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DESIGN AND DEVELOPMENT OF A STATE-OF-THE-ART UNIVERSAL LABORATORY FOR VIRTUAL REALITY, REAL-TIME SIMULATION AND HUMAN-MACHINE INTERACTION

Examiner(s): Professor Heikki Handroos
D. Sc. (Tech.) Hamid Roozbahani

ABSTRACT

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Keywords: Laboratory of Intelligent Machines, Simulation laboratory, Visualization, Projection systems, Display systems, Virtual Environment.

This Master's Thesis is focused on design and development of the LUT Laboratory of Intelligent Machines as the cutting-edge Simulation Laboratory, which includes HMI, VR and real-time research areas. Composing of the future laboratory concepts and studying of the possible options for the visualization system were priority tasks. Developed visualization system was presented in two options: display-based and front projection system.

The information about equipment, its requirements and compatibility was gathered from the open-sources, project meetings and consulting. Design of the Display Visualization Platform and Projection System was made based on average human eye properties, industry guidelines and standards.

As the result of the project, technical comparison of studied equipment was made, and procurement documents were designed. Two feasible concepts for the Visualization Platform were suggested in this paper. Obtained results can be applied in further business and academic activities of the Laboratory and University in general.

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LIST OF SYMBOLS AND ABBREVIATIONS

ALR screens	Ambient Light Rejecting screens
API	Application Programming Interface
AR	Augmented Reality
CAVE	Cave Automatic Virtual Environment
CRT	Cathode Ray Tube
DLP	Digital Light Processing
DOF	Degree of Freedom
EMG	Electromyography Sensor
ET	Eye Tracking
HD	High Definition
HFOV	Horizontal Field of View
HGA	Half Gain Angle
HMI	Human-machine interaction
LCD	Liquid Crystal Display
LUT	Lappeenranta University of Technology
MAR	Minimum Angle of Resolution
MoCap	Motion Capture
PC	Personal Computer
PR	Public Relations
RFI	Request for Information
ROM	Rough Order of Magnitude
SDK	Software Development Kit
SMPTE	Society of Motion Picture & Television Engineers
UFOV	Useful Field of View
ULtRa-SimMI Lab	Universal Laboratory on Virtual Reality, Real-time Simulation and Human-Machine Interaction
VFOV	Vertical Field of View
VR	Virtual Reality

1 INTRODUCTION

1.1 Motivation

State-of-the-art computer-based analysis and design tools helps engineers and researchers to develop different kinds of products and to discover new practical and scientific fields. Lappeenranta University of Technology and Saimaa University of Applied Sciences (Saimaa UAS) are interested in building brand new Simulation Lab. In collaboration with Saimaa UAS by integrating novel real-time human interaction technologies into simulation platform, LUT can implement various researches in such areas as Artificial Intelligence, Human Machine Interaction, and Virtual Reality. Future cooperation with state structures and private companies are expected as well. Implementation of these cutting-edge technologies will provide more technically sophisticated researches and development of real products, which can lead to a positive economic effect to LUT and Saimaa UAS.

Present case is actually essential for LUT development strategy – to be in the leadership group of Universities, which do researches in the same scientific areas, mostly in simulation aspects. In addition, the last key point, but not less necessary, is PR aspect.

1.2 Previous research

Current situation of existing lab is presented below. Most part of the equipment is outdated or not functioning. Motion capture camera system is out of date system, lack of enough number of high-performance cameras. Visualization software is not supporting all research needs. 3D Visualization walls (55" full HD 3D Screen) is out of service, broken projectors. (Figure 1) Motion base is not supporting all needs, crawling, has short range of movement. Laser 3D scanner is outdated, and it is limited. In addition, there were financial issues that could not let the renovation run into the business.

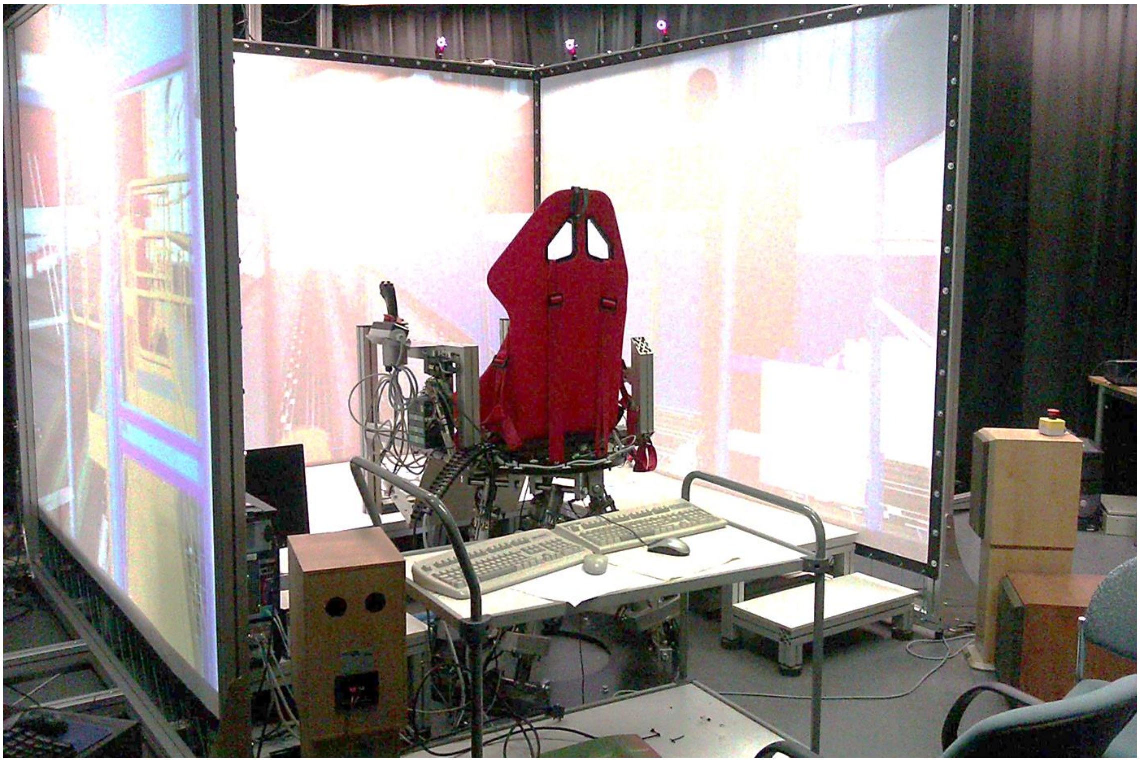

Figure 1. CAVE 3D Projection system (2016).

1.3 Framework

Main attention in the development process of the simulation laboratories is the technology infrastructure. As one can see, technological evolution goes rapidly. Laboratory system can be considered as high-fidelity robots or curved screen with 3D technology, controlled by powerful PC, along motion capture with data saved to a cloud data store, it can give huge opportunities to research projects as a whole creature. It means research flexibility and versatility. As a complex and interconnected system, it can provide more efficient results than separate items.

Definitely, laboratory area and future system should be viewed from the certain type of projects. Academic and industrial studies require different approaches and hardware in it. Knowledge about research topics and aims of each research team involved in this project will provide right attitude to design process.

Based on experience of existing simulation labs all over the world, it is possible to highlight some key equipment and software, which use average lab of this type:

1. VR headsets (almost all simulation, VR, HMI labs have this item)
2. Robotic platforms (NASA, MIT, ESA)
3. Motion capture systems (University of Texas at Austin, USC MxR Lab)
4. Motion base
5. 3D projection system
   - 5.1. Corner (Virtual Reality Technology Lab Texas State University)
   - 5.2. CAVE (3 or more sides) (Aachen University, the Translife platform)
   - 5.3. Curved (VR lab Mcquarie University)
6. Drones (IVR Lab Northern Arizona University)
7. Laser scanners (common)
8. Haptics (common)
9. Eye tracking (common)
10. Floor motion actuators (Ottawa hospital, NASA, the Beckman Institute's Illinois Simulator Laboratory)
11. EMG sensors (Laboratories studying medical issues)
12. Driver (flight) simulators as single unit (the Beckman Institute's Illinois Simulator Laboratory, the Translife platform)

According to this data and scientific requirements of LUT and Saimaa UAS, design and development of ULtRa-SimMI lab is performed. Laboratory equipment overview is presented in Chapter 2. Possible options and calculations of 3D Visualization system are given in Chapter 3.

1.4 Research problem and objectives

Referring to current situation and available resources in Simulation laboratory next research problems can be formulated:

1. There is a recognized lack of information about current state of existing labs to compare equipment and to make starting point for development.
2. The most challenging point is positioning of 3D projection system.
3. It is difficult to forecast the compatibility of all equipment and software in different combinations.
4. Interests of several stakeholders and collaboration of different research teams should be handled at the same time.
5. Simulation lab must satisfy demands of Saimaa UAS and LUT.

Following objectives are presented below:

1. Arrangement and compatibility of all equipment
2. 3D Projection system

These objectives are essential for the project, without either of them, implementation of the ULtRa-SimMI Lab will be incomplete. For example, without right arrangement and compatibility-making future laboratory will not be as a whole system, which can provide full immersion and possibilities to user. On the other hand, absence of 3D Projection system will make senseless other equipment in cause of impossibility of visual presentation of achieved results.

1.5 Scope

Contrariwise, besides aims and wishes of project stakeholders there are several limitations, which are leading to development process and to final result of its implementation. From the beginning, ULtRa-SimMI project of LUT and Saimaa University of Applied Sciences has budget on the sum of 606,500 €. 65% of total sum would be given by LUT and 35% by Saimaa UAS side. Budget is separated between LUT and Saimaa UAS, according to the needs and average prices for each product from the list. However, during the process budget of LUT shortened by almost 30%, what led to additional reduction of purchasing equipment.

Next essential point in presented research is laboratory dimensions. Current dimensions of the room are 8 x 8.6 x 2.74 m. Limited area and height of the room restrict easiest ways to build 3D projection system, description of this problem and details of its solving will be presented in Part Three.

Finally, existing equipment should be also considered in design of new laboratory. For example, motion platform from the horse simulator might be applied in several projects of the new laboratory: during the considering phase of Ambulance Simulator, there was possible option to merge existing 6DOF Motion Platform MEVEA500 with equipment and driving software from Creanex Oy to reduce final cost of this product.

Research infrastructure of LUT and Saimaa University is used only. It provides independence in research activity from other national and international scientific institutions.

1.6 Timetable

Table 1. ULtRa-SimMI project timetable.

Main stages	**2018-2019**										
Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI
background research (overview existing laboratories of the same type)											
data collection (study the available options to equip the lab and prepare a list of different alternatives for each section)											
design of the lab											
evaluation of the prices and costs of the equipment and services											
approval the equipment lists											
purchasing phase (put order for equipment and services)											
installation phase											
adjustment phase											

1.7 Research methods

In presented paper next qualitative and quantitative research methods were considered and used:

1. Qualitative methods
   - Inquiries and DELPI interviews dealing with a characteristic of equipment and its possible aims.
   - Survey in open sources for existing types of equipment.
   - Utilization of specialists or experts to formulate feasible options for compilation of purchasing equipment.

2. Quantitative methods
   - Technical drawings of the laboratory and 3D Visualization platform options.
   - Technical calculations of the implementation of future laboratory.

Concerning to DELPHI interview, it could be reliable and precise method for determining right and necessary equipment for each potential user and research group. Experts from different structure branches from related area (technicians, professors, manufacturers) from Saimaa UAS, LUT and companies, which are involved in production of given item. For implementation of this method to present case, it is sufficient to have group of ten experts (four from LUT, four from Saimaa UAS and two from external organizations) and one supervisor/interviewer, who collects and analyses received data. In DELPHI methodology, number of interviewers is not connected with statistical power, it can be said only for group decision dynamics. Consequently, it is recommended to have between 10 and 18 experts in the group. (Linstone, 2002.)

Questionnaires are sent to each member of the group. After that, two or more (if it is needed) rounds of the interview are held with markings and evaluation. After all rounds, supervisor/interviewer collects commentaries and presents report.

DELPHI method avoids halo effect, which can be received in regular interview (Moutinho et al. 2014). Retesting is important part to ensure reliability assurance. Validity of the method provides by itself - method allows self-validation by questioning involved experts to assess the interpretation and categorization of these variables. What about saturation, it would be decided that it is enough to have 70% of opinion identity in question.

Possible DELPHI questions about each position in investment (product):

1. In your opinion, what list of specs we should use in terms of this item?
2. What value of each parameter it is necessary to obtain?
3. Which parameters are critical for this item?
4. Which software/hardware will be feasible for it?
5. What is your preference?
6. Based on these answers, if there was enough information to start marketing survey?

Technical drawings of the laboratory are necessary part of design of the lab: it is convenient to take dimensions and position of equipment in the lab and referring to that make suitable decisions about general positioning.

1.8 Laboratory overview

Laboratory of Intelligent Machines is structural subdivision of LUT. Laboratory of Intelligent Machines has received the optimal place to create the new simulation laboratory from April 2018. Future place for ULtRa-SimMI project is located on the first floor, close to the entry, in the first building of the University. The room area is about 70 m^2. Height of the room is 2.74 m. Ceiling has a mesh with the attitude equal to 3.4 meters. Besides mentioned characteristics, there are two columns: one column is combined with wall, another stands by itself near the entry. Laboratory room has light grey coloring of walls and dark grey floor. Room has no windows. Doors are transparent to the light. Panoramic view of the current laboratory is given on Figure 2.

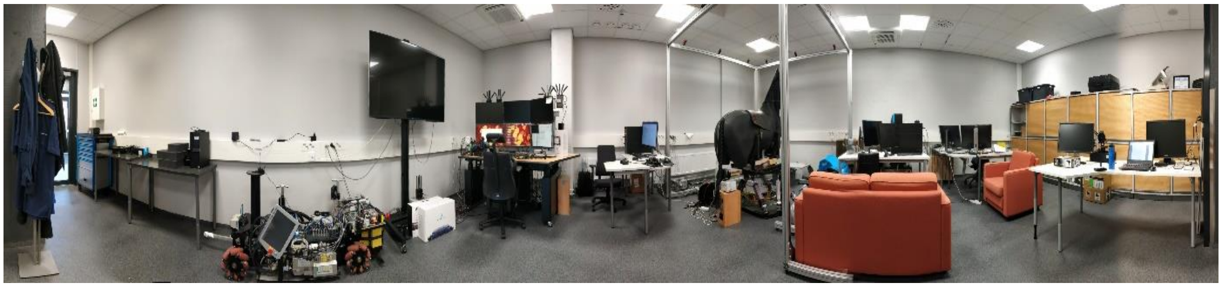

Figure 2. Panoramic view of the laboratory.

In the beginning of the project, laboratory was measured, measurement error is around one mm. Based on received dimensions, 3D model and drawings were created (Figure 3). It was found that there is obvious height limitations in laboratory, it might cause issues with developing of projection systems. More detailed information is presented in Chapter 3.

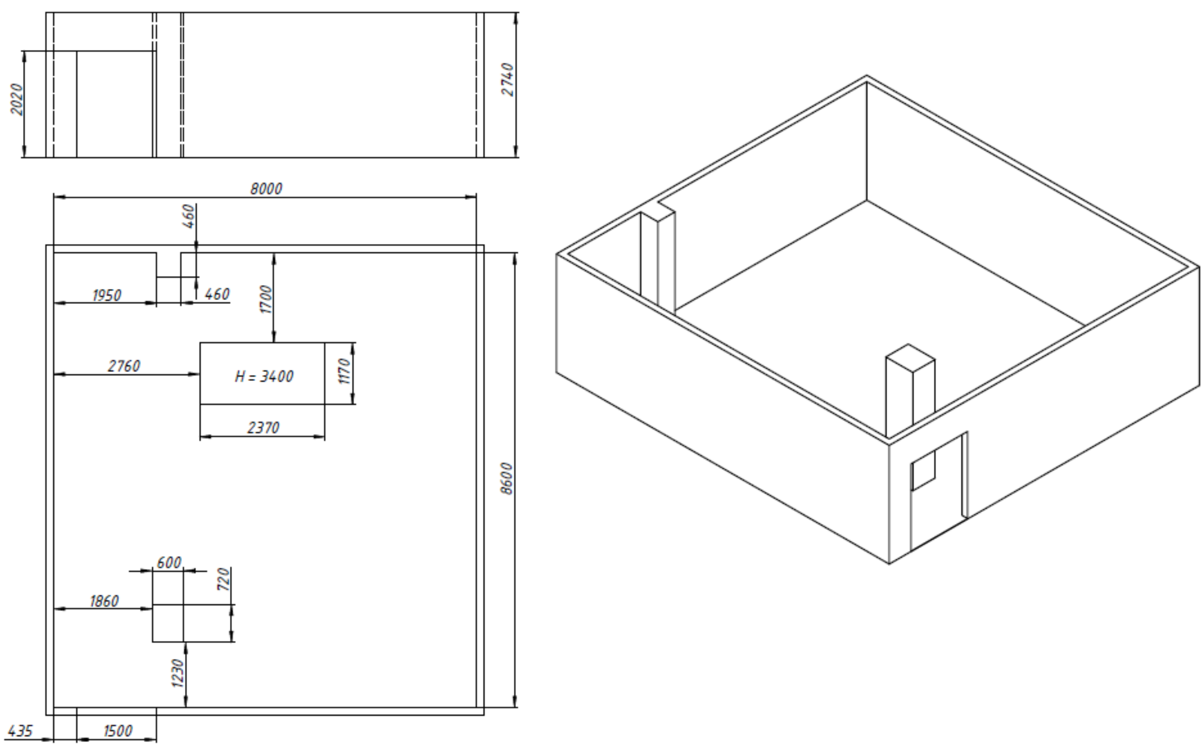

Figure 3. Dimensions of Laboratory.

This area is planned to be used as the shared research lab for LUT and Saimaa UAS. Saimaa UAS will cover a part of the rent of the current simulation laboratory.

2 LABORATORY HARDWARE

Starting point of current research is review of existing simulation laboratories. In this review, open sources like internet-based data were used. Searching algorithms in Google, Yandex, Mozila Firefox and similar aggregators strongly depends on language preferences and default country. English language preference and next countries: USA, UK and Germany as a local were used in the search.

More than 20 simulation, VR, HMI labs all over the world laboratories were overviewed during the search. Based on open data and received emails from universities, which are owners of these labs used equipment and software were compared. Besides that, research purposes of existing labs were examined and, referring to our purposes, decisions were made about reliability and how it fits to our tasks. Finally, created comparative base to next surveys of required items of future LUT laboratory (Figure 4).

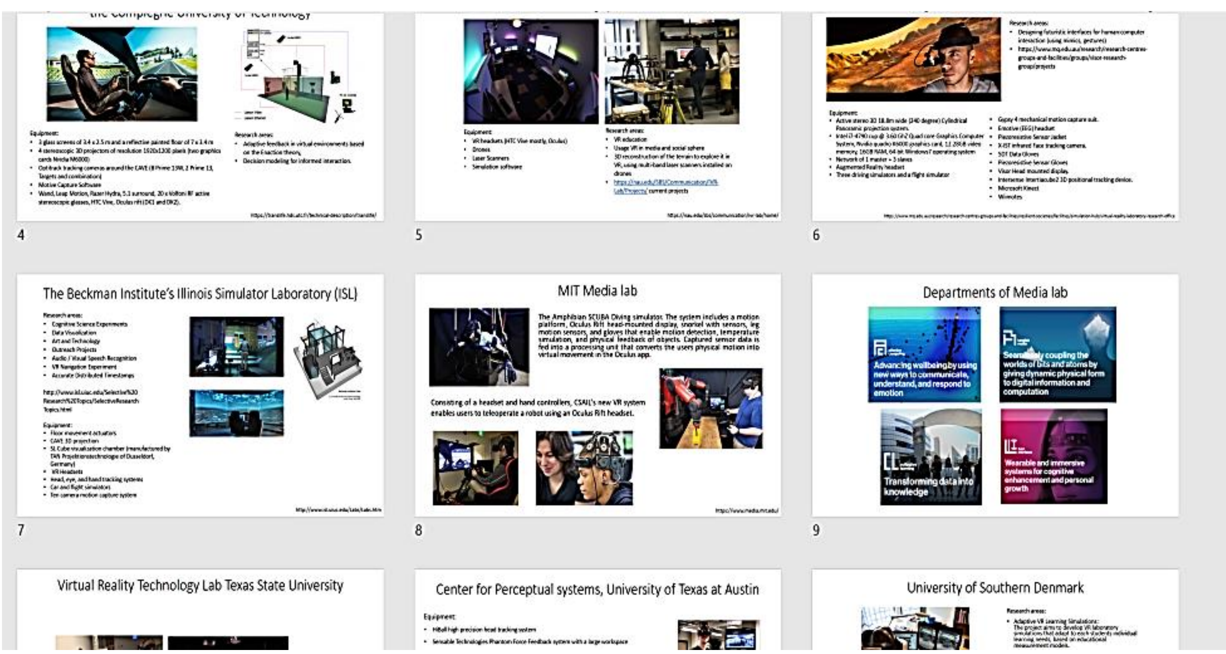

Figure 4. Comparative base of existing simulation laboratories in the world.

Biggest part of all simulation labs is presented in United States and the most sophisticated laboratories are also presented here due to huge private and state investments in this area. Implementation of Virtual Reality and Real-Time simulation is required when we have a deal with dangerous environment like open space or in a shuttle. There is structural subdivision of NASA - The Virtual Reality Laboratory (VRL) that is aimed for astronauts training, simulating the real-time activities in space by using robotic devices and virtual reality visualizations. Equipment provides the physical feeling of the objects' mass characteristics (less than 227 kg) which can be manipulated by user (Figure 5) (Valipe, 2017).

Figure 5. The Virtual Reality Laboratory (NASA VRL).

Laboratory states its research areas as training flights and different work-in-space situations. Using open information in online non-fiction magazines articles dedicated to this lab (Silverman, 2018) and photos on official website, next information about applied equipment has been received. VRL has:

1. VR headsets (some items seem to be HTC)
2. Motion capture camera system with relevant software

3. Professional haptic systems
4. Motion base
5. Robotic arms

Second biggest agglomeration dedicated to similar scientific areas is located in MIT Media lab. It is difficult to define exact simulation or VR lab, because every research group collaborate with other teams using shared material base. One example of interdisciplinary collaboration is the Amphibian SCUBA Diving simulator. The system consists of a 3DOF platform, VR headset, snorkel with body motion sensors, and haptic devices which detect motion, simulation of the temperature changes, including physical feedback from simulated objects. Real-time simulation data is converted into physical feedback, and the users' motion is transferred into virtual environment vice versa in special software. (Jain et al., 2016.)

Other Universities in the USA and the rest of the world has either the same level of being equipped, of course, with special features, which can be used as examples for LUT lab development. Rehabilitation Virtual Reality Lab located in Ottawa hospital can be used as an example for 3D Projection system with floor movement actuators. Bradford construction has implemented front projection system with walking treadmill simulator to treat disabled people (Figure 6). (The Ottawa Hospital, 2018.)

Figure 6. Rehabilitation Virtual Reality Lab (Joseph Eddins, 2017).

This type of system was also considered in designing phase like standalone system for VR and projected simulation with curved screen. But necessity of changing equipment in front of projection system and arrangements with Saimaa UAS to store and use ambulance simulator have forced to not have this kind of system.

VR Lab Mcquarie University also has variety of using equipment. The most impressing and logically expensive part of their lab is active stereo 3D 18.8-meter wide (240-degree) Panoramic curved projection system (Macquarie University, 2018). Besides that, they have Gypsy 4 mechanical motion capture suit, Emotive (EEG) headset and different motion capture systems, but most part of them are outdated and old comparing to available options on markets.
One of the main purposes of simulation lab development is creating of the 3D model of the Lappeenranta city center with laser scanners mounted on robotic system. Similar research purposes and related equipment are used by IVR Lab Northern Arizona University. Drones with installed multi-band laser scanners are used for 3D reconstruction of the terrain to explore it in VR. (IVR Lab, 2018.)

USC MxR Lab in South California University is well-known in scientific society by its motion capture oriented field of study. It has different types of capture system, one of them is semispherical with more than 3 meters. (Krum and Aptaker, 2018.) Concerning to common equipment used among most laboratories they are presented below:

1. VR headsets (almost all simulation, VR, HMI labs have this item)
2. Robotic platforms (NASA, MIT, ESA)
3. Motion capture systems (University of Texas at Austin, USC MxR Lab)
4. Laser scanners (common)
5. Haptics (common)
6. Eye tracking (common)
7. Floor motion actuators (Ottawa hospital, NASA, the Beckman Institute's Illinois Simulator Laboratory)
8. EMG sensors (Laboratories studying medical issues)
9. Driver (flight) simulators as single unit (the Beckman Institute's Illinois Simulator Laboratory, the Translife platform)
10. PC workstations for control and simulation

Information from open-sources does not allow forming comparative table with defined products. E-mail interviewing has not given any sufficient and valid results because of expected secrecy and rare use of public mailboxes. Received data about using types of equipment was applied in marketing survey.

For each position in investment excel file and presentation were created. In every product more than 4-5 possible options available on the market were presented. Using received specs comparison tables were made. Before project meetings, presentations with results of research were prepared. Initial purchasing items in ULtRa-SimMI project are given in Table 2.

Table 2. ULtRa-SimMI investment list.

	Item	Cost estimation, Euro
1.	Motion capture camera system	60,000
2.	Motion capture software	5,000
3.	Visualization software	1,000
4.	3D Visualization platform	100,000
5.	High performance workstation for AI-algorithm computing including DAQ system, UPS and rack	50,000
6.	VR Glasses	20,000
7.	Professional haptic system	60,000
8.	Eye tracking	35,000
9.	EMG sensors	25,000
10.	Faster motion base	50,000
11.	Floor movement actuators	35,000
12.	Human Collaborative Mobile Robotic Platforms (Saimaa)	55,000
13.	3D laser scanner for industrial scale use (Saimaa)	60,000
1.	3D Point Cloud Processing Software (Saimaa)	12,000
2.	Driving simulator for emergency vehicle use (Saimaa)	25,000

Positions 10 and 11 in Table 2 were excluded from the investment due to LUT budget reduction. Saimaa UAS developed positions 12-15 by itself, final decisions about individual investment parts were made separately. Development of mentioned positions is the topic of another Master's Thesis. According to it, this equipment is not described in present paper.

2.1 Motion capture camera system and software

Motion capture (MoCap) is the procedure of the movement tracking of different objects or people. It has wide area of implementation: military service, entertainment (film production, computer games), physiotherapy applications biomechanics and robotics (Yamane and Hodgins, 2009).

In MoCap sessions, movements of the object are recorded with high frame rate, impossible for basic cameras. Recently, in the beginning of technology application several cameras are used to reconstruct object or human 3D model (Cheung et al., 2000).

Mostly motion capture aim is to sample just the movements of the user, rarely – his real appearance. Recorded markers are transferred to the software, where they transform to 3D model. Finally, 3D model represents movements of the real object in virtual environment.
Motion capture camera systems are divided based on type of using markers:

- With passive markers
- With active markers
- With time modulated active markers
- With semi-passive imperceptible marker
- Markerless

Cameras are mounted on a rigid frame, if experiments are held in one area, or can be used with tripods. Tripod's option give more flexibility during the tracking process (Figure 7).

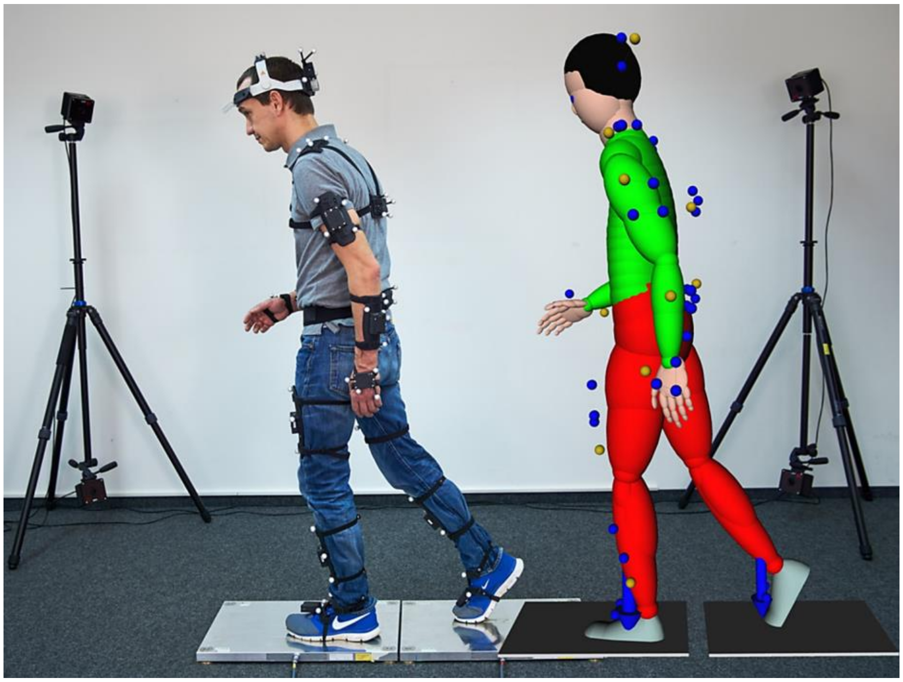

Figure 7. Application of MoCap with passive markers in VR (Ar-tracking.com, 2019).

Initially, in existing Laboratory of Intelligent Machines there were Motion Capture cameras Flex 3 produced by Optitrack Company. New budget investment in this item is 60 000 Euro, and it was decided to put 3000-4000 Euro per camera. Current camera system are based on Optitrack Flex 3 cameras (Figure 8).

Figure 8. Laboratory MoCap system.

Flex 3 is positioned as a Motion Capture camera with sufficient resolution and good frequency for sampling on small volumes research objects. It has proved this statement during life-time and it is still in working condition. Nonetheless, product survey about new MoCap cameras system was held. Starting point and requirements for new system were:

- Tracking human motion during simulation process, for example, on motion seat or when he/she will move during VR-simulation.
- Speed is about 3 m/s maximum
- Space of the lab is 70 m^2
- Tracking space is appr. 25 m^2
- Possible outdoor research
- Higher characteristics

During the search, it was found that there are six companies presented on the market:

- Optitrack
- Vikon
- Motionanalysis
- Qualisys
- BTSbioengineering
- x2e motion capture

From the beginning, x2e motion capture solution was excluded, because it does not have world camera, just tracking sensors. It can show position of the points in the space, but ability to show the experiment environment is neglected. Then, comparison of suitable cameras to laboratory purposes in range of 3000-4000 Euro was made (Table 3).

Table 3. Comparison of cameras available on the market.

	Optitrack/ Prime 41	**Optitrack/ Prime 13**	**Vikon/Vantage V8**	**Vikon/Vantage V5**	**Motion Analysis/Raptor-12HS**	**Motion Analysis/ Kestrel 4200**	**Qualisys/ Oqus 3+**
Resolution	1664×1088	1280×1024	8MP	5MP	12.5MP	4.2MP	1.3MP
Frame rate	360 FPS	240 FPS	260@ 8MP (max 2000)	420@ 5MP	300 fps	200 fps	500 fps (1.3MP) 1750 fps (0.3)
Latency	2.8 ms	4.2 ms	5.5 ms	4.7 ms	-	-	-
Maximum range (using 5/8 inch markers)	15.2 meters	6.1 meters	-	-	-	-	-
Horizontal FOV	70	82°	61	63.5	-	-	70, 56, 47, 40, 20
Vertical FOV	49	70°	47	55.1	-	-	70, 56, 47, 40, 20

Table 3 continues. Comparison of cameras available on the market.

	Optitrack /Prime 41	**Optitrack /Prime 13**	**Vikon/Vantage V8**	**Vikon/Vantage V5**	**Motion Analysis/ Raptor-12HS**	**Motion Analysis/ Kestrel 4200**	**Qualisys /Oqus 3+**
Interface	GigE/PoE	GigE/PoE	PoE+	PoE+	HCP-8, LTPoE++	HCP-8	-
Synchronization Method	Network	Network	-	-	Ethernet, Sync in/out	Ethernet, Sync in/out	Ethernet (hub-less & daisy-chained); WiFi 802.11n/g3
Shutter type	Global	Global	Global	Global	Global	Global	-
Strobe	-	-	IR	IR	Near Infrared (750 nm)	Near Infrared (750 nm) Full Infrared (850 nm)	-

Price of the camera unit and specs are changing tremendously from lowest to highest values. Mostly it depends on application type of the motion capture system and its configuration. Preliminary evaluation of possible configuration can be done by comparing maximum range of the cameras and fields of view providing by lenses.

Nevertheless, some of the suppliers gives opportunity to check option for common cases in motion capture area. For example, Optitrack Company has its own motion capture system generator, which provide standardized configuration for required research problem (OptiTrack, 2019).

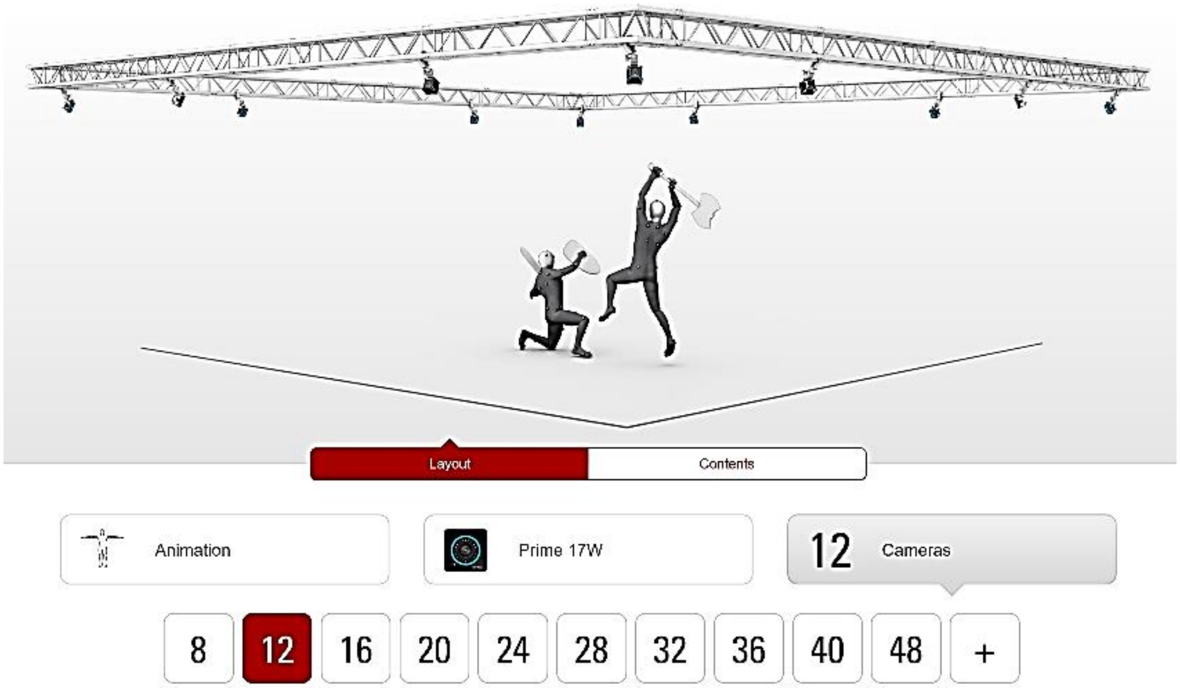

Figure 9. Visual representation of motion capture system configuration. (OptiTrack, 2019.)

Optitrack recommends suitable computer requirements for chosen system. For instance, in presented figure above, it is sufficient to have Windows OS 7, DirectX 9 API, more than 3.0 GHz with i5 processor, 8 GB of memory and 2 ports (USB and Ethernet). Besides mentioned comparison (Table 3), assessment of the current system also has done to determine degree of necessity (Table 4).

Table 4. Comparison with current system Optitrack Flex 3.

	Price [$]	Resolution [MP]	Frame Rate [fps]	Horizontal FOV	Filter Switcher	Interface	Num. of LEDs	Latency [ms]
Flex 3	599	0.3	100	38, 46, 58	Optional	USB 2.0	26	10
Prime 13W	2 499	1.3	240	82	Included	GigE/PoE	10 (UHP)	4.2
Vantage V16	2000-3000	16	120	54.7 (76.4)	-	PoE+	24	8.3
Vero v2.2	2000-3000	2.2	330	27.2 (55,2)	-	PoE	-	3.6

After receiving initial information, Laboratory of Intellectual machines got in contact with potential suppliers of Motion Capture systems and received four quotes from Optitrack, Vikon, BTS and Qualisys, but due to financial updates and more important directions in investment, purchasing of this system was closed. Based on new restrictions, it was decided to focus on current camera system: twelve motion capture cameras Flex 3, mounted on rigid cubic frame.

Nonetheless, up-to-date motion capture software must be purchased. Motive 2.2.1 has the best compatibility with existing system, because of intercompany solution. Motive can record data in real time (depending on camera FPS) and stream data to most types of connection (locally or other IPs). It allows posting the process to C++ Net or other languages. Moreover, it is possible to stream real time to Unity in case of building up own virtual environment for simulation and interaction with other research gear. (OptiTrack, 2019.)

Based on mentioned advantages and grounds, purchasing of Motive software was approved and all contact data transferred to laboratory research technician, who will conduct further procurement process. Procurement of the cameras is delayed until next investments.

2.2 Visualization software

Visualization software is graphical engine used to create graphical reproduction and interfaces for various software packages. Graphical reproduction might be in 3D, 2D, in Virtual Reality or using Augmented Reality technology for simulation or gamification (Axon, 2016). Visualization software is used in number of industries, for instance, automotive production, cinematograph and engineering (Figure 10).

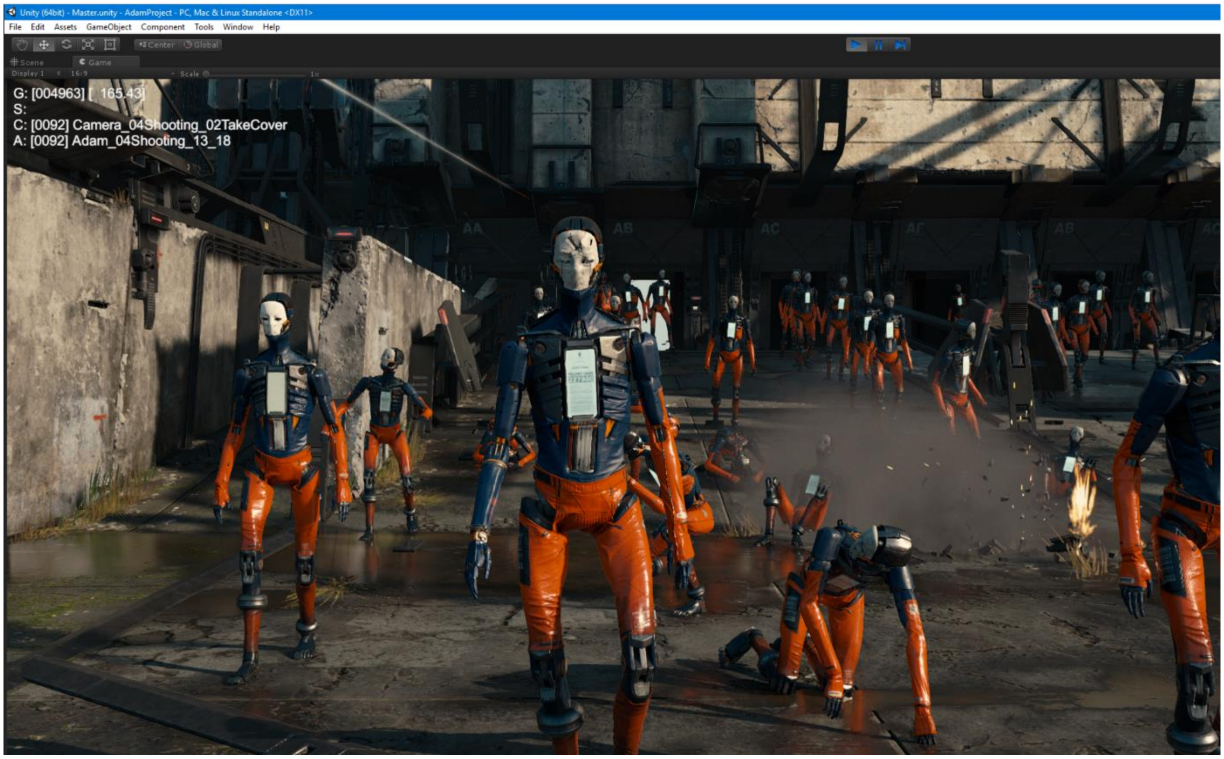

Figure 10. Example of Unity performance. (Oats Studio, 2018.)

Situation with visualization software have been already clear for stakeholder's group. This situation was based on previous researches of LUT Intelligent Laboratory and its breadth of use. Graphical solution using Unity 3D software is common for entertainment, simulation and research purposes. It is stated as industry-leading multiplatform, powering over two-thirds of VR and AR experiences with high performance. Unity uses C# language, supported by several graphics APIs such as Direct3D, OpenGL WebGL and others. Cloud resources are included in software package. Besides aforementioned specialties, it allows to use custom tools, what is essential in laboratory and research tasks. (Unity, 2019.) Physics can be applied from Mevea or other physics simulation software.

Unity 3D is chargeless software for individual designers and engineers but offer for institutions and companies is 125$/month to obtain access to Pro version with extended functions and support. Contact information was transferred to laboratory research technician and further to purchasing department.

2.3 3D Visualization platform

3D Visualization system is foundation stone of entire project. Based on this system all devices will interact with each other and user will see processed data on the screen such as gaze position from Eye Tracking, muscles activity from EMG sensors atop of simulation environment. Moreover, the biggest part of investment was allocated to this system, around ¼ of whole budget. It means that the purchasing of 3D Visualization platform will be more complicated and requires tendering process due to EU law restrictions, especially for academic institutions.

Concerning tendering process, there are several preparing phases such as request for information (RFI), which gives preliminary criteria for forming the procurement documents for tender. Traditionally, RFI consists of four parts: presentation of the contracting authority, procurement background, description of current state, description of the target state. RFI for 3D Visualization platform is in Appendix I.

RFI's were sent to the companies, which were found during the search in open resources – mostly Internet. The list of companies, which can provide complete solution, is presented below:

1. Barco (Belgium)
2. Christie Digital (Germany)
3. Optoma (UK)

Abovementioned companies transferred received RFI's to distributors located nearby to Finland (Scandinavia region). In distributor's turn, companies sent proposals (quotes) for specified requirements in RFI.

1. 3D Perception (Norway)
2. CAVE Oy (Finland)
3. Vioso (Germany)
4. Warpalizer (Norway)

Only two companies got in price limitation: Warpalizer and CAVE Oy. Moreover, their solutions are not comparable, because they use different configuration. Remaining companies were out of budget scope, prices for their systems were more than 160 000 Euro (more than 60% overshoot). Selection of two companies is not sufficient, it was decided to renew requirements criteria and start procurement process with updated and more specified values of the system, make it more open for innovative and unpredicted solutions from interested suppliers. The 3D projection platform development is fully discussed later in this thesis and more detailed overview is given in Chapter 3.

2.4 High performance workstation for AI-algorithm computing

Computer science defines the artificial intelligence (AI) as the intelligence performed by computers, in turn to inborn human or animal intelligence. AI usually describes machines that copy basic cognitive functions of living creatures, "learning" and "task-solving" (Russell and Norvig, 2009).

D.Sc. (Tech.) Ming Li (Lappeenranta University of Technology, Department of Mechanical Engineering) was preparing specs for tender. Based on selected criteria, AI computer was bought. It was DGX Station powered by four NVIDIA TESLA V100 graphical cards (Figure 11). It provides the computational power of 500 TFLOPS for AI calculations. Comparing to 2X CPU Servers it can work more than 47 times faster. Station has reduced noise level comparing to other stations from NVIDIA product line. (NVIDIA, 2019.)

Figure 11. DGX station and spaced view (right). (NVIDIA, 2019.)

Robovision Company (EU) provided DGX Station with installed learning and analytics software and access to cloud services. AI Computer will be located out of the considering laboratory area, and will be under supervision of D.Sc. (Tech.) Ming Li.

2.5 VR Glasses

VR Glasses (or VR headset) - head-mounted equipment which creates virtual reality effect for the user. Generally, it consists of an installed stereoscopic display (merged image from both eyes), sound system, motion tracking sensors for head position tracking (Kuchera, 2016). Additionally, virtual reality headsets may be equipped with gyroscope, accelerometer and even eye tracking (Robertson, 2017) (Miles, 2015). Hand controllers ordinarily are included in headset package; they are used to track arm position during the simulation or gaming. Typical structure of headset display is given below on the example of LCD-based headset (Figure 12).

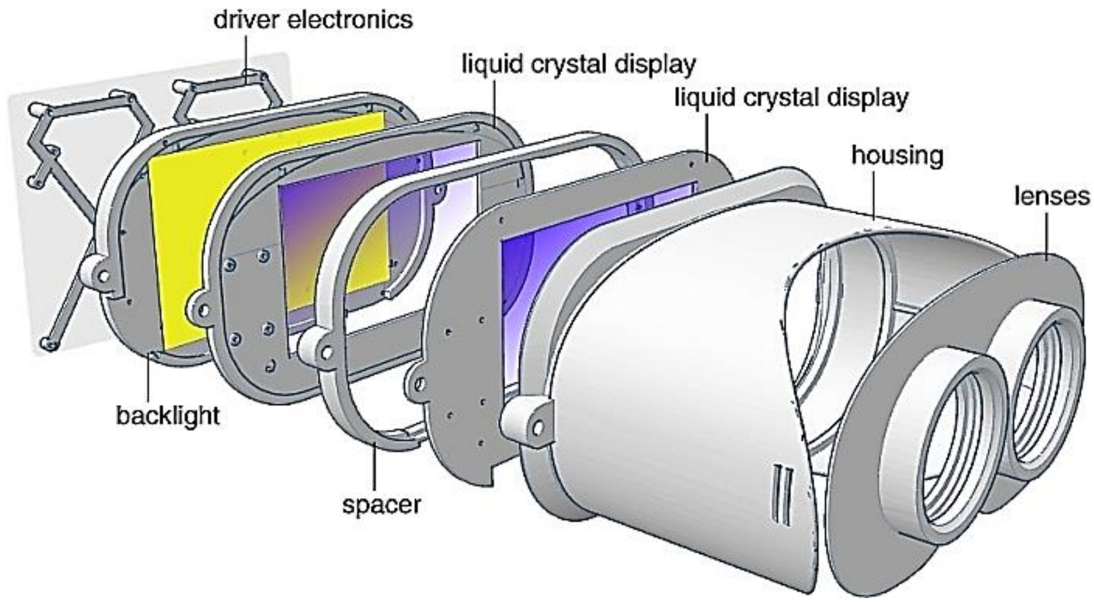

Figure 12. Structure of LCD VR headset. (Huang, Chen and Wetzstein, 2015.)

One of the most critical requirements for VR glasses is its latency – from input to visualization. High latency can lead to dizziness and feel of sickness during the use of device. Main reason of low latency issue is the refresh rate, simulation resolution and graphics processing unit efficiency. Sufficient value of latency lays between 7 and 15 milliseconds (Orland, 2013). Nowadays, foveated rendering is implemented to decrease time of rendering and processing load. Eye tracking sensor determines pupil position and based on this information resolution can be dropped off on peripheral zone from gaze point (Mason, 2016). Along with latency, display resolution, frame rate (refresh rate), fields of view (vertical and horizontal) and optics quality are necessary in consideration and choice of virtual reality headset. Mentioned characteristics directly effects on image quality (Tricart, 2018).

Headsets using Virtual Technologies are modern and widely-spreading technology in both academic and industry stages. General application of VR headsets is simulation and training, besides entertainment purposes. Nowadays, it is almost developed system, in which one can see simple improvements such as increasing of resolution and brightness, decreasing amount of used material and volume of the device.

During the survey, eight VR Headsets and three AR Glasses were found:

1. HTC Vive
2. HTC Vive Pro
3. Oculus Rift
4. Oculus Go
5. Lenovo Explorer headset
6. Samsung Odyssey
7. Visor Windows Mixed Reality Headset
8. PSVR
9. Vuzix Blade® OS2.1 *
10. Microsoft HoloLens 2 *
11. DAQRI Smart Glasses *

StarVR (StarVR, 2018) and FOVE VR (FOVE Eye Tracking Virtual Reality Headset, 2018) were excluded from the survey list for reason that companies-producer have not started mass production of these items, it is on prototyping stage.

Based on found data about characteristics and specs of VR and AR headsets, pivot table was created. In this document all specifications, contact information, prices and suppliers were mentioned.

PSVR has high color transferring quality comparing to other devices, which is less harmful to human eyes. On the other hand, originally PSVR is not compatible with PCs, it is mandatory to crack device drivers and use special software to communicate with it via personal computer. (Painter, 2018.)

Lenovo Explorer headset, Samsung Odyssey, Visor Windows Mixed Reality Headset are acceptable options for their price, sufficient quality and for their compatibility with most operational systems on PC (Windows, Linux). Contrarily, comparing to top-ranked VR products

* Augmented Reality glasses

such as Oculus and HTC mentioned companies are runner-ups in terms of specs values (especially, resolution) and spread value on the market. Moreover, Lenovo Explorer headset and Visor Windows Mixed Reality Headset don’t have installed audio system in headset comparing to HTC or Oculus devices.

Therefore, during project progress and current meeting it was decided to focus on two biggest and developed companies in VR headsets market: HTC and Oculus. Oculus was presented by Oculus Rift 2, HTC: by HTC Vive and HTC Vive Pro. Price of intimated brands varies dramatically: from $399 (Oculus Rift 2 with controllers) to $1399 (HTC Vive Pro full kit).

Laboratory of Intelligent Machines have been involved in experiments using Oculus Rift recently. During experiments, it was found that Oculus Rift has issues with compatibility and merging two or more VR headsets in one environment. Moreover, it was found that the most developed laboratories (such as MIT and NASA), which are interested in HMI, VR and real-time simulation areas, prefer to use HTC VR glasses instead of Oculus. Oculus VR decisions mostly are directed to game and social network industry.

Vive Pro has dual OLED display and 2880x1600 pix resolution. Oculus Rift has OLED display and 2160x1200 resolution in turn. Maximum tracking area in Oculus is limited by 2.6 m (8 feet x 8 feet), while in HTC zone of tracking is 6 x 6 meters. (Vive.com, 2019.) As one can see, in general there is no big difference between considered Virtual Reality headsets in terms of optical specs (Table 5).

Table 5. Comparison of VR headsets.

	Oculus Rift	HTC Vive	HTC Vive Pro	Lenovo Explorer	Samsung Odyssey	Visor
Resolution	1080x1200	1080x1200	1440x1600	1440x1440	1440x1600	1440x1440
Position tracking	Outside-in	Yes	Yes	Inside-out	Inside-out	Inside-out
Display	OLED	OLED	OLED	LCD	AMOLED	LCD
Aspect ratio	9:10	9:10	9:10	1:1	9:10	1:1
Refresh rate	90 Hz	90 Hz	90 Hz	90 Hz	90 Hz	90 Hz
Field of view	110°	110°	110°	110º	110º	110º
Weight	470 g	555 g	470 g	380 g	644 g	-

Besides pure VR decisions, it was considered to purchase one VR headset with installed ET system. It was found that Eye Tracking Company Tobii AB provides VR glasses with integrated eye tracking, which can be used in various VR simulations and experiments in future researches. Advantage of suggested solution that it is standalone device, which does not require any additional action to install extra system in headset.

Attributing abovementioned quotes from product specification and overall experience it was agreed that final package of VR headset will be next:

1. 5 HTC Vive Pro
2. 2 Oculus Rift 2
3. 1 HTC Vive with Eye Tracking sensor integration.
4. 1 AR Headset Microsoft HoloLens II

AR glasses position was added at the latest, and it was suggested on the project meeting 11.04.2019 to have in Laboratory at least one augmented reality device. In the market, there are more than 10 different options for AR solutions, but only three of them satisfy required specs, the condition of mass producing and pre-order possibility. The most powerful and multitasking device is Microsoft HoloLens II with additional cloud software, which allow handling diversity of standard and uncommon tasks. Price of Microsoft Hololense is $3500 on the moment of search (White, 2019). Based on found information, Microsoft HoloLens II was bought.

2.6 Professional haptic system

Haptics technology is the technology that provides sensitive experience of touch and shape of the object by force, vibration or motion. Mechanical feedback of haptic systems allows to imitate shape and properties of real objects, to control them and to improve HMI aspects. Tactile sensors that estimate applied force to the virtual object are able to upgrade haptic systems. Most common haptic devices are game controllers (gamepads, joysticks and even steering wheel controller).

In 3D modelling, OEM applications and academic researches several types of haptic devices are used. Two the most spread technologies are 6DOF haptic devices (for instance, 3D Systems Touch) and haptic gloves (Figure 13). The goal of haptic gloves is to provide sense of touch and in the same time to track the position of the hand in virtual reality environment.

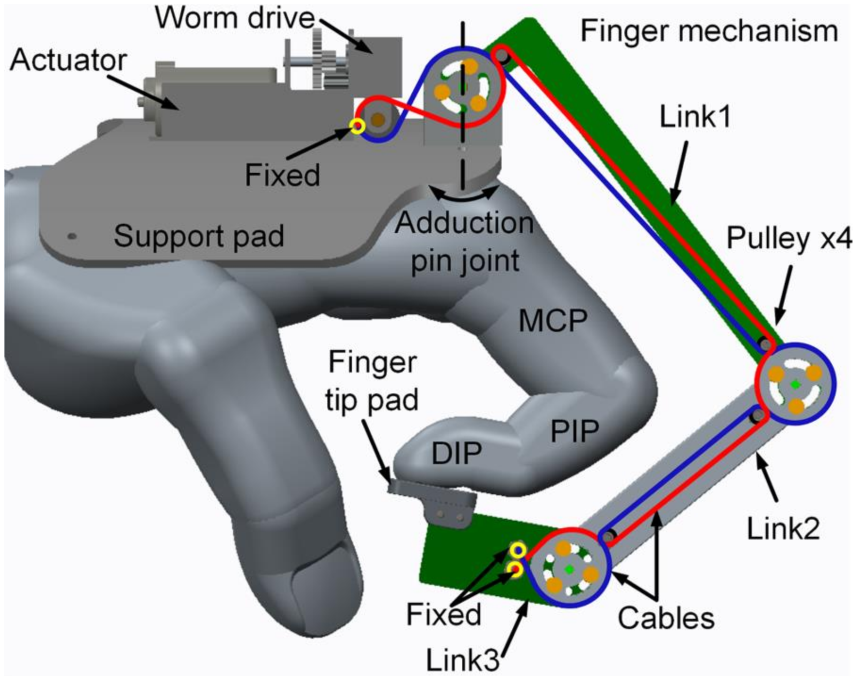

Figure 13. Glove-type haptics mechanism. (Ma and Ben-Tzvi, 2015.)

Almost each laboratory, which is involved in researches related to HMI and robotics in general, applies haptic devices to control movements of the different robotic systems. Innovative clusters such as Silicon Valley annually provides number of companies and startups, which are aimed to produce haptic systems (Nanoport, Joyhaptic, Immersion, Holland Haptic). However, mostly solutions presented on websites are just prototypes and production will start in one-two years.

It was overviewed more than 12 different companies involved in haptic system development. Based on received data, pivot table was created. During the project meetings (18.01.2019, 25.02.2019 and 20.03.2019), it was reported about each of reviewed option. For final acceptance, it was chosen five products:

- HaptX Gloves Development Kit
- VRgluv
- Senseglove
- Hi5VRglove
- Plexus

HaptX Gloves Development Kit, Plexus, VRgluv and Senseglove have exoskeleton design; external drives block movements of fingers to simulate shape of the modelling creature. Hi5VRglove has vibrotactile feedback from the simulation environment: fingers can move freely without any constraints from glove, only vibration shows the position of the modelling object. Due to intention to obtain more immersive simulation environment Hi5VRglove was excluded. Priority option among left four haptic systems was HaptX Gloves Development Kit (Figure 14).

Figure 14. Use of HaptX Gloves in virtual reality with HTC Vive (Lang, 2017).

Distinctive feature of HaptX is realistic touch. It is able to imitate texture and relative motion of virtual objects (for example wind or rain) by using more than 100 actuators of feedback, which can displace user’s skin up to 2mm. Exoskeleton can apply around 4 lbs. of resistive force feedback per finger to simulate the shape of the objects. Moreover, HaptX is equipped with magnetic motion tracking 6 DOF per digit with precision less than 1 mm. SDK contains plugins for Unity, Unreal Engine 4, and a low-level C++. Present SDK gives opportunity to develop and integrate haptic device to the technical systems, which can be used also in mentioned simulation software. (HaptX, 2019.)

Despite of all advantages of HaptX Gloves it was impossible to purchase it, because it is on testing phase and it will be put into production in 2020. And for beginning of 2019 there were next possible options: Pilot Program and Priority Access. The Pilot Program is option to lease HaptX Gloves Development Kit hardware for a designated period (typically 2-6 weeks) at the end of 2019. Pilot Programs start at USD $20,000 and are priced on a per-project basis. The Priority Access is list of companies that will be the first to order the next-generation of HaptX Gloves, when it will be produced in repetition work. Company anticipates to open orders 2020 as it was said before. Based on received information from supplier, it was decided to focus on other brands.

In the beginning of 2019 VRgluv was still developing, there was no open sales of this device. Plexus has just force feedback for fingers without vibrational feedback; it is aimed mostly for position tracking in space. (Plexus, 2019.)

Senseglove besides motion tracking and force feedback (1.8 kg per finger) has vibrotactile feedback provided by buzz motors comparing to Plexus gloves. Company has sponsorship from Siemens, BMW and Kella companies.

During visit XXI International Exhibition on VR/AR & Immersive Techniques (Laval, France) (Laval Virtual, 2019) D.Sc. Hamid Roozbahani and Research Technician Juha Koivisto tested Senseglove haptic device and evaluate its capabilities. One pair of Sensegloves costs 2500 Euro, with integration in existing Unity-based system and training it costs 7500 Euro (Senseglove.com, 2019). It was agreed to buy Senseglove haptic device by the common decision of project group. Rest of the budget from haptic device position will be transferred to another project item.

2.7 Eye tracking

Eye tracking (ET) is a research technology that affords objective data about place and reasons of respondent's sight. To apply technology the device (eye tracker) is used, that determines and tracks pupil position and gaze movements. The device can be portable (eye tracking glasses) or stationary - on the monitor screen or near to research object. Research areas, where ET is utilized, are psychology, marketing, physiology, HMI, robotics and design of new products (Figure 15).

Figure 15. Marketing research using ET glasses. (Elder, 2014.)

ET can be implemented using several types of measuring eye positions and movements. Prevalent method is to extract eye position from recorded or real-time transmitted image. In common practice, measurement types are categorized on 3 groups:

- Contact measurement (via special contact lenses)
- Remote tracking (without contact)
- Electric potential method

Remote tracking (video-based ET) was spread among other methods in practical researches because of its relative simplicity and non-invasive approach. Reflected infrared light from the eye point is sensed by infrared sensor and it is transferred into electrical signal. Information about reflections is assessed and can be used in extraction of the eye rotation and eye position (Figure 16).

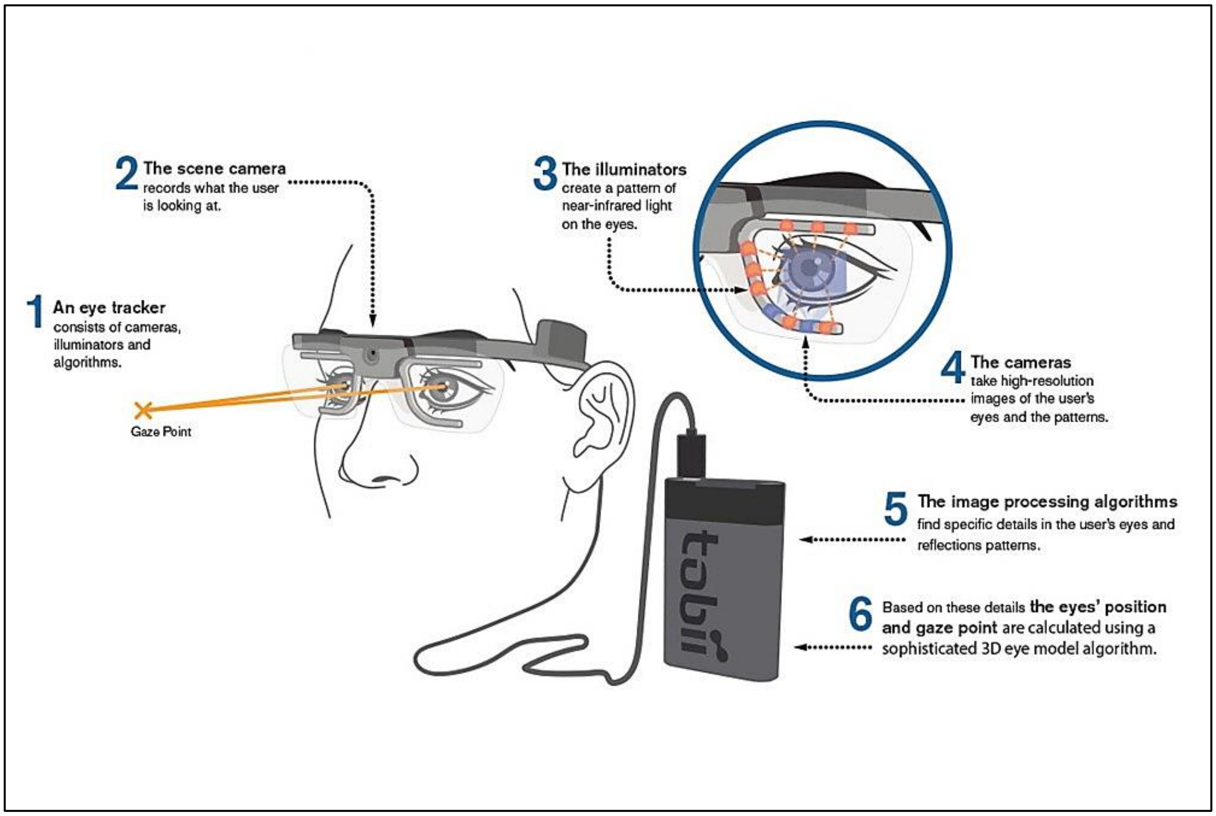

Figure 16. Remote ET principle of operation. (Tobii AB, 2018.)

For each person ET device should be adjusted due to natural differences between eye size and its properties. Based on this statement simpler calibration process before work should be provided (Hansen and Ji, 2010). For infrared ET there are two techniques that are applied in practice: dark-pupil and bright-pupil techniques.

Technically all ET systems can be divided into head-mounted and device-mounted, for example, on computer display. Sampling rate of ET devices varies from 30 Hz to more than 500 Hz. High sampling rate is required for accurate tracking of the eye dynamics. Eye dynamics is represented by series of saccades and fixations – movements and pauses in certain points. Resulting line is named a scan path. The scan path can be used in HMI researches, where user-friendly interfaces and gaze-based displays can be launched (Majaranta et al., 2012).

So-called heat maps are used in static representations and analysis of interest zones of the users, where they focus mostly their gaze. The more frequent scan paths are in certain areas of the object, the more “hotter” or brighter these zones will be represented. (Nielsen and Pernice, 2009.) Reverse method is blind zones maps, it shows less interesting areas for the users.

In ULtRa-SimMI project eye tracking glasses and processing software are one of the most important positions in the investment. Tentative academic applications are HMI interaction and user behavior studies. Budget restrictions for this investment position was 35 000 Euro.

Based on desired research areas and offers presented on the market, list for comparison and assessment was created. Available proposals on the market are presented below:

- EyeLink II
- Tobii Pro Glasses 2 (extra option Tobii Pro Glasses 2 API)
- Pupil lab glasses
- Eye Tracking Dikablis Glasses
- ETMobile Eye Tracking System

All devices except EyeLink II are wireless. Eyelink II is wired, on the other hand, it has the biggest frequency rate 500 Hz and the clearest resolution 0.01 degree. It can be upgraded to EyeLink III next year (2020) for free, but date of release is unknown. One of disadvantages is significant size, weight, and inability of outdoor researches. Price from the quote (03.12.2018) was 33 900 Euro, that almost cover whole budget.

Argusscience (ETMobile Eye Tracking System) did not provide any specs and price for their product, and company have been excluded from the consideration. Ergoneers GmbH (Eye

Tracking Dikablis Glasses) sent specifications for their device and unofficial quote with the price via e-mail. (Polz, n.d.)

Pupil Lab has product information in open access on their webpage with current price. Tobii AB have been contacted by LUT and all required data and offer were provided. Comparison table was created (Table 6) to compare and to select suitable provider:

Table 6. ET devices comparison.

	Tobii pro 2	Pupil Lab	Eye Tracking Dikablis Glasses
Gaze accuracy	0.50 deg	0.60 deg	-
Gaze precision		0.08 deg	-
Calibration	1-point	9-point and 5-point	-
Number of eye cameras	4	2	2
Sampling frequency Eye Camera	50 or 100 Hz	200hz/200x200px	60hz
Sampling frequency World Camera	25fps/1920x1080	30hz/1080p 60hz/720p 120hz/vga	30hz/1920x1080 p
Camera latency	-	4.5 ms	-
Processing latency	-	>3ms	-
Weight	45 g	37 g	52 g
Battery recording time	120 min	-	-
Additional sensors	Gyroscope and accelerometer	-	-
Recording angle of scene camera	82 deg horiz, 52 deg vert	-	-
Price	12510 €	2150 € + support for add price	14,900 €

Eyelink II was excluded from comparison table and generally during the project meeting because of its size and absence of wireless model and, finally, high price for one unit. It was decided to split the budget of ET to three different directions: outdoor solution, indoor solution and VR-integration. For outdoor purpose Pupil Lab device was chosen due to price-quality ratio and sufficient resolution.

Tobii Pro 2 will be indoor device: one of the most powerful and common equipment available in the market. Easy calibration process. LUT School of Business and Management already has this system, based on gained experience, it totally fits with laboratory requirements. Moreover, it is planned to obtain VR integration solution from Tobii. Tobii VR integration with HTC Vive is almost the one professional proposal in the market for VR Eye Tracking. One of the advantages of present solution that VR integration and Tobii Pro 2 use one software to process data that will save huge amount of money on a license.

2.8 EMG sensors

Electromyography Sensor is a diagnostic physiotherapy technique for assessment and recording the muscle activity generating electrical signals (Kamen, 2004). EMG instrument is electromyograph, which produces a recorded data called an electromyogram. Cell when they are activated (electrically or neurologically) generate electric potential, which can be detected by electromyograph. Usually methods related with EMG used in biomechanics, human movement and diseases with it, and HMI.

There are two types of EMG:

- Surface EMG
- Intramuscular EMG

First type allows to study muscular activity without invasion into the body tissues. It is used in various kinds of researches, connected with muscular activity and motions (Figure 17). However, surface EMG is not precise method, it cannot record data from one muscle bundle, only form the group of muscles. In addition, it has not direct access to the muscle. Data from the muscle's activity is recorded by an electrode pair located on the skin or by using more complex electrode systems. Obvious limitation of this method is depth of tracking muscles, it can record only muscles groups which are laying under the skin.

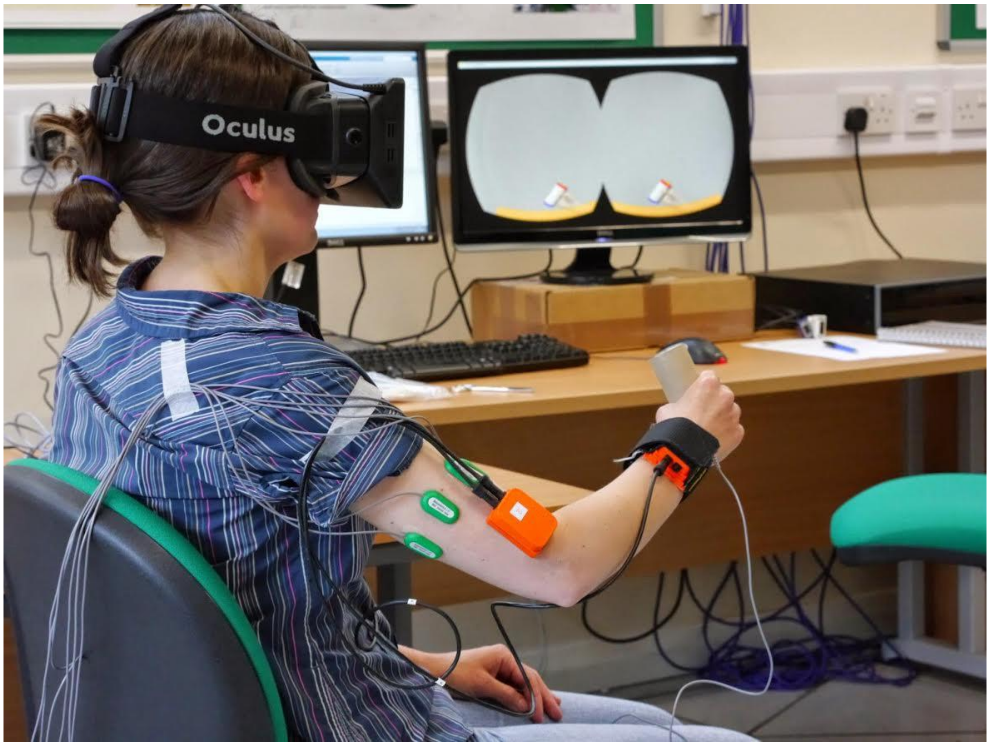

Figure 17. Open Science experiment with surface EMG sensors and VR headset. (Blana, 2018.)

Intermuscular EMG is presented usually by needle EMG. It consists of two electrodes. Sensor, a conductive wire, is inserted into muscle tissue, penetrating the skin. Second electrode is attached to the skin for reference. This method can be used in studying static muscle activity with high accuracy: even tiny deep muscle fibers can be determined. Nonetheless, intermuscular EMG is mostly medicine approach, simulation laboratory purposes do not fit to application area of this method. That’s why it was decided to concentrate on surface EMG.

Budget limitation for EMG sensors kit with included software is 25 000 Euro. Based on mentioned main limitation the survey was started. Seven companies and provided products were found during the survey:

- Trigno
- Cometa
- Ultium EMG
- FreeEMG
- Biometric

- Consensys EMG
- Somaxis

After meetings and discussions, consulting with physiotherapy department in Saimaa University, it was concluded, that Trigno will be suitable option for existing laboratory. Arguments for this decision are presented below.

DELSY Trigno Avanti model is multi-purpose human movement sensor for the laboratory, classroom, and clinic aims (Figure X). In general, only DELSY is positioning in the market as company, which provides hardware and software for robotics and mechatronics, not only clinic and therapy purposes (YouTube, 2018).

In advantage to DELSY's EMG, it is wireless, and it provides connection via Bluetooth or via Radio Frequency up to 40 meters range. It can use up to 16 Trigno sensors at once (32-sensor tandem configuration also available). Rechargeable battery lasts up to 8 hours; this is one of the highest values among EMG wireless sensors. (Delsys, 2019.) It can integrate with Motion Capture, Force Plate and other systems. CMRR is less than -80 dB (lowest value among comparing EMGs). Sensor block is cubic sensor without any external wires unlike to Noraxon Ultium EMG (Figure 18).

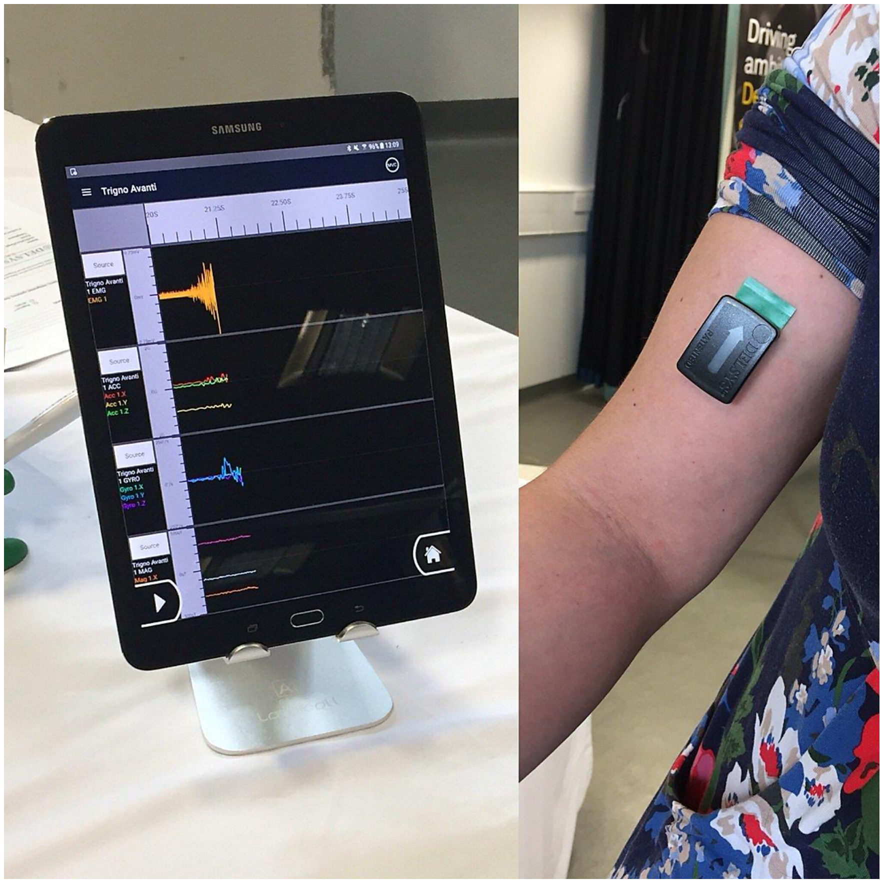

Figure 18. Real-time measurement of muscle activity. (Crawford, 2018.)

On other hand, Optitrack supplier DevinSence AB (Motion Capture systems and attendant software) advices to use DELSY's EMG systems with their systems, because of its better compatibility with existing and possible MoCap system. Moreover, DELSY's supplier and contact persons provided completely needed information about their products, its characteristics and different types of packages.

Quote for a 16x sensor system: for investment restrictions 25 000 Euro it was suggested following system configuration with final price 25 260 Euro:

1. Delsys Trigno Lab Base station
    - 1.3 Digital and Analogue Output
    - 1.4 16 x Trigno Avanti Sensors
    - 1.5 Power and USB cables

2. Delsys Software
    2.3 Delsys EMGworks (10 x licences)
    2.4 Delsys Software Development Kit (SDK)
    2.5 Delsys Application Programming Interface (API)
    2.6 Delsys Mobile Applications
3. Delsys Trigger Module (for 3rd party synchronisation)
4. 10 x packs of Trigno Adhesives (to affix the sensor-electrode to the skin)

Also included in the quote:

- 2-year manufacturer's warranty
- Free remote training
- Free technical support (no recurring costs)
- Free software updates (no recurring costs)
- Included user training at Delsys Europe office and select locations

Differences between EMG sensors are not dramatic as in VR headsets section, one can see it during the comparison. Main issue is absence of data about special characteristics from different suppliers. In Table 7 comparison of considered EMG systems is given.

Table 7. Comparison of EMG systems.

	Delsys/Trigno Avanti	Cometa systems/Pico EMG	Noraxon/Ultium
Operating Range	40 m (RF)	30 m	30 m
CMRR	< -80 dB	-	< -100dB
Resolution	16 bit	16 bit	16 bit
Noise	<2.5 uV RMS @ 20-450 Hz <3 uV RMS @ 10-850 Hz	-	<1μV
Sampling Rate	up to 2000 Hz	2000 Hz	Up to 4,000 Hz

Table 7 continues. Comparison of EMG systems.

	Delsys/Trigno Avanti	Cometa systems/Pico EMG	Noraxon/Ultium
Inter-sensor latency	0 ms (RF)	-	
RF Frequency Band	2400-2483 MHz (ISM band)	-	2402-2480 MHz
Dimension	27 x 37 x 13 mm	-	37x24,5x16,5mm
Mass	14 g	7 g	14 g
Memory	-	up to 8 hours	>8 hours of data logging
Battery life	-	12 hours	8 hours
Temperature Range(1)	5 - 45 degrees Celsius	-	-
EMG Signal Bandwidth	20-450 Hz / 10-850 Hz	-	-
Accelerometer Range	±2g, ±4g, ±8g, ±16g	-	-
Accelerometer Bandwidth	24 Hz – 470Hz (configurable in software)	142 Hz sampling frequenc y	-
Latency	-	20 ms	300 ms

Considering overviewed specifications of each product, their reliability and extent of distribution, it was decided to purchase DELSY's Trigno Avanti EMG kit. All technical data and recommendations were transferred to research technician for the further procurement.

3 3D PROJECTION SYSTEM

Building of 3D projection system is the most essential part of current work; this is central item in terms of investment, research orientation and PR opportunities for School of Energy Systems and LUT in general. That is why it should be done at the highest level and be calculated from different positions of design.

Strategy for development of the 3D projection system was:

- To find reliable producers, that recommends themselves on the market
- To get in contact with them and to obtain preliminary information about company facilities
- To form RFI
- To adjust laboratory requirements and to form procurement documents (invitation for tendering)
- To consider about received proposals
- To meet with representatives of the companies on-site
- To sign a contract

Besides official strategy, it was decided to develop concepts of future Visualization system independently to make the survey more reliable and veracious.

3.1 Theoretical background

Visualization technologies (displays, holograms and projection systems) have developed dramatically during the XX and XXI centuries. Because of this evolution, basic electronic beam monitors and displays are being shifted by 3-Dimensional visualization with depth perception. Generally, every display and projector are a translator which converts analog or digital electrical signals (time sequential) into configured visible light signals (image or video).

The first official prototype of projection or visualizing of the image was in 15th century (1420) by Johannes de Fontana. He projected image of the Christian evil creature on the wall using light of the candle and tiny painted glass (Figure 19).

Figure 19. Illustration of first documented projection (De Fontana, 1420).

Performance of each type of visualization platform depends on how effectively light will be modulated to obtain required quality of the image. In XX century, it was discovered that the light is electromagnetic wave. Frequency ν and wavelength λ are related by next equation (in vacuum):

$$v=c/\lambda \tag{1}$$

Where, c – speed of the light (300 000 km/s).

One of the most essential terms in optics - spectrum is segment of electromagnetic frequencies. Visible light is wavelength from 380 nm to 780 nm, frequencies in 10^{15} Hz range. Color and its intensity depend on wavelength and amplitude of oscillations. For instance, blue color is a wavelength of about 400 nm, red - about 700 nm and circa 550 nm wave is perceived as green. (Hainich and Bimber, 2016.) Besides wavelengths characteristic of the color there is more practical and using another physical phenomenon characteristic – color temperature. In simple words, it is characteristic of the intensity of the light source radiation as a function of the wavelength in the optical range (measured in Kelvins). Color temperature is extensive for image recording. To transfer digital or analog data to image various types of light sources are used:

- Fluorescent lamps.
- LED
- OLED.
- Laser

Fluorescent lamps utilize discharges in low-pressure gas within a glass case. Vaporized mercury in the gas radiate UV light, and phosphor layer on the inside of the glass converts it to visual light spectrum. In displays, it is used for panel backlighting. Nowadays, LCD screen works remarkably by fluorescent lamps with cold cathodes and special high-voltage converters. Performance of fluorescent light source based on color reproduction (used materials), thus it is challenging to design lamp with proper characteristics. To solve this problem color filter are used in LCD.

Light emitting diodes (LED) is a semiconductor device with an electron-hole transition, which generates optical radiation when an electric current is passed through it in the forward direction. OLED - a semiconductor device made of organic compounds that effectively emit light when an electric current pass through them. If we compare LEDs and OLEDs in terms of luminous efficiency: they are among the most efficient light source (about the same level of performance). The main application of OLED-technology is creating display devices

Laser is a device that converts the pump energy (light, electric, thermal, chemical, etc.) into the energy of a coherent, monochromatic, polarized and narrowly directed radiation flux.The physical basis of laser operation is the quantum mechanical phenomenon of stimulated (induced) radiation. Lasers become more important in terms of light source for various kinds of displays and projectors.

To obtain full gamut of display colors red, green, and blue lasers are required. Application with laser diodes for now more difficult comparing to LEDs, it can be designed only according to the existing materials.

One of the most important quality of the light sources is durability, which varies from type to type dramatically. Tungsten lamps usually work between 1000 and 2000 hours. Gas discharge and fluorescent lamps can achieve five times longer worktime; finally, LED lamps reach 50000 hours. Besides durability, in display technology, necessary consideration is duty time - the length of time a display performs during preset period.

3.1.1 Photometry

Photometry is a scientific discipline common to all sections of applied optics, on the basis of which quantitative measurements of the energy characteristics of the light radiation field are made.

Photometric units totally depend on color and credible for visual range only. The eye's light sensitivity is a function of wavelength, function maximum is approximately 555 nm (green light). Photometric units are presented in following table (Table 8):

Table 8. Basic photometric units.

Quantity	Symbol	Definition	SI unit
Luminous energy	Q	lm·s	lm·s
Luminous flux	F	cd· sr	lm
Luminous intensity	Iv	lm/sr	cd
Luminance	Lv	cd/m^2	cd/m^2
Illuminance	Ev	lm/m^2	lx
Luminous emittance	Mv	lm/m^2	lx
Luminous efficiency	η	lm/W	lm/W

Mostly in projection system or display design illuminance or luminous emittance of a surface (brightness nevertheless of external conditions: lightened or not) expressed in lux (Unit expression: lx). Sky has 1000 lux; indoor lighting varies between 500 lux (in work) and 20 lux (living room). Display surface light emission is characterized usually in cd/m2, which indicates sensed brightness if counted for a specific viewing position (angle).

3.1.2 Basics of Visual Perception

The human eye is a complex optical system, created by nature in evolution process. The eye resolution based on the density of photoreceptors on retina, among numerous assorted factors. Human vision is sharp only in the center of the retina (Figure 20). Daylight-adapted vision and night-adapted vision are different in color perception and spectral sensitivity.

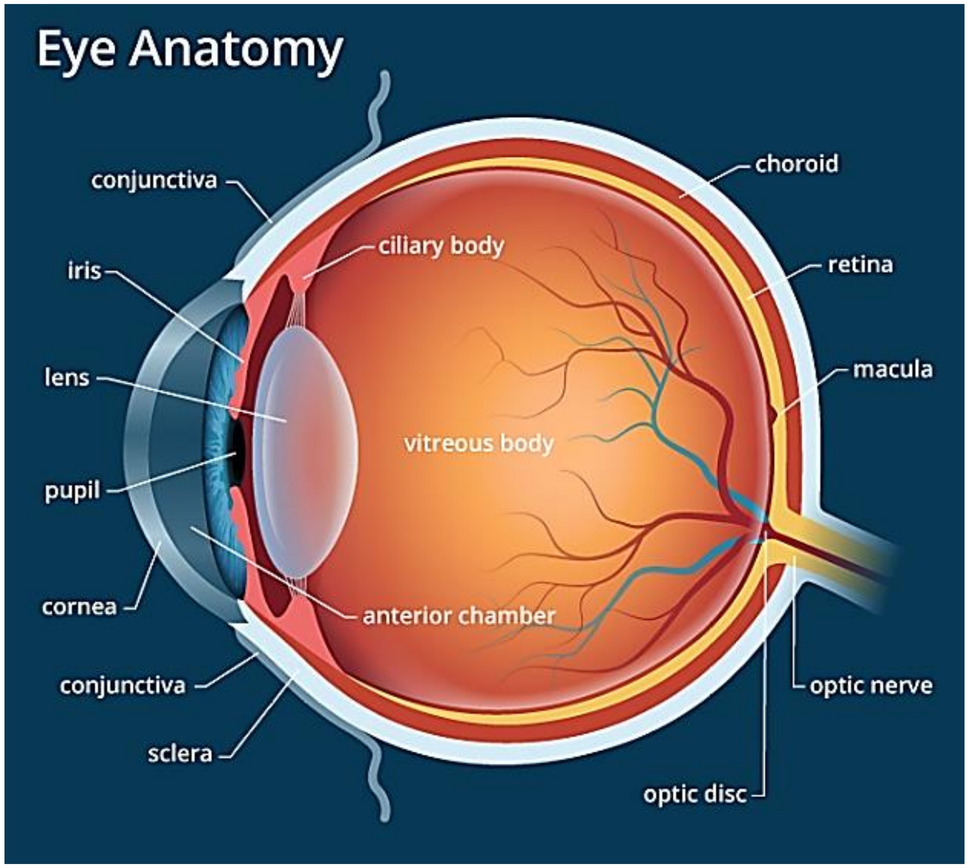

Figure 20. Human Eye Anatomy (Allaboutvision.com, 2019).

Frame rate of all visualization systems should be done according to human temporal response: more than 70 frames per second (Hz) are sufficient for a reliable impression with significant light intensities at the perimeter, while low Hz can be enough at the focal area with moderate light conditions. Refresh rates of the system must not decrease below the flicker fusion threshold. But as one can see, flickering can be detected above 70 Hz indeed: high-speed motion either of the spectator or object can result stroboscopic multiple images or image blur (Figure 21). This effect is known as phantom array effect (rainbow effect with DLP projectors). (Hainich and Bimber, 2016.)

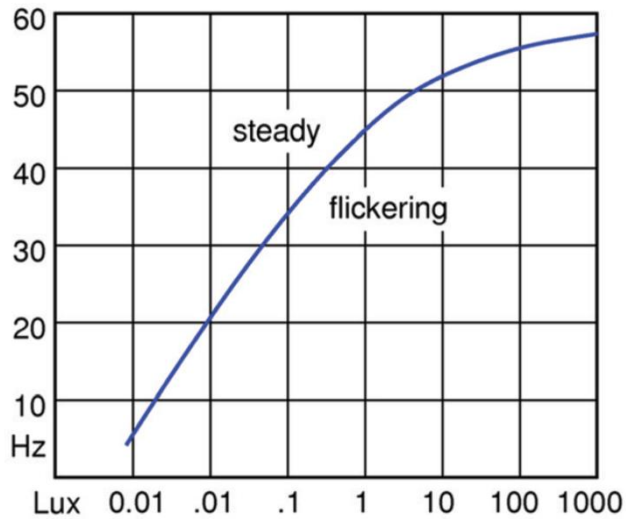

Figure 21. Average flicker fusion curve for the human eye: frequency with respect to brightness. (Hainich and Bimber, 2016.)

The eye is able to distinguish brightness range of nine orders of magnitude, however not concurrently (on the same frame). It covers a considerable range of light intensity from the starlight intensity of 1/1000 lux to nigh 100,000 lux of the sunlight. The human's feedback to brightness levels is typically logarithmic, comparable to the responses of the rest human senses. The certain function can be shown using Weber-Fechner law (exponent) or by gamma value within certain limits. The contrast that can be recognized as one on same frame hinge on human's adaptation, image brightness, and spatial-detail recurrence (frequency) in the image.

Brightness is a principal display characteristic. It is more deeply described in cd/m2. For the best image visualization, the device should emit brightness grades at least on the level of its environment. Brightness levels can range from circa 100 cd/m2 for projection in dark conditions to thousands of cd/m2 for displays used with intense lighting or during the daylight.

In practice, several displays produce brightness values in a range starting from 200:1 and up to thousands-to-one ratio in special cases. To obtain high contrast image on displays it is required to have effective anti-reflective coating.

Resolution, as the most well-known parameter in visual industry, plays significant role in visualization system assessment. For better understanding, which resolution should be in projection system, human eye resolution should be determined. It was found that for a wavelength of λ =550 nm and a pupil diameter of a=2 mm, angular resolution is one arcmin with the focus point on the retina 6 micron. (Hainich and Bimber, 2016) Smallest length where two line or two dots are resolved is the Minimum angle of resolution (MAR). MAR values are different from person to person, according to eye health and the visual system accuracy.

TV standards try to coincide this nature resolution and to obtain “crisp” image. It should be taken into account that eye resolution is connected also with contrast ratio of the picture, and 1.5 arcmin can be sufficient value for the system. Sometimes, at 100 percent image contrast two arcminutes can be acceptable. (Webvision.med.utah.edu, 2019.) Moreover, it is important to note that eye resolution depends on viewing angle (Figure 22).

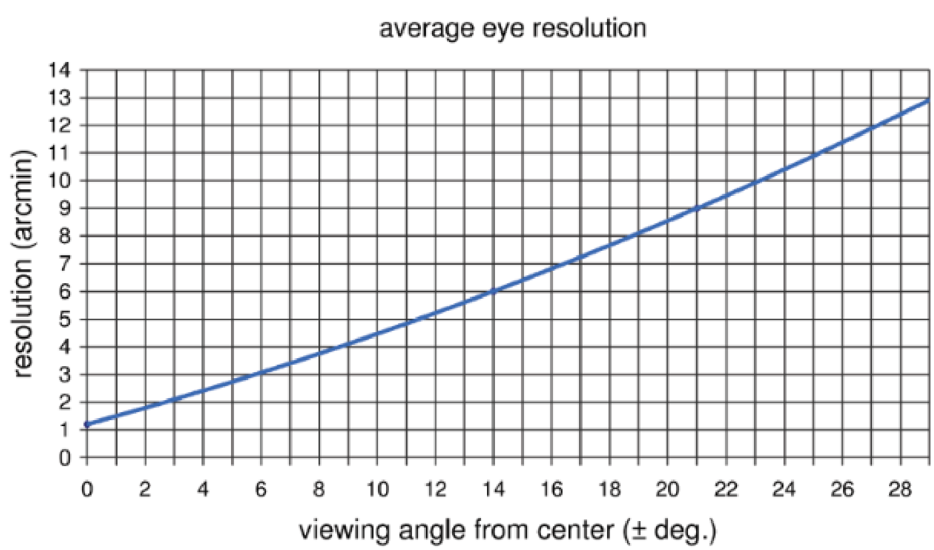

Figure 22. Average human eye resolution y with visual field x (Hainich and Bimber, 2016).

Angular resolution represents importance for displays located near eyes, by reason of its screen dimensions is virtual and display crispness can best be assessed by comparing the monitor's angular resolution to that of the eye (1 arcmin in best case scenario). One arcminute means that the small-scale object resolved by the eye can be determined about 1/3438 of the observing distance. Table 9 presents some existing typical TV formats for display's resolution:

Table 9. Current displays formats with aspect ratio.

Name	Resolution (HxV)	Aspect ratio
HD1080	1920x1080	16:9
2K	2048x1080	17:9
UWHD	2560x1080	21:9
UWQHD	3440x1440	21:9
WQHD	2560x1440	16:9
UHD-1	3840x2160	16:9
4K	4096x2160	17:9

Of course, there are many others aspect ratios and resolutions that can be used in visualization, but referring to given case, whole display/screen should have dimensions in ratio at least 1.38 to cover H- and VFOV. Nearest aspect ratio is 17:9 and 21:9. Another popular aspect ratio 4:3 is used mostly for reading and document work unlike to 16:9, 17:9 and 21:9.

In case of new laboratory project, it is required to have a space between user and a screen. Due to dimension of the motion platform planned distance is 1-2 meters. To choose correct display in terms resolution, preliminary approximations are used (Table 10) for 2- and 3-meters distance. It is standard way to choose preliminary the display with quality HD, further, it will be calculated more precisely. Undoubtedly, larger screens can be used for better performance, even if sufficient options are given. It is tip for standard practical situations.

Table 10. Minimum screen diagonals for fully visible detail (1 arcmin) (Chen et al., 2012).

Format	Lines	Aspect	Distance 2 m	Distance 3 m
HD (720p)	720	16:9	85 cm	128 cm
HD (full)	1080	16:9	128 cm	192 cm

With the advent of 3D technologies and requests for more immersive visualization, depth perception develops more and more swiftly. However, replicating of the real 3D effect optically is a challenging venture. Perspectives as seen by a device or a human can be right reproduced if image size and distance are able to produce picture on the wiever's retina, through producing the same converging perspective lines as in the original case. Situation aggravates with 3D visualization - the discrepancy between live and shown perspectives becomes more obvious.

Next restriction for display design is the human visual field. Monocular field is the total scope of the environment that can be reached by single eye independently. It ensures about 180 degrees horizontally and 130 degrees vertically (Traquair, 1928) (Figures 23, 24).

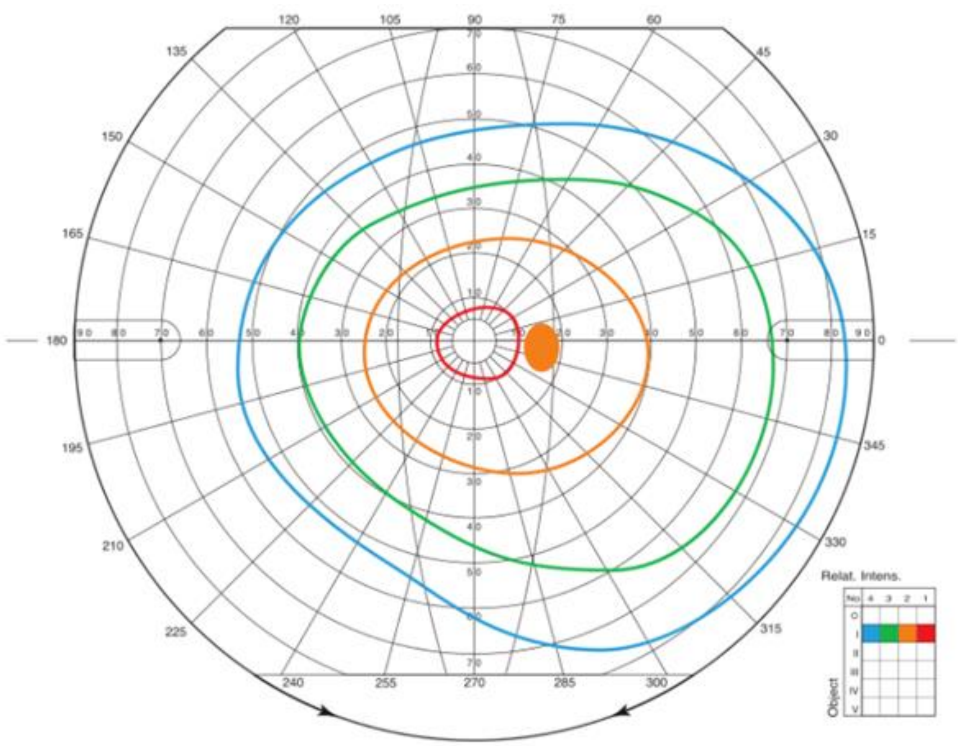

Figure 23. The field of view of the right eye (parametric card, the numbers on the scale are in angular degrees) (Dersu et al. 2006).

Orange spot - the place of projection of the blind spot of the fundus. The field of view of the eye does not have the shape of a regular circle, due to the restriction of the gaze with the nose from the medial side and for centuries above and below (Dersu et al. 2006). The fact of presence of two visual sensors gives opportunity to have stereo (binocular) vision for human. Nonetheless, this area occupies approximately one third of full FOV (Figure 24).

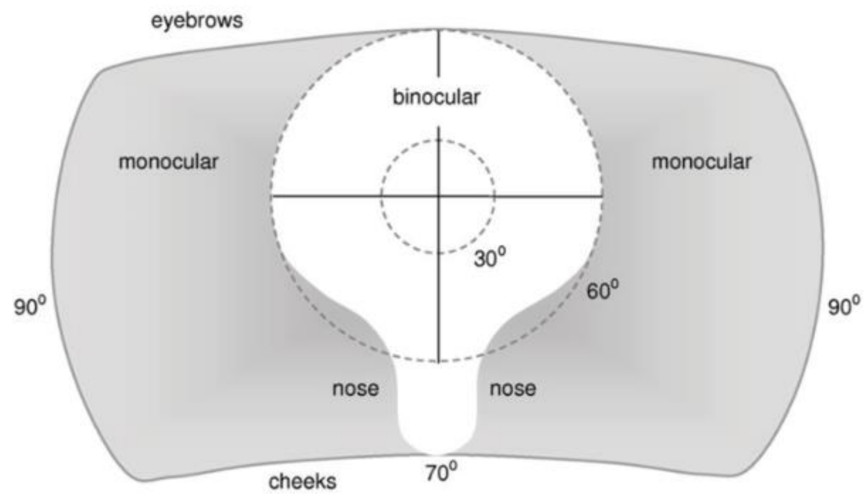

Figure 24. Human field of view scheme with monoscopic and stereoscopic parts (Hainich and Bimber, 2016).

FOV, including VFOV and HFOV, is general term. In practice Useful Field of View is used in assessment of visual sensitivity. On Figure 25 UFOV concept is given:

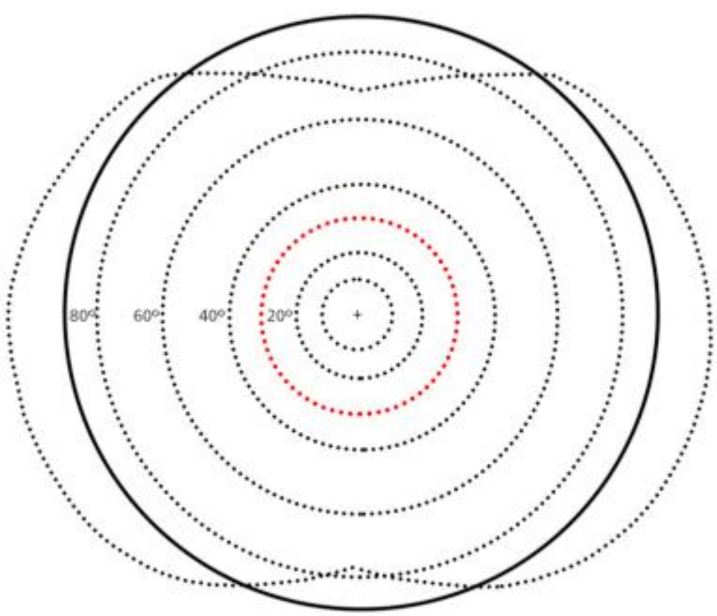

Figure 25. Comparison of full human FOV with Useful Field of View. (Ball and Owsley, 1991.)

By Ball and Owsley (1991), red circle marking the 30-degree border shows the range of UFOV, where people perform given visual tasks successfully; average values are located near this line. Area of UFOV depends on several physiological and external factors: age, health, physiological state, work conditions.

90-degree bold black circle represents area around the point of fixation, average FOV. It should be noted that real HFOV and VFOV varies inside these values. Human FOV is a lot more than assessed area in UFOV tests. It was made several studies to measure certain human UFOV but depends on methodology different results can be shown: in 2009, by adapting classic test, it was discovered that UFOV is bigger than 20-30-degree area; UFOV is extending to 40° in special cases (Itoh et al., 2009). Term Useful Field of View is practical tool in optics and visual studies, it provides numerical data about the ability to notice objects for researches such as driving and industry work activity.

3.1.3 Projection systems

Projector-based systems are able to generate huge images with tiny device, unlike for screen displays, which are not significantly but always larger than the generated images. Historically projector systems were developing earlier than various types of displays, for instance, first visualization was introduced in movie production. Usually projectors are used in dark conditions, because ambient light effects on brightness level of the system, on other hand, screen displays (LCD, LED, CRTs) are suitable to use in regular room lighting without considerable disadvantages. (Chen et al, 2012.)

Due to developing technologies, projectors become more sophisticated and efficient to provide new technical possibilities. Digital devices with increased resolution and power used nowadays in cinemas, theatric performances and for different simulation purposes. On other side - micro projectors that are integrated into cellphones and similar gadgets, producing the projection of relatively big images on desired surface. Projectors are adjustable in a way of resolution and size of emitting image, and more flexible to use than rigid displays.

Several projectors can be united in one simulation platform to obtain larger image without seams and to provide 3D perception for user. Besides main equipment, feedback line via brightness and color sensors can be added to self-adjust projecting settings. (Chen et al, 2012.)

In common practice, projection types are divided on two big groups: front and rear projection. Typical advantages and disadvantages are presented in Table 11.

Table 11. Comparison of front and rear projections.

	Front projection	Rear projection
Space	Does not need extra space, but possible shadow should be considered	Significant space behind the screen
Ambient light	Darkness required	Can work with high ambient light
Brightness	Brightness depends typically on device output and screen gain. More efficient in dark rooms	Brightness losses when light transfers the screen. This disadvantage can be neglected in bright light conditions
Viewing angle	Depends on gain	Depends on material selection for the screen (different diffusion coefficients)
Contrast	Ambient light effects	Ambient light does not effect

Basing on current area, ambient light background and application, projection type and using projectors should be chosen. Referring to chosen type, screen material, support structure and properties for projection should be also specified.

There is common way to obtain bright and clear image and sufficient diffusion – traditional white screen, but significant disadvantage is that it will reflect also ambient light and consequently decrease overall contrast level (blurring image). White screen diffuses light beams consistently along the screen surface.

Coating with darker colors from light grey to black will create deeper level of black, which make image more stable with higher contrast level. Besides classic solution with setting the color, there is special material solutions for these intense conditions - ambient light rejecting

(ALR) screens. Screens based on ALR technology absorb indirect and off-axis ambient light, which is redirected from the observer.

In addition, gain screens, which ratio of screen reflectivity compared to matte white is bigger than one, improve projecting conditions in ambient light environment: increase on-axis brightness and remove some part of off-axis light from the onlooker. For instance, it will be useful in conference auditorium. (MDI, 2019.)

Some screens materials provide flexibility to use either front or rear projection in special cases. For instance, new screen materials with aluminum-based coating and perforation (sound transparency) can decrease hot spot effect and increase brightness of the reflecting light, leaving the wide viewing angle compared to a standard white board (magnesium oxide) like in HGA screens (Figure 26) (Spectroscreen.com, 2019). Right choice of screen material is critical as choice of projector using in the system.

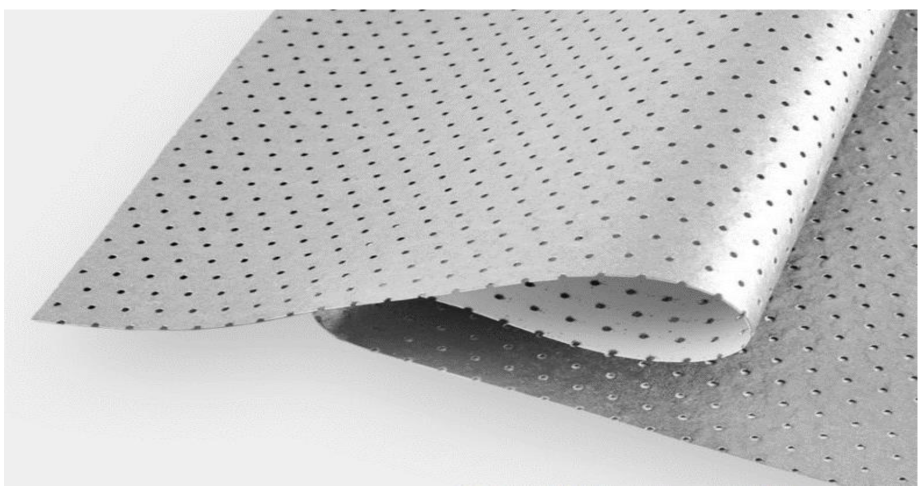

Figure 26. HGA screen “3D silver”. (Strong / MDI Inc.)

Effectiveness of the chosen screen depends on next factors:

- Light output of selected projector
- Lens type
- Ambient light level

- Dimensions of the screen
- Loudspeakers location

Screen frames is the base for flexible reflecting material. It can provide flat or curved configuration for the screen. Typically, it is metal rigid self-supportive mesh or mounted to wall or other rigid structures (Figure 27). Screen material is held by springs attached to the frame. Moreover, speakers holding parts can be added to the frame. Screens should have gap (plinth) between floor and the bottom of the screen, approximately around 8-10 cm.

Figure 27. Screen frame part. (Strong / MDI Inc.)

In common practice, manufacturers use four standard types of screens: electric-driven, fixed, pull-down (manual) and portable:

1. Driven screens shift up and down by the control of the actuator, electric motor.
2. Fixed screens, which are installed on the rigid base like floor or walls; it requires a permanent space, but it does not have any actuators.
3. Manual projection screens are simple and can be retracted when it is not in use; this solution can save space in home or educational conditions.
4. Portable option with tripods or other similar equipment.

Mirrors systems are used for redirecting light in complex-shaped screens. However, use of mirrors reduces amount of the light which is translated to viewer.

The main part of every projection system is projector. Projector is an optical device intended for creating a valid image of an object on the surface. Projectors can be split in groups based on applied technology principle: CRT, DLP, LCD and laser-based projectors. Besides utilized technology projectors can support 3D imaging or not: some of them have initially built-in 3D capability, the rest requires additional plugin - a 3D emitter to provide 3D picture. Optical principle of light emitting in projector is given on Figure 18. Instead of lamp on Figure 28 there can be different types of light source (LED, lasers). (Chen et al, 2012.)

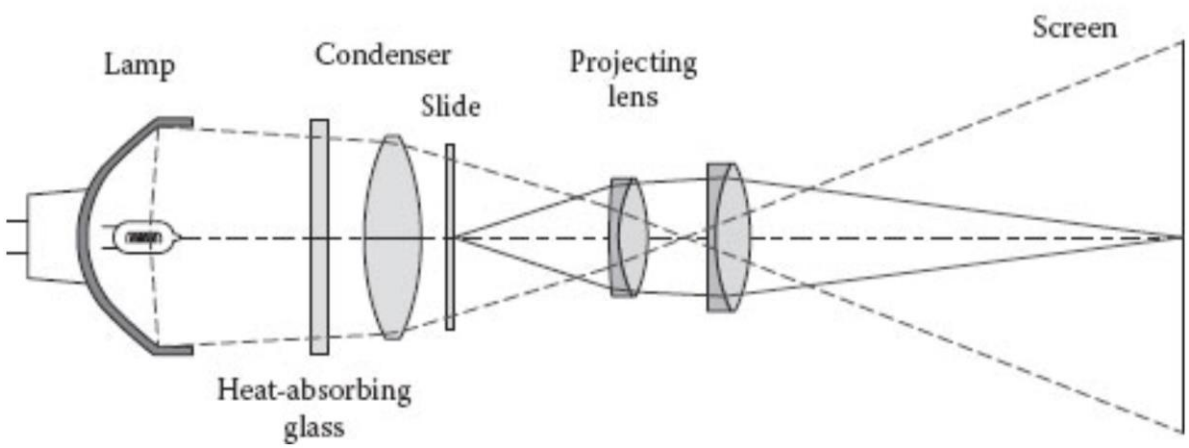

Figure 28. Optical scheme of a typical lamp projector. (Malacara et al, 2004.)

Higher lumen output projector can compensate the brightness deprivation from a low gain surface or bright ambient light, either rear projection. Screen-projector combination is efficient when surface material limits the effects of ambient light, and more powerful projector compensates reducing reflectivity from the viewing surface by overcome of external light and material properties. Per contra, high lumen projector critically effects on contrast ratio and lead to distressing glares for the eyes. In case of ALR screens, it is important to adjust the angle of incidence because this type of screens redirect off-axis light, what can be also an additional cause of brightness drop. Color brightness of the projector should be at least as its white brightness to have vivid images without dull colors.

High contrast ratio of the projector is essential to define shadow details and various levels of black, which are giving the sense of deepness and dimension to the image. In dark light conditions, contrast ratio is noticeable comparing to well-lit rooms.

Top-ranked projection system manufacturers have special product line for simulation and training purposes. Projectors are broken down into this group due to their specs, which satisfy purposes similar to present case.

3.2 Requirements

The target is to update the visualization system to 180-degree cylindrical screen. The diameter of the screen is about five meters. Position of eye-point is dynamic. User must be able to walk in 3D simulation, install motion platforms and use it in front of the screen. Low latency of the system is very important for simulation purposes.

Many research groups, like mechanical engineering, civil engineering and health care, will use visualization system. System must be universal, flexible and easy to use.

Specifications of the space:

1. The space of the lab is about 70 m^2
2. The height of the room is 2.74 m
3. Ceiling has a mesh H=3400 (Figure 29)

Figure 29. Ceiling mesh (3400).

There is no ambient light during simulations. Color of the walls and ceiling is light grey, and floor is dark grey. Software maintenance and support for 3 years must be provided. Equipment assemblies must include necessary software and partial submissions are not allowed.

Also should be included:

- Shipping of parts directly to Lappeenranta University of Technology. On-site installation.
- Project Management, Design Engineering (Installation Drawings, 2D Manufacturing Drawings & Training Notes), Installation, Calibration and Training are performed by Contractor side.
- Warranty on 3D Visualization system must be not less than 3 year since installation and calibration stage.

The following minimum requirements are so far planned (Table 12):

Table 12. LUT preliminary requirements.

Form	Cylindrical (curved)
Angle	At least 180 ^{o}
Diameter	Approximately 5 m
Room height (max)	2,74 m (mesh 3,4 m)
Shadow free	Yes
Position of eye-point	Dynamic
Frame rate at full resolution	At least 60 Hz
Angular resolution	Less than 3 arcmin
Auto-Calibration System	Yes

Basic requirements are given in Procurement Document in Appendix II.

Besides sent requirements, next practical questions were considered during the design process:

1. What kind of activities have to be in laboratory? Is it only visualization or it is planned to have a place for robots and Ambulance Simulator?
2. Is it acceptable to decrease radius of the screen to save the space and the cost?
3. Rear of front projection?
4. If Ambulance Simulator, 6DOF or other platforms will be using 3D Projection platform, how mentioned platforms will be put and removed in and out of the curved screen? Where they will be stored? How to change it easily?
5. Where Saimaa's robots and scanners will be stored?
6. Will door type of the laboratory change?
7. Will metal frame for motion capture be reconstructed?

According to paragraph 1: after project meeting with Saimaa UAS professors (17.04.2019) it was decided to use existing motion platform in Saimaa University to make Ambulance Simulator for teaching purposes and finally it will stay outside the Laboratory of Intelligent Machines on current place. Collaborative robots with scanners will also stay in Professor Timo Eloranta laboratory. Tiera Robot will be shifted to Heavy Laboratory in third Building of LUT. Therefore, Laboratory of Intelligent Machines will be only for simulation researches.

According to paragraph 2: It is acceptable, but undesirable, because it will decrease area of free movement inside Projection System and effect of immerse will cut down. It can be done due to design constraints.

Paragraph 3 is controversial in terms of different advantages and disadvantages of each type of projection. Final decision will be made by comparing own design with suggested solutions from producers.

According to paragraph 4: there only can be presented in laboratory: motion seat based on 6DOF motion platform, Horse Simulator and future designed own 6DOF motion platform. Motion seat is the main simulation object in terms of studying 3D Projection system, most kinds of industry machines have almost the same operator’s seat. New 6DOF platform will have comparable to old one’s dimensions and characteristics. Horse Simulator will be challenging item to be integrated with visualization platform. One general issue is attitude of the screen and attitude of the horse with rider: horse with rider can be more than 2 meters in height when maximum height of the screen is less than 2.6 meter. Moreover, if front projection will be used, shadow-free mode cannot be resolved, and motion tracking will be difficult.

Right now, motion platform with the horse is mounted using bolted joints. In future, it is planned to use the same system, because of its stability, stress-resistance and safety principles. For easy transporting and changing of the objects inside the simulation environment, using wheels can be the solution.

For effective use of Visualization platform and for reducing of installing-removal actions it is suggested to form the research plan for the whole laboratory with time periods when certain type of equipment will be used in simulation. For storage of unused equipment will be given another place, at least in case of rear projection.

Paragraph 5: In Saimaa University of Applied Sciences laboratories.

Paragraph 6 (Figure 30): Definitely, yes. It is necessary to avoid external lighting during the experiments. Simple toning or painting of the glass, thick shutters or to change doors to completely light impenetrable ones can solve this problem.

Figure 30. Entry doors of the Laboratory of Intelligent Machines.

According to paragraph 7: based on fact that old motion capture camera system will stay in the laboratory, and mostly motion seat will be used it is possible to leave the frame. However, according to curved screen geometry and possible shadows and obstacles for sight it is recommended to enlarge frame dimensions. Increased dimensions can cover the Horse Simulator in motion capture, while now it is impossible to track head motion.

3.3 Possible options

There are three possible option to visualize simulations in laboratory conditions:

- Projection system (rear/front)
- Monitor system
- VR headset solution

Solution using 3D Projection system are more interesting for laboratory purpose, because it can provide seamless image on a large diameter screen. In addition, with projection it is possible to obtain screen surface with complex geometry (1 or more bending axis). In practice, two types of projection are identified: rear and front (MDI, 2019).

Front projection screens use reflection of the light, rear type of screens diffuses the light beams through the screen material, on other side. Choice of the suitable type of projection system mostly depends on area where it will be situated, light conditions, simulation properties, importance of shadow-free projection.

Based on existing requirements and conditions, front projection will be more reasonable: laboratory can have almost absolute darkness inside simulation environment subject to closed all windows on doors and turned off lighting. Walls have light grey color, but it is not the issue, side in front of projected screen can be repainted or covered with light absorbing material. Front projection can provide more brightness comparing to rear one and it occupies less space that can be used for storing other equipment such as human-collaborative robots from Saimaa UAS and existing Tiera Robot (Lut.fi, 2019).

Notwithstanding, mentioned advantages of front projection cannot be reached because of attitude of the lab (2.74 m) without huge plinth and shadows. That is why focus was changed to rear projection type, which can be used in cases where attitude can be neglected. With rear projection desired shape of the screen can be obtained without big plinth and image will be totally shadow-free, because on the light way there will not be obstacles. Unfortunately, main advantage of the rear projection cannot be afforded because of the light conditions inside the room. Moreover, it will occupy most part of the lab area and more brighter projectors should be considered in design.

Solution with monitor can be done in single display and multiple displays option. Single display is the simplest and the cheapest way to implement this system despite of how large it will be comparing to projection system. On the other hand, even 3D display does not provide immersive simulation for human due to obvious parameters such as field of view, perspective of the image. With several monitors, it is possible to shape assembled screen into desired configuration. The main disadvantage of this screen is that displayed image will be with seams due to constructional limits of the screen. This fact significantly decreases value of provided performance eliminates effect of reality, but it is still cheaper than 3D Projection platform and it can be constructed by LUT without external services.

VR solution will be presented in new laboratory design; however, it will be used not like general visualization tool. VR headsets are imperfect on the current stage, because of insufficient precise in transferring physics it might cause discomfort, for instance, dizziness. Nevertheless, for 30-40 minutes trial it is quite powerful and effective device.

3.3.1 Projection system option

Note: design of multi-projector systems with seamless image, which can support 3D technology, requires special blending and warping software. This fact makes significant restrictions on developing curved screen systems by non-professional research teams and organizations. However, basic optic principle are legitimate and can be used during approximate calculations. Calculations are made for 1-projector system with flat screen; these approximations have a place to be, because curved system can be split on 3 sub screens. Curvature radius does not play significant role in this case and it can be stated as “flat”. From the beginning, initial data should be given such as screen material, preliminary projector, required brightness, size of the screen and finally desired resolution.

Screen was chosen from the product list of Spectroscreen Company, aluminum-based perforated screen with high gain, improved contract and uniformity characteristics. This kind of screens allows watching dynamic 3D content on a comfort level. Screen Silver240 has 240% gain comparing to matte white screen and HGA value is equal to 22 degrees. (Spectroscreen.com, 2019.)

Screen Brightness, according to the SMPTE and THX Company standards, system should have at least 12 foot-Lamberts (ft-L) in a full ambient light controlled room. (Smpte.org, 2019) (THX, 2019) Minimum standard value for screen brightness is 16 foot-Lamberts. For instance, in cinemas 12 and 22 ft-L projection is commonly used solution, or TV generates more than 35 ft-L. In our case, 16 foot-Lamberts brightness was taken into account.

Desired solution for Intelligent Laboratory is 4K (3840x2160 pix). Screen is a half-sphere with 5-meter diameter and 2.5-meter height. Based on overviewed specifications it is possible to choose preliminary the suitable projector from official suppliers. Three companies were chosen for consideration:

- Barco (Barco, 2019)
- Sony (Sony, 2019)
- Christie Digital (Christiedigital.com, 2019)

For the calculation, VPL-GTZ240 projector (4K, 2000 ANSI lumens) was taken. Three projectors will insure whole image. Referring to Carlton Bale (engineer, visual technology researcher) (Bale, 2019) projection system assessment was done. Length of the screen is equal to 7.85 m, thus, 1/3 of the screen, which was considered is 2.7 m. Height is 2.5 meter. Blend might be up to 15%. Feasible projectors configuration and blending zones are presented on the Figure 31.

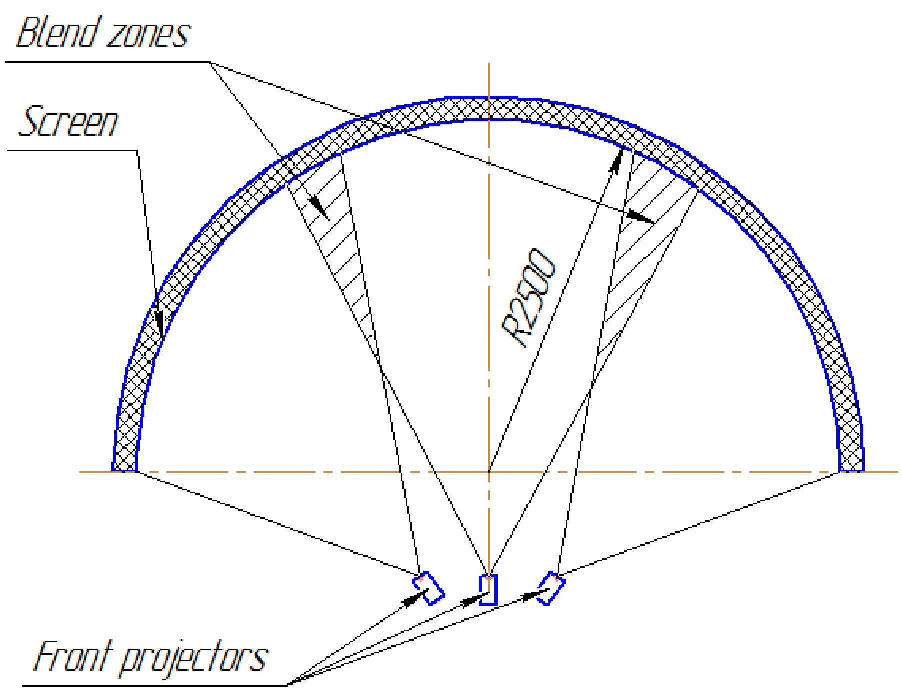

Figure 31. Blending scheme of front projection.

Longest endorsed viewing distance, according to the SMPTE EG-18-1994 standard, should cover at least 30 degrees (Equation 2):

$$VD_{SPMTE} = \frac{SW}{2 \cdot \tan(\frac{30}{2})} \tag{2}$$

Where, VD_{SPMTE} – viewing distance, m; SW – screen width, m; tan $\left(\frac{30}{2}\right)$ in radians.

$$VD_{SPMTE} = \frac{2.7}{2 \cdot \tan(\frac{30}{2})} = 5.03\ m$$

Obtained value completely satisfies standard requirements, because due to planned viewer's position (2.5 meter from the screen) it will cover more than 30 degrees (the SPMTE recommendations). According to THX standards minimum viewing angle is 26 degrees.

The most important aspect is screen brightness, how much light reflect chosen screen during the projection (Equation 3). It is necessary to remember that final value of screen brightness depends on lens type. If anamorphic type of front projection is used (it leads to horizontal expansion), than we should consider lens coefficient (K = 0.9).

$$SB = G \cdot \frac{PB}{(SW \cdot SH)} \tag{3}$$

Where, SB - screen brightness, foot-Lamberts; G - screen gain; PB - projector brightness, lumens; SW-screen width, foot; SH - screen height, foot.

$$SB = 2.5 \cdot \frac{2000}{(8.86 \cdot 8.20)} = 68.82 \text{ foot} - \text{Lamberts or } 235.78 \text{ cd}/m^2$$

Brightness level is 4 times bigger than minimal standard value, it means that this system is allowed to use with presence of ambient light. Moreover, light level can be decreased by replacement of screen material to less reflective.

On other hand, it is required to know minimal sufficient projector brightness, which is compulsory (Equation 4).

$$PB = \frac{RSB \cdot (SW \cdot SH)}{G} \tag{4}$$

Where RSB – required screen brightness, foot-Lamberts.

$$PB = \frac{16 \cdot (8.86 \cdot 8.20)}{2.5} = 465 \; lumens$$

To find correct distance for projector relatively to the screen, minimum and maximum throw distances should be stated. Besides computational methods, developed by companies Projector Throw Distance Calculators, for example Sony, can be used (Figure 32).

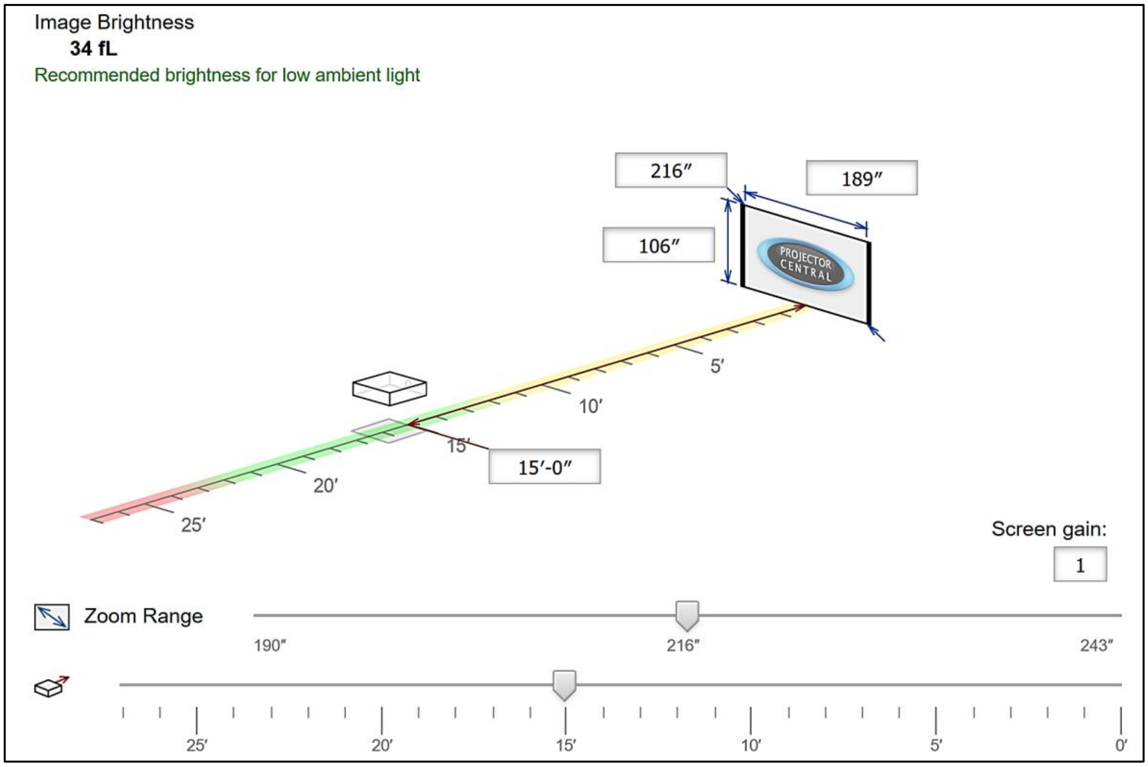

Figure 32. Online-calculation of Throw Distance (Projectorcentral.com, 2019).

Projector have to be in front of the screen in range 2.5...3 m. Screen width ratios can be found in Equations 5, 6:

$$WTR_{min} = \frac{TD1}{SW} \tag{5}$$

Where, WTR_{min} is minimum screen width throw ratio; TD1 is minimal throw distance, m; SW is screen width, m.

$$WTR_{min} = \frac{TD1}{SW} = \frac{2.5}{2.7} = 0.926$$

$$WTR_{max} = \frac{TD2}{SW} \tag{6}$$

Where, WTR_{max} is maximum screen width throw ratio; TD2 is maximal throw distance, m; SW is screen width, m.

$$WTR_{min} = \frac{MTD}{SW} = \frac{3}{2.7} = 1.111$$

Using the values obtained simple projection system can be built; more complex curved screen projection requires computer simulation of the light processes, how projecting images from each projector will interact with each other. However, for simple assessment it is sufficient amount of information.

3.3.2 Monitor system

Monitor system can be configured as a CAVE simulation platform with three display walls or as a semi-curved option, where segments are located with obtuse angles between each other, forming circular arc screen. Minimal required distance for simulation purposes, for instance, with 6DOF motion seat is 100 cm (3.28 feet). Maximum diagonal 127 cm (50 inch) where benefit of 4k can be seen. If there would be bigger screen it is advised to use 8k technology (Figure 33).

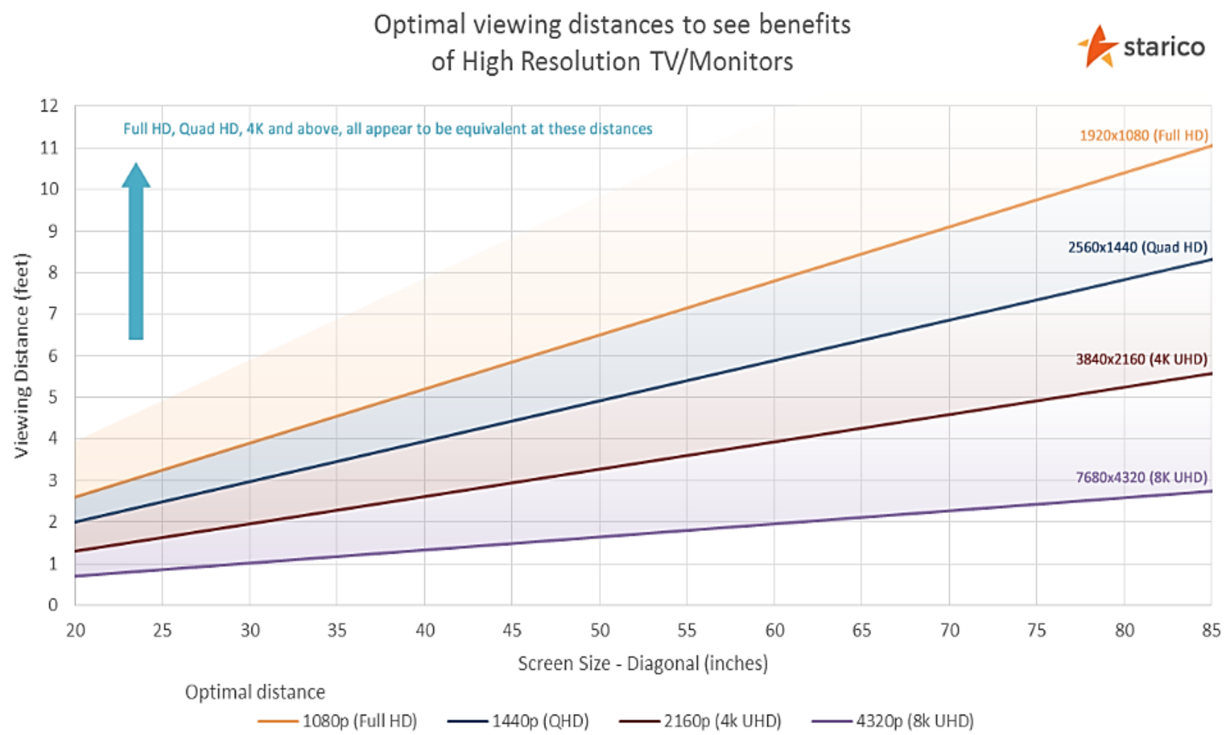

Figure 33. Optimal distance to achieve angular resolution 1 arcmin (Starico, 2019).

Required screen diagonal calculations are presented below. (Jansen, 2014) Starting point is calculating screen diagonal basing on human field of view. HFOV is not essential, because it can be reached by adding extra displays in a row to fulfill required angle. Accordingly, the base of this assessment is VFOV.

Recently, it was shown that VFOV values are between 130-140 degrees, but full VFOV does not suitable in this case, because density of photoreceptors varies from center to periphery of the eye. Consequently, we should add characteristic as UFOV - Useful Field of View. UFOV shows area where human eye can process data and react on the triggers. It ranges in depends on speed of action and information overload. Average angle of UFOV lies between 20 and 40 degrees in vertical and horizontal axis. In our case, it is assumed that UFOV is equal to 40 degrees due to typical simulation research problems. Scale factor should be also considered to obtain immersive experience during the simulation. It was taken as Ks = 1.2.

Distance from user head to monitors is a = 1 m due to safety principles and necessity to create free-obstacle zone. Height of the display system will be counted by Pythagoras theorem, basing on known angles and one leg (Figure 34). Dimensions of the unite display will be found in next equations: it can be done as assemble of several displays or as one to provide seamless image. Main restrictions are cost and available products on the market.

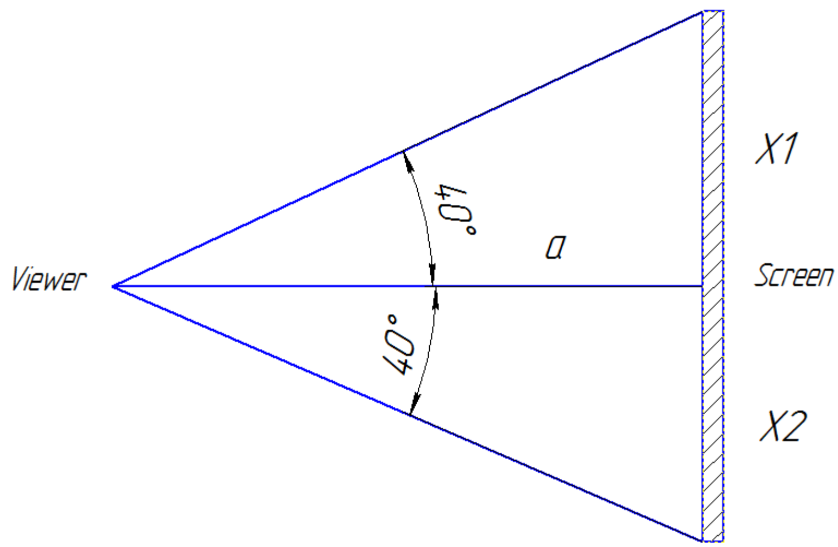

Figure 34. Optical scheme for VFOV (X1+X2 is height of the screen, a is distance).

$$X1 = X2 = a \cdot tg40° \tag{7}$$

Where, X1, X2 – heights of the screen, m; a – distance, m.

$$H = 2a \cdot tg40°$$

$$H = 2a \cdot tg40° = 2 \cdot 1 \cdot 0.8391 = 1.6782\, m \approx 1.7\, m$$

It should be noted that if full FOV would be used, that values of required screen will be enormous. Height will be around 4.3 meters (130° VFOV).

As it was mentioned to ensure immersive experience of the displays, scale coefficient was added (Equation 8).

$$Hperf = Ks \cdot H = 1.2 \cdot 1.7 = 2.04\ m \tag{8}$$

Hperf will be increased or decreased due to available display product line.
Length of the screen should be in standard ratio, it was decided to use 4K resolution (3840x2160 or) which have 16:9 ratio (Equation 9).

$$L = \frac{16}{9} H \tag{9}$$

Where, L- Length of the screen, m; H – height of the screen, m;

$$L = \frac{16}{9} H = 1.78 \cdot 2.04 = 3.63\ m$$

Calculated screen diagonal can be found using Equation 10.

$$D = \sqrt{H^2 + L^2} \tag{10}$$

Where, D – diagonal of the screen, m

$$D = \sqrt{H^2 + L^2} = 4.16\ m \approx 164\ inch$$

Based on received value, it can be suggested 3 possible options from the standard display product line (Figure 35):

- 12 x 85" displays
- 27 x 55" displays
- 36 x 42.51" displays

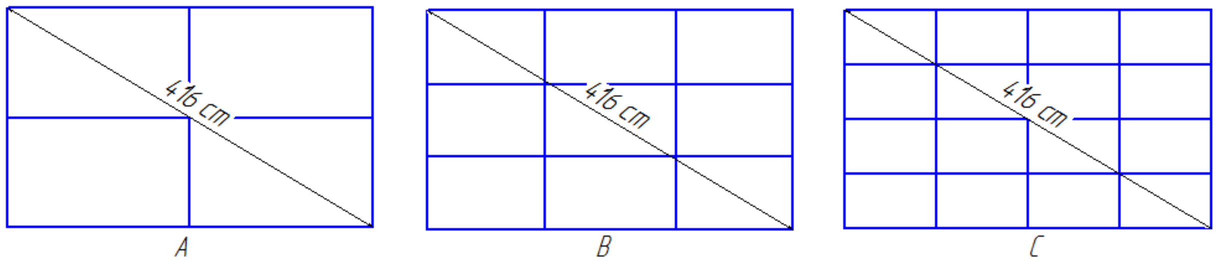

Figure 35. Possible configuration for visualization wall. A - 4 displays per wall; B - 9 displays per wall; C - 12 displays per wall.

Obviously, that with decreasing of displays number image becomes more seamless, that allows obtaining visualization that is more “real”. In case of making round-shaped screen, it is better to use more screens to get smoother shape. There is some standard line of displays on the market: diagonals from 3.5 to 152 inches. It was chosen three types of the screen 42.51”, 55” and 82” (Samsung, 2019). Resolution for 42.51” and 55” is 4K, for 82” – 8K referring to angular resolution requirements.

Finally, maximum viewing distance, where advantages of selected resolution are significant, should be checked (Equation 11):

$$CVD = \frac{DS}{39.37 \cdot \sqrt{(\frac{NHR}{NVR})^2 + 1} \cdot CVR \cdot tan\frac{1}{60}} \tag{11}$$

Where, CVD - calculated viewing distance, m; DS - diagonal size of the display, inch; NHR - Display horizontal resolution, pix; NVR – display vertical resolution, pix; CVR - vertical resolution of image, pix.

$$CVD(82") = \frac{82}{39.37 \cdot \sqrt{(\frac{3840}{2160})^2 + 1} \cdot 2160 \cdot tan\frac{1}{60}} = 1.62\ m$$

$$CVD(55") = \frac{55}{39.37 \cdot \sqrt{(\frac{3840}{2160})^2 + 1} \cdot 2160 \cdot tan\frac{1}{60}} = 1.09\ m$$

$$CVD(42.51") = \frac{41.51}{9.37 \cdot \sqrt{(\frac{3840}{2160})^2 + 1} \cdot 2160 \cdot tan\frac{1}{60}} = 0.84\ m$$

Thus, as one can see displays with diagonals 82" and 55" are efficient on selected distance. Screen configuration based on 42.51" monitors can be removed by lower resolution displays (QHD 2560x1440).

Present QLED 82" Display was designed with native resolution 8K, this resolution is redundant for our system and it is not adequate due to budget restrictions. Consequently, previous generation 82" 4K display can be used (82" Class Q6FN QLED Smart 4K UHD TV (2018), but with loss of resolution advantage (Samsung Electronics America, 2019). 55" is optimal and relatively cheap option to provide visualization platform. On Figure 36 there are two possible configurations for suggested display size.

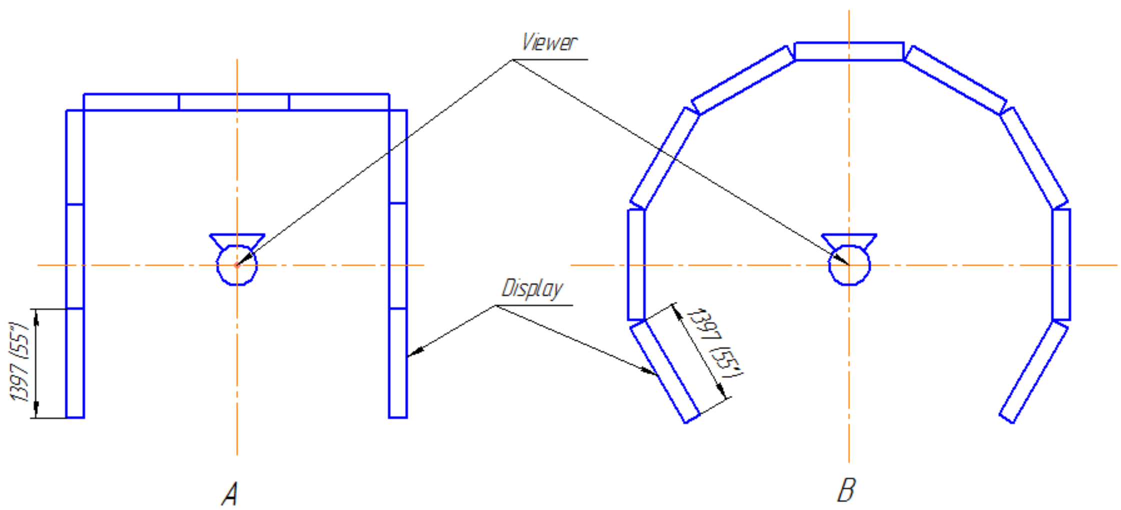

Figure 36. Possible display configurations. A - CAVE, B - 270-degree segmented screen.

Moreover, Horizontal Field of View of calculated screen wall can be found (Equation 12):

$$HFOV = 2 \cdot \arctan(\frac{DS \cdot 2.54 \cdot a}{2 \cdot \sqrt{a^2 + b^2} \cdot CVD}) \qquad (12)$$

Where, DS - screen diagonal, inch; a, b - aspect ratio coefficients; CVD - viewing distance, cm.

$$HFOV = 2 \cdot \arctan\left(\frac{166 \cdot 2.54 \cdot 16}{2 \cdot \sqrt{16^2 + 9^2} \cdot 100}\right) = 122.9°$$

One display wall covers 68% of full Horizontal Field of View; rest two sidewalls will complete deficient degrees. Cornering of the screen will make the imaging more natural. It should be noted that the smaller the size of the diagonal of the display, the more smooth the shape will be (Figure 37).

Figure 37. Curved screen configuration (EVL, 2019).

It should be added that viewing angle has to be comfortable for viewer (to avoid neck strain and headaches): basing on the SMPTE guidelines, the critical viewer sightline angle has to be less than 35° (Smpte.org, 2019). By another SMPTE guideline, screen configuration and its position should have horizontal viewing angle of 36 degrees and more (for theatric and visualization purposes) (Smpte.org, 2019).

Main disadvantages of monitor-based screen solution are: screen may cause eye discomfort due to high brightness and close viewer position, screens system may overheat after continuous work. Possible issues might be: LUT should design and create unique support frame for this system, sound system should be situated upper or from the sides of the screen, because screens are not sound transparent as projection screens.

3.4 Overview of received offers from suppliers

After sending RFIs (03.01.2019) to contacted companies, LUT side received four draft offers from next companies:

1. 3D Perception (Norway)
2. CAVE Oy (Finland)
3. Vioso (Germany)
4. Warpalizer (Norway)

All companies except Vioso sent technical data such as graphs, drawings and short description of their solution.

3D Perception is Norwegian company, which suggested to their customers assemble solutions based on own software and sensors. Offer is one of the most expensive among other companies. ROM pricing for 3D perception solution is € 160,000. This price includes system delivery, all parts (screen, projectors with lenses, frame, and additional units), “WarpLite” system, on-site building. For supplementary price (€ 27,580) calibration platform “StarScan” can be provided (6 licenses).

The concept is to use rear projection instead of front one, that will eliminate height restrictions, but it will occupy more useful place and decrease level of brightness (Figures 38, 39):

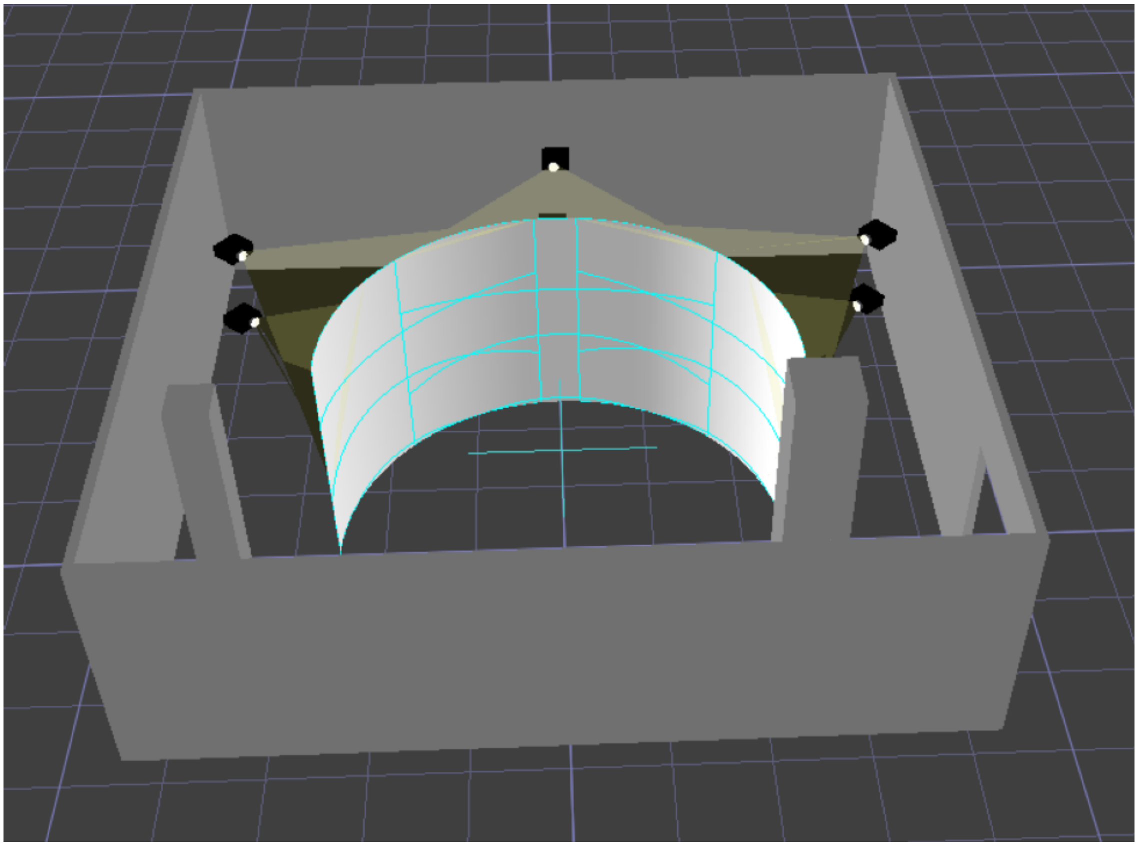

Figure 38. Draft of the projection system (3D Perception, 2019).

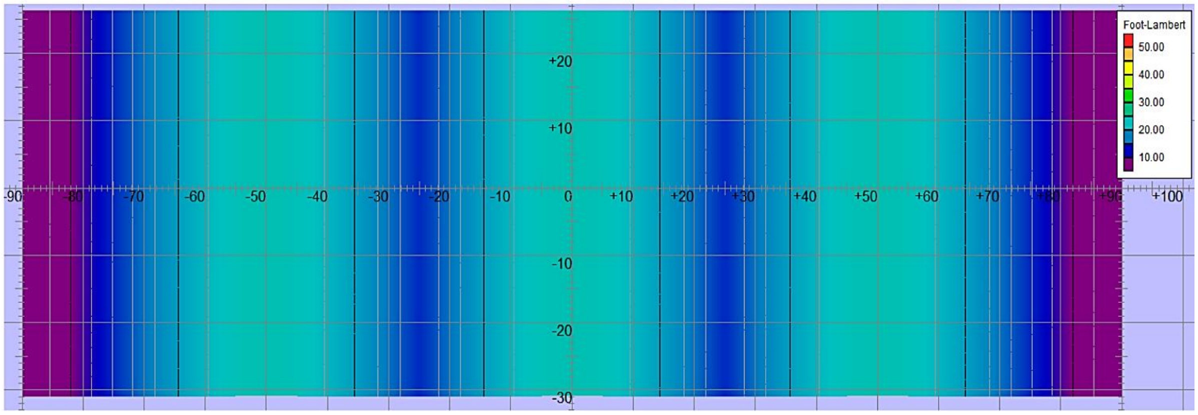

Figure 39. Image brightness simulation (3D Perception, 2019).

As one can see, on the screen there are areas, where brightness is less than 16 Foot-Lamberts. These values are not acceptable due to the SMPTE standards. It can be said that for presented solution it is required completely dark room. Angular resolution is 1.6 arcmin per pixel average. The worst values are located on blending areas (Figure 40).

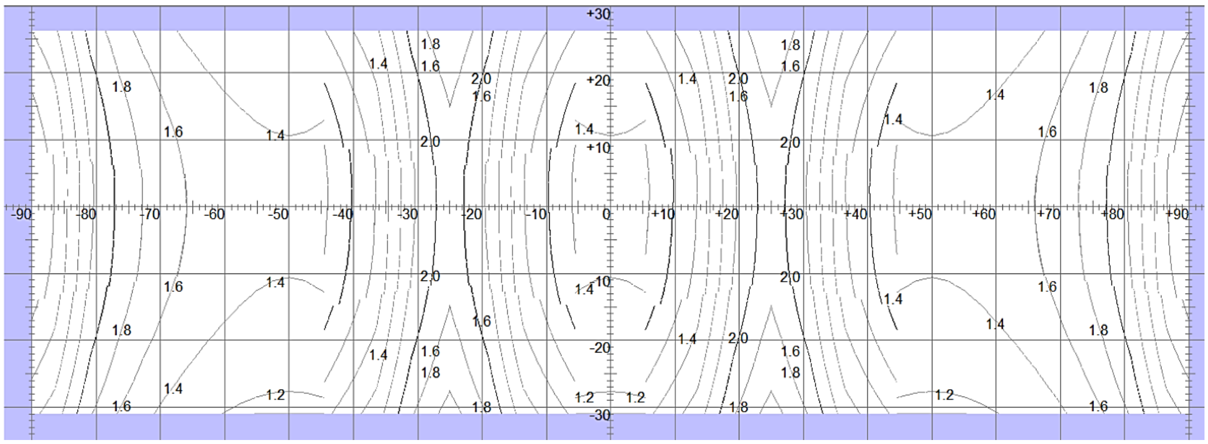

Figure 40. Angular resolution (3D Perception, 2019).

Warpalizer (Norway) solution costs around € 80,000. Cost also includes auto-calibration camera and software. Company suggested building of front projection system with 180-degree HFOV and 75-degree VFOV. Angular resolution is about 2.0-3.0 arcmin – for current requirements it is 2-3 times less than LUT wants to get. Schematic technical draw of the system is presented below:

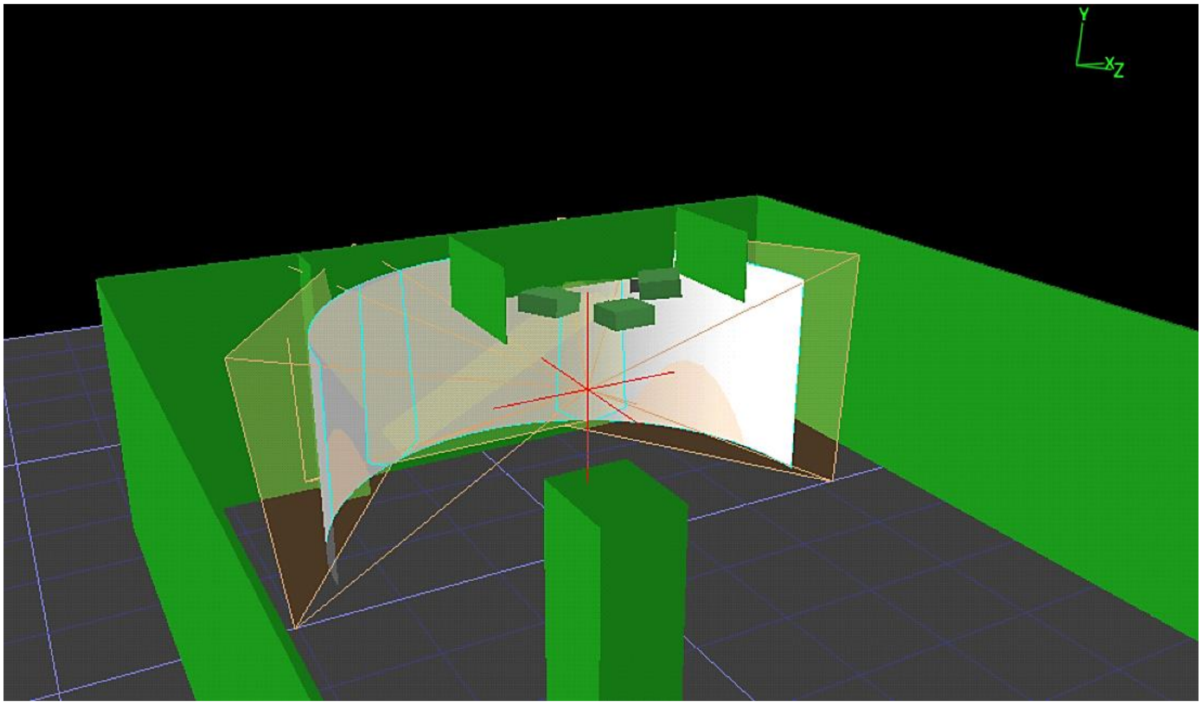

Figure 41. Projection scheme (Warpalizer, 2019).

As it was mentioned before, front projection type provides brighter imaging in comparison to rear projection. As one can see from the Figure 42, level of the luminance is about 40-60 Foot-Lamberts.

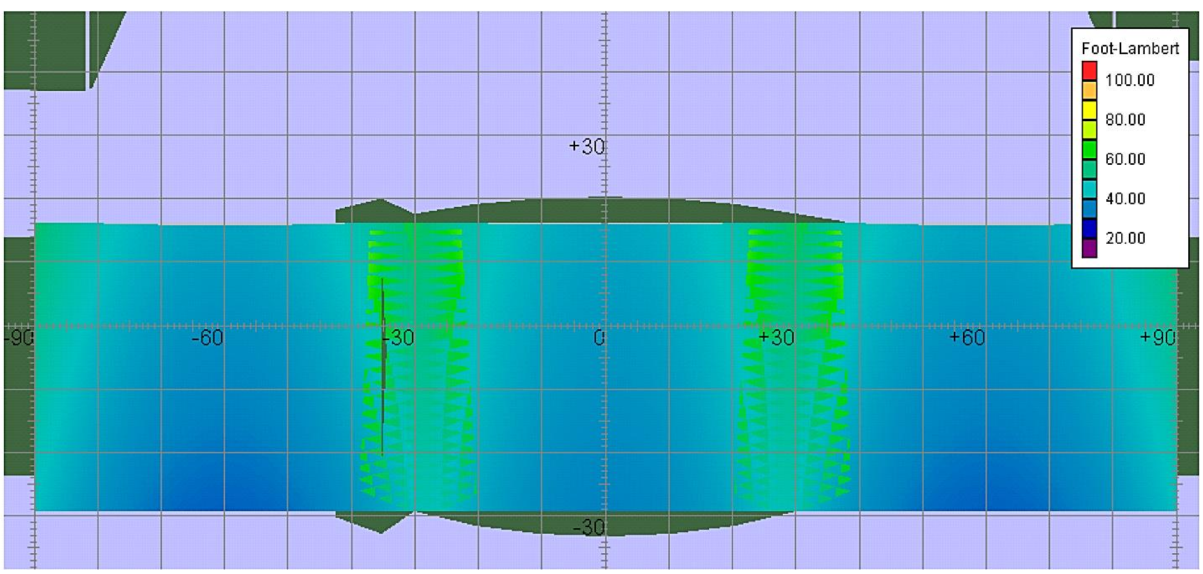

Figure 42. Luminance plot (Warpalizer, 2019).

Offer from CAVE Oy (Finland) was received in April 2018, when the Laboratory Development was in planning stage. Idea of the CAVE Oy is to construct a front projection system, based on WQXGA Barco projectors. Overall system resolution is four arcmin. Blend effect have 15% overlapping between two near projectors. Image height is 1.8 m. Optical configuration is presented below (Figure 43):

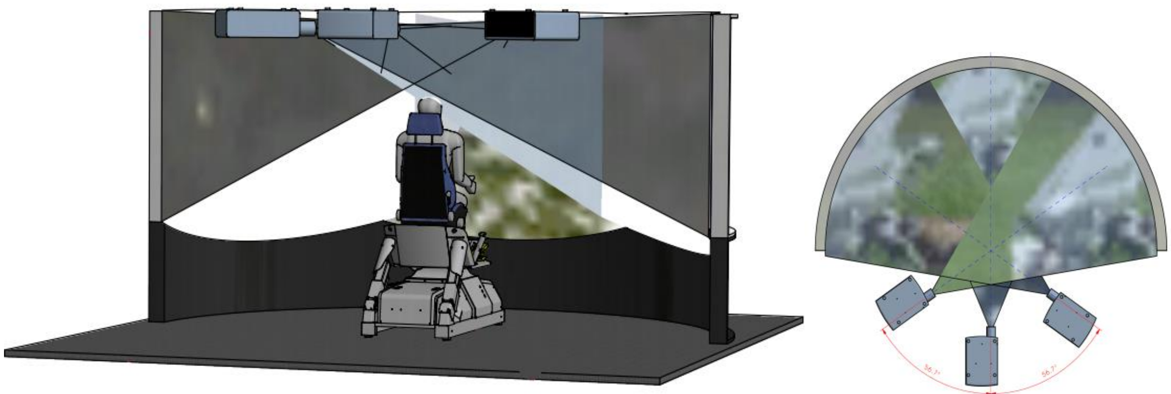

Figure 43. CAVE Oy Concept (CAVE Oy, 2018).

Based on overviewed quotes from suppliers and information from literature review, procurement documents: description for tendering and requirement list were created. (Appendices II and III)

4 DISCUSSION

4.1 Laboratory hardware

Overview of existing simulation laboratories is the basis which supported further research and gave the guidelines for the product survey. Authorities of the overviewed laboratories have been contacted, however, only few of them gave some comments on asked requests. Certainly, requested information about used hardware and software might be confidential for some organizations. Nonetheless, based on found data it is possible to start own laboratory equipment research.

Implementation of DELPHI method was not fit in work conditions: due to time restrictions (Table 1) and timetables of different departments, it was decided to exclude this method in final version. DELPHI method was shifted by direct interviews and consultations.

As one of the results of this project, technical and economical comparison for each investment position were created. Ten products were developed by LUT side, three items were excluded due to financial restrictions:

- 6DOF motion base
- Floor movement actuators
- Motion capture camera system

By the decision of the project team of ULtRa-SimMI project, 6DOF platform will be designed and manufactured in next academic year by LUT to achieve local academic goals besides simple application of new equipment.

Floor movement actuators were excluded due to low-priority projects connected with it. Planned solution for this item is use of next subsidies for purchasing. A number of research projects are stopped according to this issue.

Motion camera system can stay in old configuration in regard to current activities, because Flex 3 cameras are designed especially for the small space researches with relatively slow movements. At present, motion capture camera system is used for tracking of the horse-rider motion (area of the tracking is less than 20 m^2).

For other products, decisions were finalized and, based on provided specifications, final product list was approved by project meeting with stakeholders. By the moment of Master Thesis submission, it was purchased:

- HTC Vive Pro headsets
- Oculus Rift DK2 headsets
- Microsoft HoloLens AR headset
- Pupils Lab Eye Tracking glasses
- DELSYs Trigno Avanti EMG sensors
- Unity software license
- Motive software licence
- Tobii Pro 2 Eye Tracking glasses
- Tobii VR integration Eye Tracking camera

Most of the presented devices are compatible among each other. In case of ET, EMG sensors and motion capture providers stated that their product are suitable in terms of compatibility and possible issues with compatibility should be resolved due to specific research problem.

4.2 3D projection system

Optics and ophthalmology are the basis of the design and construction different visualization platforms, starting from simple monitors and finishing with warped projected screens. Certainly, designer should have all technical data to calculate precisely all properties of the future system. It includes type of lenses, screen material, geometry, ambient light conditions with reflection properties of the walls, floor and ceiling, all specifications from projector supplier. Without some of them, calculations of the simple system can be done roughly.

Concerning on basic human eye properties, initial requirements for the projection systems are made and placed in RFI and procurement documents. After business meetings with projection systems suppliers, tender documents were updated and run into the business.

Received offers were considered and also taken into account during specification process. For instance, it gave information about angular resolution, which can be afforded by certain type of projectors.

Besides official tendering process and searching the solution outside the institution, internal research and calculations were done about two possible options:

1. Projection system
2. Display-based system

Display-based system might be like a CAVE configuration with three wall and segmented curved configuration. For required FOV it was found three possible configuration and optimal solution was given.

Projector system was calculated concerning necessary simplification to flat-type screen and by separating the whole system into three equal segments. It can be stated in this way, because each projector produces its own image, when special warping and blending software allows merging the image. Calculations were done based on chosen screen material and projector as an example. For preliminary assessment, it is reliable methodology and can be used for comprehension of suggested professional offers.

The most challenging part of present paper was to find related and, in the same time, reliable sources for design principles of 3D projection systems due to companies' policies and absence of up-to-date literature. The SMPTE and THX Company Standards are closed to non-related persons. Besides that, in survey part, prices and specs for available products on the market can be given in most cases only after official request for information, that increase processing time of each procurement process or even it has not given any results.

5 CONCLUSION

Importance of present project cannot be underestimated. Based on updated equipment base, Laboratory of Intelligent Machines can provide completely new types of scientific researches such as Eye Tracking during work performance and related cases, EMG sensors for HMI interaction area; both 3D Visualization platform and VR headsets allow several academic applications. Software base was updated, and existing motion camera system can be used from the next academic period.

Product survey and project affaires were finished. Based on received information, design and calculations of two possible option for 3D Visualization platform were suggested.

By the moment of Master Thesis submission, next items were purchased:

- HTC Vive Pro headsets
- Oculus Rift DK2 headsets
- Pupils Lab Eye Tracking glasses
- DELSYs Trigno Avanti EMG sensors
- Unity software license
- Motive software licence
- Tobii Pro 2 Eye Tracking glasses
- Tobii VR integration Eye Tracking camera
- Microsoft HoloLens 2

However, positions of 6DOF Motion platform and Haptic device have not been covered by this investment and will be developed by LUT in next academic year (2019-2020).

Laboratory of Intelligent Machines should do further research in compatibility and complex integration of the system in near future after purchasing of the remaining equipment. Various combinations of used equipment will lead to new research areas and projects for the Laboratory.

Present research created the extended database for next surveys in development process and allowed to do procurement of required equipment. Procurement documents for the 3D Projection System were created and designed requirements were updated. As the result, mentioned document will be implemented for the purchasing process. Designed concepts of 3D visualization platforms might be launched as a tentative solution due to its relative simplicity.

LIST OF REFERENCES

Allaboutvision.com. (2019). [online] Available at: https://www.allaboutvision.com/resources/anatomy.htm [Accessed 27 Feb 2019].

Axon, S. (2016). Unity at 10: For better—or worse—game development has never been easier. [online] Ars Technica. Available at: https://arstechnica.com/gaming/2016/09/unity-at-10-for-better-or-worse-game-development-has-never-been-easier/ [Accessed 12 May 2019].

Bale, C. (2019). Home Theater Calculator: Viewing Distance, Screen Size – Carlton Bale. [online] Carltonbale.com. Available at: http://carltonbale.com/home-theater/home-theater-calculator/ [Accessed 27 Apr 2019].

Ball, K. and Owsley, C. (1991). Identifying Correlates of Accident Involvement for the Older Driver. Human Factors: The Journal of the Human Factors and Ergonomics Society, 33(5), pp.583-595.

Barco. (2019). Simulation projectors - Products. [online] Available at: https://www.barco.com/en/products/simulation-projectors [Accessed 01 May 2019].

Blana, D. (2018). Our Open Experiment. [online] Medium. Available at: https://medium.com/the-quest-for-a-life-like-prosthetic-hand/our-open-experiment-9ac4923a210f [Accessed 7 Apr. 2019].

Chen, J., Chen, J., Cranton, W. and Fihn, M. (2012). Handbook of Visual Display Technology. 2nd ed. Heidelberg: Springer, pp.43-66, 2545-2557, 2907-2917, 3089-3109, 3265-3281.

Cheung K. M. G., Kanade T., Bouguet J and Holler M. (2000) A real time system for robust 3D voxel reconstruction of human motions. Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Vol. 2, pp. 714-720.

Christiedigital.com. (2019). Simulation Projector Systems | Christie - Visual Solutions. [online] Available at: https://www.christiedigital.com/emea/simulation/simulator-projector-systems [Accessed 01 May 2019].

De Fontana, J. (1420). Bellicorum instrumentorum liber cum figuris - BSB Cod.icon. 242. Venedig: Bayerische Staatsbibliothek (Germany).

Delsys. (2019). Delsys – Wearable Sensors for Movement Sciences. [online] Available at: https://www.delsys.com/home/ [Accessed 23 March 2019].

Dersu, Inci & N. Wiggins, Michael & Luther, Anne & Harper, Richard & Chacko, Joseph. (2006). Understanding Visual Fields, Part I; Goldmann Perimetry.

EVL (2019). EVL | Electronic Visualization Laboratory. [online] Available at: https://www.evl.uic.edu/ [Accessed 20 May 2019].

FOVE Eye Tracking Virtual Reality Headset. (2018). Home - FOVE Eye Tracking Virtual Reality Headset. [online] Available at: https://www.getfove.com/ [Accessed 26 Dec 2018].

Hainich, R. and Bimber, O. (2016). Displays: fundamentals and applications. 2nd ed. Natick: CRC Press, pp.24-63, 122-143, 221-223.

Hansen, D. and Ji, Q. (2010). In the Eye of the Beholder: A Survey of Models for Eyes and Gaze. IEEE Transactions on Pattern Analysis and Machine Intelligence, 32(3), pp.478-500.

Huang, F., Chen, K. and Wetzstein, G. (2015). The light field stereoscope. ACM Transactions on Graphics, 34(4), pp.60:1-60:12.

IVR Lab. (2018). IVR Lab - Northern Arizona University. [online] Available at: https://in.nau.edu/ivr-lab/ [Accessed 15 Nov 2018].

Jain, D., Sra, M., Gro, J. and Marques, R. (2016). Immersive Scuba Diving Simulator Using Virtual Reality. UIST '16 Proceedings of the 29th Annual Symposium on User Interface Software and Technology, pp.729-739.

Jansen, K. (2014). Visual Acuity - The Sense and Non-sense of Ultra High Definition Displays - TFTCentral. [online] Tftcentral.co.uk. Available at: https://www.tftcentral.co.uk/articles/visual_acuity.htm [Accessed 19 April 2019].

Kamen, G. (2004) Electromyographic Kinesiology. In Robertson, DGE et al. Research Methods in Biomechanics. Champaign, IL: Human Kinetics Publ.

Krum, D. and Aptaker, A. (2018). Mixed Reality Lab. [online] Projects.ict.usc.edu. Available at: http://projects.ict.usc.edu/mxr/ [Accessed 25 Nov 2018].

Kuchera, B. (2016). The complete guide to virtual reality in 2016 (so far). [online] Polygon. Available at: https://www.polygon.com/2016/1/15/10772026/virtual-reality-guide-oculus-google-cardboard-gear-vr [Accessed 9 May 2019].

Lang, B. (2017). Hands-on: HaptX Glove Delivers Impressively Detailed Micro-pneumatic Haptics, Force Feedback. [online] Road to VR. Available at: https://www.roadtovr.com/haptx-vr-glove-micro-pneumatic-haptics-force-feedback-axonvr/ [Accessed 17 May 2019].

Laval Virtual. (2019). Laval Virtual 2020 - Exhibition and Conference on VR/AR - France. [online] Available at: https://www.laval-virtual.com/ [Accessed 03 May 2019].

Linstone, H. and Turoff, M. (1975). The Delphi method. Reading, Mass.: Addison-Wesley Pub. Co., Advanced Book Program, pp.21-62.

Lut.fi. (2019). Mobile Assembly Robot - LUT. [online] Available at: https://www.lut.fi/web/en/school-of-energy-systems/research/intelligent-machines/mobile-assembly-robot [Accessed 21 April 2019].

Ma, Z. and Ben-Tzvi, P. (2015). Design and Optimization of a Five-Finger Haptic Glove Mechanism. Journal of Mechanisms and Robotics, 7(4), pp.41-49.

Macquarie University (2018). Macquarie University - Virtual reality lab. [online] Available at: https://www.mq.edu.au/research/research-centres-groups-and-facilities/resilient-societies/facilities/simulation-hub/virtual-reality-laboratory-research-office [Accessed 28 Oct 2018].

Majaranta, P., Aoki, H., Donegan, M. and Hansen, D. (2012). Gaze interaction and applications of eye tracking. Hershey, PA: Medical Information Science Reference.

Malacara, D., Malacara, Z. and Malacara, D. (2004). Handbook of optical design. 2nd ed. New York: Marcel Dekker, pp.1752-1805.

Mason, W. (2016). SMI's 250Hz Eye Tracking and Foveated Rendering Are For Real, and the Cost May Surprise You - UploadVR. [online] UploadVR. Available at: https://uploadvr.com/smi-hands-on-250hz-eye-tracking/ [Accessed 9 May 2019].

MDI, (2019). [online] Available at: https://strongmdi.com/medias/documents/specific/products/related/Domino.pdf [Accessed 05 May 2019].

MDI, (2019). How to Combat Ambient Light in Commercial Venues - Blog - Strong MDI. [online] Strong MDI. Available at: https://strongmdi.com/blog/how-to-combat-ambient-light-in-commercial-venues/ [Accessed 05 May 2019].

MDI. (2019). Front or Rear Projection? - Blog - Strong MDI. [online] Strong MDI. Available at: https://strongmdi.com/blog/front-or-rear-projection/ [Accessed 05 May 2019].

Miles, S. (2015). Forget head tracking on Oculus Rift, Fove VR headset can track your eyes - Pocket-lint. [online] Pocket-lint. Available at: https://www.pocket-lint.com/ar-vr/news/oculus-rift/133835-forget-head-tracking-on-oculus-rift-fove-vr-headset-can-track-your-eyes [Accessed 9 May 2019].

Moutinho, L., Bigné, E. and Manrai, A. (2014). The Routledge companion to the future of marketing. 1st ed. New York: Routledge, p.429.

Nielsen, J. and Pernice, K. (2009). Eyetracking Web Usability. Indianapolis: New Riders, p.11.
OptiTrack. (2019). Build Your Own Motion Capture System. [online] Available at: https://www.optitrack.com/systems/ [Accessed 23 Feb 2019].

OptiTrack. (2019). Flex 3 - An affordable motion capture camera. [online] Available at: https://www.optitrack.com/products/flex-3/ [Accessed 23 Feb 2019].

Orland, K. (2013). How fast does “virtual reality” have to be to look like “actual reality”. [online] Ars Technica. Available at: https://arstechnica.com/gaming/2013/01/how-fast-does-virtual-reality-have-to-be-to-look-like-actual-reality/ [Accessed 9 May 2019].

Painter, L. (2018). Here's how you can use PSVR to play your favourite Steam VR games. [online] Tech Advisor. Available at: https://www.techadvisor.co.uk/how-to/game/use-playstation-vr-on-pc-3682369/ [Accessed 17 Nov 2018].

Plexus. (2019). Plexus / High-performance VR/AR Gloves. [online] Available at: http://plexus.im/ [Accessed 11 Jan 2019].

Polz, M. (n.d.). Ergoneers solution. [email].

Projectorcentral.com. (2019). Sony VPL-GTZ270 Projection Calculator - Throw Distance and Screen Size. [online] Available at: https://www.projectorcentral.com/Sony-VPL-GTZ270-projection-calculator-pro.htm [Accessed 06 May 2019].

Robertson, A. (2017). The ultimate VR headset buyer’s guide. [online] TheVerge.com. Available at: https://www.theverge.com/a/best-vr-headset-oculus-rift-samsung-gear-htc-vive-virtual-reality [Accessed 9 May 2019].

Russell, S. and Norvig, P. (2009). Artificial intelligence: A Modern Approach. 3rd ed. London: Pearson. pp. 26-41.

Samsung Electronics America. (2019). 82" Class Q6F 4K Smart QLED TV (2018) TVs - QN82Q6FNAFXZA | Samsung US. [online] Available at: https://www.samsung.com/us/televisions-home-theater/tvs/qled-4k-tvs/82-class-q6f-4k-smart-qled-tv-2018-qn82q6fnafxza/ [Accessed 06 May 2019].

Samsung. (2019). QE55Q90RAT | QE55Q90RATXXU | UK. [online] Available at: https://www.samsung.com/uk/tvs/qledtv-q90r/QE55Q90RATXXU/ [Accessed 06 May 2019].

Samsung. (2019). QE82Q950RBT | QE82Q950RBTXXU | UK. [online] Available at: https://www.samsung.com/uk/tvs/qledtv-q950r/QE82Q950RBTXXU/ [Accessed 06 May 2019].

Senseglove.com. (2019). [online] Available at: https://www.senseglove.com/ [Accessed 14 Feb 2019].

Silverman, D. (2018). NASA's virtual reality journey uses same software, hardware as gamers. [online] HoustonChronicle.com. Available at: https://www.houstonchronicle.com/techburger/article/NASA-s-virtual-reality-journey-uses-same-12745239.php [Accessed 21 Nov 2018].

Smpte.org. (2019). We are SMPTE | Society of Motion Picture & Television Engineers. [online] Available at: https://www.smpte.org [Accessed 08 May 2019].

Sony. (2019). Simulation Projectors | Sony Professional. [online] Available at: https://pro.sony/en_LU/products/professional-projectors/simulation-projectors [Accessed 01 May 2019].

Spectroscreen.com. (2019). [online] Available at: http://www.spectroscreen.com/download/ENG_SILVER_SERIES.pdf [Accessed 01 May 2019].

Spectroscreen.com. (2019). Beyond the view | SPECTRO SCREEN (digital cinema screen, IMAX 3D silver screen, 4D, 4K, Laser projector screen, frames, etc.). [online] Available at: http://www.spectroscreen.com/eng/page.php?Main=3&sub=1 [Accessed 01 May 2019].

Starico. (2019). TV Monitor Viewing Distance Calculator. [online] Available at: https://stari.co/tv-monitor-viewing-distance-calculator [Accessed 29 April 2019].

StarVR. (2018). StarVR. [online] Available at: https://www.starvr.com/ [Accessed 27 Dec 2018].

The Ottawa Hospital. (2018). Rehabilitation Virtual Reality Lab |. [online] Available at: https://www.ottawahospital.on.ca/en/clinical-services/deptpgrmcs/departments/rehabilitation-centre/about-the-rehabilitation-centre/our-facilities/rehabilitation-virtual-reality-lab/ [Accessed 04 Nov 2018].

THX. (2019). Home - THX. [online] Available at: https://www.thx.com/ [Accessed 08 May 2019].

Tobii AB (2018). How do Tobii Eye Trackers work? - Learn more with Tobii Pro. [online] Tobiipro.com. Available at: https://www.tobiipro.com/learn-and-support/learn/eye-tracking-essentials/how-do-tobii-eye-trackers-work/ [Accessed 15 May 2019].

Traquair, H. (1928). An Introduction to Clinical Perimetry. Southern Medical Journal, 21(3), p.250.

Tricart, C. (2018). Virtual Reality Filmmaking: Techniques & Best Practices for VR Filmmakers. New York, NY: Routledge. pp. 12–14.

Unity, (2019). Technologies. [online] Available at: https://unity.com/ [Accessed 24 March 2019].

Uy, M. (2019). Best 4K monitors 2019: the top Ultra HD monitors and displays. [online] TechRadar. Available at: https://www.techradar.com/news/best-4k-monitors [Accessed 06 May 2019].

Valipe, S. (2017). Virtual Reality Laboratory. [online] NASA. Available at: https://www.nasa.gov/centers/johnson/partnerships/eddc/ra/virtual-reality-laboratory/ [Accessed 21 Nov. 2018].

HaptX. (2019). HaptX | Haptic gloves for VR training, simulation, and design. [online] HaptX. Available at: https://haptx.com/ [Accessed 30 Jan 2019].

Vive.com. (2019). VIVE Pro | The professional-grade VR headset. [online] Available at: https://www.vive.com/us/product/vive-pro/ [Accessed 22 March 2019].

Webvision.med.utah.edu. (2019). Visual Acuity by Michael Kalloniatis and Charles Luu – Webvision. [online] Available at: https://webvision.med.utah.edu/book/part-viii-psychophysics-of-vision/visual-acuity/ [Accessed 12 April 2019].

White, J. (2019). Microsoft at MWC Barcelona: Introducing Microsoft HoloLens 2 - The Official Microsoft Blog. [online] The Official Microsoft Blog. Available at: https://blogs.microsoft.com/blog/2019/02/24/microsoft-at-mwc-barcelona-introducing-microsoft-hololens-2/ [Accessed 17 April 2019].

Yamane, K. and Hodgins, J. (2009). Simultaneous Tracking and Balancing of Humanoid Robots for Imitating Human Motion Capture Data. IEEE/RSJ International Conference on. IEEE, pp 2510 - 2517.

YouTube. (2018). Trigno™ Avanti. [online] Available at: https://www.youtube.com/watch?time_continue=3&v=coe-QmJ4dqk [Accessed 19 Dec 2018].

REQUEST FOR INFORMATION

3D Visualization system

Presentation of the contracting authority

Lappeenranta University of Technology, LUT conducts scientific research and academic education. Combining technology and business, we have served as an academic forerunner since 1969. We are compact by size, with intensely focused operations. Our international science community encompasses 6,500 students and experts, who represent nearly 70 different nationalities.

The Saimaa University of Applied Sciences is an institute of higher education in Southeastern Finland in the cities of Lappeenranta and Imatra. We offer degrees in five fields. We have about 3000 students, approx. 450 of them being international degree students. The number of teachers and other personnel is about 260.

Procurement background

The Laboratory of Intelligent Machines in LUT carries out research on mechatronic machine design, especially using virtual technologies and simulators and demanding industrial robotics.

LUT collaborates closely with Saimaa University of Applied Sciences. Both universities have common interests in the fields of civil engineering and physiotherapy to access research facilities providing VR and human monitoring capabilities.

LUT and Saimia are together preparing an acquisition of 3D Visualization system.
To specify the requirements, we need more information about systems and possible solutions available on the market and the potential development of these to meet the needs. Note that this document is NOT an invitation to tender. Decisions of starting the acquisition process will be made after receiving answers to this request of information.

Description of current state

Current simulation laboratory consists of four 3D screens, six degree of freedom motion platform, head tracking system, surround sound system and multibody simulation software. Simulator is now unusable because two of the projectors are broken and no spare parts are available. The whole visualization system needs to be replaced, because it is outdated. Cube shape simulator will be replaced with cylindrical shape to be able to have more feeling of immersion.

Description of the target state

The target is to update the visualization system to 180 degree cylindrical screen. The diameter of the screen is about five meters. (see figure 1, dimensions of the simulation laboratory)

Visualization system will be used by many research groups, like mechanical engineering, civil engineering and health care. System must be universal, flexible and easy to use. Position of eye-point is dynamic. User must be able to walk in 3D simulation and install motion platforms and use floor movement actuators in front of the screen. Shadow free

Specifications of the space

The space of the lab is about 70 m2.
The height of the room is 2,74 m
Front projection may be inapplicable because of the limited height of the room.
Picture of lab is presented below (Figure 1).
There is no ambient light during simulations. Color of the walls and ceiling is light grey and floor is dark grey.

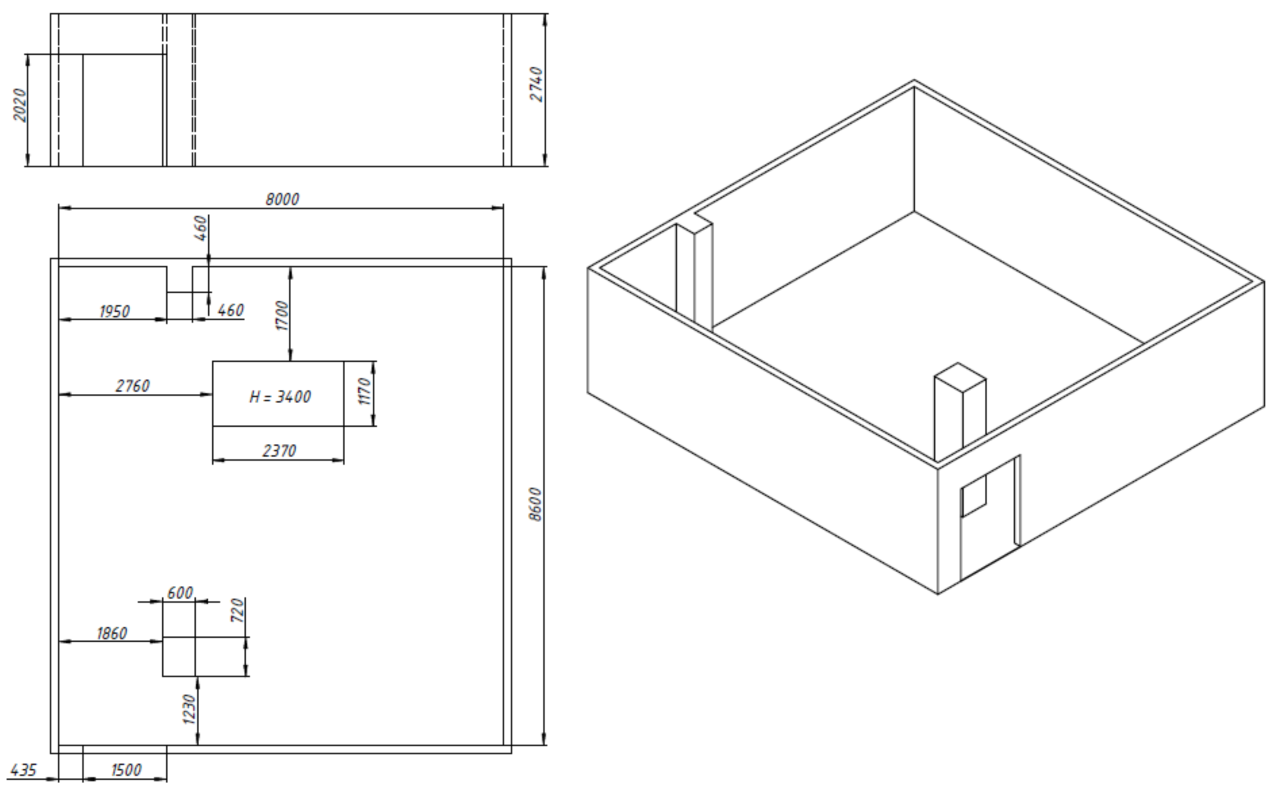

Figure 1. Dimensions of Simulation laboratory.

Specifications of the 3D Visualization platform

The following minimum requirements are so far planned:

Form	Cylindrical (curved)
Angle	180^{o}
Diameter	5 m
Height	2,5 m
Type of projection	rear / front
Position of eye-point	Dynamic
Single projector resolution	at least 1920x1080 (2560X1600)
Auto-Calibration System to create seamless image	Yes

We are inquiring information about the following matters:

1. Can you offer solutions to build a 3D visualization system considering the available space and minimum requirements? Specify possible solutions.
2. Are the above defined minimum requirements possible to fulfill? If not, please specify.
3. Cost estimate (budget price). Please note that also costs of any software maintenance and support for 3 years must be provided.
4. What would be, in your opinion, suitable evaluation criteria in the tendering process?
5. Estimated delivery time for equipment upon order.
6. What optional features or functionalities you propose for the equipment? Cost estimate for these?

In addition to this information, please provide also informal views on matters that should be considered in preparation of the invitation to tender.

Equipment assemblies must include necessary software and partial submissions are not allowed.

- Shipping of parts directly to Lappeenranta University of Technology (Skinnarilankatu 34, 53850 Lappeenranta, Finland). On-site installation.
- Project Management, Design Engineering (Installation Drawings, 2D Manufacturing Drawings & Training Notes), Installation, Calibration and Training are performed by Contractor side.
- Warranty on 3D Visualization system must be not less than 3 year since installation and calibration stage.

PROCUREMENT DESCRIPTION (3D VISUALIZATION SYSTEM)

(delivery: hankinnat@lut.fi)

Presentation of the contracting authority

Lappeenranta University of Technology, LUT conducts scientific research and academic education. Combining technology and business, we have served as an academic forerunner since 1969. We are compact by size, with intensely focused operations. Our international science community encompasses 6,500 students and experts, who represent nearly 70 different nationalities.

Procurement background

3D Visualization system for the Real-Time simulations in the Laboratory of Intelligent Machines is to be purchased. 3D Visualization system is to consist of curved screen (one or more bending axes), 3D projectors, auto calibration system, and projector support structure. It should support researches on mechatronic machine design, especially using simulation technologies, based on available software (for example, Unity or Mevea). System must be compatible with different types of motion platforms (for example, 2.5 and 6DOF motion platforms), Motion Capture camera system and EMG sensors. It should cover 100% of human VFOV and HFOV.

Description of current state

Current simulation laboratory consists of four 3D screens, six degree of freedom motion platform, head tracking system, surround sound system and multibody simulation software. Simulator is now out-of-use because two of the projectors are broken and no spare parts are available. The whole visualization system needs to be replaced, because it is outdated. Cube shape simulator will be replaced with curved shape to be able to have more feeling of immersion.

Description of the target state

The target is to update the visualization system to 180 degree cylindrical screen. The diameter of the screen is about five meters. (see figure 1, dimensions of the simulation laboratory)

Visualization system will be used by many research groups, like mechanical engineering, civil engineering and health care. System must be universal, flexible and easy to use. Position of eye-point is dynamic. User must be able to walk in 3D simulation, install motion platforms and use it in front of the screen. Low latency of the system is very important for simulation purposes.

Specifications of the space

The space of the lab is about 70 m^2.

The height of the room is 2.74 m.

Picture of lab is presented below (Figure 1).

Ceiling has a mesh, marked on Figure 1 as H=3400.

There is no ambient light during simulations. Color of the walls and ceiling is light grey and floor is dark grey.

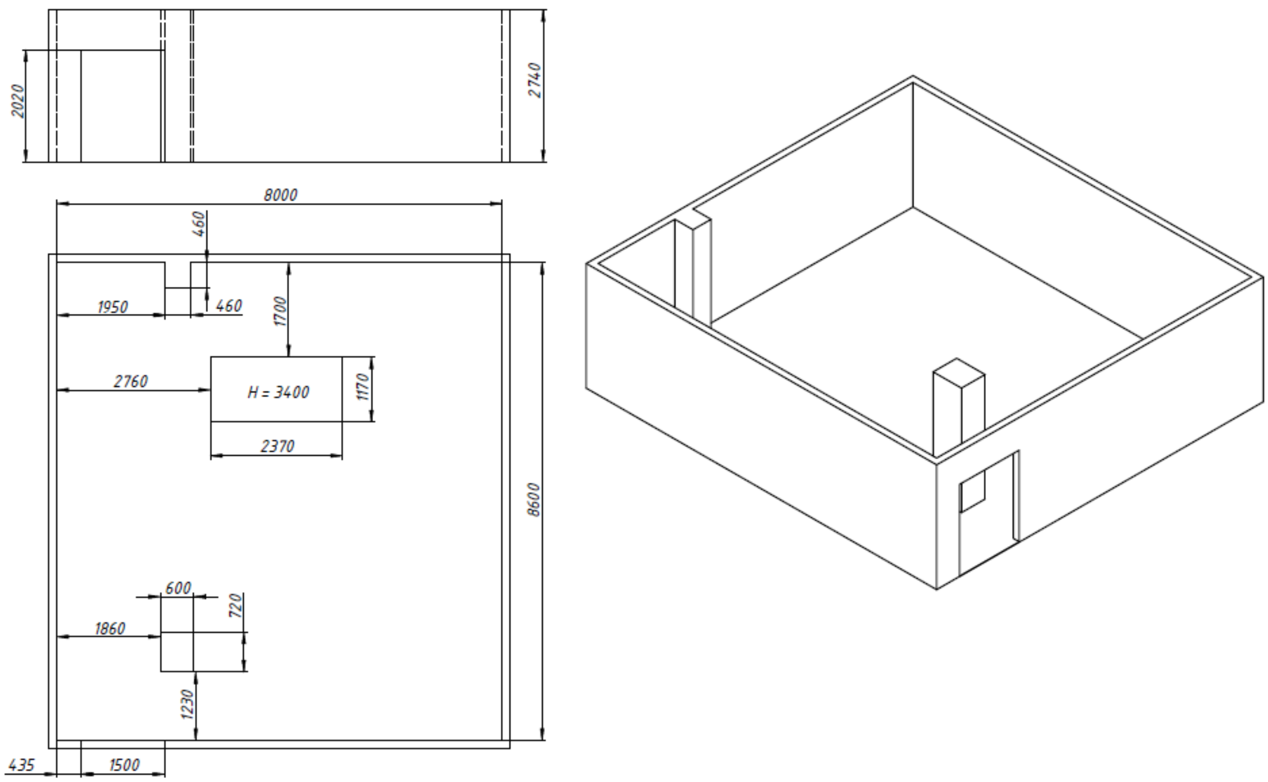

Figure 1. Dimensions of Simulation laboratory.

Software maintenance and support for 3 years must be provided.

Equipment assemblies must include necessary software and partial submissions are not allowed.

- Shipping of parts directly to Lappeenranta University of Technology (Skinnarilankatu 34, 53850 Lappeenranta, Finland). On-site installation.
- Project Management, Design Engineering (Installation Drawings, 2D Manufacturing Drawings & Training Notes), Installation, Calibration and Training are performed by Contractor side.
- Warranty on 3D Visualization system must be not less than 3 year since installation and calibration stage.

Specifications of the 3D Visualization platform

The following minimum requirements are so far planned:

Form	Cylindrical (curved)
Angle	At least 180 °
Diameter	Approximately 5 m
Room height (max)	2,74 m (mesh 3,4 m)
Shadow free	Yes
Position of eye-point	Dynamic
Frame rate at full resolution	At least 60 Hz
Angular resolution	At least 3 arcmin
Auto-Calibration System	Yes

Note: Used requirement are not fixed, companies are free to prepare proposals out of procurement scope, in case of more developed projects in other terms.

APPENDIX III

LUT
Lappeenranta
University of Technology

Please provide the Purchase Criteria (delivery: hankinnat@lut.fi)				
This form shows what factors effect points and how much. In part, a certain minimum requirement must be met, otherwise, a supplier can not give an offer.	***Instructions: Change the information to match with your own purchase. You can delete and add rows as per your purchase. Purchase can be carried out using only the price and minimum criteria or also take into account the quality criteria with scoring.You can use automatic or manual scoring. The calculating method for points must be indicated already in the call to tender. ITC Criteria will be negotiated with the IT Administration before starting the competition. Please contact miia-maarit.kukkonen@lut.fi, with security issues please contact jari.taipale@lut.fi***			
Maximum points of total price			60	smallest entered value --------------------------- * maximum points tendered value
Maximum quality points			40	tendered value --------------------------- * maximum points largest entered value
Object: 3D Visualization system				
Quantity to be procured: eur /pcs (VAT 0%)				
General criteria of the group	**Notification method**	**Minimum requirement**	**Max points**	**Calculation method for points**
Attachments				
Download this brief company presentation, max 1 A4 page	Download >>	Uploadable		no effect on the points
Download Product Brochure	Download >>	Optional		no effect on the points
Download….	Download >>	Optional		no effect on the points
Minimum criteria				
Radius is 5 meters, if it is cylindrical curved screen	Yes/No	"Yes" required		no effect on the points
System latency less or equal to 10 ms	Yes/No	"Yes" required		no effect on the points
Angular resolution less than 3 arcmin/pixel	Yes/No	"Yes" required		no effect on the points
Screen brightness at least 16 Foot -Lamberts	Yes/No	"Yes" required		no effect on the points
Shadow free	Yes/No	"Yes" required		no effect on the points
Projectors configuration excludes possibility of projectors overheating	Yes/No	"Yes" required		no effect on the points
Solid state illumination minimum 5,000 hours	Yes/No	"Yes" required		no effect on the points
Frame rate 60Hz at full resolution	Yes/No	"Yes" required		no effect on the points
Dynamic position of eye-point	Yes/No	"Yes" required		no effect on the points
Technical evaluation				
Installation by Contractor	Yes/No	Yes or No	1	no=0, yes=1.00
Possibilty of autocalibration (or calibration on-site without support)	Yes/No	Yes or No	1	no=0, yes=1.00
Field of View	%	Uploadable	10	tendered value --------------------------- * maximum points largest entered value
Area of the view-point, where the system does not loose the quality of the image	m3	Uploadable	10	tendered value --------------------------- * maximum points largest entered value
Length of the delivery time calculated from the date of purchase order	number / weeks	Uploadable	10	smallest entered value --------------------------- * maximum points tendered value
Length of the guarantee in months. Terms according to JYSE 2014 supplies at minimum.	number / months	Uploadable	10	tendered value --------------------------- * maximum points largest entered value
Additional Information				
Additional Information	Complete the text field	Optional		
Environmental report has been made	Yes / No	Optional		
Download Environmental Report	Download >>	Optional		
Maximum points total			**100**	