based experiment. In other words, the user must use teleportation to collect more points in given time. Thus, the key assumption is here that the usage of this feature indicates the motivation of the individual. Accordingly, measured data reveals that participants use the feature more frequently after the first time, with the same confidence interval. Furthermore, collected data indicates that low or none VR experienced participants did not face difficulties considerably to adapt, statistical results are presented Table 3.4. It is relevant to point out that although the analysis may provide further results, the limited sample size recommends to be cautious.

Nevertheless, participants in early stage may not improve any strategy with the focus of achieving high score. In other words, even though the point rewarding mechanism is known, it may not be practical. Therefore, the measured data–sets supported with self–evaluation implies that the application would be adaptive meaning that is able to customize based on performance of the user during the experience. Further results based on post–experience survey and subjective assessment shall be supported by measured data to evaluate accurately and to increase efficiency and engagement, at least for VR based applications. Once sample sizes increase gradually, other statistical methods might also provide remarkable, objective and accurate feedback loop to improve and assess the application. The feedback mechanism and presented methods with examples and data sets may support researchers to improve current studies and uncover pervasive unknowns towards surrounding effects of VR technology and applications delivered by HMD devices.

On the whole, understanding human behavior in VE might also encourage joyful learning approaches. Therefore, existing difficulties to ensure rewarding feedback loop for creating more efficient and compelling

Table 3.4: Statistical analysis of self–evaluation correlation with measured data

Subject	**Mean** ($\bar{x}$)	**Std** (σ)	$\left(C\bar{I}_{95\%}\right)$ *Range*	Correlation
Collected Points	38.5	30.4	24.27–52.73	Positive
Teleportation Usage	11.4	10.6	6.43–16.37	Positive

VE can be alleviated. Moreover, the collected data provides a basis for predictions towards human behavior in VE for various purposes. The feedback can be enhanced with traditional survey techniques and vice–versa.

3.2 Towards Intelligent Immersive Virtual Environments

A thorough study of the users' behavior including interactions inside IEs and emotional states can compose desired intelligence. The intelligence can be thought about as an outcome of the feedback mechanism based on user motion and actions. That intelligence shall also provide real–time proactive qualities to design adaptive user interfaces and advanced recommendation systems [186]. Furthermore, development of user experience (UX) assessment tools for VEs is seen as an important motivating factor [139]. The intelligence derived by proposed feedback mechanism can be outlined at least by two major use cases: collaborative exploration and analysis of visual representations of Big Data related challenges and adaptive VLEs based on the results obtained fully objective measures in the pursuit of behavior inside IEs. Accordingly, the actual implementation of intelligent immersive virtual environments (IIVE) should result in massive improvement in the analysis of large, complex data [115]. Moreover, the results of this part of research may also be integrated into academic teaching and/or training applications (i.e., *VR Control Systems*), but can later be extended to industrial needs as well. Therefore, evaluation of the intelligence of the developed solutions will also be possible in various educational or training simulation context.

3.2.1 Adaptive Virtual Learning Environments

Recent exponential growth towards computational power enhanced interest in VR by taking advantage of its immersion, engagement, measurement and feedback capabilities [157]. Learning experience towards VR in diversified fields is usually delivered by Realistic Environments (RE) and Imaginary

Environments (IE). RE such as digital twins let the user engage actively and cognitively; while IE mainly focus on enabling of human cognition and behavior. In any case, adaptiveness must be considered to advance the experience in VLEs that is authentic, meaningful and efficient. Initially, designers must have clear understanding how users explore virtual environments and interact within. Next, the environment should be able to provide meaningful responses based on user's behavior at the same time. Hence, in order to increase intelligence in VR based application and provide highly efficient user experience, behavior modeling should be applied. However, due to lack of feedback mechanism at present, the level of behavioral understanding of users is not sufficient to assist the experience in real–time. Therefore, designed architecture should be integrated into existing VR based applications to tackle mentioned issues.

3.2.2 Interaction with Big Data in Intelligent Immersive Environment

Human–Machine Interaction (HMI) is one of notable topics for researchers and the effectiveness of HMI related applications are usually linked with the interactivity aspect [53]. The interactivity also encourages users to be more operative and complements their learning process [43]. Meaningful visualization of Big Data raises the challenge gradually due to required computational power. Besides processing huge amount of data, potential high diversity of provided data adds to the challenge. Although traditional visualization tools have been updated continuously to ensure their effectiveness, they have already reached to their limits when encountered with very large data [4]. Hence, traditional blended techniques can be clarified by powerful modern medium—VR. Essentially, merging interactions in immersive environment provided by VR, brings different perspective to HMI. In other words, HMI can be obtained to maximize in artificial reality conditions with minimized latency [32]. Users equipped by HMD devices and controllers can navigate in IEs independently and interact with it in a meaningful way. Meanwhile, several studies have already been introduced through visualizations Big Data conducted with VR based applications to relief present difficulties and to engage users efficiently with provided data [114, 116]. Additionally, dynamic modeling of user behavior can be beneficial to decrease required high computational power for visualization purposes. Ability to predict user's behavior is one of the key issue that can lead to a coherent solution. The prediction might allow to preload only the necessary part from Big Data sets. Dynamic models would also benefit particularly VR based applications to ensure a seamless immersive experience possibly with less computational power. In order to gain the following highly important advantages in Big Data related visualizations, it is remarkable to engage with key issues which need to be investigated as follows:

1. Human movement prediction for determining the data to be preloaded into the memory of the employed device for visualization purposes.

2. Development of meaningful and intuitive interactions with the visualizations. This ensures that the data can be explored efficiently and in a way that allows to and even encourages to gain novel understanding into complicated interconnections given the three-dimensional representation of the data in VE.

3. Creating a collaborative immersive environment in order to allow researchers for interaction purposes with the data and among themselves to increase the efficiency of the data study.

Nevertheless, once relevant amount of behavior data is collected by the feedback mechanism, further effort can be devoted to the research problem of visual representation, exploration and analysis of large-scale datasets (i.e., Big Data) [115] in a collaborative multi-user environment with intelligent user interfaces [70] and agents [61].

3.3 Computational Intelligence Based Behavior Modeling

In order to increase the intelligence in VR based applications and provide highly efficient user experience, behavior modeling has applied by metrics of head movement and location data–sets of users. Collected data to deploy potential models are captured in two different applications; *Virtual Replica of the Physical Building* and *Swedbank Experience* with sampling rates $10Hz$ and $1Hz$. Identification of a system is basically obtained with measured data inside IEs while performing activities. In order to compare system identification models, the inputs are considered to be coordinates within same experiment for all models and the output is coordinates in future after certain number of steps. Although system inputs and system outputs are related to the same content, the system can be potentially demonstrated as a nonlinear system. Moreover such kind of behavioral models are usually provisioned as nonlinear systems comparing to input and output variables. Arrays of data sets are used to approach for selection of the best identical model.

3.3.1 System Identification Models

Artificial Neural Networks (ANN) based prediction has been developed since it was explored because of ANN approximation and generalization property. Many research papers in different fields like energy, finance, data mining, medical, industrial etc. are published in scientific literature, and some commercial companies claim or market the so–called advanced statistical programs using neural networks, for modeling and prediction [39, 175]. ANN, with the ability to approximate a large class of nonlinear (NL) functions, provide a feasible uniform structure for NL system representation that is usually described with differential equations (continuous-time model) or difference equations (discrete-time model). Furthermore, ANN have already been successfully used for modeling and prediction of human behavior with different perspectives [5, 187].

Input and Output Data

Collected data–sets referred to position degrees consist of orientation and location data sets. Location of the user is provided through $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates and an example of collected data in time series sets depicted in Fig. 3.8.

Gyro sensor integrated to HMD devices is used to collect information of head rotation (yaw, pitch and roll) while the user experiences the immersive environment. The head rotation is illustrated in Fig. 3.9.

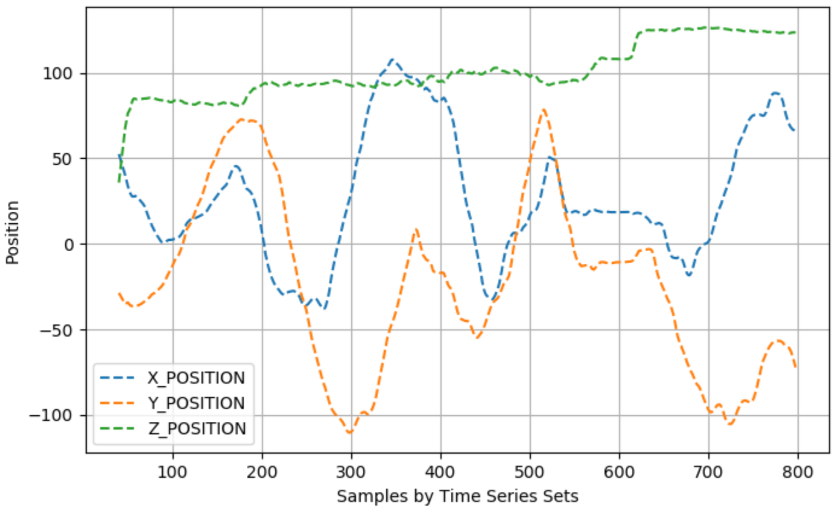


Figure 3.8: Position degrees consist of location while the user experiences VR based application

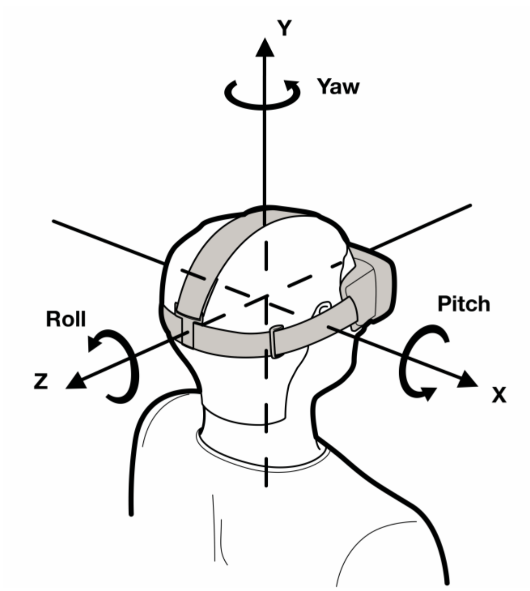


Figure 3.9: Head rotation using gyro sensor [124].

According to presented mathematical equations in [93], a single rotation matrix can be formed by multiplying the yaw, pitch, and roll rotation matrices through $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates. Hence, if any of head rotation is known, position defined $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates will be given by the matrix. However, since collected data enables investigation into head movement and location of user in the applications, the focus can move on two types of predictions:

- Performing predictions based on dynamic changes of head rotation as $\triangle(\alpha), \triangle(\beta), \triangle(\gamma)$ meaning using measured movement values to predict next values.
- Performing predictions of user's location in the application by using head movement values as exogenous inputs.

NARX Model

The model is built up with the wavelet network to create input and output non-linearity estimator. An important class of discrete–time nonlinear systems is non-linear autoregressive with exogenous inputs (NARX) model that formalized by

$$y(t) = f(u(t-n_u), ..., u(t-1); u(t); y(t-n_y), ..., y(t-1)) \quad (1)$$

where $u(t)$ and $y(t)$ represent input and output of the network at time t, n_u and n_y are the input and output order, and the function f is a nonlinear function. When the function f can be approximated by a *Multilayer Perceptron*, the resulting system is called a *NARX* network.

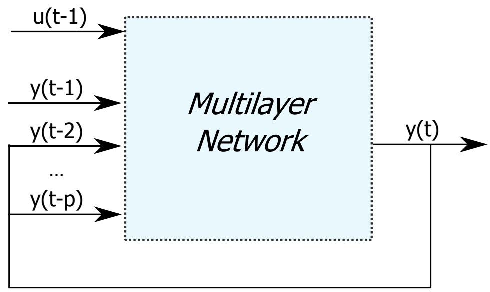
NAR Model

Another class of discrete–time nonlinear systems is non-linear autoregressive (NAR) model that formalized by [65]

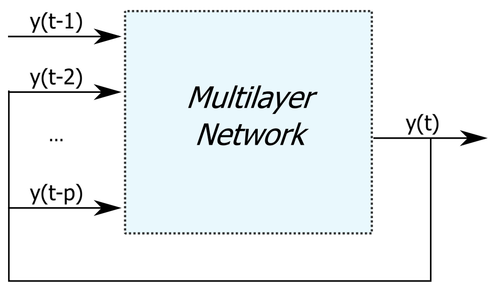
$$y(t) = h(y(t-n_u), ..., y(t-1); y(t); y(t-n_y), ..., y(t-1)) + \epsilon(t) \quad (2)$$

where $y(t)$ represent input and output of the network at time t, n_u and n_y are the input and output order, and the function $h\,(.)$ is unknown in advance, and the training of the neural network aims to approximate the function by means of the optimization of the network weights and neuron bias. Finally, the term $e(t)$ stands for the error of the approximation of the series y at time t [145]. The main difference between NAR and NARX is that external input used for NARX model.

The topology of both employed network models are depicted in Fig. 3.10.



(a) Non-linear autoregressive with exogenous inputs (NARX).



(b) *Non-linear autoregressive (NAR) network*

Figure 3.10: Topology of network models

3.3.2 Dynamic Predictive Modeling of User Behavior

This section describes the process that can perform any other user behavior prediction since the approach is general to employ both NAR and NARX neural networks. The process of implementation as follows:

1. **Data Communication and Collection**: UDP protocol is in charge of sending the real–time user movement and location data as time series to local database while the user experiences the application.

2. **Noise Filtering**: Besides the location information of user, the captured sensor information of HMD which can be sometimes noisy and unreliable. According to behavior patterns, rare outliers (below %1) of sensor data are removed.

3. **NARX Model Training**: Filtered data is divided into 70% training data, 15% validation and 15% test data. The model has been trained using by Levenberg–Marquardt algorithm that is often the fastest back–propagation function and commonly used [107, 117].

4. **NAR Model Training**: Similar procedure as NARX model training is followed for data division and selection of training function. Results of both models are addressed in the following subsection.

5. **Performance Comparison and Validation of Trained Model**: Once accurate results are accomplished, test data which is not introduced to these models are set for validation purposes.

3.3.3 Results of Prediction Performances

Virtual–world position of the user based on $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates is used to perform predictions by NARX neural network. The position is measured by the game engine unit (uu) and $1uu = 1cm$ [46]. The head movement is the rotation of the yaw, pitch, roll direction whereas the measured range of rotation for the pitch is approximately $\pm 40°$. Increasing the input delay by one (time–shift between inputs and outputs) corresponds to $100ms$. The amount of regressors are 3 and 6 for NAR and NARX models respectively. Inputs and outputs of NAR and NARX networks together with measurement units are defined in Table. 3.5.

Mean Absolute Error and Mean Square Error are two preferred parameters to present results of trained network models and to determine the model features [102].

- MAE (Mean Absolute Error): The MAE measures the average magnitude of the errors in a set of forecasts, without considering their

Table 3.5: *Measurement units of inputs and outputs for used neural networks*

	X	Y	Z	YAW	PITCH	ROLL
NARX network	I/O	I/O	I/O	I	I	I
NAR network				I/O	I/O	I/O
Measurement units	*cm*	*cm*	*cm*	°	°	°

Table 3.6: *Results of the network models compared with input delays*

(a) *Results of the NARX model compared with input delays*

NARX	$t-1$	$t-2$	$t-3$	$t-4$	$t-5$	$t-6$
MSE	0.59	0.62	0.78	1.29	1.38	1.42
MAE	0.45	0.55	0.60	0.61	0.76	0.79

(b) *Results of the NAR model compared with input delays*

NAR	$t-1$	$t-2$	$t-3$	$t-4$	$t-5$	$t-6$
MSE	0.52	0.68	0.92	0.99	1.23	1.37
MAE	0.48	0.58	0.65	0.69	0.75	0.81

direction and it is formalized by $MAE = \frac{1}{n} \sum\limits_{j=1}^{n} |y_j - y_t|$ where y_j represent predicted value, y_t is true value and and n the number of data samples.

- MSE (Mean Square Error): The MSE is arguably the most important criterion used to evaluate the performance of a predictor or an estimator. The MSE is used for measuring of the difference between values predicted by a model and the values of actual data [81]. MSE is formalized by $MSE = \left(\sum\limits_{j=1}^{n} (y_j - y_t)^2 \right) \frac{1}{n}$.

After processing the collected sample data, changes of head movement is introduced to NARX model with exogenous inputs while the location data is used as an output. The model is trained by different time delays in order to obtain feasibility of prediction towards sample data. In what follows, NAR model performed in order to predict values of head movements by using measured values. Results of MAE and MSE for both models are presented in Table 3.6. Considering approximately over 65 seconds of data which generates 663 samples with 6 elements, with MSE of 1.42 for $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates and angles with up 6-step ahead is highly satisfied for real-time implementation to perform NARX model. Furthermore, NAR model with $t-6$ time delay up to MSE of 1.37 seems relevant. Results of prediction performances reveal that NAR model is suitable to predict head movement of user while NARX model can perform to predict user‘s location in VR based application. Finally, results of NARX model with test data is drawn in Fig. 3.11. As a result of NARX model with MSE of 0.78 for $t-3$ and 1.42 for $t-6$ and with MSE of 0.92 for $t-3$ and 1.37 for $t-6$ a measure of how close the predictions are to the actual behavior is presented.

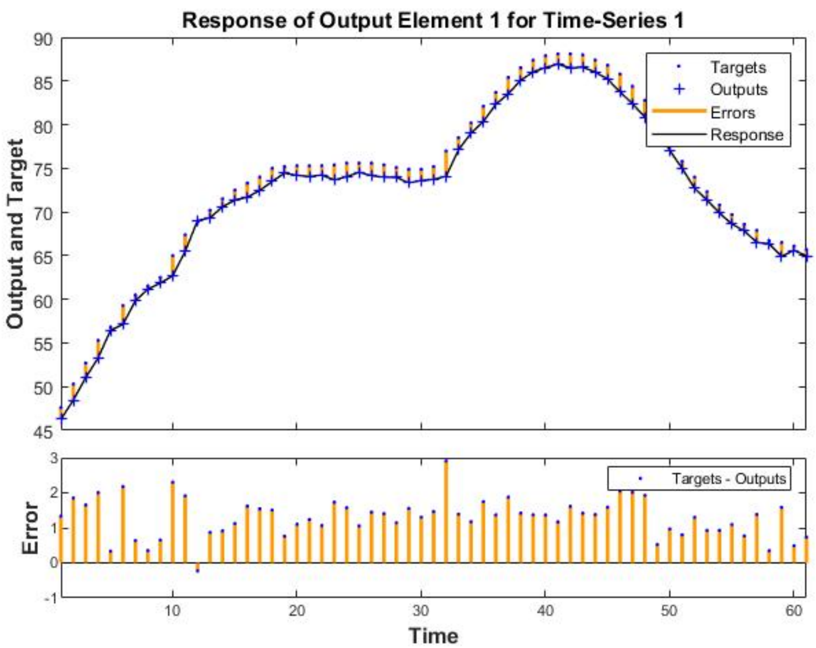


Figure 3.11: Prediction Performance of NARX Model

3.4 Conclusion

One of approaches to studying user’s behavior towards IEs is to investigate psychophysiological data may be available in a testbed that comprises additional tools to make it possible. Another approach is also considered in this chapter that is metrics data related to users’ behavior inside the virtual environment. Elements of metrics such head movement of user, interactions and teleportation which are usually feasible to capture towards VR based applications delivered with HMD devices.In order to collect metrics data in real–time and to enable automated analysis, a complete feedback mechanism is proposed. Collected metrics data can be complemented with static information such as user profiles. The mechanism consists of data preprocessing, data storage and behavior learning parts in addition to previously introduced UDP communication tool. The demonstration of mechanism is obtained with a particular implementation that is designed as a gaming–oriented VR application by conducting twenty volunteers. A number of figures are depicted to visualize collected data set and conducted survey results are presented.

A thorough study of the users' behavior including interactions inside IEs and emotional states can compose desired intelligence. The intelligence derived by proposed feedback mechanism can be utilized at least by two major use cases at present: adaptive virtual learning environments to increase learning efficiency and user experience; user behavior modeling to reduce cost of visualization (e.g. computational power for Big Data visualization). Accordingly, the motivation of use cases and key issues to investigate are described. Featuring elements of behavioral metrics data–sets such as head motion and distances between HMD device and controllers can already be used to identify and authenticate users at present. The uniqueness derived from behavioral data may advance authentication methods to customize the experience efficiently in IEs [130]. Besides that, pattern recognition of user's behavior may increase the performance of system by using advanced machine learning methods. In the future, the feedback mechanism may help to motion tracking method to capture whole body motion to exploit for user identification and user behavioral analysis in large population. An enabled capturing of human actions may also complement to generate intelligent virtual assistants by visual–motor action adaptation [37].

Additionally, the introduced framework in this section enables dynamic modeling of user behavior in VR based applications. In conducted experiments, collected data is utilized to provide a methodology to apply dynamic modeling. Nonlinear auto–regressive model (NAR) is performed to predict head rotation meaning using measured movement values to predict next values. Performing predictions of user's location is accomplished by utilizing also head movement values with the nonlinear auto–regressive neural network with exogenous inputs model (NARX). Results suggest both neural networks are suitable for performing prediction which can be used to achieve an improved feeling of presence while reducing required high computational power.

Conclusions and Future Research

Recent great interest in VR technology also exposes a number of challenges that decelerates this technology to become a modern medium at present such as feedback mechanism towards user's behavior related to immersive environments. The motivation that implies to the feedback mechanism can be drawn from the fact that whereas methods and infrastructure for user action and/or behavior analysis in typical computer applications (e.g., web browsers used for accessing internet content) are well established, but this is not true in general for complex 3D environments such as a VE [161]. Consequently, although VR technology can be beneficial for non–expert users with added intelligence, due to lack of feedback mechanism, it is not possible to tackle the issue of complete real–time human behavior analysis yet. Furthermore, analysis of performed activities and subjective feedback towards VR based applications are studied typically by post–experience oriented surveys at present.

Studying one type of metrics inside the virtual environment that is directly related to users' behavior can relief the challenge. In order to accomplish the objectives may compose devoted effort in presented research, a number of key aspects are followed. The studying of a number of virtual reality hardware tools (e.g. HMD devices) and software tools (e.g. 3D modeling software, game engine) was obtained at first. In terms of 3D modeling software Autodesk Maya and Blender are investigated and utilized to create many 3D models primarily. UE4 is preferred as a primary game engine to design immersive environments that also allowed to create real–time communication tool with visual scripting system. Another mainly used game engine—Unity is also used to implementation digital twins for hand tracking technology based vehicle. On the other hand, although the author also proceeded with several HMD devices including Oculus Rift, Oculus DK2, Open Source VR HMD and HTC Vive, Vive is employed to deliver created immersive environments at most. Independent navigational benefits, convenient hand-held controllers, high resolution display, room scale tracking to enable physical movements were some facts to prefer HTC Vive. The author developed a number of immersive environments that can be classified as realistic and imaginary environments. The first developed environment with the motivation of digital twin concept is a virtual replica as "World-in-Miniature" to discover the user feedback with performed activities. Gained knowledge and experience as well as remarkable feedback from hundreds of participants who experienced the developed application shifted the focus to relief existing challenge towards VR based applications with real–time communication capabilities. Devoted effort to accomplish real–time communication resulted with UDP communication tool that enables data transmission among VR based applications and third party software by respecting to OSI model.

The first practical utilization of the tool is obtained by providing sound visualization through the VR environment with acoustic source localization to the listener in real–time. The second experimental study was also to devoted for virtual learning environments. The created VR based application contains interactive 3D models of the dynamics of several control objects. The physical and mathematical models of those objects are utilized to provide accurate feedback for studied control systems coupled with the ability to interact resulting a visual feedback in real–time. Additionally, the work is an achievement that validates bilateral communication among VR based application and third party software. Finally, introduced implementations formed an architecture that enables realistic interactions between the user and other created objects particularly require accurate and meaningful representation in IEs, in addition to capturing capabilities for human actions in real–time. Demonstration of the feedback mechanism towards design architecture is carried out by particular implementation. The implementation was carried with two concrete experiments towards head movement, location, locomotion and interaction of the user. Furthermore, collected data is utilized to provide a methodology to apply dynamic modeling that predicting next movements of the user and location parameters in the application by performing non–linear modeling. Results suggest both neural networks are suitable for performing prediction which can be used to achieve desired intelligence.

The presented work results in a methodology for automated analysis of human behavior making possible significant improvements of VR based applications and immersive experiences. The framework of conducted research in the thesis extends beyond the state-of-the-art in that as a result of presented research a holistic framework is developed specifically tailored for creating intelligent immersive virtual environments that, in turn, can be readily applied to design of highly efficient virtual learning environments and problems of Big Data analysis. Since the presented system modeling is envisioned to be used for real–time applications to complement data visualization and exploration with diminished computational power, further development efforts also should be exhibited to run models simultaneously in order to feed output of NAR model to NARX. In addition, to increase accuracy, it would be beneficial to use motion controllers or other available technology for collecting data for modeling specific elements of diversified behavior. The obtained models could be validated not only on specifically collected data–sets, but also on other VR based applications. In order to draw statistically relevant conclusions from the particular implementation that is utilized for demonstration purposes, the number of participants should be extended.

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Abstract

Towards Dynamic Modeling in Immersive Environments with Assessment of User Experiences

The present thesis is devoted to the study possibilities for modeling and simulation of immersive environments, to the study of user behavior aspects and the possible impact immersive environment have on the efficiency of human learning and other related factors. The framework consists of three stages to evaluate different types of human activities including multimodal interaction by simulating a number of different scenes. The first stage of the framework is devoted to the development of immersive environments based on real-world architecture. The first stage grants users to perform various meaningful interactions in the environment thereby serving as the foundation for later stages. The second stage is dedicated to the development of a system that enables real-time collection of users' motion data. The data is produced by the user while performing particular tasks in the immersive environment. The third stage of the framework comprises preprocessing and analysis of the data with the goal of deriving users' behavioral models and patterns. Recent findings suggest successful application of behavioral analysis in VR, so the presently developed framework can be effectively implemented to extend and enhance field-specific VR applications.

Kokkuvõte

Dünaamilised Mudelid Virtuaalsetes Keskkondades ja Kasutajakogemuste Hindamine

Käesolev väitekiri on pühendatud ümbritsevate keskkondade modelleerimise ja simuleerimise võimaluste uurimisele. Väitekirjas väljapakutud raamistik võimaldab uurida modelleeritud kaasahaaravate keskkondade mõju inimeste käitumisele ja õppimisele. Raamistik koosneb kolmest komponendist erinevate inimtegevuse liikide hindamiseks. Esimene komponent koosneb kunstlikest keskkondadest, mis on reaalelu sise– ja välisruumide koopiad. Selle komponendi põhipunktiks on kasutajale spetsiifiliste tegevuste teostamise võimaldamine (näiteks, tuli sisse– ja väljalülitamine siseruumides, või mõni objekti haaramine ja/või liigutamine). Teine osa on süsteem liikumise andmete mõõtmiseks ja kogumiseks reaalajas. Kolmas komponent koosneb algoritmidest kogutud andmete eeltöötlemiseks, automaatseks analüüsiks ja käitumise mudelite ja mustrite identifitseerimiseks. Kasutaja käitumise modelleerimine on hiljutiste avastuste kohaselt väga tähtis VR rakendustes, seega loodud raamistik peab aitama kaasa spetsiifiliste VR rakenduste täiendamiseks ja tõhustamiseks.

Appendix 1

Publication 1

A. Köse, A. Tepljakov, E. Petlenkov, K. Vassiljeva. Virtual Reality Meets Intelligence in Large Scale Architecture. *in 4th International Conference on Augmented and Virtual Reality*, pages 297—309, Lecce, Italy, Jun. 2017.

Virtual Reality Meets Intelligence in Large Scale Architecture

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Abstract. This paper presents the process for a case study concerning fully immersive application of physical environment. The paper considers intelligent systems integration to VR and self-learning activities with sociological aspects by significant experimental platform. Authors aim to detail the process of systematical design including modelling, computing, intelligence and an initial evolution of virtual environment. Also practical usage and futuristic aspects are included for the concept. As the project based on physical environment, target of the work is concentrated to give high presence feeling for end-users. To increasing presence feeling, authors aim to maximize immersion level. Self-learning activities based on the perception of supervised and unsupervised learning. The activities are engaged to immersive and entertaining structure. Heterogeneous intercontinental participants provide unique feedback source. The environment is research and development center of Tallinn University of Technology. The virtual environment of the center has been evaluated based on realistic conditions.

Keywords: Virtual Reality · Intelligent systems · Cyber-physical systems · Supervised learning · Architecture modelling · 3D modelling · Unreal Engine 4

1 Introduction

Virtual reality (VR) has become a significant field for computer-simulated environment recently. VR is a high-end human computer interface that strives to immerse the designers and users completely in a virtual interactive environment for a simulation of real world [1]. Although VR has been issued for more than half century, it has become more popular with rapid development of its technology in recent years [2]. Man et al. claims that VR is one of the three most promising computer technologies in the 21st century along with Internet technology and multimedia technology [3]. Interactive devices including head-mounted display, controllers are usually referred to VR technology. That development brought different experiences to world in virtual reality. Arguably, relevant implementations of virtual environment such as interactivity, presence, high degree of exposure etc. are applied successfully. Besides that, virtual environment (VE) may be

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considered the crucial part of virtual reality. Additionaly VE gives access to users who are able to interact with objects and characters in virtual space. That advanced interaction may enhance the feeling of presence. Those approaches can be useful for improvements and teaching methods. Some researchers believe that virtual reality can bring new horizons in education and contemporary learning activities efficiently to students. They assume learning in 3D virtual reality environments can be stated as a desired reality among young students [4]. This paper presents an interactive walkthrough of immersive environment with unique self-learning activities by using virtual reality devices. The creation of immersive environment is based on large scale building located in Tallinn/Estonia. Artificial exterior architecture of the building is shown in Fig. 1. The building is contributed as a research and development center of Tallinn University of Technology. The center meets descent number of intercontinental visitors daily considering demonstration of current work including prototypes, futuristic applications, start-up ideas etc. The structure also contains intelligent systems in considerable fields such as telecommunication, logistics, healthcare, avionics. The center has welcomed around 200000 visitors in three years [5]. Those conditions also provide high effiency for self-learning based on physical activities. Hence, experimental evolution can be assumed to unique regarding universal participants where they can demonstrate their actual knowledge in immersive environment. In Cyber-Physical Systems (CPS), there are essential units such as systems, sensors and actuators, which follow different data models and interaction paradigms. The set-up of a CPS in an architecture that combines heterogeneous components and allows for the integrated processing of data is therefore challenging [6]. Designing an intelligent systems for architectures based on VR provides greater interaction and higher usability [7]. The application compiles human factors and CPS based on VR. That approach might help to improve the process for practical CPS integrated VR applications. Additionally, the terminology of joyful learning mainly originated from the concept of "Game Based Learning". It arranges the teaching content and concept with the game-design mode, applies fun, challenges, competition, cooperation, self satisfaction and a sense of achievement of games to provide the learners with motivation, promote continuous learning willingness, effectively retain and organize skills or knowledge, and further improve learning effectiveness. The inner process of learners' joyful learning can be divided into digital game learning mode [7] and experience game mode [8]. The basic concept of the two both corresponds with flow theory; they both think that with the guidance of game characteristics, the learners will be able to enter the learning cycle, repeat the same learning experience, and achieve the expected target in a joyful situation [9]. The centre organizes competitions, cooperations, challenges for their visitors constantly with particular aims. Therefore, the VE of the center has relevant conditions and possibilities to apply joyful learning approaches. Nevertheless, provided VR experience may take as replacements for real visitations by students and visitors. Hence the application is relevant and it has also high practical values.

Fig. 1. Virtual Environment of the physical building

2 System Design

Successful immersive applications based on realistic environment minimize difference between physical reality and virtual reality (VR). However large scale environments require longer period of time and intensive work for realistic representation [10]. The application integrates computer graphics and simulation, dynamic interaction in real-time, computational intelligence, motion capturing and interconnected computer networks etc. Regardless, teleportation feature of VR technology is implemented for the application. That feature allows users to move independently and effortless in computer simulated realistic architecture. Although the environment is unique and subsections are slightly relevant, the process for creating the virtual environment is familiar with related researches. The process is as follows: (A) Environmental Creation and System Design, (B) Modelling and Texturing, (C) Materials and Hardware Integration, (D) Web Camera Entegration, (E) Interactions (F) Optimization. Unreal Engine 4 is chosen to create the virtual environment as the engine is the one of most known and used physics engine. High efficiency for VR applications, compability and does not require high maintenance cost could be considered as some of prior advantages for the preferred physics engine. Furthermore, Unreal Engine meets beneficial expectations like other common game engines. The concept of object oriented programming, process of computer generated graphics, reusable code with libraries might be main benefits of using primary game engines [11]. Autodesk Maya 3D animation, modeling, simulation, and rendering software is used to model meshes and partly environment as a preference [12]. OpenCV is a open-source computer vision library and it is implemented to display a webcam in virtual environment. OpenCV allows to develop Mixed Reality (MR) environments. MR is usually represented in three forms. Those forms can be defined as Augmented Reality (AR), Augmented Virtuality (AV) and VR. In AR, the virtual and real content can be implemented through the physical world by mixing and registering. AV is slightly closer to VR, which refers to approaching physical objects in to a virtual world. Real objects can be integrated to the virtual world, hence it is possible to interact with them synchronously in MR [13]. Detailed process is shown in Fig. 2. Nevertheless, the hardware integration includes Oculus Rift Development Kit 2 (DK2) and HTC Vive. Integrating two VR devices allows us to compare usability and efficiency for the VE.

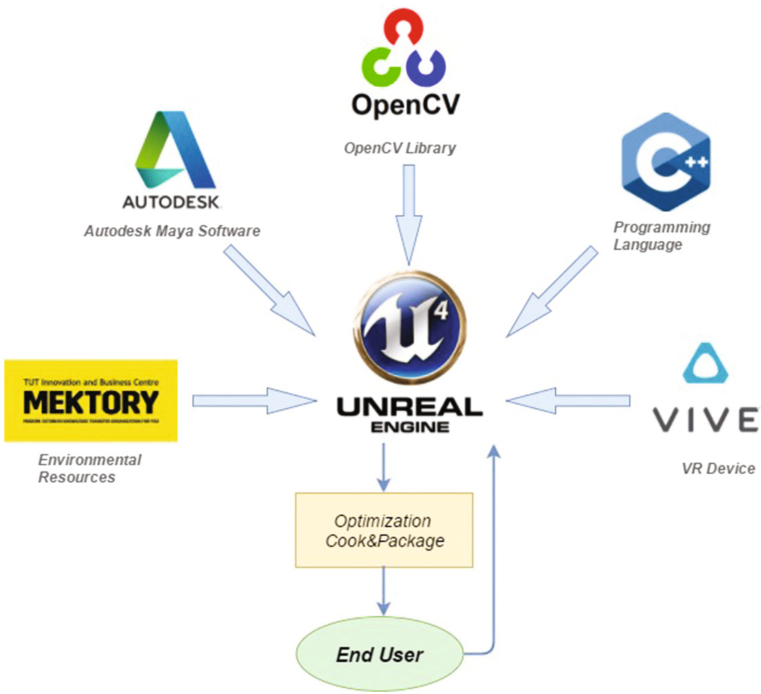

Fig. 2. Process of the application

2.1 Modelling and Texturing

In this phase, the 3D model and rendering of the building were progressed. Creating replicated components for virtual environment is another significant part of the process. The whole concept is accomplished to receive high efficiency for supervised and unsupervised human learning. Interior design is referred to the physical design. Hence, modelling and texturing for the center is based on physical assets which are located in the center. Those assets has been rendered and 3D modelled by using Autodesk Maya software [14]. The architecture components were developed using polygon shape and modified using functions such as extrudes, append etc. as shown in Fig. 3. The physics engine can respectfully identify the material components and map file (Textures) with FBX file format. Texture map is directly related to the quality of the model for the physics engine. In addition, Using Level of Detail (LOD) feature is utilized to simplify the 3D models. LOD is useful to reduce the number of polygons for rendering. It is important to receive better vision on VR devices with better performance. Overall, the design should ensure the virtual quality to achieve good results [15].

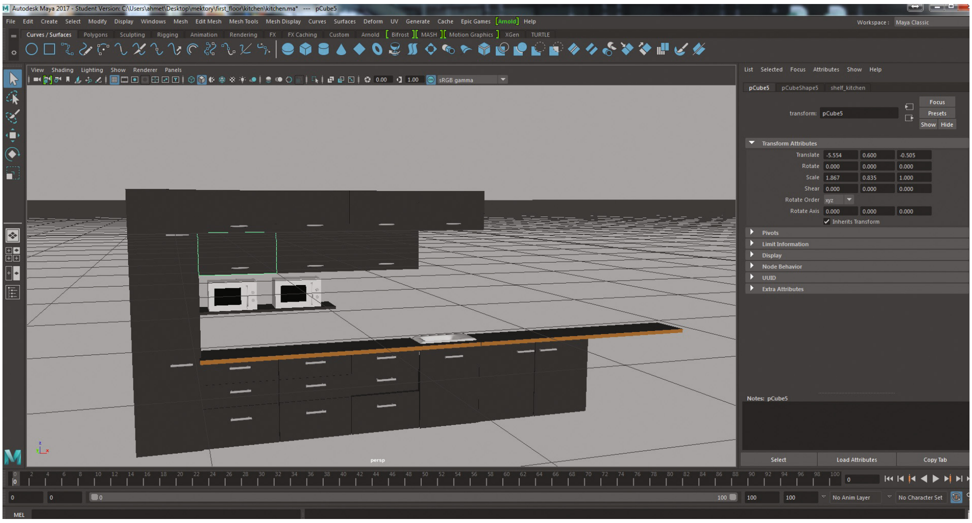

Fig. 3. Modelling and texturing interior part of architecture

2.2 Environmental Creation and Software Management

Visualization is applied in various fields related to such as education, product visualization, interactive multimedia and in architecture. Bresciani et al. [16] claims that visualization is useful to construct intellectual procedures. Successful immersive environments should include accurate design to give presence feeling for users. Additionally the virtual environment is used for multiple purposes such bridging CPS to VR interface, self-learning activities, physiological and psychological aspects of virtual reality. Floor plan of center is used for accurate virtual environment based on physical assets. Although creating an environment is the most time consuming of stage in process, significant accuracy would reduce harder rework. The chosen engine allows to create realistic environments and simulate realistic affects. Hence users can feel lifelike interaction during experiencing the application. Flexible massive terrain is done by the Landscape tool in Unreal Engine 4. The landscape system can be applied for different devices [17]. Terrain is an essential part of environment where the artificial building lie on. Otherwise the user would be in fully infinitive virtual environment where the presence feeling may not be applied. Fundamental parts such as walls, columns etc. are inserted in physics engine according to suggested scale compability of physics engine (1 unreal unit is equal to 1 cm) [18]. Repeating some fundamental parts are applicable regarding the floor plan. Once modelling and texturing are processed, all the content is created in the physics engine. In other words, we assembly all the artificial models based on physical world in the immersive environment. The world includes more than 4400 actors including navigation meshes collision, lights, blocking volumes, light mass importance volumes, ambient sounds, brushes, trigger boxes, materials and meshes. The principle logic of the application is referred to predefined VR class of the engine: Motion Controller Pawn, HUD, VR GameMode, Player Controller. The operation in physics engine is shown in Fig. 4.

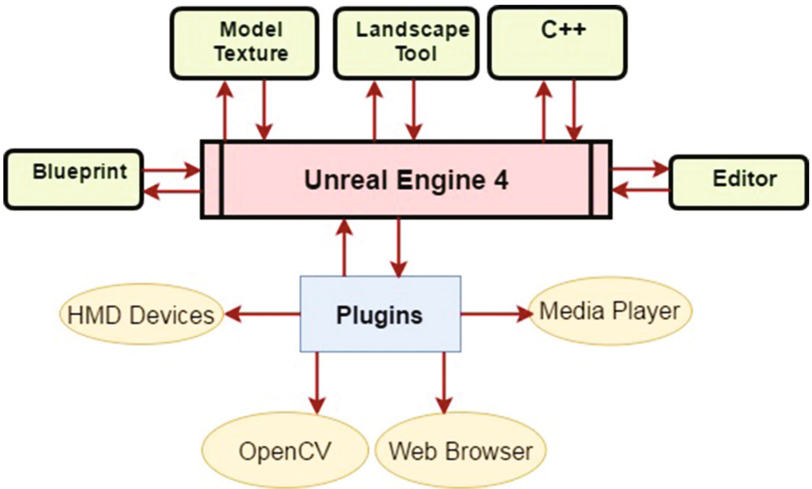

Fig. 4. Working process of the physics engine

2.3 Materials and Hardware Integration

Materials are significant for 3D models. Reactions of those models to the lighting depend on information from the materials. We also use roughness to identify how rough the material is, metallic to reflect model surface, emissive color and normal 3D model. Head tracking devices are in charge of dynamic alterning for the vision of users. The application with the main VR devices provides physical mobility in real room scale, real-time positioning and tracking with advanced display resolution. Oculus Rift DK2 is used in the first stage of application [19]. Although the development started with Oculus Rift DK2 in the early stage of project, authors accomplished the application with HTC Vive VR headset. Independent navigational benefits, convenient hand-held controllers, high resolution display are some facts to prefer HTC Vive. The HMD provides 1080×1200 resolution per eye, and the 9-DOF with 2 lighthouse base stations for tracking. Also the HMD set has two sets of controller. The controller features 24 sensors, dual-stage trigger and multifunction trackpad [20]. The application was implemented using the Unreal Engine 4.14 game engine. Developing with the engine and running the serious game require specific hardware and software requirements. The application run on a PC equipped with a 4.00 GHz Intel i7-6700 processor, 32 GB RAM, and an NVidia GTX 980 graphic card. HTC Vive HMD used for running the project.

2.4 Web Camera Integration

HMD devices can still be considered very new hardware devices for VR. Those devices also have somehow limited ergonomics. During testing period, some difficulties for users such as insecure emotions were observed. Some participants were not satisfied to experience HMD devices. Furthermore they did not want to be isolated from the physical world in some points. The engine provides the features and interfaces needed for camera integration. In order to display actual web-camera in the room where the application is presented for participants, an OpenCV plugin is utilized [21]. The plugin enables to display user physical environment in virtual world. Additionaly this setup of the camera provides more than single camera application for scenarios. Web camera implementation is shown by Fig. 5. That feature will be used for future work. Although the plug-in further takes care of all the HMD-specific tasks such as rendering the viewport separately for each eye, and dealing with the pre-warping of the image [22].

Fig. 5. Real time camera implementation

2.5 Interactions

Human - Machine Interaction (HMI) has always been significant research approaches. Merging interactions in virtual reality, brings different perspective to HMI. In other words, HMI can be obtained to maximize in artificial reality conditions [23]. A sample of HMI in Blueprint design is shown in Fig. 6. The figure presents display structure for CPS [24]. Nevertheless, one of the main attitude of VR development is allow user to interact as much as they desire. It gives them independent movement, thinking and improving themselves with support of VE. Moving in the scene of VR can be operated through HMD controller using teleporting, physicalmovement etc. Users can direct any locations where navigation maps are implemented. The application allows users to manipulate by handles are provided with VR device. Manipulations such as: open and close doors, switch lights, turn on and offf display screens are implemented in two different approaches. Those approaches can be described as self-controlled systems and an automated systems. We aim to allow users to have meaningful CPS experience in VE. We believe that users might have better understanding for CPS. Additionaly it is possible to grab some objects in architecture to interact independently by physics handle component. Furthermore, those interactions grant us to sense self-learning activities in VE. As soon as we complete the process, the application has been tested. The test period was purposed to recognize usability scale of the application and to concrete heuristic evolution for valuable feedback. Received feedbacks are considered to improve the project. Also those feedbacks are used to analyse human behaviours in immersive environment.

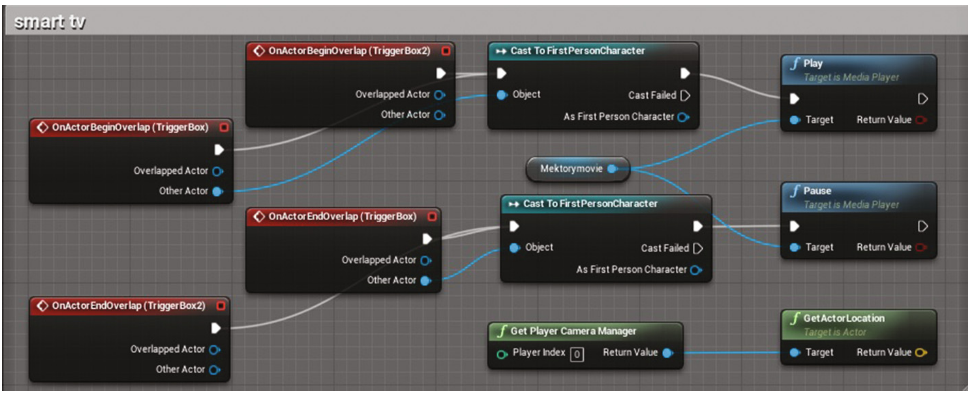

Fig. 6. Blueprint implementation of display located at lobby

2.6 Optimization

Optimization is processed in the last stage synchronously with the testing period. We insert advance details in the architecture like sounds, lights and CPS and artificial intelligence (AI). The editor of the engine allows us to implement three kind of lights: Stationary, Movable and Static. Besides atmospheric light source, particular point lights and spot lights are set up stationary in immersive environment to understand evolution of user experience. Stationary lights are also engaged to the virtual environment where the interactions are not actively applicable. The Blueprints Visual Scripting system in Unreal Engine is a complete gameplay scripting system based on the concept of using a node-based interface to create gameplay elements from within Unreal Editor [25]. The Blueprint system allowed us to create CPS and AI prototypes.

3 Evolution

3.1 Preparation

The VR application is referred to the research and development center of Tallinn University of Technology. The center welcomes numerous international visitors continously. In addition, those visitors often concern to experience VR applications. Hence, we had relevant conditions to demonstrate different cases to evaluate different approaches. Although we collaborate with heterogeneous participants, we preferred to divide participants randomly into two groups. To establish a baseline, first group of participants had excursions inside of the large scale building. The guide directed those participants to accomplish the practice. Subsequently, members of the first group experienced in a virtual replica of the physical environment. Second group of participants repeated the same process backwards. In other words, second group of people had an excursion individually in VE. We navigated participants to complete their virtual excursion then in real world. This allowed us to evaluate differences between VE and the physical architecture. The part of experimental platform is shown by Fig. 7. Furthermore we received relevant outcomes from both groups. We ask seven questions to participants and we expected to receive ranking between 0 to 10 (0 = not agree at all, 10 = completely agree). Questions are shown in Table 1. Finally, we asked them to inform us concerning their preferences in four different segments including AI, CPS, hardware and interactions.

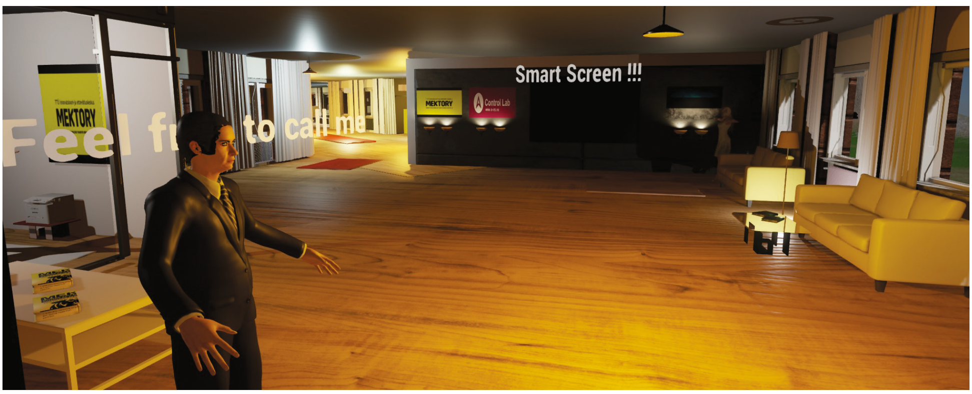

Fig. 7. Evolutionary platform of the architecture

3.2 Results

According to participants, we experienced that there is no major differences between real building and virtual replica. However functionalities of virtual environment is limited considering some participants would like to demonstrate practical life activities such as using coffee machine, ordering a food in cafeteria etc.

Table 1. Questionnaire result. Proportion is referred to average of responses

Questions for participants	First group	Second group
How was your recognition between VE and real world?	6	7
What was difference between VE and real world?	4	3
Do you prefer to experience VE again?	8	9
Do you think physical world can be replicated?	3	5
Could VR be alternated to physical environments?	6	7
Did you enjoy VR experience?	8	9
Are HMD devices are suitable?	6	6

Besides that, major participants claim that experiencing immersive environment is definitely worth it and presence feeling is considerably high. Also they would prefer to run the application in their residences whether the application could integrate another players in real time. They desire to arrange meeting in the application and using functions what can be placed in real life such as voice communication, document presentation, social interaction. Participants have experienced CPS in different cases. We deployed two different cases for CPS. CPS prototypes are self-controlled for first case. In other words, users can control functionalities of components. In second case, CPS components are set due to activities in VE. Major part of participants preferred self-controlled CPS. They claim that self-dependency is crucial point to optimize systems. Analysis of the results for CPS and interactions is shown in Table 2. VE is cost-free environment to recognize whether standard practical solutions are suitable. Density, brightness, lighting color might be changed in order to preferences in VE. Also they would optimize sensibility distance for CPS by deployments in VE. Moreover, users are able to experience optimization segments such as sensors activities, contrast and size for realistic visualization devices. Large amount of participants experienced VE and majority of those people claimed that HTC Vive would be their primarily VR headset. Independent movement in room scale, motion controllers and high degree resolution are some facts for their selection. Besides that some participants mentioned that Oculus Rift DK2 with default controller caused motion sickness. Some researchers also determined statements of motion sickness recently [26,27]. Additionally, the controller for Oculus Rift DK2 is some how limited. Therefore, presence feeling was not applicable for participants. Analysis results for hardware preferences and AI perspective is shown in Table 3. As we thought in the first stage of project, huge portion of participants like to interact actively with objects in their VE. They claim that it definitely would be joyful to learn with VR technology. Moreover, independent and unlimited actions make them feel self-confident. Some of them also claims that interacting with meshes could be helpful for designing creative environment.

Table 2. Hardware and artificial intelligence analysis

	Oculus DK2	HTC Vive		The guide in VE	Real guide
Participants	80	200	Participants	80	200
Preferences	22	155	Preferences	34	186

Table 3. CPS and interactions analysis

	Self control CPS	Automated CPS
Participants	120	200
Preferences	69	117
	Active interactions	Passive interactions
Participants	200	120
Preferences	174	58

4 Conclusion

This paper introduced the fully immersive environment based on the physical architecture. The architecture is named Mektory House is used as a research and development center of Tallinn University of Technology. Then we proposed the process for creating virtual environment. We investigated approaches for maximize immersion level. We also presented integration of several relevant software programs to the physics engine. We created a virtual environment to demonstrate CPS, AI and self learning activities. Nevertheless, entire process of the application was effort more than 800 working hours including evolution stage. Finally, we allow users to experience our approaches. It brought us valuable feedback to recognize expectations. We received relevant outcomes by participants during demonstration. We also compared two VR devices and evoluated them according to participants.

4.1 Future Work

People suffering from severe physical disabilities (paraplegia, amyotrophic lateral sclerosis, etc.) have very limited movement options [28]. We believe that VR might be relevant solution and the application might help those people to experience immersive environment based on physical center of Tallinn University of Technology. Hence, we aim to set up convenient physical platform for those people to experience the VE. We also believe that platform will provide us unique feedback source. Nevertheless, we aim to create relevant integration tools with physical objects locate in the center related to intelligent systems such as logistics, healthcare, avionics etc. Nevertheless, the VE would give possibilities to implement joyful learning approaches adequately.

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Appendix 2

Publication 2

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Real-time Localization and Visualization of a Sound Source for Virtual Reality Applications

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***Abstract*—In this paper, we present our findings related to the problem of localization and visualization of a sound source placed in the same room as the listener. This is a part of a larger research effort devoted to studying the effects of synesthesia—the act of experiencing one sense modality as another, e.g., sound as flashes of colors—in virtual reality. Towards that end, we apply a series of recently developed methods for detecting sound source in a three-dimensional space around the listener. We also apply a Kalman filter to smooth out the perceived motion. Further, we transform the audio signal into a series of visual shapes, such that the size of each shape is determined by the loudness of the sound source, and its color is determined by the dominant spectral component of the sound. The developed prototype is verified in real time. The prototype configuration is described and some initial experimental results are reported and discussed. Some ideas for further development are also presented.**

***Index Terms*—virtual reality, synesthesia, acoustic localization, microphone array, therapy**

I. Introduction

Virtual Reality (VR) provides novel means to visualize and interact with virtual environments including complex visualizations [1], [2]. The advent of low-cost head-mounted display (HMD) devices such as Oculus Rift [3] and HTC Vive [4] made this technology accessible at large, whereas before it was only available to a few specialized laboratories, private companies, and military bodies [5]. Present day advances in VR technology allow to induce a persistent effect of presence in a visual world created using advanced user real-world position and orientation tracking in head-mounted displays (HMDs). Virtual environments, including those already adopted to make use of VR, have proven effective in a number of scientific, industrial and medical applications [6], [7], [8], [9], [10], [11] including but not limited to: underground cave analysis and archaeology, architecture, paleontology, geographic information systems, geosciences, shape perception, physics, organic chemistry, education, MRI and brain tumor analysis, rehabilitation and therapy.

Synesthesia—the act of experiencing one sense modality as another—is an interesting phenomenon that provides many exciting opportunities when applied to VR. For example, some promising results on cross-modal sensory integration in virtual environments were reported in [12]. The ultimate goal of the project, the development of which is documented in this paper, is to provide means for inducing voluntary synesthetic experiences through the VR environment. In our earlier work [13], we have reported initial findings related to acoustic localization and sound processing based on prerecorded data. In this work, we describe the revised technical solution meant to deliver the synesthetic experience to the listener in real time.

We now outline the main contribution of the present paper. First, we apply an acoustic localization method to the problem of locating the sound source. We also apply a Kalman filter to reduce motion noise generated by the uncertainty of sound source location prediction. Next, for consistency, we summarize the method for extracting dominant features from the audio spectrum of the sound source and mapping those to the object representing the sound source in the VR environment [13]. Then, we provide the description of the proposed VR system prototype and the complete experimental configuration and present the novel developments related to the real-time implementation thereof. Finally, we report and analyze the initial findings related to the synesthetic experiences and outline some items for future research.

The structure of the paper is as follows. In Section II the proposed acoustic localization and feature extraction method is described. In Section IV the reader is introduced to the developed real-time VR system prototype. Experimental results are discussed in Section V. Finally, conclusions are drawn in Section VI.

II. Proposed Method for Sound Localization, Processing, and Visualization

In what follows, we outline each stage of the method in a separate subsection.

A. Acoustic Localization

The acoustic data related to the sound source of interest is acquired by an array of spatially distributed audio sensors (microphones). This paper considers a conical configuration of sensors, however, the approach presented below can be applied to other configurations with minimal modifications.

The task of three-dimensional acoustic localization in spherical coordinates lies in estimating the parameters (r, θ, ϕ) of the sound source, where r is the distance to the source, θ is elevation, and ϕ is azimuth. For our VR simulation we assume that r is known, as discussed in Section V, therefore, the task of localization comprises estimation of the Direction of Arrival (DOA) consisting of angles ϕ and θ. For DOA estimation we apply the Steered Response Power with Phase Transform (SRP-PHAT) method, which is highly robust and tolerant to reverberation [14].

The SRP $P(\boldsymbol{a})$ is a real-valued functional of a spatial vector $\boldsymbol{a}$, which is defined by the Field of View (FOV) of a specific array. The maxima of $P(\boldsymbol{a})$ indicate the direction to the sound source. $P(\boldsymbol{a})$ is computed as the cumulative Generalized Cross-Correlation with Phase Transform (GCC-PHAT) across all pairs of sensors at the theoretical time delays, associated with the chosen direction. Consider a pair of signals $x_k(t)$, $x_l(t)$ of an array consisting of M microphones. The time instances of sound arrival from some point $a \in \boldsymbol{a}$ for the two microphones are $\tau(a,k)$ and $\tau(a,l)$, respectively. Hence the time delay between the signals is $\tau_{kl}(a) = \tau(a,k) - \tau(a,l)$. The SRP-PHAT for all pairs of signals is then defined as

$$P(a) = \sum_{k=1}^{M} \sum_{l=k+1}^{M} \int_{-\infty}^{\infty} \Psi_{kl}(\beta) X_k(\omega) X_l^*(\omega) \mathrm{e}^{j\omega\tau_{kl}(a)} \mathrm{d}\omega, \tag{1}$$

where $X_i(\omega)$ is the spectrum (i.e., the Fourier Transform) of signal $x_i(t)$, $X_i^*(\omega)$ is the conjugate of that spectrum and $\Psi_{kl}(\beta)$ is the β-PHAT weight, defined as

$$\Psi_{kl}(\beta) = \left(|X_k(\omega) X_l^*(\omega)|\right)^{-\beta}. \tag{2}$$

The PHAT is used for eliminating reverberation effects, though, it can over-sharpen the SRP. Applying the more flexible β-PHAT weight allows to adjust to specific reverberation levels. We use the coefficient $\beta = 0.8$ in our experiments.

Though SRP-PHAT is effective and robust, it requires significant amounts of computational power if computed in the frequency domain and applied to large spatial vectors $\boldsymbol{a}$. In order to be able to compute the SRP in real-time, we calculate the GCC in the time domain using an integer delay step beamformer and also reduce the spatial vector. To reduce vector $\boldsymbol{a}$, it is proposed to perform horizontal and vertical DOA estimation separately. In this manner the horizontal plane is divided into n_h and the vertical plane — into n_v possible discrete angles, respectively. The points are chosen in the volumetric FOV along a spherical surface with radius r_{FOV}. The horizontal evaluation is performed along a circumference of a half circle, which covers the front FOV of the array, i.e., in the angle interval of $[0, \pi]$. The discrete angle step is calculated as $\phi_h = \frac{\pi}{n_h}$. The horizontal evaluation is performed for the points $a_h(i) = (x_h(i), y_h(i), 0)$:

$$\begin{aligned} x_h(i) &= r_{FOV} \cos(i\phi_h), \quad (0 \le i \le n_h), \\ y_h(i) &= r_{FOV} \sin(i\phi_h), \quad (0 \le i \le n_h). \end{aligned} \tag{3}$$

The azimuth ϕ is estimated in the directions of elevated SRP values. For a single source case it is equal to

$$\phi = \arg\max\left(P(\boldsymbol{a}_h)\right) \cdot \phi_h. \tag{4}$$

After obtaining ϕ, the vertical SRP-PHAT evaluation is performed over the vertical half-circumference from the positive z-axis downward, i.e. $[0, \pi]$, with a discrete angle step of $\theta_v = \frac{\pi}{n_v}$, in the direction of established azimuth ϕ for the points $a_v(i) = (x_v(i), y_v(i), z_v(i))$:

$$\begin{aligned} x_v(i) &= r_{FOV} \cos(\phi) \sin(i\theta_v), \quad (0 \le i \le n_v), \\ y_v(i) &= r_{FOV} \sin(\phi) \sin(i\theta_v), \quad (0 \le i \le n_v), \\ z_v(i) &= r_{FOV} \cos(i\theta_v), \quad (0 \le i \le n_v). \end{aligned} \tag{5}$$

The elevation angle is estimated in the direction of elevated SRP, and also brought to a more comprehensive interval $\left[\frac{\pi}{2}, -\frac{\pi}{2}\right]$ from the positive z-axis downward:

$$\theta = \frac{\pi}{2} - \arg\max\left(P(\boldsymbol{a}_v)\right) \cdot \theta_v. \tag{6}$$

In our experiments a single degree angle resolution is chosen for both azimuth and elevation, therefore, parameters are set as $n_h = 180$, $n_v = 180$; the radius is set to $r_{FOV} = 0.5$ m.

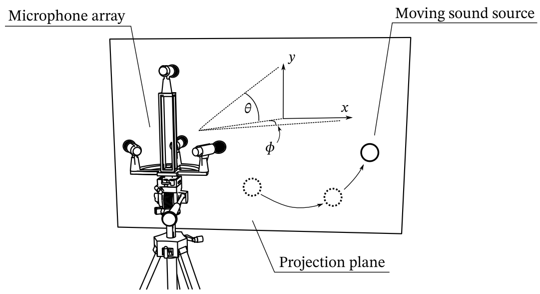

Fig. 1. Localization principle: The sound source is assumed to be moving in a plane

B. Kalman Filter for Motion Tracking

The discrete time Kalman filter (KF) is a linear quadratic estimator [15], which provides the closed form recursive solution for a linear discrete-time dynamic system of the form:

$$\begin{aligned} \mathbf{x}_k &= \mathbf{A}_{k-1}\mathbf{x}_{k-1} + \mathbf{q}_{k-1} \\ \mathbf{y}_k &= \mathbf{H}_{k-1}\mathbf{x}_k + \mathbf{r}_{k-1} \end{aligned}, \tag{7}$$

where $\mathbf{x}_k$ is the system state vector at time step k, $\mathbf{y}_k$ is the measurement vector at k, $\mathbf{A}_{k-1}$ is the transition matrix of the dynamic model, $\mathbf{H}_{k-1}$ is the measurement matrix, $\mathbf{q}_{k-1} \sim \mathrm{N}(0, \mathbf{Q}_{k-1})$ is the process noise with covariance $\mathbf{Q}_{k-1}$ and $\mathbf{r}_{k-1} \sim \mathrm{N}(0, \mathbf{R}_{k-1})$ is the measurement noise with covariance $\mathbf{R}_{k-1}$. Kalman filtering consists of a prediction step, where the next state of the system is predicted given the previous measurements, and an update step, where the current state is estimated given the measurement at that time instance. The prediction step is characterized by the following equations:

$$\begin{aligned} \hat{\mathbf{x}}_k^- &= \mathbf{A}_{k-1}\hat{\mathbf{x}}_{k-1} \\ \mathbf{P}_k^- &= \mathbf{A}_{k-1}\mathbf{P}_k\mathbf{A}_{k-1}^T + \mathbf{Q}_{k-1} \end{aligned}, \tag{8}$$

where $\hat{\mathbf{x}}_k^-$ and $\mathbf{P}_k^-$ are the system *a priori* (i.e., before observing the measurement at time k) state and covariance estimates, and $\hat{\mathbf{x}}_k$, $\mathbf{P}_k$ are *a posteriori* (i.e., after observing the measurement) estimates. The update step is performed as:

$$\begin{array}{c} \mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}_k^T \left(\mathbf{H}_k \mathbf{P}_k^- \mathbf{H}_k^T + \mathbf{R}_k \right)^{-1} \\ \hat{\mathbf{x}}_k = \hat{\mathbf{x}}_k^- + \mathbf{K}_k \left(\mathbf{y}_k - \mathbf{H}_k \hat{\mathbf{x}}_k^- \right) \\ \mathbf{P}_k = \left(\mathbf{I} - \mathbf{K}_k \mathbf{H}_k \right) \mathbf{P}_k^- \end{array}, \quad (9)$$

where $\mathbf{K}_k$ is the Kalman gain of prediction correction at time instance k. KF is optimal for a linear system with Gaussian measurement and process noise [15], [16], which applies to our situation.

Acoustic object movement is described as a discrete Wiener process velocity model [17] with the state vector defined as $\mathbf{x}_k = \begin{bmatrix} x_k & y_k & \dot{x}_k & \dot{y}_k \end{bmatrix}^T$, where (x_k, y_k) denotes object position and $(\dot{x}_k, \dot{y}_k)$ — the velocity in a two-dimensional Cartesian space. The transition and measurement matrices for model (7) are then defined as:

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \quad (10)$$

where Δt is the time interval between consecutive estimates in seconds. The process and measurement noise variance is specified by matrices

$$\mathbf{Q} = \begin{bmatrix} \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 & 0 \\ 0 & \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 \\ \frac{1}{2}\Delta t^2 & 0 & \Delta t & 0 \\ 0 & \frac{1}{2}\Delta t^2 & 0 & \Delta t \end{bmatrix} q,$$

$$\mathbf{R} = \operatorname{diag}(r_1, r_2), \quad (11)$$

where q and r_k are the power spectral densities of process and measurement noise, respectively. For our conditions the parameters are set as $\Delta t = 0.1$ s, $q = \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix}^T$, $r_1 = 0.1$, $r_2 = 0.3$.

C. Acoustic Feature Extraction and Mapping

Mel-Frequency Cepstral Coefficients (MFCC) is a popular method for extracting features from an audio signal and is used in speech detection and recognition. An interesting property of this approach is that it is based on psychophysical studies that reveal that human perception of the sound frequency contents for speech signals does not follow a linear scale [18]. A Mel scale is used instead:

$$f_m = 2595 \log_{10} \left(1 + \frac{f}{700} \right),$$

where f_m is the subjective pitch in Mel units corresponding to a frequency f in Hz. Thus, applying this method can be beneficial in improving the interplay of sound and visual excitation in a psychophysically coherent way. Moreover, studies also show that MFCC can also be applied to modeling music [19] which can also be advantageous in enhancing the experience of synesthesia. The computation of the MFCC comprises the following steps [19]. Starting from a waveform:

1) Convert waveform to frames;
2) Take Discrete Fourier Transform (DFT);
3) Take Log of amplitude spectrum;
4) Apply Mel-scaling and smoothing;
5) Apply Discrete Cosine Transform (DCT).

Once the procedure is complete, MFCC features are obtained. In this work, we consider the auditory spectrum portion of the features, hereinafter denoted as A_{spec}. To produce the visualization, the acoustic features of the sound source must be examined. At the moment, a simple approach is employed, such that the incoming sound waves are visualized as spheres moving towards the listener. The color, size, velocity of travel, and sampling rate for generating the spheres can be determined experimentally. The incoming waveforms are broken down into frames and analyzed as discussed previously. Currently, the following mappings are in effect:

- The size of a single sphere is determined by the scaled maximum amplitude of the sampled waveform in the frame;
- The color of the sphere is determined by the dominant feature in A_{spec} obtained by applying the MFCC approach. A transform is thus defined as $\xi : \mathscr{I} \to \mathscr{C}$, where $\mathscr{I} \subset \mathbb{N}$ is the index of the dominant feature in A_{spec}, and $\mathscr{C} \subset \mathbb{R}^3$ is the color specification in a particular color space. For this work, we consider the Red-Green-Blue (RGB) color space.

The signal processing described above is completely done in MATLAB environment and sent to the visualization engine for further processing.

III. Real-Time Application to a Virtual Reality Environment

The virtual environment is used for multiple purposes such as bridging Cyber-Physical Systems (CPS) to VR interface, self-learning activities, physiological and psychological aspects of virtual reality. Although the environment is unique and subsections are slightly relevant, the process for creating the virtual environment is familiar with related researches. The process is as follows:

(a) Environmental Creation and System Design,
(b) Modeling and Texturing,
(c) Materials and Hardware Integration,
(d) Software Integration,
(e) Optimization.

Unreal Engine 4 is chosen to create the virtual environment as the engine is the one of most known and used physics engine. High efficiency for VR applications, compatibility and does not require high maintenance cost could be considered as some of prior advantages for the preferred pyhsics engine. Furthermore, Unreal Engine meets beneficial expectations like other common game engines. The concept of object oriented programming, process of computer generated graphics, reusable code with libraries might be main benefits of using primary game engines [20]. Those benefits are also used to create communication tool between software linked to the project.

Regardless, successful immersive applications based on realistic environment minimize difference between physical reality and VR. Hence, we considered to create virtual environment based on physical conditions significantly. Additionally, floor plan of laboratory is used for accurate virtual environment based on physical assets. Those assets has been rendered and 3D modeled by using Autodesk Maya3D animation, modeling, simulation, and rendering software [21]. 3D models of physical assets located at laboratory were developed using polygon shape and modified using functions such as extrudes, append etc. The physics engine can respectfully identify the material components and map file (Textures) with FBX file format. Fundamental parts such as walls, columns etc. are inserted in physics engine according to suggested scale compatibility of physics engine (1 unreal unit is equal to 1 cm) [22]. The chosen engine allows to create realistic environments and simulate realistic affects. Hence users can feel lifelike interaction during experiencing the application. Moreover, teleportation feature of VR technology is implemented for the application. That feature allows users to move independently and effortless in computer simulated realistic laboratory during experiencing synesthesia effect. Furthermore, independent movement may also grant us to sense self-learning activities in VE. The user can still ascertain sound source localization during continuous movements. The principle logic of the application is referred to predefined VR class of the engine: Motion Controller Pawn, HUD, VR GameMode, Player Controller. The Blueprints Visual Scripting system in Unreal Engine is a complete gameplay scripting system based on the concept of using a node-based interface to create gameplay elements from within Unreal Editor [23].

The Blueprint system allowed us to create a UDP interface [24] to communicate between MATLAB and the physics engine based on a custom C++ class. To avoid problems with Blueprint multithreading in Unreal Engine 4, the implementation uses a custom class variable to transfer data between threads to avoid a racing condition in requesting/getting new data from the UDP socket. With this approach, reliable communication via a UDP socket at high sampling rates such as f_s=1kHz is easily achieved.

The complete visualization thus comprises the following components:

- A C++ class based UDP socket implementation available to the UE4 Blueprint scripting system;
- All necessary animations are scripted in UE4 Blueprints and are based on the information received via the UDP socket from MATLAB software;
- The room where the prototype is located is recreated as a Virtual Reality environment.

Since HTC Vive is used, the corresponding UE4 VR template is employed and thus the user can navigate the VR room. The main idea here is to synchronize the user real-world location and that in the VR environment.

IV. Experimental Setup

The proposed prototype comprises several components: a microphone array with four Behringer C2 microphones, an USB audio card—Focusrite Scarlett 18i20 Gen 2—for sound data acquisition, a personal computer running MATLAB/Simulink environment and the VR sound visualizer, the HMD device—HTC Vive, and the emulated sound source represented by a Creative T15 Bluetooth speaker. The user wearing the HMD device and the microphone array are assumed to be stationary. The distance between the user and the conical array is constant and the corresponding VR environment position offset may be computed and applied within the VR room scale. The complete prototype configuration is depicted in Fig. 2.

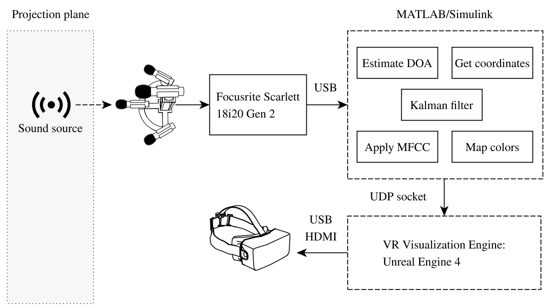

Fig. 2. Experimental configuration and signal flow

We use MATLAB software due to the availability of necessary toolboxes for real-time data acquisition and processing. We have previously successfully used MATLAB/Simulink for rapid prototyping of computationally intensive real-time control algorithms [25]. Once the data is processed within MATLAB, the necessary information (spatial coordinates of the sphere, its size and color) are sent via a socket connection in real time to the visualizer application that drives the HMD.

Developing with the engine and running the serious game and MATLAB software at once prompts the use of specific hardware and software requirements. The applications run on a PC equipped with a 3.20GHz Intel i5-4570 processor, 8GB RAM, and an NVidia GTX 980 graphic card driving the HTC Vive HMD.

V. Experimental Results

For initial verification of the designed prototype we consider two types of experiments. First, we observe how well the acoustic tracking part works. Second, we verify the real-time VR application. In both cases, the distance from the sound source to the microphone array is $r = 1.5$m. An audio clip with modern music is used as audio such that has no distinct spectral features. The real-life experimental layout is shown in Fig. 3.

For the first experiment, the sound source, represented by the speaker, is moved in a rectangular motion in the projection

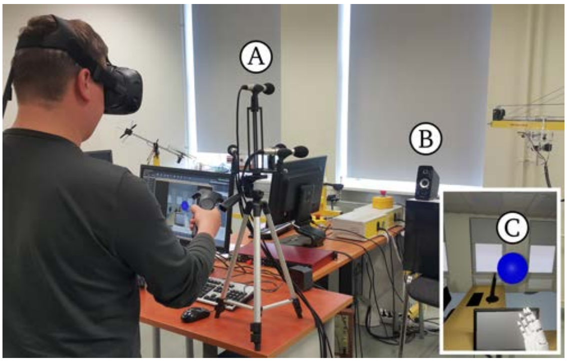

Fig. 3. Experimental real-time prototype setup. Elements on image: A—Microphone array; B—Emulated sound source (Bluetooth speaker); C—Spherical visualization as it appears in the recreated room VR environment

plane for 100 seconds. The sampling rate is 10Hz. The resulting scaled circles with colors obtained using the procedure described above as well as corresponding trajectories are shown in Fig. 4. It can be seen that although the manually delivered sound source motion trajectory is approximately rectangular, the location is oftentimes misclassified in the vertical direction which results in erroneous upward and downward motions. For this reason horizontal movement cannot be easily read back from this figure. However, the motion is smooth due to the additional Kalman filtering step. The larger circles represent a louder section of the audio clip in the lower frequency range. Yellow circles represent features in the higher frequency range.

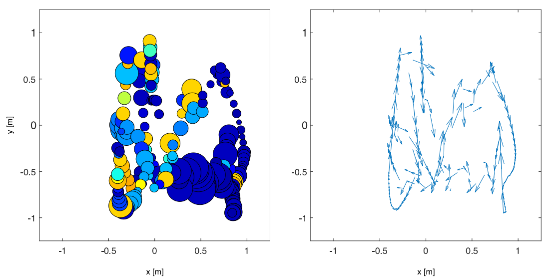

Fig. 4. Features and spatial dynamics of the emulated sound source captured during a real-time experiment

The second experiment was concerned with initial impressions from using the prototype in VR. The following observations can be made:

- When two people are talking in to each other in the room, the sphere correctly identifies the speaker location. While plain speech does not by itself give rise to special features, a sharp difference in color can be observed when the "s" sound is produced.
- The current implementation introduces a noticeable delay of about 500ms. This is distracting, though does not break the effect of immersion.
- Colors produced by playing simple musical instruments fall inside an almost indistinguishable color spectrum (shades of blue, since jet is used).
- The overall effect seems interesting, however, as mentioned above certain technical limitations have to be overcome before further investigation with a control group is conducted.

In what follows, several ideas related to the improvement of the proposed solution are provided:

- A graphical user interface for selecting various parameters of the sound processing algorithm should be implemented for convenience. Most importantly, color mapping should be made easily selectable. Furthermore, since we know that Mel's scale is nonlinear, the color mapping may also follow a nonlinear scale to improve color variation in the visualization.
- The errors in vertical localization are not as significant for initial subject-based tests because in general a sound emitter remains at the same height. However, to improve vertical localization, we currently consider the possibility to add one microphone to the array and arrange all microphones in a symmetric way.
- Depth (third coordinate) detection should be available. To achieve this, it is possible to place HTC Vive standalone trackers directly on the sound source. This can be used for initial experiments as well as calibration of the developed hardware prototype.
- Finally, once the technical limitations are overcome, we shall proceed with the assembly of the control group and do subject based testing. Towards that end, subjects who experience synesthesia naturally should be interviewed, their responses documented and analyzed and corresponding color mapping methods implemented in the prototype. An ethics committee approval should be sought beforehand.

We have repeated the first experiment to verify some of the proposals above. For this, we quickly added one more microphone in-between the two vertical microphones in the array. Furthermore, we have revised the implementation of the acoustic localization algorithm such that instead of directly using Eq. (5), we adopted a similar approach as in Eq. (3). This means that we skip information about the horizontal location and use only the three vertical microphones to determine the vertical location. The resulting trajectory is depicted in Fig. 5. It can be seen that a significant improvement in accuracy of acoustic localization is achieved.

VI. Conclusions

In this work, we have described a prototype for acoustic sound localization, processing, and visualization for the purpose of inducing a synesthetic experience in a VR environment. The proposed prototype and corresponding methods have been described. In this contribution, the real-time solution was implemented in a VR environment. Initial experiments are partially successful. Although vertical localization has issues,

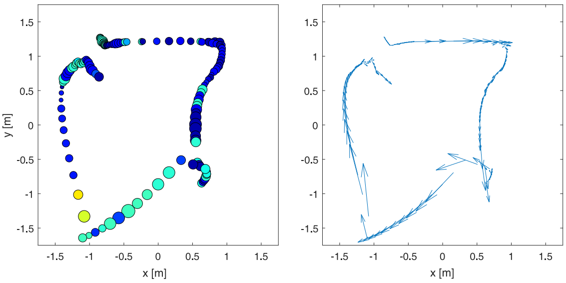

Fig. 5. Features and spatial dynamics of the emulated sound source captured during a real-time experiment with an improved configuration

this does not necessarily affect immersion in the VR environment, although for accurate tracking this must definitely be improved. This can be solved by further tuning the software algorithms, one more possibility is considering a different microphone array shape and adding more microphones—with the current data acquisition solution we can use up to 8 microphones. Kalman filter smooths out the motion and improves the experience. The developed application can be used in subject based testing following an ethics committee approval. Since the prospective application is envisioned to be used for real-life medical and artistic application, further development efforts must also be exhibited towards an embedded system prototype. Finally, multiple sound source localization should also be considered.

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Appendix 3

Publication 3

A. Köse, A. Tepljakov, S. Astapov, D. Draheim, E. Petlenkov, K. Vassiljeva. Towards a synesthesia laboratory: Real-time Localization and Visualization of a Sound Source for Virtual Reality Applications. *Journal of Communications Software and Systems*, vol 14, pages 112–120, 2018.

Towards a Synesthesia Laboratory: Real-time Localization and Visualization of a Sound Source for Virtual Reality Applications

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***Abstract*—In this paper, we present our findings related to the problem of localization and visualization of a sound source placed in the same room as the listener. The particular effect that we aim to investigate is called synesthesia—the act of experiencing one sense modality as another, e.g., a person may vividly experience flashes of colors when listening to a series of sounds. Towards that end, we apply a series of recently developed methods for detecting sound source in a three-dimensional space around the listener. We also apply a Kalman filter to smooth out the perceived motion. Further, we transform the audio signal into a series of visual shapes, such that the size of each shape is determined by the loudness of the sound source, and its color is determined by the dominant spectral component of the sound. The developed prototype is verified in real time. The prototype configuration is described and some initial experimental results are reported and discussed. Some ideas for further development are also presented.**

***Index Terms*—virtual reality, synesthesia, acoustic localization, microphone array, therapy**

I. Introduction

VIRTUAL Reality (VR) provides novel means to visualize and interact with virtual environments including complex visualizations [1], [2]. The advent of low-cost head-mounted display (HMD) devices such as Oculus Rift [3] and HTC Vive [4] made this technology accessible at large, whereas before it was only available to a few specialized laboratories, private companies, and military bodies [5]. Present day advances in VR technology allow to induce a persistent effect of presence in a visual world created using advanced user real-world position and orientation tracking in head-mounted displays (HMDs). Virtual environments, including those already adopted to make use of VR, have proven effective in a number of scientific, industrial and medical applications [6], [7], [8], [9], [10], [11] including but not limited to: underground cave analysis and archaeology, architecture, paleontology, geographic information systems, geosciences, shape perception, physics, organic chemistry, education, MRI and brain tumor analysis, rehabilitation and therapy. Besides that, VR applications also aim to alleviate obstacles of physical environments, particularly for education purposes. Assuring quality of practice in facilities has become rather difficult problem with correlation between complexity of equipment and its cost. Moreover, the substantial increase in the number of students enforces the limited capacity of facilities. Facing inconvenient conditions have convinced researchers to employ meaningful replicated tools in virtual environments. They have also accomplished several real-time VR applications to avoid if not relief continuous difficulties to engage students with experiments adequately [12], [13], [14], [15].

Synesthesia—the act of experiencing one sense modality as another—is an interesting phenomenon that provides many exciting opportunities when applied to VR. For example, some promising results on cross-modal sensory integration in virtual environments were reported in [16]. The ultimate goal of the project, the development of which is documented in this paper, is to provide means for inducing voluntary synesthetic experiences through the VR environment. In our earlier work [17], we have reported initial findings related to acoustic localization and sound processing based on prerecorded data. In this work, we describe the revised technical solution meant to deliver the synesthetic experience to the listener in real time.

We now outline the main contribution of the present paper. First, we provide a firm motivation for a full-scale synesthesia laboratory to be developed during the course of related research activities—this largely complements the contribution described in [18]. Then, we describe the first technological contribution towards the development of such a laboratory. Namely, we investigate the application of an acoustic localization method to the problem of locating the sound source in a room. We also apply a Kalman filter to reduce motion noise generated by the uncertainty of sound source location prediction. Next, for consistency, we summarize the method for extracting dominant features from the audio spectrum of the sound source and mapping those to the object representing the sound source in the VR environment [17]. Then, we provide the description of the proposed VR system prototype and the complete experimental configuration and present the novel developments related to the real-time implementation thereof. Finally, we report and analyze the initial findings related to the synesthetic experiences and outline some items for future research.

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The structure of the paper is as follows. Section II is dedicated to outline of general concept of the Synesthesia Laboratory for initial experiments. In Section III the proposed acoustic localization and feature extraction method is described. The creation of VR environment is explained and data communication is pointed out in Section IV. In Section V the reader is introduced to the developed real-time VR system prototype. Experimental results are discussed in Section VI. Finally, conclusions are drawn in Section VII.

II. Towards a Synesthesia Laboratory

A. Sense Swapping

The current achievement of turning 3D sound occurrences into 3D visual signals represents a step of a larger programme. The ideal target is the ability to completely swap senses, i.e., turning all audio signals that can be heard by an individual human being, from arbitrarily many sources into video signals and, vice versa, turning everything that can be seen by a person into a sound carpet. Given a preset sound-to-light mapping: how would Gustav Mahler's 2nd symphony look like [19]? We consider the ideal concept of *sense swapping* as a research challenge to drive the development of increasingly better tools in sense-crossing and sense-mapping. In particular, if integrated into augmented reality scenarios, real-life applications for such technologies can be found immediately in numerous domains: from architecture over education, supportive technology for the elderly and people with special needs, therapy and rehabilitation, to rescue systems and all kinds of mission-control systems. Furthermore, and this is particularly important for us, we see such technologies as enabling technologies for foundational research in synesthesia, as we will argue in due course in Sects II-B and II-C.

B. The Synesthesia Laboratory and Knowledge Base

In a broad sense synesthesia [20], [21] is about merging different senses' stimuli. The concrete meaning of synesthesia is usually said to be the experience of a so-called cross-modal sense perception, i.e., the experience that a stimulus triggers a perception with regard to a sense different from the one that it usually belongs to. People that regularly or intensively experience synesthesia are called synesthetes, compare with Fig 1 that shows how synesthete Alexander László perceives certain chords as colors if played on a piano.

When does a person start to be a synesthete? This question is hard to answer. Actually, due to lack of a joint reference framework, it is impossible to decide this question. For example, we can test whether a person has the perfect pitch, but we do not know how to test whether he or she is a synesthete. Such considerations will lead us to a discussion of the theoretical foundations of synesthesia later in Sect. II-C. For the moment, it is important to see that all people experience synesthesia to a certain degree at some level. We all know that we would associate some *music* pieces with a warm *temperature* and with an orange or red *color*, whereas we would judge other music as cold and maybe green or blue. It is that day-to-day form of synesthesia that makes the concept so relevant. We have seen massive efforts in synesthesia throughout the ages,

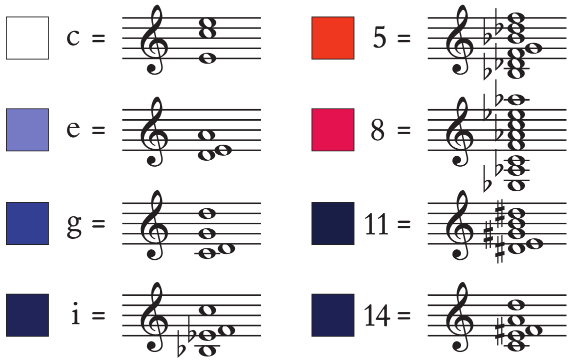

Fig. 1. How synesthete Alexander László perceives certain chords if played on piano, compare with Fig. 18 in 'Die Farblichtmusik' [22].

ranging from the holistic design of the medieval cathedrals to the different forms of multimedia in contemporary pop music.

To explain the relevance and importance of synesthesia let us discuss the Weimarer Bauhaus. It was the Bauhaus that aimed at the renaissance of the cathedrale's Bauhütte. Here, the Bauhaus vision was a holistic approach to architecture, painting, and sculpture in service of the *complete building* [23]. However, a different viewpoint on the Bauhütte is possible, i.e., as (i) an even more holistic approach to all fine arts, including music[1], that is (ii) not in service of the complete building, but in service of the *synesthetic experience*, i.e., the cathedral can also be considered a music instrument—*form ever follows function* [25].

In practice and also in research synesthesia is often used, rather loosely, to refer also to the design of synesthetic scenarios, i.e., to refer to multimedia design efforts. This does not harm, but in order to explain our vision of the synesthesia laboratory better, it is helpful to delve into the differences. If we want to approach terminology accurately, synesthesia stands for cross-modal perceptions. In our endeavors, we also want to use it for cross-modal associations, which applies to more people and is at the same time less contradictory. Multimedia design efforts, or just multimedia for short, are intentional multi-modal compositions – the different simultaneous channels mutually support each other, created harmonies, as well as tensions between them are in service of a holistic experience.

Given its relevance, synesthesia has been subject of investigation from different perspective, including music theory, psychology, and neurology [21], [26]. Consequently, music in virtual reality forms a quickly emerging field with a plethora of exciting projects [27]. Also, we see first endeavors in systematic reasarch on cross-modality in virtual environments, e.g., [28], [16].

Artists and multimedia designers rely on artistic inspiration to create multimedia art [29], [19], [30]. Here is where our vision of a *synesthesia laboratory* enters the scene. The vision might be best described as a *synesthesia experience*

[1] Note that architecture, painting, and sculpture are incorrectly translated as fine arts in the English version of the Bauhaus Manifesto [24]

factory. It is about creating and providing leading-edge tools for the systematic generation, comparison and assessment of cross-modal experiences involving virtual reality. It aims at foundational insights in cross-modal experience, building, step-by-step, a *synesthesia knowledge base*. As an example, consider case no. 5 in Fig. 1. It tells of that Alexander László perceives the chord B♭m7 as an orange color. Does the color change if the chord is played on a guitar rather than a piano? What is the color if the notes of the chord are not played simultaneously but one by one? With appropriate tools we can start experimenting. Which kind of sound-to-color mapping do we like best for a melody floating through a 3D virtual world? Which sound-to-color mapping fits best to visualization of a whole symphony orchestra, a choir or a Jazz band. The single individual can experiment, but from there we could start seeking for group-specific synesthesia or asking whether there exist anthropological constants. Is Alexander László the only one, who perceives B♭m7 as an orange color or is that rather the rule? Perceive people with different cultural background, age, gender the chord differently?

The vision of a *synesthesia laboratory* is crucial building block of the encompassing Re:creation Virtual and Augmented Reality laboratory [31] vision, compare with [32].

C. Monad Theoretical Foundation

An original trigger for *swapping senses* has been the Leibniz anniversary year 2016. The intention is to create a living metaphor for Leibniz' monad theory [33], [34], primarily for its cognitive aspects that are concerned with *communication and perception* and not so much for its meta-physic conclusion that are about the concept of *pre-stabilized harmony* [35]. For this purpose, the concrete way how senses are mapped to each other is not important. What is important is the fact that the senses are exchanged at all. Crucial and at the same time a challenge is that all information is conserved by concrete exchanges. In Leibniz' theory monads are the smallest building blocks of mind. Monads interact only via their senses. Opinions about impressions are just learned. They are just negotiated between individuals. Actually, it turns out that it even makes no sense to ask how others materialize sensual impressions in their mind, because of the lack of a joint reference framework. We believe that the experience of exchanged senses can serve as a great didactical device to help understanding the cognitive part of monad theory.

III. Proposed Method for Sound Localization, Processing, and Visualization

In what follows, we outline each stage of the method in a separate subsection.

A. Acoustic Localization

The acoustic data related to the sound source of interest is acquired by an array of spatially distributed audio sensors (microphones). This paper considers a conical configuration of sensors, however, the approach presented below can be applied to other configurations with minimal modifications.

The task of three-dimensional acoustic localization in spherical coordinates lies in estimating the parameters (r, θ, ϕ) of the sound source, where r is the distance to the source, θ is elevation, and ϕ is azimuth. For our VR simulation we assume that r is known, as discussed in Section VI, therefore, the task of localization comprises estimation of the Direction of Arrival (DOA) consisting of angles ϕ and θ. For DOA estimation we apply the Steered Response Power with Phase Transform (SRP-PHAT) method, which is highly robust and tolerant to reverberation [36].

The SRP $P(\boldsymbol{a})$ is a real-valued functional of a spatial vector $\boldsymbol{a}$, which is defined by the Field of View (FOV) of a specific array. The maxima of $P(\boldsymbol{a})$ indicate the direction to the sound source. $P(\boldsymbol{a})$ is computed as the cumulative Generalized Cross-Correlation with Phase Transform (GCC-PHAT) across all pairs of sensors at the theoretical time delays, associated with the chosen direction. Consider a pair of signals $x_k(t)$, $x_l(t)$ of an array consisting of M microphones. The time instances of sound arrival from some point $a \in \boldsymbol{a}$ for the two microphones are $\tau(a,k)$ and $\tau(a,l)$, respectively. Hence the time delay between the signals is $\tau_{kl}(a) = \tau(a,k) - \tau(a,l)$. The SRP-PHAT for all pairs of signals is then defined as

$$P(a) = \sum_{k=1}^{M} \sum_{l=k+1}^{M} \int_{-\infty}^{\infty} \Psi_{kl}(\beta) X_k(\omega) X_l^*(\omega) \mathrm{e}^{j\omega\tau_{kl}(a)} \mathrm{d}\omega, \tag{1}$$

where $X_i(\omega)$ is the spectrum (i.e., the Fourier Transform) of signal $x_i(t)$, $X_i^*(\omega)$ is the conjugate of that spectrum and $\Psi_{kl}(\beta)$ is the β-PHAT weight, defined as

$$\Psi_{kl}(\beta) = \left(|X_k(\omega) X_l^*(\omega)|\right)^{-\beta}. \tag{2}$$

The PHAT is used for eliminating reverberation effects, though, it can over-sharpen the SRP. Applying the more flexible β-PHAT weight allows to adjust to specific reverberation levels. We use the coefficient $\beta = 0.8$ in our experiments.

Though SRP-PHAT is effective and robust, it requires significant amounts of computational power if computed in the frequency domain and applied to large spatial vectors $\boldsymbol{a}$. In order to be able to compute the SRP in real-time, we calculate the GCC in the time domain using an integer delay step beamformer and also reduce the spatial vector. To reduce vector $\boldsymbol{a}$, it is proposed to perform horizontal and vertical DOA estimation separately. In this manner the horizontal plane is divided into n_h and the vertical plane—into n_v possible discrete angles, respectively. The points are chosen in the volumetric FOV along a spherical surface with radius r_{FOV}. The horizontal evaluation is performed along a circumference of a half circle, which covers the front FOV of the array, i.e., in the angle interval of $[0, \pi]$. The discrete angle step is calculated as $\phi_h = \frac{\pi}{n_h}$. The horizontal evaluation is performed for the points $a_h(i) = (x_h(i), y_h(i), 0)$:

$$\begin{aligned} x_h(i) &= r_{FOV} \cos(i\phi_h), \quad (0 \le i \le n_h), \\ y_h(i) &= r_{FOV} \sin(i\phi_h), \quad (0 \le i \le n_h). \end{aligned} \tag{3}$$

The azimuth ϕ is estimated in the directions of elevated SRP values. For a single source case it is equal to

$$\phi = \arg\max\left(P(\boldsymbol{a}_h)\right) \cdot \phi_h. \tag{4}$$

After obtaining ϕ, the vertical SRP-PHAT evaluation is performed over the vertical half-circumference from the positive z-axis downward, i.e. $[0, \pi]$, with a discrete angle step of $\theta_v = \frac{\pi}{n_v}$, in the direction of established azimuth ϕ for the points $a_v(i) = (x_v(i), y_v(i), z_v(i))$:

$$\begin{aligned} x_v(i) &= r_{FOV}\cos(\phi)\sin(i\theta_v), \quad (0 \le i \le n_v), \\ y_v(i) &= r_{FOV}\sin(\phi)\sin(i\theta_v), \quad (0 \le i \le n_v), \\ z_v(i) &= r_{FOV}\cos(i\theta_v), \qquad (0 \le i \le n_v). \end{aligned} \tag{5}$$

The elevation angle is estimated in the direction of elevated SRP, and also brought to a more comprehensive interval $\left[\frac{\pi}{2}, -\frac{\pi}{2}\right]$ from the positive z-axis downward:

$$\theta = \frac{\pi}{2} - \arg\max\left(P(\boldsymbol{a}_v)\right)\cdot\theta_v. \tag{6}$$

In our experiments a single degree angle resolution is chosen for both azimuth and elevation, therefore, parameters are set as $n_h = 180$, $n_v = 180$; the radius is set to $r_{FOV} = 0.5$ m.

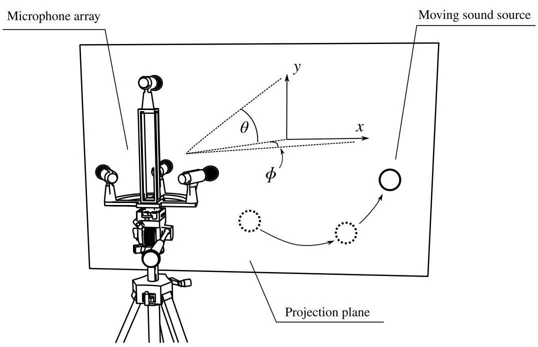

Fig. 2. Localization principle: The sound source is assumed to be moving in a plane

B. Kalman Filter for Motion Tracking

The discrete time Kalman filter (KF) is a linear quadratic estimator [37], which provides the closed form recursive solution for a linear discrete-time dynamic system of the form:

$$\begin{aligned} \mathbf{x}_k &= \mathbf{A}_{k-1}\mathbf{x}_{k-1} + \mathbf{q}_{k-1} \\ \mathbf{y}_k &= \mathbf{H}_{k-1}\mathbf{x}_k + \mathbf{r}_{k-1} \end{aligned}, \tag{7}$$

where $\mathbf{x}_k$ is the system state vector at time step k, $\mathbf{y}_k$ is the measurement vector at k, $\mathbf{A}_{k-1}$ is the transition matrix of the dynamic model, $\mathbf{H}_{k-1}$ is the measurement matrix, $\mathbf{q}_{k-1} \sim \mathrm{N}(0, \mathbf{Q}_{k-1})$ is the process noise with covariance $\mathbf{Q}_{k-1}$ and $\mathbf{r}_{k-1} \sim \mathrm{N}(0, \mathbf{R}_{k-1})$ is the measurement noise with covariance $\mathbf{R}_{k-1}$. Kalman filtering consists of a prediction step, where the next state of the system is predicted given the previous measurements, and an update step, where the current state is estimated given the measurement at that time instance. The prediction step is characterized by the following equations:

$$\begin{aligned} \hat{\mathbf{x}}_k^- &= \mathbf{A}_{k-1}\hat{\mathbf{x}}_{k-1} \\ \mathbf{P}_k^- &= \mathbf{A}_{k-1}\mathbf{P}_k\mathbf{A}_{k-1}^T + \mathbf{Q}_{k-1} \end{aligned}, \tag{8}$$

where $\hat{\mathbf{x}}_k^-$ and $\mathbf{P}_k^-$ are the system *a priori* (i.e., before observing the measurement at time k) state and covariance estimates, and $\hat{\mathbf{x}}_k$, $\mathbf{P}_k$ are *a posteriori* (i.e., after observing the measurement) estimates. The update step is performed as:

$$\begin{aligned} \mathbf{K}_k &= \mathbf{P}_k^-\mathbf{H}_k^T\left(\mathbf{H}_k\mathbf{P}_k^-\mathbf{H}_k^T + \mathbf{R}_k\right)^{-1} \\ \hat{\mathbf{x}}_k &= \hat{\mathbf{x}}_k^- + \mathbf{K}_k\left(\mathbf{y}_k - \mathbf{H}_k\hat{\mathbf{x}}_k^-\right) \\ \mathbf{P}_k &= \left(\mathbf{I} - \mathbf{K}_k\mathbf{H}_k\right)\mathbf{P}_k^- \end{aligned}, \tag{9}$$

where $\mathbf{K}_k$ is the Kalman gain of prediction correction at time instance k. KF is optimal for a linear system with Gaussian measurement and process noise [38], [37], which applies to our situation.

Acoustic object movement is described as a discrete Wiener process velocity model [39] with the state vector defined as $\mathbf{x}_k = \begin{bmatrix} x_k & y_k & \dot{x}_k & \dot{y}_k \end{bmatrix}^T$, where (x_k, y_k) denotes object position and $(\dot{x}_k, \dot{y}_k)$ — the velocity in a two-dimensional Cartesian space. The transition and measurement matrices for model (7) are then defined as:

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & \Delta t & 0 \\ 0 & 1 & 0 & \Delta t \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{H} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, \tag{10}$$

where Δt is the time interval between consecutive estimates in seconds. The process and measurement noise variance is specified by matrices

$$\mathbf{Q} = \begin{bmatrix} \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 & 0 \\ 0 & \frac{1}{3}\Delta t^3 & 0 & \frac{1}{2}\Delta t^2 \\ \frac{1}{2}\Delta t^2 & 0 & \Delta t & 0 \\ 0 & \frac{1}{2}\Delta t^2 & 0 & \Delta t \end{bmatrix} q,$$
$$\mathbf{R} = diag(r_1, r_2), \tag{11}$$

where q and r_k are the power spectral densities of process and measurement noise, respectively. For our conditions the parameters are set as $\Delta t = 0.1$ s, $q = \begin{bmatrix} 0.2 & 0.2 & 0.2 & 0.2 \end{bmatrix}^T$, $r_1 = 0.1$, $r_2 = 0.3$.

C. Acoustic Feature Extraction and Mapping

Mel-Frequency Cepstral Coefficients (MFCC) is a popular method for extracting features from an audio signal and is used in speech detection and recognition. An interesting property of this approach is that it is based on psychophysical studies that reveal that human perception of the sound frequency contents for speech signals does not follow a linear scale [40]. A Mel scale is used instead:

$$f_m = 2595\log_{10}\left(1 + \frac{f}{700}\right),$$

where f_m is the subjective pitch in Mel units corresponding to a frequency f in Hz. Thus, applying this method can be beneficial in improving the interplay of sound and visual excitation in a psychophysically coherent way. Moreover, studies also show that MFCC can also be applied to modeling music [41] which can also be advantageous in enhancing the experience of synesthesia. The computation of the MFCC comprises the following steps [41]. Starting from a waveform:

1) Convert waveform to frames;
2) Take Discrete Fourier Transform (DFT);
3) Take Log of amplitude spectrum;

4) Apply Mel-scaling and smoothing;
5) Apply Discrete Cosine Transform (DCT).

Once the procedure is complete, MFCC features are obtained. In this work, we consider the auditory spectrum portion of the features, hereinafter denoted as A_{spec}. To produce the visualization, the acoustic features of the sound source must be examined. At the moment, a simple approach is employed, such that the incoming sound waves are visualized as spheres moving towards the listener. The color, size, velocity of travel, and sampling rate for generating the spheres can be determined experimentally. The incoming waveforms are broken down into frames and analyzed as discussed previously. Currently, the following mappings are in effect:

- The size of a single sphere is determined by the scaled maximum amplitude of the sampled waveform in the frame;
- The color of the sphere is determined by the dominant feature in A_{spec} obtained by applying the MFCC approach. A transform is thus defined as $\xi : \mathscr{I} \rightarrow \mathscr{C}$, where $\mathscr{I} \subset \mathbb{N}$ is the index of the dominant feature in A_{spec}, and $\mathscr{C} \subset \mathbb{R}^3$ is the color specification in a particular color space. For this work, we consider the Red-Green-Blue (RGB) color space and jet color mapping, the latter shown in Fig 3.

Fig. 3. Jet Color Mapping

The signal processing described above is completely done in MATLAB environment and sent to the visualization engine for further processing.

IV. Real-Time Application to a Virtual Reality Environment

The VR environment conducted with synesthetic experiences is advanced for various purposes such as bridging Cyber-Physical Systems (CPS) to VR interface, self-learning activities, physiological and psychological aspects of VR based real-time simulation. Although the immersive environment is unique and subsections are slightly relevant, the process for creating the virtual environment had been familiar with ordinary VR applications. The process is as follows:

(a) Environmental Creation and System Design,
(b) Modeling and Texturing,
(c) Materials and Hardware Integration,
(d) Software Integration,
(e) Optimization.

Unreal Engine 4 was employed to create the virtual environment as the engine is well known, feature-complete and capable solution for VR development purposes [42]. Robustness, compatibility and low maintenance cost could be considered as some of prior advantages for the preferred pyhsics engine. Overall, using primary game engines is relevant to benefit prominent VR development methods such as the concept of object oriented programming, process of computer generated graphics, reusable code with libraries[43]. Those benefits are also used to create communication tool between software linked to the project.

Regardless, successful immersive applications based on realistic environment minimize difference among physical and virtual environments. Hence, authors considered to create the virtual environment based on physical conditions significantly. Additionally, the floor plan of facility is utilized used for accurate virtual environment based on physical assets [44]. Those assets have been rendered and modeled in three dimensions (3D) by using Autodesk Maya3D animation, modeling, simulation, and rendering software [45]. 3D models of physical assets located at laboratory were developed using polygon shape and modified using functions such as extrudes, append etc. The physics engine can respectfully identify the material components and map file (Textures) with Filmbox format (FBX). We also aimed to maximize impact of synesthesia during the experiment. Whereas, existing objects in virtual environment should be perceived in minimum acceptable level. Therefore, we preferred to avoid emissive color contents for replicated objects. Fundamental parts such as walls, columns etc. are inserted in physics engine according to suggested scale compatibility of physics engine (1 unreal unit is equal to 1 cm) [46]. The chosen engine allows to create realistic environments and simulate realistic affects. Hence, users can feel lifelike interaction during experiencing the application. Moreover, teleportation feature of VR technology is implemented for the application. That feature allows users to move independently and effortless in computer simulated realistic laboratory during experiencing synesthesia effect. Furthermore, independent movement may also grant users to sense self-learning activities in VE. The user can still ascertain sound source localization during continuous movements. The principle logic of the application is referred to predefined VR class of the engine: Motion Controller Pawn, HUD, VR GameMode, Player Controller.

User Datagram Protocol (UDP) provides a procedure for application programs to send messages to other programs with a minimum of protocol mechanism [47]. The lightweight procedure does not acquire specific requirements when running in numerous platforms. UDP transport protocol provided us a straight method to transfer packets over local network among MATLAB and the physics engine.

The Blueprints Visual Scripting system in Unreal Engine is a complete gameplay scripting system based on the concept of using a node-based interface to create gameplay elements from within Unreal Editor [48]. The Blueprint system allowed us to create a UDP interface [49] to communicate between MATLAB and the based on a custom C++ class. To avoid problems with Blueprint multithreading in Unreal Engine 4, the implementation uses a custom class variable to transfer data between threads to avoid a racing condition in requesting/getting new data from the UDP socket. With this approach, reliable communication via a UDP socket at high sampling rates such as f_s=1kHz is easily achieved.

The complete visualization thus comprises the following components:

- A C++ class based UDP socket implementation available to the UE4 Blueprint scripting system;

- All necessary animations are scripted in UE4 Blueprints and are based on the information received via the UDP socket from MATLAB software;
- The room where the prototype is located is recreated as a Virtual Reality environment.

Since HTC Vive is used, the corresponding UE4 VR template is employed and thus the user can navigate the VR room. The main idea here is to synchronize the user real-world location and that in the VR environment.

V. Experimental Setup

The proposed prototype comprises several components: a microphone array with four Behringer C2 microphones, an USB audio card—Focusrite Scarlett 18i20 Gen 2—for sound data acquisition, a personal computer running MATLAB/Simulink environment and the VR sound visualizer, the HMD device—HTC Vive, and the emulated sound source represented by a Creative T15 Bluetooth speaker. The user wearing the HMD device and the microphone array are assumed to be stationary. The distance between the user and the conical array is constant and the corresponding VR environment position offset may be computed and applied within the VR room scale. The complete prototype configuration is depicted in Fig. 4.

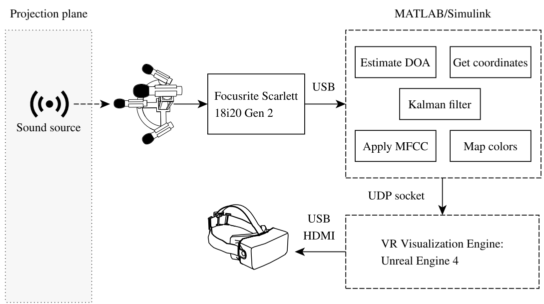

Fig. 4. Experimental configuration and signal flow

Compared to the original configuration described in [18], the following changes to the prototype configuration have been made. We have revised the implementation of the acoustic localization algorithm such that instead of directly using Eq. (5), we adopted a similar approach as in Eq. (3). This means that we skip information about the horizontal location and use only the three vertical microphones to determine the vertical location. This resulted in a significant improvement in accuracy of acoustic localization.

We use MATLAB software due to the availability of necessary toolboxes for real-time data acquisition and processing. We have previously successfully used MATLAB/Simulink for rapid prototyping of computationally intensive real-time control algorithms [50]. Once the data is processed within MATLAB, the necessary information (spatial coordinates of the sphere, its size and color) are sent via a socket connection in real time to the visualizer application that drives the HMD.

Developing with the engine and running the serious game and MATLAB software at once prompts the use of specific hardware and software requirements. The applications run on a PC equipped with a 3.20GHz Intel i5-4570 processor, 8GB RAM, and an NVidia GTX 980 graphic card driving the HTC Vive HMD.

VI. Experimental Results

For verification of the designed prototype we consider two types of experiments. First, we observe how well the acoustic tracking part works. Second, we verify the real-time VR application. In both cases, the distance from the sound source to the microphone array is $r = 1.5$m. An audio clip with modern music is used as audio such that has no distinct spectral features. The real-life experimental layout is shown in Fig. 5.

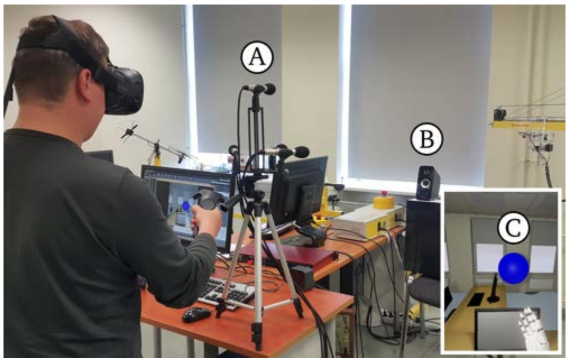

Fig. 5. Experimental real-time prototype setup. Elements on image: A—Microphone array; B—Emulated sound source (Bluetooth speaker); C—Spherical visualization as it appears in the recreated room VR environment

For the first experiment, the sound source, represented by the PC speaker, is moved in a rectangular motion in the projection plane for a 100 seconds. The sampling rate is 10Hz. The resulting scaled circles with colors obtained using the procedure described above as well as corresponding trajectories are shown in Fig. 6. It can be seen that although the manually delivered sound source motion trajectory is approximately rectangular, the location is sometimes misclassified in the vertical direction which results in erroneous upward and downward motions. The motion is smooth due to the additional Kalman filtering step. The larger circles represent a louder section of the audio clip in the lower frequency range. Yellow circles represent features in the higher frequency range.

The second experiment was concerned with initial impressions from using the prototype in VR. The following observations can be made:

- When two people are talking in to each other in the room, the sphere correctly identifies the speaker location. While plain speech does not by itself give rise to special features, a sharp difference in color can be observed when the “s” sound is produced.
- The current implementation introduces a noticeable delay of about 500ms. This is distracting, though does not break the effect of immersion.

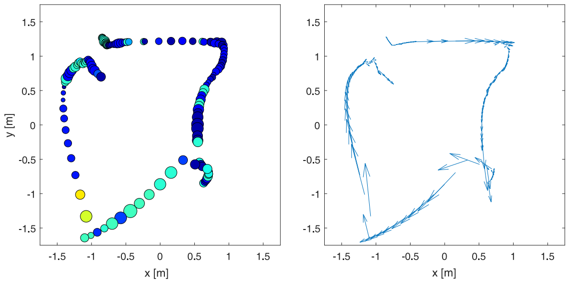

Fig. 6. Features and spatial dynamics of the emulated sound source captured during a real-time experiment with an improved configuration

- Colors produced by playing simple musical instruments fall inside an almost indistinguishable color spectrum (shades of blue, since jet is used).
- The overall effect seems interesting, however, as mentioned above certain technical limitations have to be overcome before further investigation with a control group is conducted.

To provide a further illustration of the visualization part, we moved the prototype to Re:creation Virtual and Augmented Reality laboratory [31]. Therefore, the virtual environment is recreated to represent the actual laboratory. In Fig.7 one can observe a snapshot of the visualization resulting in a speaker in the real environment pronouncing the word “hats”. It can be noticed, as mentioned previously, the sound “s” with the *jet* color mapping results in a yellow sphere being produced.

Fig. 7. Visualization resulting from pronouncing the word “hats”

In what follows, several ideas related to the improvement of the proposed solution are provided:

- A graphical user interface for selecting various parameters of the sound processing algorithm should be implemented for convenience. Most importantly, color mapping should be made easily selectable. Furthermore, since we know that Mel’s scale is nonlinear, the color mapping may also follow a nonlinear scale to improve color variation in the visualization.
- Depth (third coordinate) detection should be available. To achieve this, it is possible to place HTC Vive standalone trackers directly on the sound source. This can be used for initial experiments as well as calibration of the developed hardware prototype.
- Finally, once the technical limitations are overcome, we shall proceed with the assembly of the control group and do subject based testing. Towards that end, subjects who experience synesthesia naturally should be interviewed, their responses documented and analyzed and corresponding color mapping methods implemented in the prototype. An ethics committee approval should be sought beforehand.

Most importantly, the experiments allowed us to gain deeper insight into the effect generated by introducing sound visualization with source localization in a VR environment. It is also of interest to repeat the experiment in an Augmented Reality (AR) environment where the spheres would overlap an existing real-life environment.

VII. Conclusions

In this work, the general framework towards developing a full-scale synesthesia laboratory has been introduced. Then, the first technological contribution in the scope of this laboratory was presented—we have described a prototype for acoustic sound localization, processing, and visualization for the purpose of inducing a synesthetic experience in a VR environment. The proposed prototype and corresponding methods have been described. In this contribution, the real-time solution was implemented in a VR environment. Initial experiments were successful and provided important insights into the development of synesthetic experiences. While the acoustic localization aspect has some issues, these can be resolved by means of revising the physical configuration and localization algorithm as it was shown in the present effort. Moreover, these tracking issues do not strongly affect the VR immersion aspect, especially due to the application of the Kalman filter which smooths out the motion and enhances the experience, hence the improvement of tracking is not presently seen as top priority. Rather, efforts are being put into research and development of a multiple sound source localization algorithm and a coherent visualization mechanism. The developed application can be used in subject based testing following an ethics committee approval. Since the prospective application is envisioned to be used for real-life medical and artistic applications, further development efforts must also be exhibited towards an embedded system prototype. Furthermore, due to its importance in medical and industrial applications, implementing the synesthetic experience in augmented reality will be investigated since the resulting application will complement the actual real-life environment.

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Appendix 4

Publication 4

A. Köse, A. Tepljakov, E. Petlenkov. Towards Assisting Interactive Reality: Interactive Reality for Education, Data Analysis and Industry. *in 5th International Conference on Augmented and Virtual Reality*, pages 569–588, Lecce, Italy, Jun. 2018.

Towards Assisting Interactive Reality

Interactive Reality for Education, Data Analysis and Industry

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Abstract. This paper addresses an interactive virtual reality based application of a physical environment. The application presents notable aspects for education, data analysis and industry since the physical building serves as a research and development center. As the project based on physical environment, one of the main target for the work is also concentrated to give high presence feeling for end-users. The developed application is verified in real time. We also introduced our findings in real-time data communication, detection and analysis of human behavior in immersive environment, control systems integration to VR. Data analysis part of the research is linked to human behaviors based on the perception of computational intelligence methods. The activities in immersive environment are engaged to entertaining and joyful learning approaches. Some ideas for further development are also described.

Keywords: Virtual Reality · Real-time communication
Human behavior · Architecture modelling · Intelligent systems
Data analysis

1 Introduction

Recent significant growth in computer science and technology has complemented computer–simulated environments such as Virtual Reality (VR). Revolutionary growth in computational power in the last few decades gave rise to interactive graphical representation. The rise in high-end human computer interface including VR enhances to immerse completely in virtual environment (VE). The advent of low-cost head-mounted display (HMD) devices such as Oculus Rift [1] and HTC Vive [2] made this technology accessible at large and featured VR with user real-world position and orientation tracking. Therefore, present advancement in VR technology allows to induce a persistent effect of presence in a visual world [3]. Virtual environments (VE) have proven effective in a number of scientific, industrial and medical applications such as [4–7] are employed to, including but not limited to: computer-simulated environments, visualizations of complex data, joyful learning tools etc.

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VR can be considered a very convenient tool to complement learning aspects, particularly for education in engineering. One of great example to point out is as an extension of VR – Virtual Labs (VLs) are usually referred to computer based simulations. They offer similar vision and methods of work to their traditional counterparts [8]. VLs can give access to large number of users at once. Users likewise gain an experience by interacting with accurate replications of physical objects or artificial equipment in VLs. In our earlier work [9], we have introduced the fully immersive environment based on the physical architecture. The architecture includes significant amount of laboratories in diversified fields, particularly conducted with engineering fields. The facility is also used as a research and development center of Tallinn University of Technology [10]. Replication of the building is shown in Fig. 1.

Fig. 1. Exterior visualization based on a real-life building [9]

In this work, we advance interior design of the building. We also present the improved replication of the architecture to deliver VLs experience linked to two laboratories – Electronics laboratory and control systems laboratory. Besides that, novelty approach of the framework in this paper is real–time data communication between the game engine and third party software to apply accurate mathematical models for replications of laboratory equipment. As a remarkable benefit of this framework, interactions by users receive real–time feedback with realistic perspective as original objects. Therefore, the VR based interactive application gives better understanding of control systems and allow users to have more efficient learning experience than existing familiar VR based applications.

We now outline the main contribution of the present paper.

First, we create 3D models of objects located in the facility. We also apply texturing to maximize a persistent effect of presence in a visual world. Next, we import created and rendered models to the game engine where we actually create the application. In following section, we describe current problems based on the real-life objects in educational facilities and we introduce our framework to alleviate conditions and alternate laboratories. Then, we provide the description of the proposed VR environment with the complete interaction configuration.

Next, we present the novel developments related to the real-time implementation. Finally, we report and address the initial findings related to the human behavior while the user experiences the application and outline some related items for future research. We also describe our vision to apply computational intelligence methods linked to human behavior in this framework.

The structure of the paper is as follows. In Sect. 2, the replication process of large scale building is described. In Sect. 3, the reader is introduced to human-computer interaction conducted with the immersive environment. Process of real-time data communication with digital twins (DT) objects are explained in Sect. 4. The concept of human behavior is addressed in Sect. 5. Finally, conclusions are drawn in Sect. 6.

2 Replication of Large Scale Building

Successful immersive applications based on realistic environment minimize difference among physical and virtual environments. Hence, authors considered to create the virtual environment based on physical conditions precisely. The presented application integrates interactive graphical presentation of the physical building, data communication in real-time, corresponding mathematical models and feasibility study of computational intelligence methods. Although the physical building is unique and extended features are relevant, the process for composing the architecture replica is familiar with existing VR applications. The process is as follows:

(a) Environmental Creation and System Design,
(b) Modeling and Texturing,
(c) Software and Hardware Integration,
(d) Optimization.

Unreal Engine 4 was employed to create the virtual environment as the engine is well known, feature-complete and capable solution for VR development purposes [11]. Robustness, compatibility and low maintenance cost could be considered as some of prior advantages for the preferred physics engine. Overall, using primary game engines is relevant to benefit prominent VR development methods such as the concept of object oriented programming, graphics, reusable code with libraries [12]. Those benefits are also used to create communication tool between software linked to the project. The chosen engine allows to create realistic environments and simulate realistic affects. Head tracking devices are in charge of dynamic altering for the vision of users. Hence users can also feel lifelike interaction during experiencing the application.

As a matter of fact, the teleportation feature is considered to be very suitable tool for the application like other large scale environments. That feature allows users to move independently and effortless in computer simulated realistic facility during investigating the environment. Furthermore, independent movement may also grant users to sense self-learning activities in VE. The user can still interact and during continuous movements.

In what follows, we outline primary stages of the recreation process in a separate subsection.

2.1 3D Modeling

In this phase, the 3D model, texturing and rendering of the building were progressed. Creating replication of components for virtual environment is a remarkable part of the process. The whole concept is accomplished to receive high efficiency for supervised and unsupervised human learning. The floor plan of facility is utilized used for accurate virtual environment based on physical assets. Features of those assets are referred for 3D modeling, texturing and rendering by using Autodesk Maya software [13]. 3D models of physical objects were developed using polygon shape and modified using functions such as extrudes, append etc. Reactions of those models to the lighting depend on information from the materials. The physics engine can respectfully identify the material components and map file (Textures) with film-box (FBX) file format. Texture map is directly related to the quality of the model for the physics engine. In addition, Using Level of Detail (LOD) feature is utilized to simplify the 3D models. LOD is useful to reduce the number of polygons for rendering. It is important to receive better vision on VR devices with better performance. Overall, the design should ensure the virtual quality to maximize impact of presence feeling during the experience [14]. Whereas, existing objects in virtual environment should be presented with

Fig. 2. Screenshots from two rooms in the VR based application

high rendering aspect. Therefore, we likewise preferred to avoid emissive color contents for replicated objects. Some replication of rooms are shown in Fig. 2.

2.2 Recreation of Environment and Software Management

Visualization is applied in various fields related to such as education, product visualization, interactive multimedia and in architecture etc. It is claimed in [15] that visualization is useful to construct intellectual procedures. The virtual environment is employed for multiple purposes such bridging Cyber-Pyhsical Systems (CPS) to VR interface, self-learning activities, physiological and psychological aspects of virtual reality. Although creating an environment is the most time consuming of stage in process, significant accuracy would reduce harder rework. At first, terrain is an essential part of environment where the artificial building lies on. Otherwise the user would be in fully infinitive virtual environment where the presence feeling may not be applied. Flexible massive terrain is done by the Landscape tool in preferred game engine which can be applied for different platforms [16]. Fundamental parts such as walls, columns etc. are inserted in physics engine according to suggested scale compatibility of physics engine (1 unreal unit is equal to 1 cm) [17]. Repeating some fundamental parts are applicable regarding the floor plan. Once modeling and texturing are processed, all the content is created in the physics engine. In other words, we assembly all the artificial models based on physical world in the immersive environment. The principle logic of the application is referred to predefined VR class of the engine: Motion Controller Pawn, HUD, VR Game-mode, Player Controller.

Some users are still inexperienced in using HMD devices. Some difficulties such as insecure emotions were observed occasionally thereof. In addition, it was not pleasant to be isolated from the physical world. Therefore, we decided to benefit from Open Source Computer Vision (OpenCV) library to employ a webcam in virtual environment. The plugin enables to display physical environment at same time while the user experiences in VR. The screenshot of implementation is depicted in Fig. 3. The library also allows to develop Mixed Reality (MR) environments. MR is usually represented in three forms. Those forms can be defined as Augmented Reality (AR), Augmented Virtuality (AV) and VR. In AR, the virtual and real content can be implemented through the physical world by mixing and registering. AV is slightly closer to VR, which refers to approaching physical objects in to a virtual world. Real objects can be integrated to the virtual world, hence it is possible to interact with them synchronously in MR [18]. MR extension of the application will be implemented during further developments.

The application is served with Oculus Rift and HTC Vive. Therefore, users can experience physical mobility in real room scale, real-time positioning and tracking with advanced display resolution. Integrating two most common VR devices also allows us to compare usability and efficiency for the VE. Although authors also proceed with Oculus Rift, HTC Vive is employed more frequently. Independent navigational benefits, convenient hand-held controllers, high resolution display are some facts to prefer HTC Vive. The HMD provides 1080×1200

Fig. 3. Display of physical environment while VR based experience

resolution per eye, and the 9-DOF with 2 lighthouse base stations for tracking. Also the HMD set has two sets of controller. The controller features 24 sensors, dual-stage trigger and multi-function trackpad [19]. Developing with the engine and running the serious game require specific hardware and software requirements. The application run on a PC equipped with a 4.00 GHz Intel i7-6700 processor, 32 GB RAM, and an NVidia GTX 980 graphic card. HTC Vive HMD used for running the project.

3 Human Computer Interaction in Immersive Environment

Research and development abilities directly connected with growth in computational power. In other words, the ability to deal with more complicated problems has become within reach while computer science and technology expands significantly [20]. Educational facilities, particularly education in engineering also have been complemented with the recent growth. Researchers have been able to investigate theoretical knowledge and present findings in greater complex levels. It is important to point out that the formal verifications of theoretical findings are presented most commonly with mathematical models. On the other hand, majority of courses including education in engineering are usually introduced by traditional teaching approaches in classroom settings. Moreover, if those approaches are also merged with recent findings, the content of courses can be filled up heavily with math intensive, also remain abstract. The adversity might likely cause failures to enlighten the realities of different types of system implementations [21]. Unlike education served by traditional way, practices linked to laboratory based environments may provide remarkable educational benefits. For instance, students who enroll to experiments are able to investigate the resulting dynamics immediately. Besides that, practical objects can give access to them in order to interact with some physical parameters of the sample system. Therefore, those advantages would lighten students regarding some physical phenomena that are inconvenient to perceive by only a theoretical point of view thought in classroom [22]. Consequently, in this framework, authors likewise concentrate to conduct practical objects with the VR based application in order to obtain efficient and joyful learning experience.

3.1 Interactions

Human–Machine Interaction (HMI) is one of notable research topics. The efficiency of learning process is directly conducted with the interactivity. The interactivity encourages students to play a more active role and to get involved in learning process [22]. However, assuring quality of practice in interactive laboratories might be rather difficult problem with correlation between complexity of laboratory equipment and its cost. Furthermore, the magnificent increasing number of students in engineering enforces the limited capacity of laboratories. Hence, large groups of students must then be divided into smaller groups for direct guidance, which significantly increases the workload of the academic staff [23]. Interactive graphical representation of physical equipment can be sufficient approach to avoid previously mentioned difficulties. In addition, accurate simulated replications can complement important aspects of learning different types of systems dynamics. Students likewise can understand dynamics of systems and validate their theoretical knowledge with prototypes [24]. As a matter of fact, merging interactions in virtual reality, brings different perspective to HMI. In other words, HMI can be obtained to maximize in artificial reality conditions [25].

One of the main attitude of VR development is allow user to interact as much as they desire. It gives them independent movement, thinking and improving themselves with support of VE. Moving in the scene of VR can be operated through HMD controller using teleportation, physical movement etc. Users can direct any locations where navigation maps are implemented. Recently, immersive environments have been enriched with interactive graphical user interfaces that let students manipulate the experiment parameters and, explore their evolution [26]. Meanwhile, researchers accomplished several VR based applications in educational aspects to avoid if not relief continuous difficulties to engage students with experiments [27–30]. In general, large amount of students can gain an experience at once by interacting with replications of physical objects within limitations of accurate system identifications, if it is possible to run VR based applications simultaneously.

The presented VR based application allows users to interact by handles are provided with VR device. Although basic interactions have already implemented on previous contribution, major parts of present work is linked to HMI. Previously, we provided an questionnaire to participants who had experienced the replication of the architecture [9]. According to results, we experienced that there is no major differences between real building and virtual replica. Basic interactions in the application also engaged their attention. However, we also observed that functionalities of virtual environment were limited. They would like to demonstrate practical activities. Therefore, presented VR based application concentrate to grant users to have efficient learning experience and minimize limitations. In order to let users experience with real-time applications, we provide an experiment with visual representation of sound source comes through reality. Besides that, we created accurate replications of laboratory equipment supplied with mathematical models. We employ those objects in real-time to give better understanding of control systems. Lastly, we have assembled a vehicle controlled via hand tracking technology and replicated in VR to illustrate. The VR application hereby is complemented with practical activities. Those applications are described in following sections.

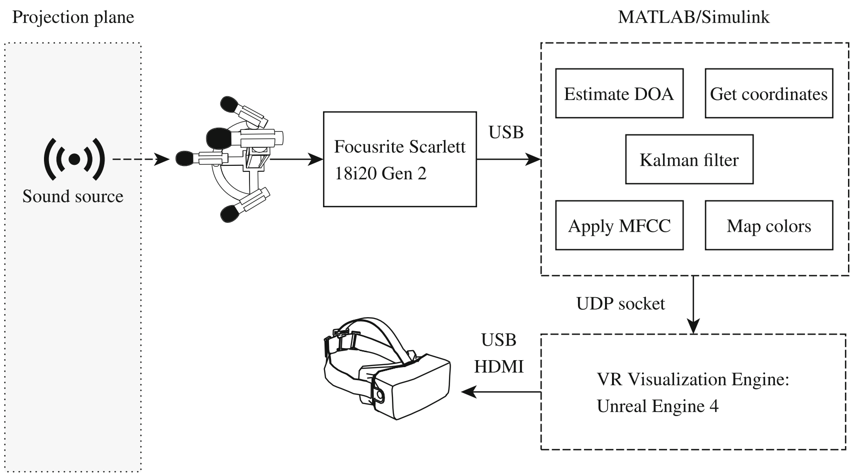

Fig. 4. Experimental configuration and signal flow

3.2 Experimental Study–Synesthesia

Synesthesia is the act of experiencing one sense modality as another. For example, a person may vividly experience flashes of colors when listening to a series of sounds. Virtual Reality allows to achieve this transition easily, since it can be used to present the spatial whereabouts of the sound source as well as visualize the sound content in a meaningful way. The ultimate goal of the experiment is to provide means for inducing voluntary synesthetic experiences through the VR based application. In our earlier work [31], we have reported initial findings related to acoustic localization and sound processing based on prerecorded data. In further work [3], we describe the revised technical solution meant to deliver the synesthetic experience to the listener in real time. The process of the experimental setup as follow; First, we apply an acoustic localization method to the problem of locating the sound source. We also apply a Kalman filter to reduce motion noise generated by the uncertainty of sound source location prediction. Next, for consistency, we summarize the method for extracting dominant features from the audio spectrum of the sound source and mapping those to the object representing the sound source in the VR environment. Then, we provide the description of the proposed VR system prototype and the complete experimental configuration is shown in Fig. 4. Finally, we present the novel developments related to the real-time implementation thereof. The real-life experimental layout is shown in Fig. 5. Most importantly, the experiments allowed us to gain deeper insight into the effect generated by introducing sound visualization with source localization in a VR environment. It is also of interest to repeat the experiment to analysis human behavior with corresponding artificial sensing. To provide a further illustration of the visualization part, we moved the prototype to Re:creation Virtual and Augmented Reality laboratory [32] located in the same building. Therefore, the real-time migrated experiment to the laboratory where the application is launched is shown in Fig. 6. In this figure, one can observe a snapshot of the visualization resulting in a speaker in the real environment pronouncing the word "hats". It can be noticed, as mentioned previously, the sound "s" with the jet color mapping results in a yellow sphere being produced.

Fig. 5. Experimental real-time prototype setup. Elements on image: A—Microphone array; B—Emulated sound source (Bluetooth speaker); C—Spherical visualization as it appears in the recreated room VR environment

4 Real Time Data Communication

Learning management systems are utilized commonly within distance education in the last years. Although the usage of those systems can be addressed to complement educational aspects, they do not usually ensure any possibility of illustrating scientific phenomena [33]. Hence, experiment devices could be linked to advance alternative methods. Due to paradigm conducted to distance education, particularly in scientific and technical areas, creation of virtual and/or remote laboratories have become high priority for educational facilities to be universal, successful and advanced environment [34]. Remote Labs (RLs) are broad facilities which use physical devices and plants at distance [35]. RLs have

Fig. 6. The migrated experiment presents visualization resulting from pronouncing the word "hats" (Color figure online)

an advantage to receive real time feedback from physical objects with realistic perspective. Moreover, RLs grant flexibility feature to change parameters of implementation. On the other hand, RLs also have considerable limitations. Experiments in RLs cannot be carried out in parallel since equipment is in charge of corresponding. In other words, a student who is not conducting an experiment can only watch the student who is performing an experiment remotely, if only laboratory is utilized with observation tools. Limitation of active users in a time might also cause the drop of motivation among students.

In order to gain the main advantage of RLs into VR based applications successfully, we created a real-time data communication tool. The Blueprints Visual Scripting system in Unreal Engine is a complete game-play scripting system based on the concept of using a node-based interface to create game-play elements from within Unreal Editor [36]. The Blueprint system allowed us to create a User Datagram Protocol (UDP) interface [37] to communicate between MATLAB and the physics engine based on a custom C++ class. To avoid problems with Blueprint multi-threading in Unreal Engine 4, the implementation uses a custom class variable to transfer data between threads to avoid a racing condition in requesting/getting new data from the UDP socket. With this approach, reliable communication via a UDP socket at high sampling rates such as $f_s = 1\,\text{kHz}$ is easily achieved.

The complete visualization thus comprises the following components:

- A C++ class based UDP socket implementation available to the UE4 Blueprint scripting system;
- All necessary animations are scripted in UE4 Blueprints and are based on the information received via the UDP socket from MATLAB software;
- The area where the equipment is located is recreated in the virtual environment.

Since HTC Vive is used, the corresponding UE4 VR template is employed and thus the user can navigate inside of the virtual environment. The main idea here is to synchronize the user real-world location and that in the VR environment.

4.1 Digital Twins into Education

The framework is dedicated to creating virtual objects for real-time experiments. The concept of DT is creating and interacting a digital representation of the real world objects by the means of optimization and simulation tools, which are fed with real and updated data [38]. In addition, the concept of DT from the VR perspective in this paper is referred to realistic replications of corresponding original objects by identifying mathematical models of the system to maximize the feeling of physical interaction in immersive environment. Initially, we model objects located in educational facilities such as laboratory, because this allows us to obtain highly accurate mathematical models of their dynamic systems. Thus, the educational value of the complete visualization should be high. A specific goal is to mathematically model and implement physically accurate interactions between the user and the virtual objects. Future goals also include modeling real-life industrial objects for implementing specialized virtual training, also decreasing cost of research and development aspects.

4.2 Digital Twins Approach of Control Systems in Immersive Environment

Hereinafter, the process of the development of several DT is provided. The original real-life control objects that served as reference for the DT were produced by Inteco [49]. So far, three objects have been modeled: The Magnetic Levitation System, the 3D Crane, and the Inverted Pendulum. The diagram showing the prototyping configuration is depicted in Fig. 7. The process of the development as follows:

Mathematical Modeling. It is previously mentioned in Sect. 3 that mathematical models are applied to achieve accurate replications. In our case, the purpose of mathematical modeling is to establish a dynamic relationship between the states of the system and also the inputs. States and inputs represent some physical parameters of the system. The usual "box" models are commonly used for modeling approaches. In this work, we have proceed with grey box and black box modeling. The grey box model can be defined as the structure of the model is known and the model is derived from physical laws. Certain parts of the model are approximated adequately for modeling purposes. In addition, black box modeling is usually referred to the system does not provide relevant information about its physical structure [39]. Hence, the model is complemented by fitting experimental data to identify mathematical model of the system accordingly.

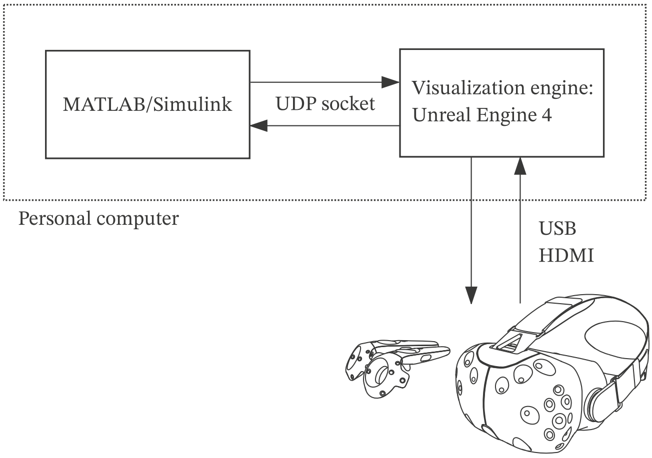

Fig. 7. Process of the application for real-time platform

To accomplish accurate modeling of physical objects in this work, we followed two methods: We sample meaningful data by the sensors of the real-life control object. The devices are also connected to the desktop computer through a data acquisition device. We analyze video to derive data in the way to validate our findings. More precisely, we record a video clip contains motion of a certain part of the control object to analyze. We also take into account that stability is not required for control objects. The reason for that introduced virtual objects in the frame of DT should be able to illustrate various related concepts. Thus, DT of physical objects are complemented with a proportional-integral-derivative (PID) controller which is also used frequently for industrial applications [40].

Interaction Implementation. The efficiency of learning process is directly conducted with the interactivity which can be considered the primary component of an immersive VR environment. Therefore, the process of DT objects are composed to ensure efficient laboratory instruction. Set points of control objects are changeable to give a better understanding of the system for the user. Besides that, one of the most interesting part of replicated objects give access the user to interact directly with moving parts of virtual objects. Controllers of employed VR device are used to maximize the feeling of physical interaction which causes disturbances in the controlled systems. From the user perspective, such interactions are of curiosity driven experimental nature. Applying responses to interaction mechanics are challenging. Hence, we repeat revisions the mechanics of DT by the subject-based evaluation method until results have become satisfactory.

3D Modeling and Prototyping in Real Time. 3D modeling of those objects are implemented the similar process with the creation of virtual environment which detailed in Sect. 2.1. It is likewise important to point out that creation of objects are completed in other modeling software – Blender 3D modeling

Fig. 8. Physical object -ML and its 3D model

software [41]. The reason for that to compare two different 3D modeling software according to our needs as well as expectations. One of physical objects and its 3D model is shown in Fig. 8. Previously mentioned UDP communication plugin in Sect. 4 for the game engine that makes real-time simulation possible with Matlab. In order to progress the prototyping in real time, we export validated mathematical models to the game engine as C++ code and/or featured visual scripting method discussed in Sect. 4. By this approach, we enhance flexibility in terms of amount of inputs and outputs for the system and corresponding mathematical models of dynamics. UDP plugin as well as exported modules can also be reused in any project. Once, we set up Matlab via Simulink Desktop Real-Time toolbox and the application via the game engine, created prototypes in the same platform are effectively used to teach control system design. The platform includes modeled objects described in Sect. 4.2 enables to work as a group or as a single user. For instance, the application can run simultaneously if Matlab is set up another computer. Besides that, meanwhile a student is experiencing the virtual object, another student can modify the mathematical model if it is desired. Figure 9 presents the replication of inverted pendulum while the user experiences interactivity in VR based application.

4.3 Implementation of Digital Twins for Hand Tracking Technology Based Vehicle

In what follows, to illustrate DT aspect, we have created a vehicle controlled via Leap Motion [42]. First, we assembled the vehicle and attached an arduino board to join interactive electronic objects. Since arduino is known as an open-source electronic prototyping platform, the project has been accomplished adequately. As soon as the assembling phase was completed, we wanted to complement the vehicle with hand tracking device. Finally, the controller was optimized in order to run the vehicle with its replication simultaneously. The completed vehicle is shown in Fig. 10. Practically, Leap Motion is designed to be embedded directly

Fig. 9. Inverted Pendulum in immersive environment

into VR/AR headsets. Therefore, we suppose that merging such technology in physical object with its DT would serve for demonstrating purposes. Once, the vehicle is completed, its 3D model was created with relevant texturing and rendering aspects. The process of 3D model has been similar to the immersive environment. Next, the 3D model is exported to the game engine where the VR based application is placed. To present a relevant output, we prepared a small track to run both at same time in physical facility and immersive environment. The starting point has been chosen the same reference as well as the track for racing is shown in Fig. 11. Lastly, to validate the achievement, we let users experience the object in both environment. According to their feedback, we ensure that virtual replica has been modeled and functioned successfully the way how the physical is operated. It was exciting to be able to drive the vehicle and meanwhile, to understand how the hand tracking technology works. Most of the participants were attracted by virtual object rather than its physical asset.

5 Merging Big Data Visualization and Analysis with VR

Big Data has taken attention of all the industries including, educational facilities, public sector, commercial companies [43]. Investigation of large data-sets usually require visual analytic. On the other hand, the challenge of meaningful visualization of Big Data increases exponentially with significant growth of computational power. Actual challenge is not only to process provided huge amount of data but to process data with high diversity. Although traditional visualization tools have been enforced to extend, they have already reached to their limits when encountered with very large data which are evolving continuously [44]. Therefore, it is necessary to investigate present possibilities to clarify traditional blended techniques such as Virtual Reality (VR). In our perspective, we aim to

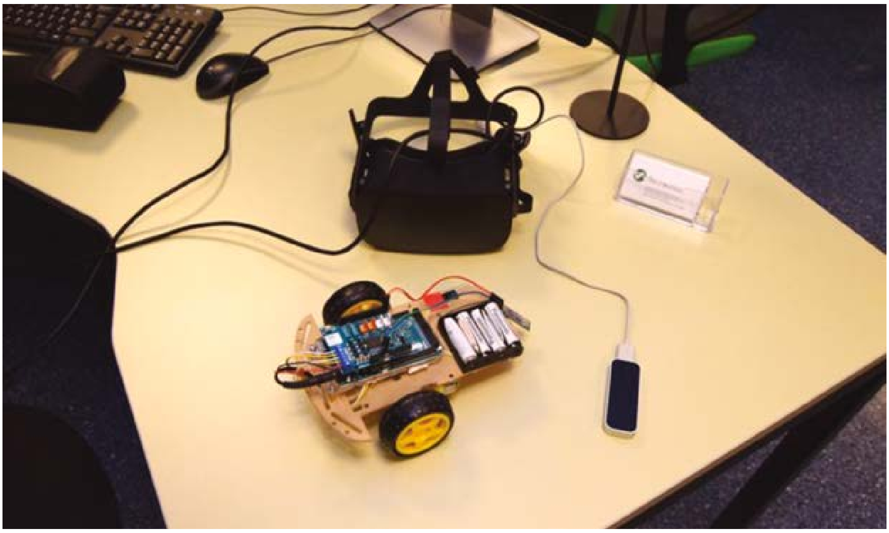

Fig. 10. The physical vehicle joined with leap motion and arduino

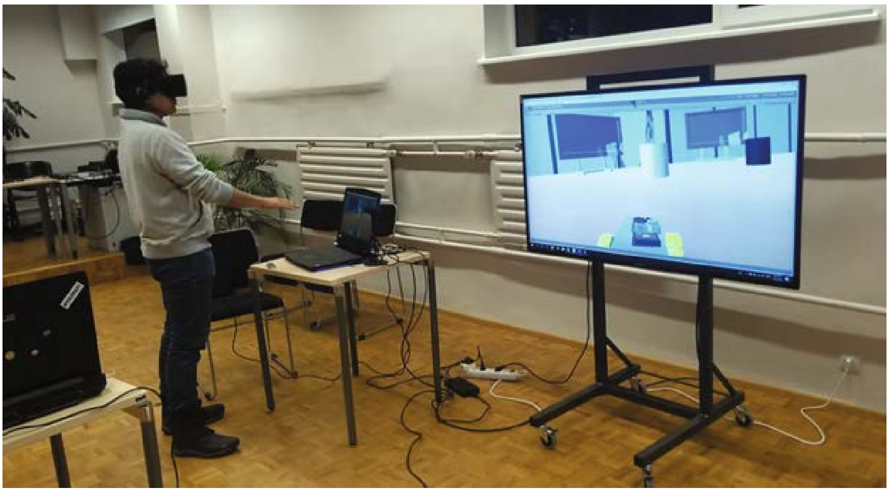

Fig. 11. Digital replication of the physical vehicle controlled via leap motion

use dynamic modeling to alleviate difficulties linked to data visualization. The dynamic modeling can ensure to make short time predictions and proactively start downloading the part of the system or process that have to be visualized next. This will make possible high quality and smooth visualization of Big Data based complex systems. Therefore, VR models of real systems and processes will be much more realistic and immersive.

5.1 Methodology

Visualization of complex processes (for example chemical processes on atomic level, movements of the layers of the Earth during millions of years etc.) requires downloading huge amounts of data. When working in spatial and geographical domains, simulations and VR can lead to better discovery [45]. In order to alleviate the problem of visualization of Big Data with VR, accurate mathematical model of human behavior using computational intelligence methods can be applied. One of the key issue that investigating a solution to predict user's behavior. The prediction might allow to preload the necessary data from a large visualization dataset. In addition, the solution would also benefit VR based applications to provide a seamless immersive experience to the user. In order to gain the following highly important advantages in complex visualizations, it is notable to engage with key issues which need to be investigated as follows:

1. Development of fast and accurate tracking of human movement in virtual reality, the CAVE [7] and similar VR and AR visualization systems. In addition, to increase accuracy, it would be beneficial to use Microsoft Kinect and the Leap Motion sensor as well as any other available technological means for collecting data for modeling specific elements of user's behavior.
2. Human movement prediction for determining the data to be preloaded into the memory of the visualization device.
3. Development of meaningful and intuitive interactions with the visualizations. This ensures that the data can be explored efficiently and in a way that allows to and even encourages to gain new insights into complex interconnections and relationships given the three-dimensional representation of the data in a virtual reality environment. New efficient forms of perception are expected to arise in this context.
4. Creating a collaborative immersive environment where data scientists can interact with the data and among themselves to increase the efficiency of the data study.

5.2 System Identification and Modeling

It is apparent that accurate mathematical model of human behavior in VR requires significant amount of time and effort. In order to process efficiently in the framework of this research, we created a prototyping platform with similar vision described in Sect. 4.2. The platform is also implemented with three software packages: Unreal Engine 4 is employed as the visualization platform while the user experiences the virtual facility with interactive equipment. Motion capture is achieved using present HMD technology which provides access to user movement data. UDP serves as a communication plugin between the game engine and software environment that makes real-time data communication and simulation possible. To proceed with modeling of user head and controller movement, the data of user is sent out to MATLAB to analysis and apply computational intelligence methods. Authors already investigated possible system identification modeling in [39,46,47] including artificial neural networks for different contents. In addition to that in [48], novel findings are introduced in various VR applications of data analysis including video cuts, panorama thumbnails, panorama video synopsis, and saliency-based compression. Those findings will be considered for our research. The present configuration and future aspect can be seen in Fig. 12. The project is in the stage of collecting sufficient amount of data sets to employ computational intelligence methods completely.

Fig. 12. Data analysis of behavior, (a) Present configuration (b) Forthcoming setup

6 Conclusions

In this paper, the general framework towards developing a full-scale interactive VR based application has been introduced. First, the procedure of recreating the architecture was presented– we have described replication of physical assets, creation of virtual environment based on the physical building and integration of hardware devices. In this contribution, the real-time solution was implemented in a VR environment. We created the virtual environment to also demonstrate real-time experiments. The real-time data communication is employed to complement virtual objects in terms of interactivity and accuracy. Those experiments were successful and provided important insights into the development of interactive VR based application. Moreover, recent developments of VR based learning aspects linked to virtual laboratories were reviewed. As a result, the application enhances remarkable advantages of using VR technology in practice. It is also actively used for learning aspects at the present time. Provided feedback from users validate the significant potential in order to benefit from DT approach in VR. Since the present application is envisioned to be used for real-time educational and industrial applications, further development efforts also should be exhibited to different systems. Besides that, the results of proposed dynamic modeling of human behavior is in the stage of collecting sufficient amount of data to apply computational intelligence methods and further results for this research will be presented in future.

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Appendix 5

Publication 5

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Towards Assessment of Behavioral Patterns in a Virtual Reality Environment

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Abstract. Virtual Reality (VR) is a powerful modern medium for immersive data visualization and interaction. However, only a few research efforts targeted the issue of complementing VR applications with features derived from real-time human behavior analysis in virtual environments. This paper addresses an interactive application for analysis of user behavior in a VR environment. In this work, real-time data communication is employed to collect data about the VR user's location and actions in the virtual environment. To ensure the authenticity of interactions in the virtual environment, the VR application aims at achieving complete immersion. Our findings pertaining to behavioral patterns in immersive environment suggest that there is a potential in applying knowledge of user behavior models to improve the interactivity between the user and the virtual environment. Analysis of VR users' behavioral models also complements studies typically performed by traditional survey techniques.

Keywords: Virtual Reality · Real-time communication · Data analysis · Tracking systems · Interactions · Human behavior

1 Introduction

Virtual Reality (VR) is a computer generated audio-visual environment that strives to immerse users completely in a simulated interactive environments [1]. Therefore, present advancement in VR technology allows inducing a persistent effect of presence in visual world. This technology has become available for a broader audience in recent years with the advent of low-cost head-mounted display (HMD) devices such as Oculus Rift [2] and HTC Vive [3]. These plug and play devices are also featured with user virtual-world position and orientation tracking that complement the presented work. Virtual environments (VE) have proven effective in many scientific, industrial and medical applications [4–8] and are applied in, including but not limited to: computer-simulated environments, visualizations of complex data, joyful learning tools, etc.

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VR is also a favored tool to utilize interactions in various fields. The interactivity usually encourages users to be more operative, complements their learning process and assists them in exploring the virtual environment and complex data visualizations [9]. Furthermore, one of attractive extension of interactive applications is to examine behavioral aspects mainly for research purposes [10]. In other words, VR provides an opportunity to evaluate human performance and perception in a specific task orientated VE by eliminating distractions and granting them with artificial skills. Accordingly, we aim to provide a solution for analysis of users' behavior to complement interactive VR applications. Consequently, the analysis part of the research into user's behavior will provide more advanced knowledge compared to traditional survey techniques.

In our earlier work [11], we have introduced the fully immersive environment and we followed a similar process to create the presented application. In this work, we describe our approach to analyze behavioral and attentional aspects by delivering a VR based application. The aim is to investigate success rate of the player and the efficiency of the application in different categories by taking into account the player's profile. Besides that, we try to answer the question whether the subjective self-evaluation of the player correlates the objective measurement data by monitoring movements and actions in immersive environment. Previously implemented real-time data communication [12] is also improved to collect and store necessary data for this work. As a remarkable benefit of this framework, interactions by users are stored in real-time and further feedback with realistic perspective can be provided based on the user's actions.

The main contribution of the present paper as follows: First, we present the framework used to conduct the experiments. In following, we explain a customized User Interface (UI) and we present a system configuration in order to enable real-time data communication. We also investigate the employed communication protocol to minimize latency during the VR experience. Next, we introduce created 3D models and used the game engine to create the application. In the following section, we describe preferred methods to provide novel findings and the outcome of the conducted experiment respectively. We also evaluate the application based on collected data and survey results. Finally, we report and address the conclusion towards behavioral aspects while the user experiences the application and outline some related items for future research.

The structure of the paper is as follows. In Sect. 2, the recreation process of the application, the game play and UI are described. The system configuration including technical specifications is presented in Sect. 3. In Sect. 4, the reader is introduced to human-computer interaction conducted with the immersive environment. The statistical findings towards behavioral aspects and the complementary questionnaire are addressed in Sect. 4. Finally, conclusions are drawn in Sect. 5.

1.1 Related Work

There exist a number of studies about interaction techniques considering human behavior, motion and actions. Many of such studies have focused on training with interactive VR applications. For instance, VR based application [13] is employed to train early medical professional by interactions. Participants who performed in another interactive VR training [14] increased retrieval success almost two times. Similar applications have also proven their positive impact in education. The steady decrease of students' failure rate is observed by training students with VR based application in [15]. Game-based learning using VR in education is presented in [16]. As the result, the learning efficiency is increased in terms of the time and the amount of content. Overall, VR based applications can provide a novel approach towards interactions which can be claimed one of the key factors for effectiveness [17]. Researchers have also introduced a few methods and applications towards human behavior [18], actions [19] and emotional states [20] in real-time in application-specific VEs. The user behavior and emotional state models are also used in design of user interfaces [21,22] linked to VR based applications. Furthermore, the location of participants in virtual-world is recorded in [23] to measure the engagement of participants in VR based application. It is claimed in [24] that head orientation recorded by inertial sensors may be sufficient to prediction purposes with reasonable accuracy.

2 The Framework for Analysis of Human Behavior

It is apparent that a complete analysis of human behavior in VR requires a significant amount of time and effort. In order to elaborate the framework of this research, we created a prototyping platform to acquire data necessary for assessing a user behavior in VR based applications. Replication of large scale building for interactive VR based application [25] can be considered the first stage of the framework. We gained technical experience and knowledge as well as remarkable feedback from hundreds of participants during the early stage. The gain gave rise to create another VR based application-Swedbank VR Experience [26]. The first version of the gaming-oriented VR application was completed at the beginning of 2018 in cooperation with a private bank in Estonia. The bank is now using the first version of the application for marketing purposes on various fairs, in their headquarters among Baltic countries to exhibit the innovative and entertainment sides of their business.

The first version of the application consists of three main components: starting screen with a custom UI form, tutorial level and main game level. The main level is situated in the hill-top virtual environment and the screenshot of the level is depicted in Fig. 1. It was designed to let the users perceive in a borderless environment. Secondly, the tutorial level was designed to keep the player in boundaries in order to direct the player to complete the specific tasks. The tutorial level thus took place in a modern circle shaped hall with a dome. The tutorial environment remained simple in order to induce the player to take desired actions leaving only minimal possible distractions. The primary motivation of tutorial level is devoted to giving an understanding of employed functions in the application such as teleportation, interactions etc. Additionally, users benefit from the warm-up session before the main game, precisely who does not have previous a practical VR experience.

Fig. 1. The game play view of the presented application

The tutorial level is excluded in the presented work since it would have given the player a better notion about the game-play. The dedicated experiment was designed to gather data at two different situations: before the players had some experience in VE and after. Therefore, in order to succeed with further analysis, the application is configured to provide a set of data in real-time. As we have primarily been dealing with setting up the stage for further experiments, it will be too early to draw any statistically relevant conclusions from the experiments described herein. In other words, the experiment is in early stage and the aim now is to design the experiment including the development of technical tools enabling the experiment. The experiment itself is on-going process and the number of participants is being extended constantly with the goal of obtaining statistically relevant data based on a large number of experiments.

2.1 Data Processing and Game Play

The data set is collected in three phases of the experiment. In the first phase, the customized UI is in charge of handling the collection of initial data set. The primary purpose of created UI is to collect the information about the participant's background.

In the first phase, the data is categorized based on age group, gender, education, previous gaming experience and hours spent weekly on physical activities. Users are asked to choose the best fit option based on multiple choice questions. The data collection is only activated by filling up the form and accepting to share the data for research and development purposes for each user. Options provided to the user are listed in Table 1.

Table 1. Given options in UI

Options	Age	Gender	Educational level	VR experience	Activity level
1	3–7	Female	Primary school	None	None
2	7–14	Male	High school	Low	1–2 h
3	15–24		Bachelor's degree	Moderate	3–4 h
4	25–49		Master's degree	High	4–7 h
5	50+		Doctor of philosophy		7+ h

The second phase of process is allocated into game sessions, the player's goal in the game is to collect a maximum number of points possible during the two-minutes game time. There are four different items in the game for the defined goal; yellow leaf, green leaf, orange leaf, and coin. Each item rewards the player with $1, 2, 3, 10$ points respectively.

In game level, the items are randomly generated and scattered but only around the defined play area. Those items are placed in the level by the algorithm for each game. Players are motivated to use teleportation feature to move around the play-area in VE since the distance between collectable objects are random and often the objects are far apart from each other. The objects spawn

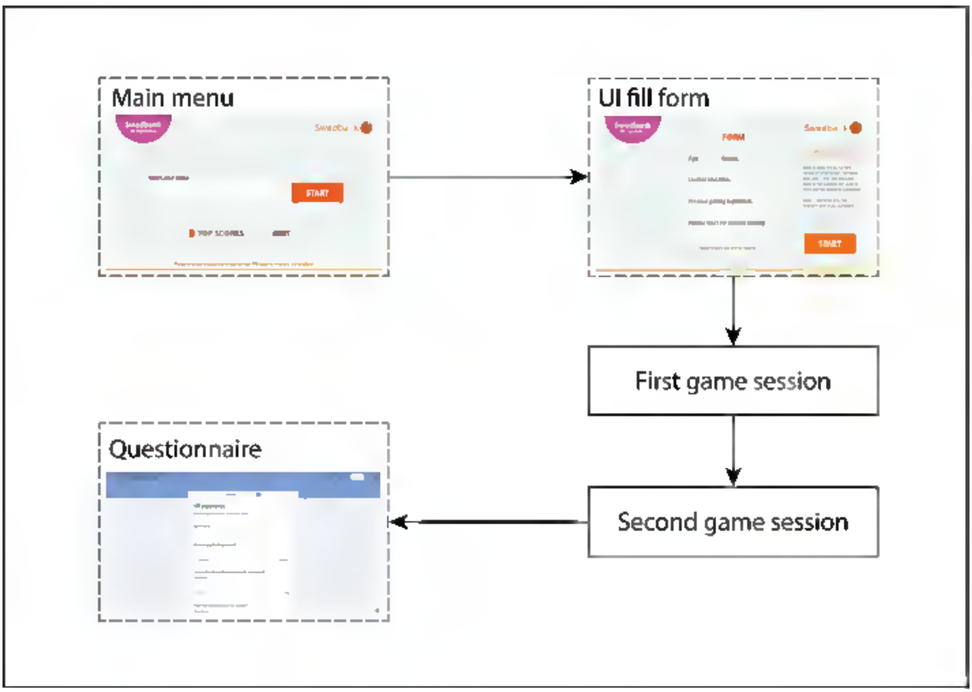


Fig. 2. Data collection process for the experiment

in different locations and at a varying distance from the ground, so the player must still move physically.

The last phase is placed after the game sessions. Each player is also asked to fill the survey that consists of seven questions by rating 1 (very low) to 5 (very high). The process of the application for experimental purposes is depicted in Fig. 2. To sum up, collected data with classified types for the framework is presented in Table 2.

Table 2. Classified types of collected data

Data type	Collected information
1	Age, gender, education level and experience in VR
2	Teleportation usage, amount of collected items
3	User location in VR, head movement of user
4	Traditional survey

On the whole, understanding human behavior in VE might also encourage joyful learning approaches. Therefore, existing difficulties to ensure rewarding feedback loop for creating more efficient and compelling VE can be alleviated. Moreover, the collected data provides a basis for predictions towards human behavior in VE for various purposes. The feedback can be enhanced with traditional survey techniques and vice-versa.

3 Software Management and System Configuration

The application is created by Unreal Engine 4 (UE4) which is a commonly used and powerful solution for VR development purposes [27]. For VR applications, efficient real-time rendering of the objects must be ensured, so the following important considerations are in effect when modeling all objects were progressed by using Autodesk Maya software [28]. We had to ensure that all 3D models are optimized, i.e., the number of polygons forming the part reduced and visualization trade-offs sought in terms of applying textures, displacement and light maps. Then, we moved to the next stage to assembly created models based on the dynamics of physical world in the game engine. Whereas, existing objects such as leaves, coins, landscape materials, etc. in the virtual environment are presented with high rendering aspect. Those created models to collect by users in the application are illustrated in Fig. 3. Overall, we have already presented detailed information of general replication process in the first phase of the framework in [11,25].

The application is served with one of the most common HMD devices–HTC Vive. The device grants users with physical mobility, positioning and tracking based on real time with high display resolution. The HMD provides 1080×1200 resolution per eye, and the 9-DOF with 2 lighthouse base stations for tracking.

(a) 3D models of green, orange and yellow leaves

(b) 3D coin model by both side

Fig. 3. Existing objects to collect in VR based application

The two sets of controller features 24 sensors, dual-stage trigger and multi-function trackpad [29]. Launching the application and running the experiment require specifications in terms of hardware and software. The application runs on a PC equipped with a 4.00 GHz Intel i7-6700 processor, 32 GB RAM, and an NVidia GTX 980 graphic card.

The real-time data communication part of this work is remarkable. The visual scripting system in UE4 typically referred to as *Blueprints* is a complete game-play scripting system based on the concept of using a node-based interface to create game-play elements from within Unreal Editor [30]. The Blueprint system allowed us to create a User Datagram Protocol (UDP) plugin [31] to communicate between local database via python made scripts and the physics engine based on a custom C++ class. In order to ensure smooth experience with minimum latency possible for the user, UDP socket is employed to collect data with $f_s = 1$ Hz sampling rate. Nevertheless, UDP plugin as well as exported modules can also be reused in any project. Since HTC Vive is used, the corresponding UE4 VR template is employed and thus the user can navigate inside of the virtual environment. The main idea here is to synchronize the user location in VE and head movements tracked via HMD device.

The UDP plugin requires custom level blueprints for communications, meaning that the reference to UDP actor in visual level can be given only into a corresponding game level. Thus, it is required to gather all the needed variables that contained desired data with "get" function from game instance blueprint. All the form input data was translated into numeric values to be stored in the local database if necessary. For instance, “Gender” is the part of the required form to fill by the user via UI and selected output is defined as 0 or 1 meaning male or female to keep the database structure steady and organized.

The game instance in the blueprints of the game engine acts as a collection of global variables. The collection can exchange values of global variables between all the blueprints within the project via “get” function. Furthermore, new values can be written into global variables by other blueprints via the “set” function. “get” function is used to get the value of certain variable and “set” function was used to forward new value to the global variable [30]. UI, teleportation and interactions with four collectable objects are composed by this approach to provide real-time data communication.

Consequently, we implemented the application and the devoted experiment with three software packages: The game engine is employed as the visualization platform while the user experiences the virtual facility with interactive equipment. Motion capture is achieved using present HMD technology which provides access to user movement data. UDP serves as a communication plugin between the game engine and software environment that makes real-time data communication and simulation possible. To proceed with modeling of the user’s head and controller movement, the data of user is sent out to Python and local database to store and apply statistical methods. The screenshot while the user is playing and all software packages are working is depicted in Fig. 4.

Fig. 4. The screenshot while experiencing VR application with timer and score

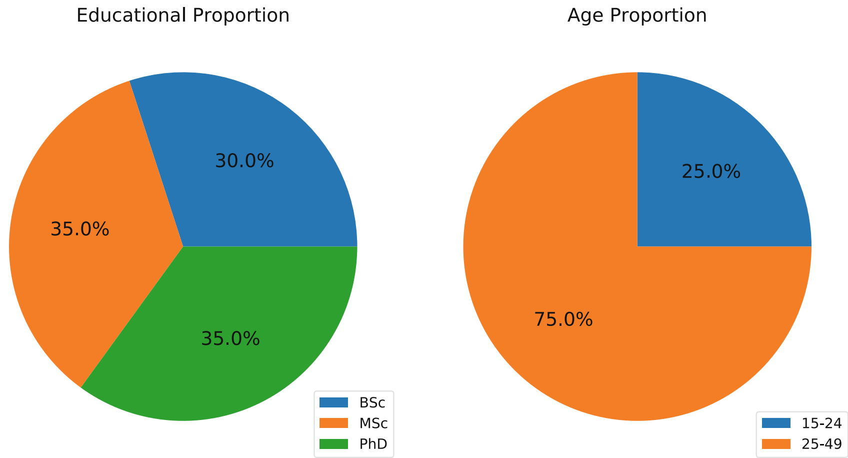
4 Human Computer Interaction in Immersive Environment

Human-Machine Interaction (HMI) is one of the relevant research topics. The interactivity directly impacts the efficiency whether HMI applications encourage users to operate, explore and manipulate. Merging interactions in VR brings different perspective to HMI. In other words, HMI can be advanced in artificial reality conditions [32]. One of the primary attitudes of VR development is to allow the user to interact as much as they desire. It gives them independent movement, thinking and improving themselves with support of VE. Moving in the scene of VR can be operated through HMD controller using teleportation, physical movement etc. The presented VR based application also allows users to interact by handles are provided with a VR device. Users can direct any locations where navigation maps are implemented. Previously, we provided an questionnaire to participants who had experienced the replication of the architecture [25]. According to results, we experienced that there are no major differences between real building and its digital twin. Basic interactions in the application also engaged their attention. However, we also observed that functionalities of virtual environment were limited. They would like to demonstrate practical activities. Therefore, presented VR based application concentrate to grant users with interactions while minimizing limitations.

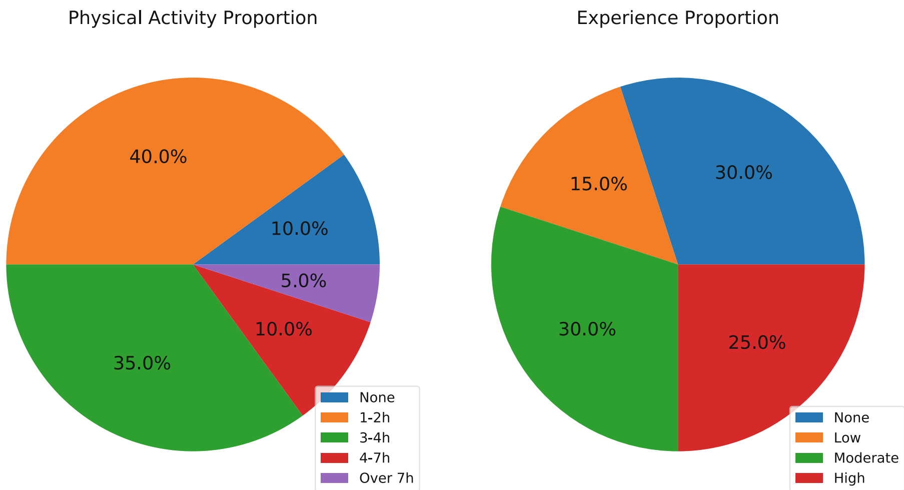
The virtual environment is employed for multiple purposes such as self-learning activities, psychological and behavioral aspects while users experience the application. We conduct our experiment with twenty volunteers. After the intro session and the UI phase, we asked to them play the game two times in a row and each time frame is restricted to 120 s. The motivation for that is to observe the difference from user perspective between first and second attempt for the VR based application. The provided results may benefit to have better understanding of behavioral aspects considering the first type of collected data-background of participants. According to collected data, most diversified information is gathered by physical activity level and VR experience. While experience in VR levels raised in all categories almost equally, activity levels of participants remain coincidental. Participants who selected low VR experience is referred to none of physical experience with HMD devices previously. Further classification is illustrated by drawing pie charts in Fig. 5. The ultimate goal of the presented framework is to endow the VE with the additional quality of intelligence derived from a thorough study of the users' behavior and the way they interact with VE.

4.1 Assessment of Interactions

One of the main attitude of VR applications is to allow users to interact. VR based applications are often delivered with the interaction that may also allow an evaluation of the engagement of participants [23]. In what follows, we present our findings by measuring user's location and action with a case study; Teleportation and Collected Items.



(a) Education and age division



(b) Physical activity and experience division

Fig. 5. Collected background profiles of participants

Experimental Study-Teleportation Within Immersive Environment. The teleportation is a type of locomotion and desired feature for the presented application like other large scale immersive environments [33]. Although the feature is only artificial and is unfamiliar to users in terms of actual experience (with the exception of users having previously used VR), it also allows users to move independently and effortless in immersive environment. Furthermore, independent movement may also grant users to sense self-learning activities in VE. Thus, the part of this work is devoted for investigating the teleportation feature which let the user interact with objects during continuous movements.

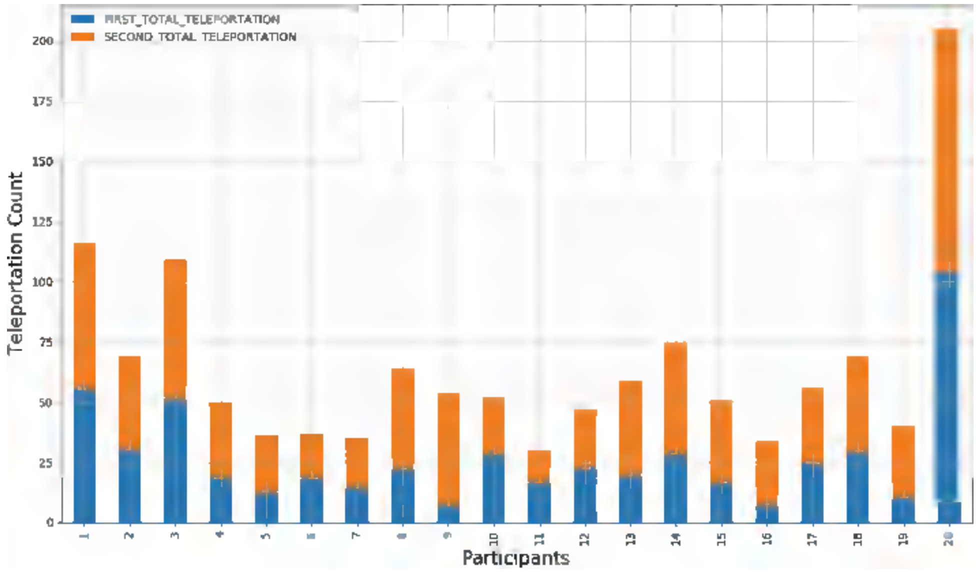


Fig. 6. Statistical view of interactions into the teleportation

Studying user behavior while using the previous version of the application, some difficulties while attempting to use teleportation such as insecure emotions were observed. Thus, tracking teleportation usage of participants seemed relevant for further research analysis. Participants who claim to have VR experience in high and moderate levels used teleportation feature at most in both times. Additionally, the rest of participants who had less VR experience have used the teleportation feature much more frequently in the second time of the experience. As a conclusion based on collected data, the teleportation feature is easy to adapt and very convenient to employ even for users who might not have previous VR experience with HMD device. Detailed information about teleportation usage for participants including first and second time is presented in Fig. 6.

Experimental Study-Decision Making in Limited Time to Collect Maximum Points. We have already described in Sect. 2.1 that the game session has a goal to maximize performance in terms of collecting items within limited time-frame. From the user perspective, such interactions linked to the gamification based engagement are of curiosity driven experimental nature. Moreover, the user can adapt to the gaming environment by interacting with it, and the perceives tasks to be completed [34]. Once the motivation is obtained, an accomplishment of attentional aspects by delivering a VR based application matters of given objects and tasks. Training for real-world scenarios with strict time limitations can be form effectively by following similar methodology [35,36]. However, applying interactions, teleportation and physical movements at once are challenging for users without previous VR experience. Hence, we let participants to try second time to observe the differences. As it is described previously in that each object in the application have different color and users are rewarded with different points adequately. Participants are introduced before the experiment and we conclude relevant finding such as most of participants perform better during the second attempt. The detailed results of each participant is shown in Fig. 7. That finding also points out one of remarkable advantages of VR based applications that is usually possible to repeat with low cost. Moreover, low or none VR experienced participants have performed much better in second try which can be considered that were able to adapt to presented the VR based application.

4.2 Traditional Evolution Results and Performance Comparison

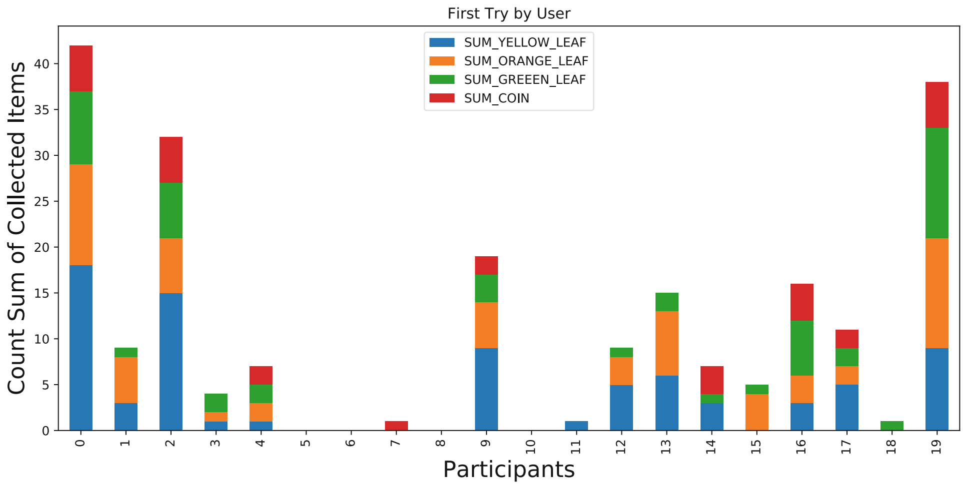
Statistical Terminology. Prior to discussing the findings towards performance analysis of participants, a brief explanation of used statistical terminology is given. The mean ($\bar{x}$) is used to summarize interval data by the sum of the set values divided by the length of set. Standard deviation (σ): An estimate of the mean variability (spread) of a sample [37].

Table 3. Survey results

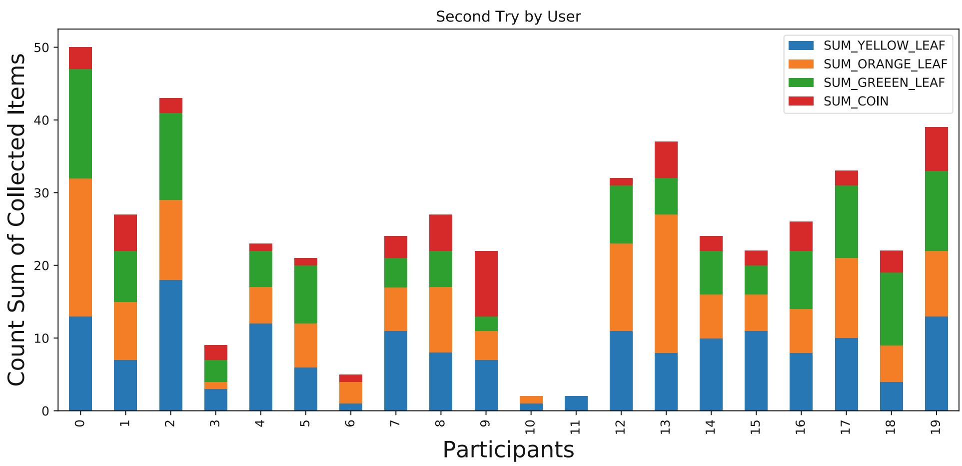
Questions	Mean ($\bar{x}$)	Std (σ)
Did you enjoy the VR application?	4.15	0.7
How much mental and perceptual activity was required?	2.75	0.9
How much physical activity was required?	2.3	1.2
How satisfied were you with your performance?	3.55	1.1
Did you perform better for the second time?	4.15	1.1
Did you have the immerse feeling while experiencing the app?	3.85	0.7
Would you like to try the VR application again?	4.3	0.7

According to survey results in Table 3, participants claim that the performed better in second time. The outcome of collected data in Table 4 also confirms the statement of participants. Utilizing basic statistical methods to support collected data has also shown that low or none VR experienced participants have performed almost four times better in the second try. The second time performance of the participant who achieved the highest difference compare first and second times is illustrated in Fig. 8. Moreover, the second attempt results indicates collected leaves do not have significant difference among participants based on VR experience level. However, participants with lower level VR experience did not pay the same level of attention for points to compare with amount of items. In other words, even though the point rewarding mechanism was known, it was not practical significantly.

Nevertheless, the results based on conducted survey can reveal subjective assessment to evaluate such as whether the application is joyful, easy, immersive, inconvenient etc. On the other hand, tracking the behavioral as well as



(a) Collected objects for first time



(b) Collected objects for second time

Fig. 7. Collected objects by users in both attempts

attentional aspects by given tasks and enabled interaction in VR based applications can validate the survey results. The method might also provide remarkable, objective and accurate feedback loop to improve and assess the application.

Table 4. Performance analysis of participants with VR experience

Parameter/collected items	VR experience level	Attempt	Mean ($\bar{x}$)	Std (σ)
Leaves	All	First	9.4	11.25
Coin	All	First	1.45	1.94
Leaves	Low or none	First	4.00	4.47
Coin	Low or none	First	0.88	1.65
Leaves	All	Second	21.65	12.17
Coin	All	Second	2.85	2.25
Leaves	Low or none	Second	17.25	10.12
Coin	Low or none	Second	1.63	1.40

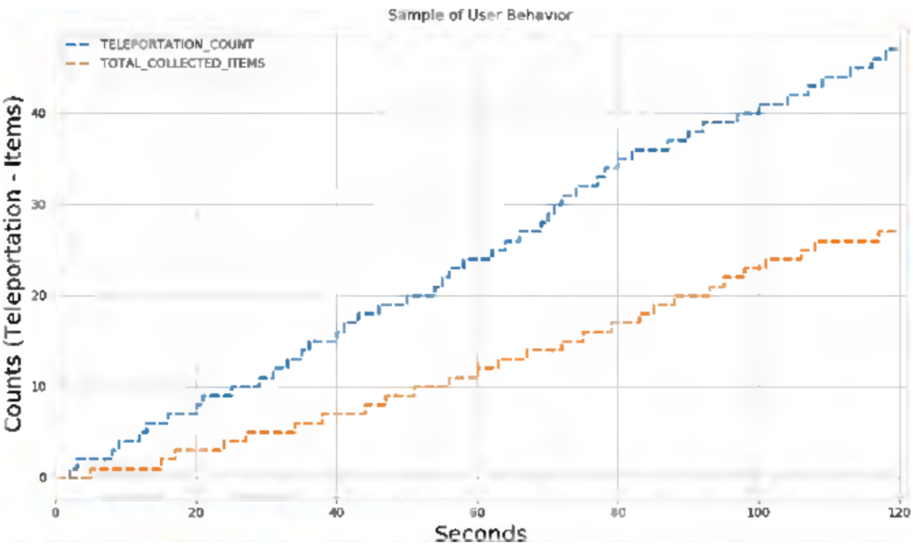


Fig. 8. Sample of interaction track of user while experiencing second time

5 Conclusions

In this paper, the general framework towards developing an interactive VR based application for analysis of user behavior was described. First, the background of the application was presented. Next, we have described complete system configuration including software management, 3D modeling, UI and integration of hardware devices. In this contribution, we have two main goals to employ the real-time streaming and collecting of datasets: to track accurate location and interaction of the user in immersive environment and orientation of HMD device worn by the user. As a result, although the experiment is in early stage, the application already illustrates the potential of using VR technology in practice. We conducted the application with two concrete experiments into assessments of locomotion and interaction features. These experiments were accomplished and provided important insights into the development of interactive VR based application. Furthermore, our findings may be beneficial for development of user experience assessment tools for VE. The data collection and automatic analysis may work in background during demonstrations when people are playing the game. Thus, the statistical relevance of the results is improved as the number of players increases. All the participants are informed in advance regarding collecting the data for research purposes. The data collection is only activated by accepting to share the data for research and development purposes. The unified and plug and play solution to integrate the other VR applications is yet to be investigated. Collected data sets of head orientation as well as user location in immersive environment will also be presented in future.

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Appendix 6

Publication 6

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Dynamic Predictive Modeling Approach of User Behavior in Virtual Reality based Application

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***Abstract*—Virtual Reality (VR) is considered to be a powerful modern medium for immersive data visualization and exploration. However, few studies have proposed solutions to complement data visualization in immersive environment considering the user's behavior. This paper addresses dynamic modeling of user behavior approach in an interactive VR based application. In this application, real-time data communication is employed to track accurate location and orientation of head mounted display device worn by the user. In our experiment, we use example of collected data and provide a methodology to predict next movements of the user by using nonlinear autoregressive (NAR) and location in the application by the nonlinear autoregressive neural network with exogenous inputs (NARX). Results suggest both neural networks are suitable for performing prediction which can be used to achieve an improved feeling of presence while reducing required high computational power. Data analysis part of the research is also linked to human behaviors to improve studies which are usually performed by traditional survey techniques.**

***Index Terms*—virtual reality, neural networks, dynamic modeling, real-time communication, human behavior**

I. Introduction

Recent exponential growth towards computational power gave rise to visualization techniques such as Virtual Reality (VR). VR is commonly considered as a computer-simulated environment which is able to provide an interactive graphical representation in a complete immersion for the user [1]. Therefore, present advancement in VR technology allows to induce a persistent effect of presence in virtual world. Besides that, accurate information about real-world position and orientation tracking of the user can also be claimed as a useful feature of VR. These features have become easily accessible with the advent of low-cost head-mounted display (HMD) devices such as Oculus Rift [2] and HTC Vive [3]. VR based applications have proven effective in number of scientific, entertainment, educational, training and industrial applications such as [4], [5], [6], [7] are employed to, including but not limited to: computer-simulated environments, visualizations of complex data, learning tools, gaming etc.

Meanwhile, analysis of large datasets has been attracting attention from various fields including, educational facilities, public sector, commercial companies [8]. Investigation of those large data-sets typically referred to as *Big Data* usually require visual analysis and naturally high computational power. We aim to use dynamic modeling to alleviate difficulties linked to data visualization towards applications in which HMD devices are employed, particularly in VR based applications. The dynamic modeling can ensure to make short time predictions and proactively start downloading the part of the data generated by a system or process that have to be visualized next. Consequently, Big Data related systems and processes will remain realistic and immersive while required computational power and network bandwidth are diminished. In our earlier work [9], we have introduced the fully immersive environment based on the physical architecture. In this work, previously implemented real-time data communication [10] is improved to collect necessary data and store in local database while the user experiences the VR based application. Besides that, novelty approach of the work in this paper is the verified architecture between the game engine and third party software to apply computational models methods including the nonlinear autoregressive (NAR) neural network and nonlinear autoregressive neural network with exogenous inputs (NARX).

We now outline the main contribution of the present paper. First, we provide a firm motivation of this work by reviewing relevant Big Data visualization aspects and discussing the analysis of human behavior in VR based applications. Then, we present configuration of the VR based application in order to enable real-time data communication. We also investigate the employed communication protocol in order to minimize latency during the VR experience. In the following section, we describe preferred methods to alleviate required computational power for performing prediction. First, we employ NARX neural network to predict the user location by the movement of HMD. Next, NAR neural network is used by previous measurements to predict the next values. Finally, results of employed network models linked to human behavior are drawn as conclusion.

The structure of the paper is as follows. In Section II,

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the reader is introduced to Big Data visualization conducted with the immersive environment. The process of creating the application and real-time data collection are also explained in this section. First results of experiment based on human behavior in VR based application is addressed in Section III. Finally, conclusions are drawn in Section IV.

II. Merging Big Data Visualization and Analysis with VR

A. Human Computer Interaction with Big Data in VR

Human–Machine Interaction (HMI) is one of notable topics for researchers and the effectiveness of HMI related applications are usually linked with the interactivity aspect [11]. The interactivity also encourages users to be more operative and complements their learning process [12]. Meaningful visualization of Big Data raises the challenge gradually due to required computational power. Besides processing huge amount of data**,** potential high diversity of provided data adds to the challenge. Although traditional visualization tools have been updated continuously to ensure their effectiveness, they have already reached to their limits when encountered with very large data [13]. Hence, we aim to clarify traditional blended techniques by one of powerful modern medium—VR. Essentially, merging interactions in immersive environment provided by VR, brings different perspective to HMI. In other words, HMI can be obtained to maximize in artificial reality conditions with minimized latency [14]. One of the main attitude of VR based applications is to grant user with interactions in virtual environment (VE) for independent movements. Users equipped by HMD devices and controllers can navigate the virtual environment efficiently and interact with it in a meaningful way. Meanwhile, several studies have already been introduced through visualizations Big Data conducted with VR based applications to relief present difficulties and to engage users efficiently with provided data [15], [16], [4]. Additionally, dynamic modeling of user behavior can be beneficial to decrease required high computational power for visualization purposes. Ability to predict user's behavior is one of the key issue that can lead to a coherent solution. The prediction might allow to preload only the necessary part from Big Data sets. In addition, the solution would also benefit VR based applications to ensure a seamless immersive experience possibly with less computational power. In order to gain the following highly important advantages in Big Data related visualizations, it is remarkable to engage with key issues which need to be investigated as follows:

1) Human movement prediction for determining the data to be preloaded into the memory of the employed device for visualization purposes.
2) Development of meaningful and intuitive interactions with the visualizations. This ensures that the data can be explored efficiently and in a way that allows to and even encourages to gain novel understanding into complicated interconnections given the three-dimensional representation of the data in VE.
3) Creating a collaborative immersive environment in order to allow researchers for interaction purposes with the data and among themselves to increase the efficiency of the data study.

(a) Interior Environment

(b) Exterior Environment

Fig. 1. Screenshots from the VR based application

B. Replication of Large Scale Building

The employed VR based application is created by Unreal Engine 4 (UE4) which is commonly used and capable solution for VR development purposes [17]. Using primary game engines is convenient to deploy with VR development methods such as object oriented programming, plugins, visual scripting, reusable code with libraries [18]. Although the physical building and its environment is unique, the process for composing the architecture replica is familiar to other VR based applications. 3D modeling and rendering of the replica were progressed by using Autodesk Maya software [19] based on accurate measurements. Screenshots from the application are illustrated in Fig. 1. In order to ensure high visual quality to maximize impact of presence feeling, the application is assembled with more than 4400 elements including meshes, navigation collision, lights, blocking volumes, light mass importance volumes, ambient sounds, brushes, trigger boxes, materials etc. [20].

The application is served with one of most common HMD device—HTC Vive—which grants users with physical mobility, positioning and tracking based on real time with high display resolution. Additionally, independent virtual navigation benefits, synchronized controllers are some of facts to prefer the HMD. The device also provides 1080x1200 resolution per eye, and the 9-DOF with 2 lighthouse base stations for tracking and two sets of controllers. The controller features 24 sensors, dual-stage trigger and multi-function track–pad [21]. It is also relevant to point out the specific hardware and software specifications for development and deployment. The application run on a PC equipped with a 4.00 GHz Intel i7-6700 processor, 32 GB RAM, and an NVidia GTX 980 graphic card.

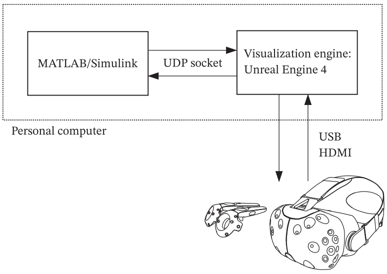


Fig. 2. Process of the application for real-time platform

C. Implementation of Real Time Data Communication

The particular visual scripting tool for the game engine allowed us to create a User Datagram Protocol (UDP) interface [22]. The interface is capable to communicate between third party software and the physics engine based on a custom C++ class. To avoid problems with multi-threading in the game engine, the implementation uses a custom class variable to transfer data between threads to avoid a racing condition in requesting/getting new data from the UDP socket. With this approach, reliable communication via a UDP socket at relatively high sampling rates such as f_s=1 kHz is easily achieved. However, in order to ensure smooth experience with minimum latency possible for the user, UDP socket is employed to collect data with f_s=10 Hz sampling rate. The diagram showing the first level prototyping configuration is depicted in Fig. 2.

III. System Identification and Modeling

A. Input and Output Data

Collected data referred to position degrees consist of orientation and location data sets. Location of the user is provided through $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates in immersive environment. Location of the user provided by example of collected data in time series sets depicted in Fig. 3.

The user behavior, $\mathbf{A}$, is translated by some $\mathbf{x}_t, \mathbf{y}_t, \mathbf{z}_t \in \mathbf{R}$ using

$$(\mathbf{x}, \mathbf{y}, \mathbf{z}) \mapsto (\mathbf{x}+\mathbf{x}_t, \mathbf{y}+\mathbf{y}_t, \mathbf{z}+\mathbf{z}_t). \quad (1)$$

Suppose $\mathbf{A} = H_i$ is translated $\mathbf{x}_t$ units in the $\mathbf{x}$ direction and $\mathbf{y}_t$ units in the $\mathbf{y}$ direction. The transformed primitive is A primitive of the form

$$H_i = \{(\mathbf{x}, \mathbf{y}, \mathbf{z}) \in W \mid \mathbf{f}_i(\mathbf{x}, \mathbf{y}, \mathbf{z}) \leq 0\}. \quad (2)$$

is transformed to

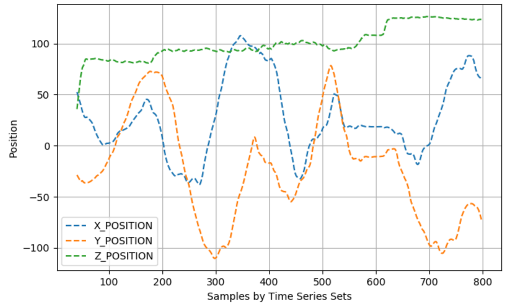


Fig. 3. Position degrees consist of location while the user experiences VR based application

$$\{(\mathbf{x}, \mathbf{y}, \mathbf{z}) \in W \mid \mathbf{f}_i(\mathbf{x}-\mathbf{x_t}, \mathbf{y}-\mathbf{y_t}, \mathbf{z}-\mathbf{z}_t) \leq 0\}. \quad (3)$$

Gyro sensor integrated to HMD devices are used to collect information of head rotation (yaw, pitch and roll) while the user experiences the immersive environment. Yaw is considered while the user looking left and right, positive when turning left. While looking up or down in the application is referred to pitch which is positive when pitching up. Finally, roll can be defined as tilting the head sideways. The head rotation is illustrated in Fig. 4.

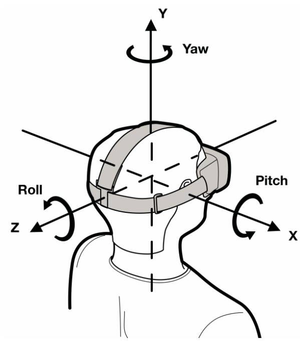


Fig. 4. Head rotation using gyro sensor [23].

1) A yaw is a counterclockwise rotation of α about the $\mathbf{z}$ axis. The rotation matrix is given by

$$\mathbf{R}_z(\alpha) = \begin{pmatrix} \cos\alpha & -\sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix}. \quad (4)$$

2) A pitch is a counterclockwise rotation of β about the $\mathbf{y}$ axis. The rotation matrix is given by

$$\mathbf{R}_y(\beta) = \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix}. \quad (5)$$

3) A roll is a counterclockwise rotation of γ about the $\mathbf{x}$ axis. The rotation matrix is given by

$$\mathbf{R}_x(\gamma) = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\gamma & -\sin\gamma \\ 0 & \sin\gamma & \cos\gamma \end{pmatrix}. \quad (6)$$

A single rotation matrix can be formed by multiplying the yaw, pitch, and roll rotation matrices to obtain [24]

$$\mathbf{R}(\alpha,\beta,\gamma) = \mathbf{R}_z(\alpha)\mathbf{R}_y(\beta)\mathbf{R}_x(\gamma). \quad (7)$$

According to described equations above, if any of head rotation is known, position defined $(\mathbf{x},\mathbf{y},\mathbf{z})$ coordinates will be given by the matrix. Since collected data enables investigation into head movement and location of user in the applications, authors focus on two types of predictions:

- Performing predictions based on dynamic changes of head rotation as $\triangle(\alpha), \triangle(\beta), \triangle(\gamma)$ meaning using measured movement values to predict next values.
- Performing predictions of user's location in the application by using head movement values as exogenous inputs.

B. System Identification and Dependence

Identification of a user's behavior is basically determined on the basis of each vector of location and orientation. The degree of association between two variables; as an input variable is for example head movement of user, the means of all corresponding values of the output variables are described by correlation [25]. In order to measure the strength of linear association between two variables, The Pearson correlation coefficient is employed [26]. Example of collected and filtered data set includes 663 time series sets of 6 elements. The correlation coefficients of each vector based on duration of experience in VR based application are presented in Table I. Correlation coefficients reveal the system can be defined potentially demonstrated as a nonlinear system. Moreover such kind of behavior related systems are provisioned as nonlinear systems comparing to input and output variables.

TABLE I
THE CORRELATION OF EACH VECTOR IN SAMPLE DATA

	X	Y	Z	YAW	PITCH	ROLL
X	1	-0.10	0.04	0.08	0.09	-0.04
Y	-0.10	1	-0.49	-0.27	0.07	-0.01
Z	0.04	-0.49	1	0.09	-0.02	0.02
YAW	0.08	-0.27	0.09	1	-0.68	-0.30
PITCH	0.09	0.07	-0.02	0.03	1	-0.16
ROLL	-0.04	-0.01	0.02	-0.30	-0.16	1

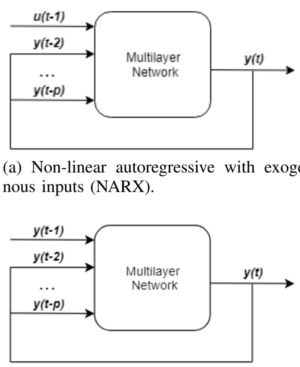
C. System Identification Using Artificial Neural Networks

ANN based prediction has been developed since it was explored because of ANN approximation and generalization property. Many research papers in different fields like energy, finance, data mining, medical, industrial etc. are published in scientific literature, and some commercial companies claim or market the so-called advanced statistical programs using neural networks, for modeling and prediction [27], [28]. ANN, with the ability to approximate a large class of nonlinear (NL) functions, provide a feasible uniform structure for NL system representation that is usually described with differential equations (continuous-time model) or difference equations (discrete-time model). Furthermore, ANN have already been successfully used for modeling and prediction of human behavior with different perspectives [29], [30].

1) NARX Model: The model is built up with the wavelet network to create input and output non-linearity estimator. An important class of discrete-time nonlinear systems is NARX model is formalized by

$$y(t) = f(u(t-n_u),...,u(t-1); \\ u(t); y(t-n_y),...,y(t-1)), \quad (8)$$

where $u(t)$ and $y(t)$ represent input and output of the network at time t, n_u and n_y are the input and output order, and the function f is a nonlinear function. When the function f can be approximated by a *Multilayer Perceptron*, the resulting system is called a *NARX* network. The topology of employed network model depicted in Fig.5a.



(a) Non-linear autoregressive with exogenous inputs (NARX).

(b) Non-linear autoregressive (NAR) network

Fig. 5. Topology of network models

2) NAR Model: An important class of discrete-time nonlinear systems is NAR model is formalized by [31]

$$y(t) = h(y(t-n_u),...,y(t-1); \\ y(t); y(t-n_y),...,y(t-1)) + \epsilon(t) \quad (9)$$

where $y(t)$ represent input and output of the network at time t, n_u and n_y are the input and output order, and the function $h(.)$ is unknown in advance, and the training of the neural network aims to approximate the function by means of the optimization of the network weights and neuron bias. Finally, the term $e(t)$ stands for the error of the approximation of the series y at time t [32]. The topology of model depicted in Fig. 5b. The main difference between NAR and NARX is that external input used for NARX model.

D. Dynamic Predictive Modeling of User Behavior

This section describes the process that can perform any other user behavior prediction since the approach is general to employ both NAR and NARX neural networks. The process of implementation as follows:

1) **Data Communication and Collection**: UDP protocol is in charge of sending the real-time user movement and location data as time series to local database while the user experiences the application.
2) **Noise Filtering**: Besides the location information of user, the captured sensor information of HMD which can be sometimes noisy and unreliable. According to behavior patterns, rare outliers (below $\%1$) of sensor data is removed.
3) **NARX Model Training**: Filtered data is divided into 70% training data, 15% validation and 15% test data. The model has been trained using Levenberg-Marquardt algorithm which is often the fastest back-propagation function and commonly used [33], [34].
4) **NAR Model Training**: Similar procedure as NARX model training is followed for data division and selection of training function. Results of both models are addressed in the following subsection.
5) **Performance Comparison and Validation of Trained Model**: Once accurate results are accomplished, test data which is not introduced to these models are set for validation purposes.

E. Results of Prediction Performances

Virtual-world position of the user based on $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates is used to perform predictions by NARX neural network. The position is measured by the game engine unit (uu) and $1uu = 1cm$ [35]. The head movement is the rotation of the yaw, pitch, roll direction whereas the measured range of rotation for the pitch is approximately $\pm 40°$. Increasing the input delay by one (time–shift between inputs and outputs) corresponds to $100ms$. The amount of regressors are 3 and 6 for NAR and NARX models respectively. Inputs and outputs of NAR and NARX networks together with measurement units are defined in Table II.

TABLE II
MEASUREMENT UNITS OF INPUTS AND OUTPUTS FOR USED NEURAL NETWORKS

	X	Y	Z	YAW	PITCH	ROLL
NARX network	I/O	I/O	I/O	I	I	I
NAR network				I/O	I/O	I/O
Measurement units	cm	cm	cm	°	°	°

Mean Absolute Error and Mean Square Error are two preferred parameters to present results of trained network models.

- MAE (Mean Absolute Error) : The MAE measures the average magnitude of the errors in a set of forecasts, without considering their direction and it is formalized by $MAE = \frac{1}{n} \sum_{j=1}^{n} |y_j - y_t|$ where y_j represent predicted value, y_t is true value and and n the number of data samples.
- MSE (Mean Square Error) : The MSE is arguably the most important criterion used to evaluate the performance of a predictor or an estimator. The MSE is used for measuring of the difference between values predicted by a model and the values of actual data [36]. MSE is formalized by $MSE = \left(\sum_{j=1}^{n} (y_j - y_t)^2 \right) \frac{1}{n}$.

TABLE III
RESULTS OF THE NETWORK MODELS COMPARED WITH INPUT DELAYS

NARX	$t-1$	$t-2$	$t-3$	$t-4$	$t-5$	$t-6$
MSE	0.59	0.62	0.78	1.29	1.38	1.42
MAE	0.45	0.55	0.60	0.61	0.76	0.79

(a) Results of the NARX model compared with input delays

NAR	$t-1$	$t-2$	$t-3$	$t-4$	$t-5$	$t-6$
MSE	0.52	0.68	0.92	0.99	1.23	1.37
MAE	0.48	0.58	0.65	0.69	0.75	0.81

(b) Results of the NAR model compared with input delays

After processing the collected sample data, changes of head movement is introduced to NARX model with exogenous inputs while the location data is used as an output. The model is trained by different time delays in order to obtain feasibility of prediction towards sample data. Table IVa shows results of MAE and MSE. In what follows, NAR model performed in order to predict values of head movements by using measured values. Results of MAE and MSE are presented in Table IVa.

Considering approximately over 65 seconds of data which generates 663 samples with 6 elements, with MSE of 1.42 for $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates and angles with up 6-step ahead is highly satisfied for real-time implementation to perform NARX model. Furthermore, NAR model with $t - 6$ time delay up to MSE of 1.37 seems relevant. Results of prediction performances reveal that NAR model is suitable to predict head movement of user while NARX model can perform to predict user‘s location in VR based application. Finally, results of NARX model with test data is drawn in Fig. 6.

IV. CONCLUSIONS

In this paper, dynamic predictive modeling approach of user behavior in virtual reality based application has been introduced. First, the background of the application with the complete system configuration was presented. In this contribution, the improved real-time solution was employed to perform prediction of user movement. Collected sample data set of user behavior was introduced to NAR and NARX model and provided findings into the development of interactive VR based application. As a result of NARX model with MSE of 0.78 for $t-3$ and 1.42 for $t-6$ and with MSE of 0.92 for $t-3$ and 1.37 for $t-6$ a measure of how close the predictions are to the actual behavior is presented. Since the present application is envisioned to be used for real-time applications to complement data visualization and exploration

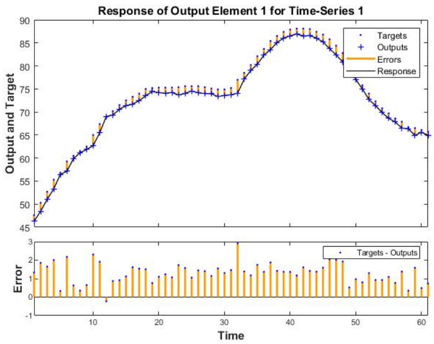


Fig. 6. Prediction Performance of NARX Model

with diminished computational power, further development efforts also should be exhibited to run models simultaneously in order to feed output of NAR model to NARX. In addition, to increase accuracy, it would be beneficial to use motion controllers or other available technology for collecting data for modeling specific elements of diversified behavior.

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Appendix 7

Publication 7

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Real Time Data Communication for Intelligent Extended Reality Applications

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***Abstract*—Virtual Reality (VR) is a powerful modern medium. Immersive qualities of VR enables the design of efficient educational, industrial and training solutions. The advent of low-cost head-mounted display (HMD) devices made this technology accessible at large and featured VR with possibilities to monitor interactions and user's motion. However, due to lack of real–time data communication and collection at present, it is still a challenge to obtain a feedback mechanism related the user's behavior. This paper addresses an architecture that is designed to implement a feedback mechanism. The architecture consists of a data communication tool, a relevant immersive environment and third party software. The communication tool is used to transmit data with different sample rates in real-time. The feedback mechanism of designed architecture is presented through a number of case studies. A solution for observing the user's behavior is also presented in this paper with the motivation to complement analysis of performed activities and subjective feedback towards VR based applications.**

***Index Terms*—virtual reality, HMD, real-time communication, human behavior, UDP, feedback mechanism**

I. Introduction

Computer simulation (CS) can be defined as a hybrid technology of using computer science and available technology to build simulation models and then performing experimentation on the models under various conditions [1]. Virtual Reality (VR) is the fruition of CS complemented with immersive technologies that is enabled by leveraging recent advances in communication, computing, analytical aspects of Big Data, artificial intelligence (AI), and other adjacent areas [2]. Virtual environments (VE) formed by VR technology have proven effective in many scientific [3], industrial [4] and medical applications [5] and are applied in, including but not limited to: computer-simulated environments, visualizations of complex data, joyful learning tools, etc. Additionally, VR technologies have been growing rapidly. It is estimated that this technology will reach over 300 million users worldwide by 2020 [6]. On the other hand, VR technology also faces challenges to become a very powerful modern medium at present such as feedback mechanism from the user what might include user motion, emotional states and interactions in real–time. Therefore, convenient methods and robust infrastructures are not available yet to analyze interaction and behavior in immersive environments (IE), however a number of studies have proposed solutions [7], [8], also with emphasizing interactions [9], [10].

In our earlier work [11], we have introduced the real time solution that implemented to allow the user to experience sound visualization of physical sound source in IE. In this work, we present the an architecture that employs improved real time solution for communication. Eventually, the architecture is devoted to enable studies towards the potential of VR in the context of IE and multi–modal interactions. In particular, real–time monitoring through designed architecture allows analytical researches focus on user's behavior in VR based applications. As a remarkable benefit of this work, presented developments may assist to form the basis for creating VR based applications towards assessment of behavioral patterns in an immersive environment.

The main contribution of the present paper is as follows: First, the developed communication protocol is described on which meaningful immersive interactions in XR environments are based. Then, we explain real-time data transmission for VR based applications. We also investigate the socket implementation for communication with different sampling rates, while considering the latency during the VR experience. Next, we briefly introduce designed VR based applications to verify real time communication. In the following section, we describe the architecture to obtain the feedback mechanism. First, we present the workflow that includes data communication, collection and preprocessing. Next, we describe our vision towards observation of behavior. Finally, we report and address the initial findings related to the proposed architecture and outline some related items for future research.

The structure of the paper is as follows. In Section II, the reader is introduced to the real-time communication tool and presented with relevant case studies. The designed architecture to obtain feedback mechanism for data transmission and storage is explained in detail in Section III. Our novel developments towards assessment of behavioral patterns and dynamic modeling by employing feedback mechanism are also addressed in this section. Finally, conclusions are drawn in Section IV.

II. Real Time Data Communication in XR: Context and Implementation

Open Systems Interconnection (OSI) model was developed to demonstrate the architecture of a network communication system that initiated by the International Organization for Standardization (ISO) [12]. The model is a reference to define message transmission between any two points in the system which is the most common networking architecture model at present [13]. The model is composed of seven layers in two main groups: The upper–layer with three layers and the lower–layer with four layers is depicted in Fig. 1. The transport layer is particularly substantial in the content of the designed architecture that locates between the network and session layer. Several different transport layer protocols (TLP) exist to accommodate different application layer needs. Despite the potential diversity in TLP, it can be categorized into connection–oriented and connectionless protocols [14]. While Transmission Control Protocol (TCP) operates in connection–oriented mode, User Datagram Protocol (UDP) is a connectionless protocol uses datagrams to send messages from one end system to another. UDP was chosen for the implementation of the real-time communication solution because it does not require any prior connection setup to transmit data [15] and hence is especially suitable for near hard real-time applications. This is possible because UDP is a connectionless protocol, it provides message delivery with minimum effort to upper–layer protocols and applications without setup a permanent connection between two end points [16], [17]. The lightweight procedure to transfer data does not have specific requirements when running on numerous platforms. UDP transport protocol provided a straightforward method to transfer packets over local network among utilized software including Matlab (where a corresponding implementation of real-time communication is also available through the use of UDP protocol), and data management systems that are used for preprocessing and storage of relevant data used in VR applications. Therefore, UDP based data communication plugin was developed to transmit data among VR based applications and third party software.

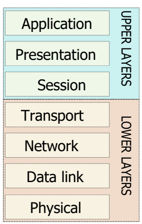

Fig. 1. The seven layers OSI architecture [18]

A. *Implementation of Real Time Data Communication*

The application is created in Unreal Engine 4 (UE4) which is a commonly used and powerful solution for VR development purposes. UE4's Blueprint visual scripting system is one of the reasons to prefer UE4 to other real-time visualization engines since it allows for rapid prototyping [19]. Blueprint is a complete gameplay scripting system based on the concept of using a node-based interface to create gameplay elements from within Editor View [20]. Furthermore, It is possible to compile Blueprints to C++ code for improving performance in the finished product. A mix of Blueprint and C++ code allowed us to create a UDP interface to communicate between a number of third party software and the game engine in real time. To avoid problems with Blueprint multi-threading for VR based applications, the implementation uses a custom class variable to transfer data between threads to avoid a racing condition in requesting/getting new data from the UDP socket. With this approach, reliable communication via a UDP socket at sufficiently high sampling rates upwards of 1kHz is achieved. However, lower sampling rates are considered for some implementations without giving rise to significant issues even if high quality visualization in VR is used at 2160x1200 pixel resolution and 90Hz. [21].

B. *Validation of Real–Time Data Communication*

VR based applications are served with one of the most common HMD devices—HTC Vive. The device grants users with physical mobility, positioning and tracking based on real time with high display resolution and 2 lighthouse base stations. It is also relevant to point out the specific hardware and software specifications for development and deployment. The application runs on a PC equipped with a 4.00GHz Intel i7-6700 processor, 32GB of RAM, and an NVidia GTX 980 Ti graphics card.

In what follows, we briefly describe two case studies that employ the real time communication tool.

1) Experiments with Inducing Synesthesia: Synesthesia is the act of experiencing one sense modality as another. For example, a person may vividly experience flashes of colors when listening to a series of sounds. VR allows to achieve this transition easily, since it can be used to present the spatial whereabouts of the sound source as well as visualize the sound content in a meaningful way. The ultimate goal of the experiment is to provide means for inducing voluntary synesthetic experiences through the VR based application. In [11], we describe the revised technical solution meant to deliver the synesthetic experience to the listener in real time. The process of the experimental setup is as follows. First, we apply an acoustic localization method to the problem of locating the sound source. We also apply a Kalman filter to reduce motion noise generated by the uncertainty of sound source location prediction. Next, for consistency, we summarize the method for extracting dominant features from the audio spectrum of the sound source and mapping those to the object representing the sound source in the VR environment. Finally, we create sound visualization in real time with the complete experimental configuration that is shown in Fig. 2. Most importantly, the experiment provided evidence that using the UDP communications plugin it is possible to ensure real time communication from third party software to VR based applications even at high sampling rates.

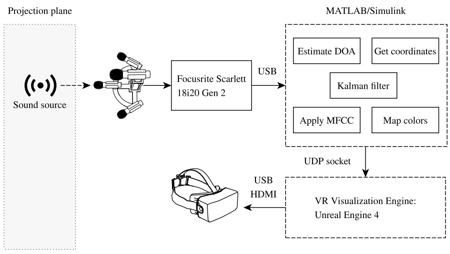

Fig. 2. Experimental configuration and signal flow of the synesthesia inductor prototype

2) Digital Twin Objects for Laboratory Experiments: The work is dedicated to creating virtual objects for real-time experiments. Realistic replications of corresponding original control objects located in our control systems laboratory are endowed with appropriate mathematical models of their dynamics. One crucial step is to mathematically model and implement physically accurate interactions between the user and the virtual objects. So far, three objects have been modeled: The Inverted Pendulum, the 3D Crane, and the Magnetic Levitation System that is shown in Fig. 3. The initial goal with replicating the objects in VR was to ensure efficient laboratory instruction, however, now they are also used for advanced real-time experiments that may allow integration of the corresponding tools into industrial processes. Set points of control objects are changeable to give a better understanding of the system for the user. Besides that, one of the most interesting part of replicated objects give access the user to interact directly with moving mechanical parts of virtual objects. Controllers of the employed VR device act as virtual hands allowing for physical interaction which causes disturbances in the controlled systems. From the user perspective, such interactions are of curiosity driven experimental nature.

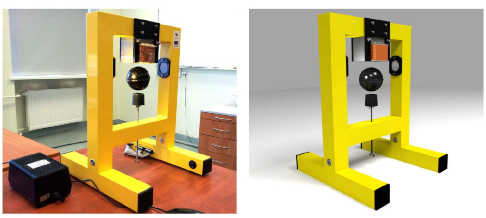

Fig. 3. The magnetic levitation System and its 3D Model

The UDP based plugin made real-time simulation possible with Matlab in two ways: hardware-in-the-loop (HIL) and software-in-the-loop (SIL) simulations. In order to enhance real-time prototyping with the SIL approach, we attach validated mathematical models to the game engine using the UDP communication solution. The diagram showing the prototyping configuration is depicted in Fig. 4. Furthermore, the environment enables to work as a group or as a single user. Essentially, the application can run simultaneously if Matlab is set up another computer. For instance, meanwhile a student is experiencing the virtual object, another student can also modify the mathematical model.

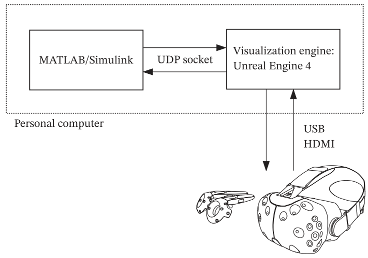

Fig. 4. Process of the digital twins of control objects in real-time

C. Implementation of the Real Time Tool for VR based Applications

UDP based connection is a remarkable part of designed architecture since it enables near hard real-time communication between VR based applications and third party software with typical delays up to one sample. The socket connection has a dependency to be updated to the same version of the game engine while development process. The protocol allows transferring up to twenty float and three integer parameters, meaning that only numerical values can be transferred using in a given implementation at present, though due to the flexibility of the implementation, the data interface can be extended in the future.

Synthesia experiment is a proof of concept implementation to provide feedback from employed third party software with high sampling rates upwards of 1kHz.

In order to achieve a complete visualization with real-time feedback for such experiments, the following components should be accomplished:

- Available a C++ class / Blueprint based UDP socket implementation must be configured.
- All necessary animations should be scripted and the information should be received via the UDP socket from third party software (e.g. MATLAB).
- Blueprint / C++ class made actors must be available in VR environment.

Since HTC Vive is used as a HMD device in applications, the corresponding VR template in UE4 can be employed. The template allows users to navigate in immersive environment directly by adding a navigation mesh.

The experiment with replicated control objects allows for two-way communication, so that user interaction also can be utilized as an input for third party software which must generate relevant feedback to the user. In this work, we consider two types of interactions which arise in the area of control systems that can be applied in various fields for similar coupled controllable objects:

- Interactive selection of the control system tracking reference (set point).
- Direct physical interaction with the moving parts of the recreated control objects. From control systems perspective, this is generally used to introduce disturbances into the studied systems.

UDP plugin as well as exported modules can also be reused in any project. In addition, Matlab via Simulink Desktop Real-Time toolbox is set up once per particular application. The latter allows to simulate any physical process that is visualized on the UE4 application side in VR.

III. Designed Architecture of the Feedback Mechanism

Immersive environments (IE) can engage with various senses of the user such as visual, auditory, gesture, haptic, etc. including any combination of these senses while allowing users to interact and move within [22] the IE. Accordingly, VR can be used for developing novel interaction means, such as those based on interchange of senses [11]. Moreover, with unprecedented capabilities for creating synthetic IE, many important questions arise to evaluate designed applications in different directions, assess the efficiency of delivered content. Therefore, it is crucial to understand how users explore virtual environments (VE) [23]. However, due to lack of feedback mechanism at present, the level of behavioral understanding of users is not sufficient and statistical models are not available to apply relevant predictions.

In order to tackle these issues, we design an architecture with the basis of the feedback mechanism implementation that can be described as follows: The game engine is employed as the visualization platform while the user experiences IE with interactive equipment. Motion capture is achieved using present HMD technology which provides access to user movement data. UDP serves as a communication plugin between the game engine and software environment that makes real–time data communication, simulation and feedback possible. To proceed with modeling of the user's head and controller movement, the data related to the user is sent out to data preprocessing layer (e.g., Python) and then to an electronic database to store and apply statistical and computational intelligence methods. Behavioral learning is occuring between the HMD device and data preprocessing layer. The workflow to illustrate the complete feedback mechanism is depicted in Fig. 5.

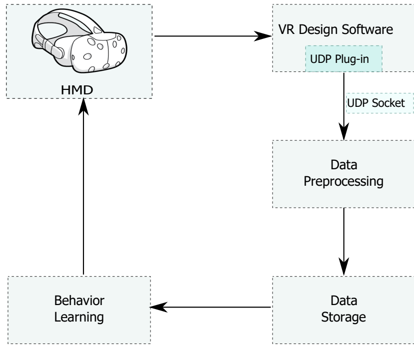

Fig. 5. Workflow of the Complete Feedback Mechanism

A. *Observation of Behavior with the Feedback Mechanism*

One of the main attractive features of VR applications is to allow users to interact with the environment and other users (e.g. the CAVE [3]). VR based applications are often delivered with the interaction that may also allow an evaluation of the engagement of participants [24]. Paliokas et Al. defines that observation of behavior particularly in the content of IE is "the collection of behavioral data on certain subjects when involved in various activities under particular conditions" [25]. Analysis of performed activities and subjective feedback towards VR based applications are studied typically by post-experience oriented surveys. On the other hand, it has become possible to alter this set of metrics recently by psychophysiological data that actually requires additional properties and advanced techniques in order to obtain fully objective measures [26]. The other family of metrics which is also the main focus of behavior learning in the feedback mechanism that is related to users' behavior inside the VE such as location and interactions of users [27]. Accordingly, elements of metrics towards VR based applications delivered with HMD devices such as location of user in IE, teleportation, head and controller movement of users, rewarding points in gaming–oriented applications should be traced to obtain behavior learning.

One of elements of metrics is that the teleportation is a type of locomotion and ubiquitous interaction for most of VR based applications [28]. Eventually, it allows users to move independently and effortless in IE. Although the teleportation let the user to navigate, it is an artificial feature and somewhat unfamiliar to users in terms of actual experience (with the exception of users having previously used VR). Consequently, some difficulties while attempting to use teleportation such as lack of presence feeling, cybersickness emotions may also be observed [29]. Thus, the part of study of users' behavior should be devoted to investigating the locomotion which let the user interact with objects during continuous movements.

From the user perspective, interactions linked to the gamification based engagement (e.g. joyful learning, serious games) are of curiosity driven experimental nature [30]. Moreover, the user can adapt to the gaming environment by interacting with it, and the perceives tasks to be completed [31]. It is essential to provide the user with motivation to engage with the VE. Training for real-world scenarios with strict time limitations can be applied effectively by following a similar methodology [32]. However, applying interactions, teleportation and physical movements at once can be challenging for users even those with previous VR experience. Hence, investigation of behavioral learning shall include all of these items to obtain meaningful evaluation.

B. Data Collection and Preprocessing in Real Time

The demonstration of the feedback mechanism, particularly data preprocessing and storage, is carried out by particular implementation—*Swedbank Experience* which is a gaming–oriented VR application that is explained with details in our earlier work [33]. The data collection is only performed upon the user filling the consent form and accepting to share the data for research and development purposes. In the VR experience, the user's goal is to collect as many game points as possible during two minutes of game time. There are four different items in the game for the defined goal: three leaves of various colors and a coin awarding $1, 2, 3, 10$ to the player if collected. In game level, the items are randomly generated and scattered but only around the defined play area. Players are motivated to use teleportation feature to move around the play-area in VE faster since the distances between collectable objects are random and often the objects are far apart from each other. The objects spawn in different locations and at a varying distance from the ground, so the player must move physically. Sample of collected data that includes teleportation and collected points of one user is illustrated in Fig 6. After the game sessions, each player is also asked to fill the survey that consists of seven questions by rating 1 (very low) to 5 (very high) to compare the subjective feedback with accurately measured data. To sum up, collected data with classified types including background and behavioral information for the demonstration is presented in Table. I.

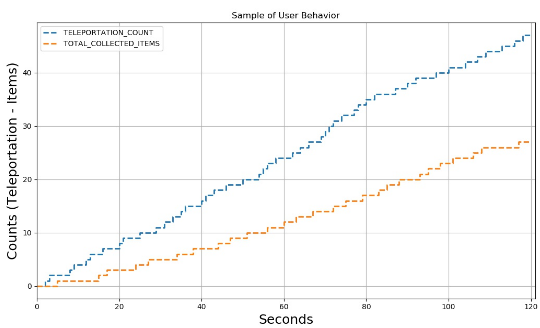

Fig. 6. Sample of interaction track of user while having the VR experience

All data types are translated into numeric values, if necessary. For example, "Gender" is the part of the required form to fill by the user via user interface and selected output is defined as 0 or 1 meaning male or female. UDP plugin is employed to collect data with $f = 1$Hz sampling rate. As a result, data preprocessing and storage through to the feedback mechanism is accomplished. Additionally, the data collection and automatic analysis can work in background during the experience.

TABLE I
COLLECTED DATA DURING THE DEMONSTRATION

Data Type	Collected Information
1	Age, Gender, Education Level and Experience in VR
2	Teleportation Usage, Amount of Collected Items
3	User Location in VR, Head Movement of User

Complete behavioral analysis inside VE is one of the most recurrent interests for researchers but requires a significant amount of time and effort. However, studying the users' behavior including interactions and physical motions can provide this information. The intelligence derived by the proposed feedback mechanism based on behavior learning can be used, for example, to create adaptive virtual learning environments to increase learning efficiency and to reduce cost of visualization (e.g. computational power for Big Data visualization) by predicting the user's behavior. We also conduct an experiment with $f = 10$Hz sampling rate of data collection in order to provide a methodology to apply dynamic modeling [34]. Location of the user that is provided through $(\mathbf{x}, \mathbf{y}, \mathbf{z})$ coordinates in IE as time series sets is depicted in Fig. 7. Predictions of user's location is performed by using head movement values with the nonlinear auto–regressive neural network model (NARX) up to 5-step ahead. Results suggest that neural network models are suitable for performing prediction which can be used for real-time applications including mentioned use cases.

IV. CONCLUSIONS

In this paper, an architecture to obtain a feedback mechanism for VR based applications is introduced. The designed architecture consists of the developed UDP based data communication tool, HMD device, VR based application and third party software. The UDP tool is developed particularly to transmit data among VR applications leveraging the connectionless property for near hard real-time communication. The feedback mechanism of the architecture is presented through a number of VR based applications including discussion of experiments for inducing synesthesia and those related to understanding the mechanics behind control systems. Then, particular applications are complemented with the mechanism to enable collecting motion data with an investigation towards behavioral learning are presented. As a remarkable outcome of the application of the presented architecture, intelligent systems based on user motion and actions that can be developed that provide real time proactive qualities to design adaptive user interfaces and advanced recommendation systems [35]. Furthermore, the designed architecture can be used for other applications since UDP plugin can be reused in any project and instructions are given in this paper. The unified and plug&play solution to integrate the other VR applications including other game engines is yet to be investigated.

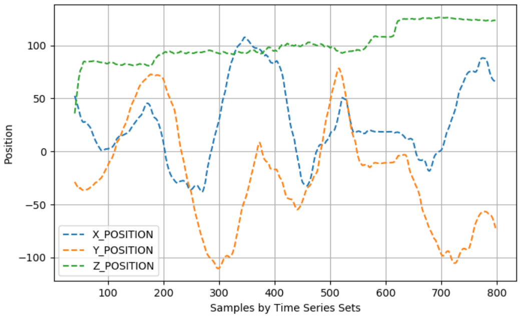

Fig. 7. Position degrees representing user's location in VE

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