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Virtual Reality based User Interface for Conceptual Design and Prototyping

A Thesis submitted in partial satisfaction of the  
requirements for the degree Master of Science

in

Engineering Sciences (Mechanical Engineering)

by

Saurabh Subhash Jadhav

Committee in charge:

Michael Tolley, Chair

Nathan Delson,

Jurgen Schulze

2017

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2017

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Chapter 5, in part is currently being prepared for submission for publication of the material. Xu, Zhuoqun; Tolley, Michael; Schulze, Jurgen. The dissertation/thesis author was the primary investigator and author of this material.

## ABSTRACT OF THE THESIS

Virtual Reality based User Interface for Conceptual Design and Prototyping

by

Saurabh Subhash Jadhav

Master of Science in Engineering Sciences (Mechanical Engineering)

University of California, San Diego, 2017

Professor. Michael T. Tolley, Chair

Computer Aided Design and Engineering (CAD/ CAE) tools currently available in the market have dramatically improved since their inception. In product development, CAD/ CAE has enabled the user to design, test, analyze and optimize the product virtually even before the first prototype is built. Use of direct modeling for product

conceptualization allows the designer to create concept design iterations freely, quickly, flexibly and fast optimization. While modeling geometric databases have been 3D since long time, the interaction technology still uses 2D input devices like mouse, with Virtual Reality (VR) as a standalone visualization tool. Over the years, it has been recognized that the conventional 2D input devices for entering 3D shape information makes the interaction cumbersome and negatively affect creativity. This research focuses on design of virtual reality based user interface for automotive chassis design

Virtual reality based user interface is developed to iteratively design and prototype various space frame chassis concepts. The tools for ergonomic analysis and center of mass visualization enable the user to rapidly optimize the design in VR. The VR environment is interfaced with commercial finite element software to test the design concepts for structural integrity. Virtual constrains aid modeling tasks and minimize the processing effort required on the conceptual model to a parametric model.

The thesis is concluded with a preliminary cognitive walkthrough study. The VR based user interface can allow the user to rapidly test various design concepts quickly, and flexibly. The user interface can reduce the concept to market time, enhance creativity, and reduce the total cost of product development. This interface can be a stepping stone for the future VR based CAD interfaces.

# Chapter 1

## Introduction

Computer Aided Design (CAD) tools resulted in the displacement of the “Sequential Engineering” process by “Concurrent Engineering”. Computer Aided Design (CAD) and Engineering (CAE) tools resulted in “front loading” in the process by allowing the user to simultaneously design, test, and analyze the product virtually before the manufacturing phase. The CAD/CAE/ Product Lifecycle Management (PLM) currently available in the market have dramatically improved and diversified in the last few decades [1] [2] [3]. However, the interaction technology has not changed significantly in field of since the advent of Computer Aided Design. The interaction and the user interface within most of the soft wares available in market are via LCD display and mouse which are just 2D devices whereas designs are 3D since long time [4]. Virtual Reality aids in the 3D visualization of complex designs but is used like a standalone visualization tool. There is no user gateway to iteratively design and manipulate an engineering design in virtual reality. This research focuses on developing and testing the feasibility of a virtual reality based user interface for iteratively designing and prototyping engineering design in virtual reality.

## 1.1 Background & Motivation

### 1.1.1 History and Evolution of Computer Aided Design

Before Computer Aided Design (CAD), most of the engineering and architectural design was done by hand using a lead pencil and drafting tools like T-squares, French curves, and the drafting board. The universal drafting machine by Keuffel and Essar which combined the T-



Square, protractor, and scale was considered a major advancement [5]. However, designing by hand on a drafting board was a time consuming and a labor intensive process [6]. Moreover, the biggest drawback of the paper based design is that it is difficult to make any major changes in the design without actually [7]reconstructing the sketch from scratch [8]. Aeronautical engineers were required to produce drawings at 1:1 scale, so that these drawings can be used as templates for producing parts [6]. The 1:1 scale of drawings required the engineers to make massive drawings of the parts (Figure 1). Dr. Ivan Sutherland presented the first interactive Graphical User Interface (GUI) to draw and manipulate lines on a cathode ray tube monitor in 1957 at MIT (Figure 2) [9] [6] [8]. With the developments in computer graphics and pointing devices and CRT displays, more interactive CAD systems came into existence [9]. J. Joyce et al., from General Motors research for the first time presented the key features of CAD systems with a special focus on user interfaces [5].

In the 1970s, the research moved from 2D to 3D due to the invention of NURBs (Non-Uniform Rational B- Splines) by Ken Versprille which form the basis of development of modern 3D curve and surface modeling. P. Bezier at Renault proposed to mathematically represent automobile surfaces using Bezier curves and surfaces. System UNISURF – a digital tool evolved from Renault eventually evolved into Dassault Systemes - CATIA software [5]. AUTOCAD developed by Autodesk was the first significant commercial CAD program but was largely a 2D drafting tool. These tools offered features such as saving, printing and editing the design. CAD tools increased the productivity of the engineers and greatly shortened the design cycle [6] [8].

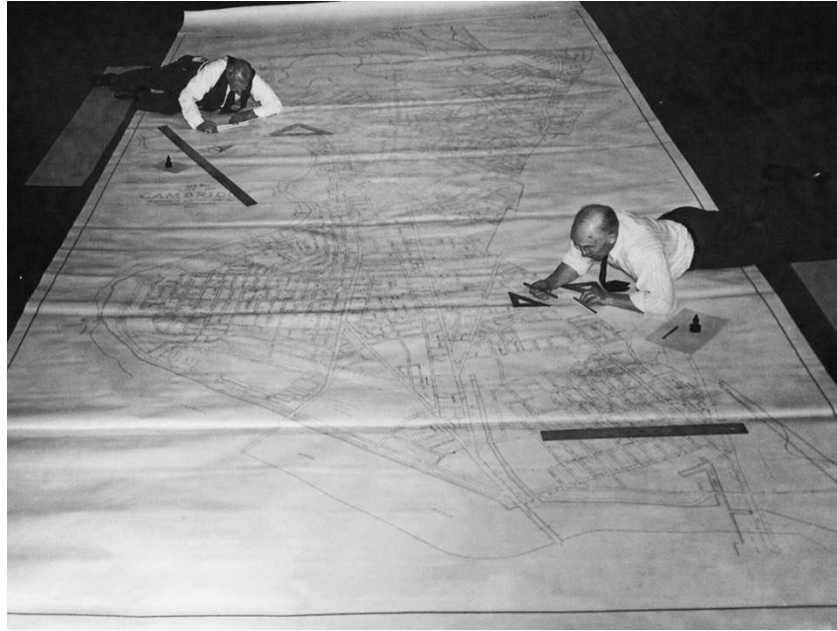


Figure 1. Designers creating a 1:1 scale drawing of the airplane component. ([www.cadhistory.net](http://www.cadhistory.net))



Figure 2. Sketchpad, Ivan Sutherland, MIT

### **1.1.2 Concurrent Engineering.**

Traditional Engineering or “Sequential Engineering” was a process in which each stage of the process like engineering design, engineering analysis, manufacturing, marketing, testing was carried out independently, and each stage of the process could only start after the completion of the previous stage in the process. The information flow in the process was in one direction. Hence, the changes, and corrections at the end of the process had to be relayed back to the beginning of the process causing increase in the overall cost of the project. Sequential engineering is also known as “Over the Wall” engineering process. The time, and the cost of the projects were usually under-estimated, since each stage of the process did not take into consideration the requirements/ limitations of the next stage of the process. Computer Aided Design tools allowed for virtual prototyping, design, and simulation of the products. It was possible to conceptualize, design, analyze, simulate the manufacturing, and to design the assembly of the products virtually in a software tool. The entire process from product conception to manufacturing could be carried out on a single tool called “Product Lifecycle Management”. This methodology gave rise to the concept of “Concurrent Engineering” [7]. Concurrent engineering emphasizes parallelization of task where the information between stages like design, analysis, manufacturing, and marketing was shared in an integrated approach. Concurrent engineering resulted in faster product development process, less number of iterations, and reduced the overall cost.

### **1.1.3 Current Commercial CAD tools.**

By the 1990s, computers were capable of computations required for 3D CAD. Pro/Engineer PTC (Parametric Technology Corporation- PTC) introduced in 1987 was a

parametric modeling based 3D design tool followed by Solid Works (Winchester Design), Inventor (Autodesk), Unigraphics (Siemens PLM), Solid Edge and others.

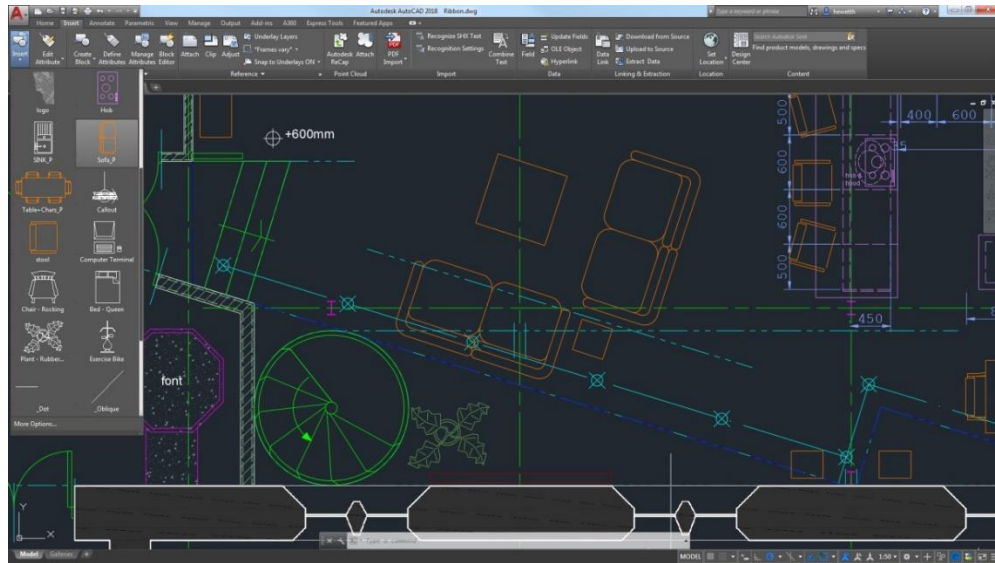


Figure 3. User interface for Autocad, Autodesk

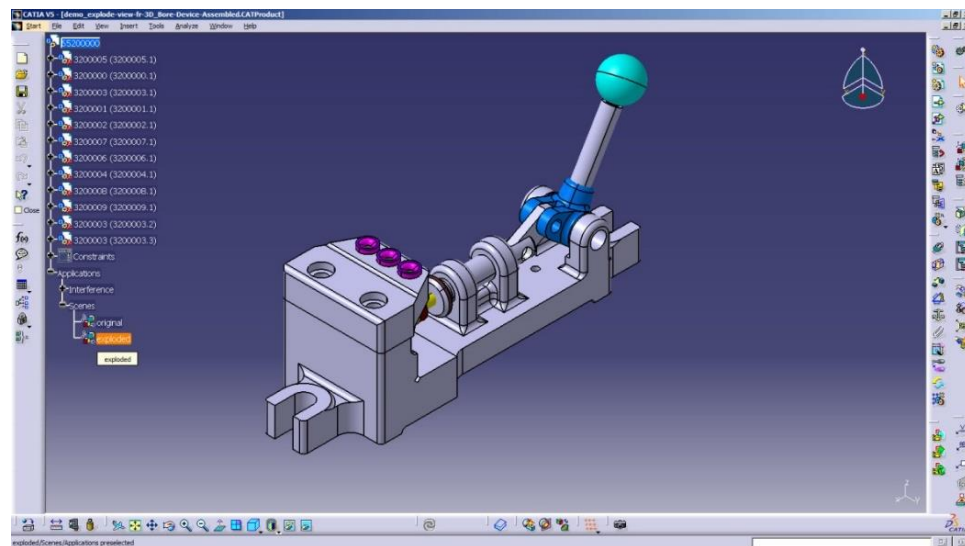


Figure 4. User interface for Catia, Dassault systems

Many CAD soft wares have improved and evolved to the present day [5] (Figure 3) (Figure 4). Existing CAD softwares provide the user design tools to perform product conception, finite element analysis, manufacturing simulations, product life cycle management and optimization. Concurrent engineering using CAD tools enhanced the quality of products and reduced cost. However, the way the user interacts with these software tools hasn't changed significantly. Attempts have been made to incorporate 3D interaction in CAD soft wares, but the interaction was mostly restricted to visualization, assembly, and navigation of the CAD data. Existing research tools did not support manipulation of CAD data, or prototyping, design, and analysis of the product totally in virtual environment.

## **1.2 Virtual Reality Technology**

### **1.2.1 Interaction Technology**

Virtual reality is a computer simulation in which the user's audio and visual sense is augmented by realistic images, sounds and other sensations generated by the computer. Virtual reality has applications in the areas of medical visualization, aerospace and automotive visualization, architecture, engineering design, education, training, entertainment and gaming [10], [11]. Virtual Reality has been used for medical visualization applications for better understanding of scans in 3D and planning of surgery. In the aerospace industry, VR is used as a Human-machine interface to control robots. VR is used as a visualization tool in the automobile and construction industries. The interaction aspect of VR allows it to be used for training environments. Computer Aided Visualization Environments (CAVEs), auto stereoscopic screens, Workbenches, Head Mounted Displays (HMD) are some of the 3D visualization modalities used in VR. Matured commercial VR devices are now available in the market at an affordable cost. These include the virtual and augmented reality HMDs, 3D workstations and 3D interaction tools. The Virtual

Reality hardware and 3D input devices have been widely adopted in the gaming industry. Space Navigator (3D connexion) and the Cubic mouse enabled the user to control the position and orientation of the object in VR on VR Workbenches. Mocap devices using infrared markers enabled for position and orientation tracking of a controller in CAVE environments. However, it is difficult to interact with the VR environments wearing a HMD using these devices. Razer Hydra (Sixsense), Sony Move (Sony), STEM (Sixsense) were 6 DOF mouse like device tracking the position and orientation of the device of controller in space wearing HMD. Leap motion allows the user to interact with computer using hand gestures by tracking hand in 3D. The latest Head Mounted Displays (HMDs) like the HTC VIVE and Oculus Rift come equipped with 3D controllers [12] [13]. These controllers have been used as 3D interaction devices in games and interactive applications. Other than games, the VIVE and Oculus controllers have been popularly used in numerous 3D applications including visual arts, medical visualization, architecture, direct solid modeling, sports training, interior designing and archeology.

Advancement in computer graphics hardware with its affordability has made 3D interaction applications possible on personal computers. Existing VR games and training applications use the interaction aspect in VR to increase immersion and to create natural interactions. Augmented Reality, and Mixed reality interactions allow the user to see holograms in their surrounding environment, and aim at making the VR, AR, and MR technology ubiquitous.

### **1.2.2 VR in Automotive Industry and Product Development**

Development of car in automotive industry involves huge investment of financial and human resources [14]. Starting from creation of styling sketches to the approval of product design and start of production process takes approximately 4 years [14]. A typical product development

cycle involves iterations starting from concept design, prototyping to evaluation and redesign. Building a prototype is expensive and time consuming [15] [16]. 3D Visualization is of prime importance in the initial stages of product development in order to avoid hassle of making any changes in the design after the prototype is manufactured. 3D printed models produced from CAD are not 1:1 scale do not provide the same spatial resolution as real world. To get a 1:1 sense of scale, a physical clay mockup called “mule” had to be produced at the each design iteration of the car, for visualizing the design. Hence, to reduce the product cycle time, automotive industry has been one of the sectors utilizing the VR technology for visualization of car designs. In automotive and aerospace industry, 3D visualization is done using Virtual Reality techniques including CAVEs (Computer Aided Virtual Environments) or HMDs (Head Mounted Displays) are common in the styling departments in the automotive industry to enhance ideas and communicate the design solutions with the high-ranking personnel in the company [10], [16]. VR stereo walls are widely used for visualization of car designs in early stages of product development to eliminate the need of a physical prototype and reduce the production cost. VR is useful in all CAx process which involves 3D visualization and interaction. These processes include styling process, ergonomic analysis, virtual prototype, virtual assembly and hose laying. Virtual reality is especially useful during the conceptual design stage. It is significantly faster to create conceptual shapes in an intuitive manner using VR [17]. Other than providing high resolution stereoscopic data, virtual model also enables the designers to make section cuts and zoom in and out of the model which is not possible using a physical prototype. In ergonomic analysis, VR allows ingress and egress analysis, realism of interior and driving simulation. Experiencing all percentiles cannot be done using a physical prototype but is possible in virtual prototype. Virtual assembly and hose laying allows simulation assembly checks for different

variants, zooming and disassembly of parts for accessibility. Use of VR in product development reduced the prototype cost, reduced change cost, reduced delay times and enabled better communication. Almost all the major automotive manufacturers today including Volkswagen, BMW, Porsche, GM, Ford, Chrysler, Honda use VR in their product development process [15]. Automotive industry also widely boosted the VR development. Volkswagen has a VR visualization center for ergonomics, driver view, interior evaluation and driving simulation. Ford has used VR for the simulation of engine maintenance task. Mazda allows customers to choose the colors and accessories for their car using virtual reality HMD [15]. Because of all these advantages, a new milestone called “Virtual Prototype” is introduced in the product development process industries which enabled front loading. However, the use of VR as a design, analysis, and prototyping tool is yet to be explored.

### **1.2.3 Direct Modeling vs Parametric Modeling**

There are two kinds of modeling approaches used commonly in industry today- Direct Modeling and Parametric Modeling. Most modeling tasks in industry and academia use parametric modeling approach. Parametric modeling is useful during detailed design of a product in an established process. Parametric modeling is history based design which allows to automate the creation of product families or parts. Parametric modeling is good for tasks that have exacting requirements and that require integration with the manufacturing process. However, during conceptual design of a new product, parametric modeling might be an overkill for the designer trying to investigate maximum 3D concepts or ideas. Parametric modeling takes more time to update when lot of changes are desired from the original design. When most of the thinking and exploring is finished; it is useful to use parametric design tools so that the future iterations do not violate the original design. Direct design on the other hand is useful during conceptual modeling-



when the product is still in define stage, and when we need to manipulate the design and do not want to be slowed down with the predefined concepts. Direct design supports geometry rather than features. Direct modeling supports conceptual efforts, offers freedom, flexibility to define the geometry quickly so that the designer is not tied down to the features. Softwares that have integrated direct modeling into their parametric environment have reported greater speed , quality and focus on innovation. Even though direct modeling allows the users to model without worrying about constrains, the interaction technique which is 2D mouse affects the creativity and the speed of the user.

#### **1.2.4 Current Research - Manipulation of 3D database in VR**

This 3D visualization is mostly based on importing geometric data from CAD system into Virtual Reality system which is used as separate visualization tool. There are no means of direct input in CAD database to manipulate the 3D data and rapidly prototype different designs using the Virtual Reality User Interface. The fundamental Graphical User Interface (GUI) for interacting with the 3D database of the design in 2D on a LCD screen. VR applications like medical scans and architectural visualization do not require iterating and directly manipulating the 3D database. Most of the medical VR applications have adopted the 3D interaction techniques which are largely for navigation and effective visualization of the data. The goal of a GUI is to provide the users with easily understandable and accessible information along with visual controls and manipulation mechanisms through which the user could interact with the computer. A good GUI allows the user to achieve goals and performs tasks with minimum commands and minimizing entering text. However, for CAD, using VR only as a 3D visualization tool with a 2D software interface to manipulate and interact with the data makes manipulation more laborious

and time consuming. There are limitations for the use of keyboard and mouse for interacting with the virtual environment.

P. Zimmerman first presented the term “Virtual reality Aided Design” which means using VR to create and manipulate CAD data rather than using VR as a standalone visualization tools. P. Zimmerman presented solutions of Virtual Reality Aided Design in digital models, ergonomic analysis, virtual assembly, hose laying and automotive development process. VRAD would significantly reduce the production cost and time to market. M. Firoentino presented a virtual rumble feedback space mouse and demonstrated a possibility of using the device for CAD. E.Varga demonstrated hand gesture interface for conceptual shape design. Vegacad presented an multimodal interface for assembly and interaction with the solid model for a CAD tool (SolidWorks). CaveCAD (J.Schulze) (Figure 5) presented a design and manipulation tool for architecture design in CAVE environments using Constructive Solid Geometry approach. However, Virtual Reality Aided Design was mostly a topic of research for academia and not much research was done in industries on the topic until 2009. Tiltbrush (Google) for HTC vive solely used 3D interaction devices for creation and manipulation of 3D paintings in VR. MasterpieceVR took the advantage of 3D interaction devices for 3D sculpting. Catia 3D experience, Autodesk VRED and IrisVr allows the user for visualization tool for aesthetic evaluation in virtual reality(Autodesk VRED). Virtualis presents a tool for visualization and assembly of CAD models in virtual reality. Minddesk presents a 3D interaction solution for the design and visualization of architectural structures that are boxy in nature. However, there was no particular application where the entire prototyping, design, and analysis process can be conducted in a single VR tool package.



**Figure 5. CaveCad: Tool for architectural design [11]**



**Figure 6. Autodesk VRED [1]**

### **1.3 Hypothesis**

The goal of this research is to develop and test the feasibility of a VR based user interface for rapid prototyping and solid modeling in Virtual Environment. We hypothesize that the 3D user interface with modeling and FEA pre-post processing capabilities in Virtual Reality will reduce the product development time (Concept to Market time), lower the overall prototyping costs of the project, and also provide a radically changed interface to the designer. The virtual reality interface will provide a technical advantage to the designer by helping in the visualization of the car frame and offering better aids to creation, manipulation and evaluation of the car frame. This project is aimed to be a stepping stone for future virtual reality based engineering design user interfaces.

# Chapter 2

## Conceptualization and Work Modeling

We hypothesize that the 3D user interface with modeling and FEA pre-post processing capabilities in Virtual Reality will reduce the product development time (Concept to Market time), lower the overall prototyping costs of the project, and also provide a radically changed interface for the designer. To test the hypothesis we were required to build an application- a “minimum viable product” that could simulate the entire product development process in virtual reality. As Interaction Design Foundation states, minimum viable product (MVP) is “a simplest thing we can build, that delivers customer value and allows us to test our hypothesis”. MVP follows the philosophy – a wheel has no value, but a skateboard does [18]. The MVP will be a short hand expression for a process we envision. The minimum viable product (MVP) will undergo lot of iterations to achieve a more state of the desired final application that we envision in the bigger picture.

### 2.1 Questions

Various aspects of the implementation must be considered before we focus on the specific process. The different questions that we need to answer for testing our hypothesis are as follows:

- Is the new process able to offer any technical and economic advantage?
- Does the new process speed up the product development process?
- Is the new process able to offer any additional benefits?

## **2.2 Objectives**

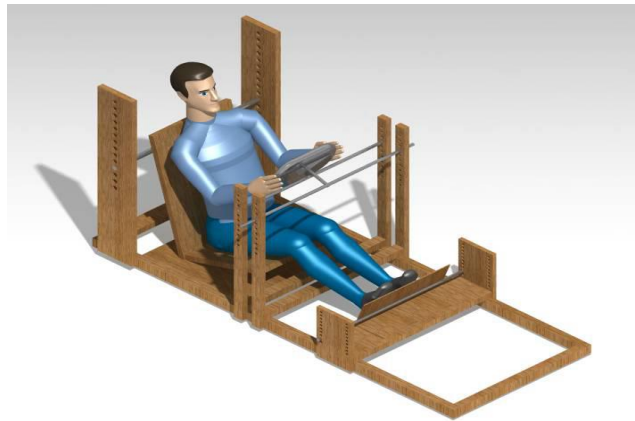
The specific objective of this research is to develop and test the feasibility of 3D interaction tool with design and analysis aids to model a space frame in virtual reality. The approach used for modeling was history free- direct modeling approach which is useful during the new product conceptualization. The specific application considered for the scope of this project was developing a modeling, manipulation and FEA analysis tool for automotive applications in virtual reality. The virtual reality environment is interfaced with a commercial finite element analysis tool for which the virtual reality interface acts as a pre-processing and post processing interface. The user can either import the Finite Element model of the prototype from ANSYS into virtual reality or manipulate the design in virtual reality or the user has been provided all the required tools to entirely design and manipulate the car design from scratch in Virtual Reality and analyze the same for all ergonomic and structural requirements.

The User Interface has been design considering the shift in paradigm from 2D to 3D user interface. The user is provided with options to create, delete, and reflect the design. The user can perform ergonomic analysis for occupant/driver comfort and aesthetically evaluate the chassis in true scale in virtual reality well before the the first prototype of the car is made. We have tested the user interface with techniques “With users” and “Without users”.

## **2.3 Automotive space frame design process**

To design and develop the VR based user interface for conceptualization of an automotive space frame, we first need to understand the existing automotive design process. The sections below briefly describe the steps in the automotive design process:

1. The first stage of the design ideation process is package ideation. At this stage, the basic exterior hard points of the car frame are decided. The objective is to get an initial idea of the size and proportions of the car. Only few elements are required for the design ideation process [19]. The architecture of the vehicle is designed taking into consideration the occupant package, functional objectives, and the bulk systems in the vehicle like engine, and powertrain. The vehicle is designed inside out- starting from the vehicle occupant package [20] [19].



**Figure 7. CAD mockup of the fixture [19]**



**Figure 8. Mockup of the driver posture [19]**

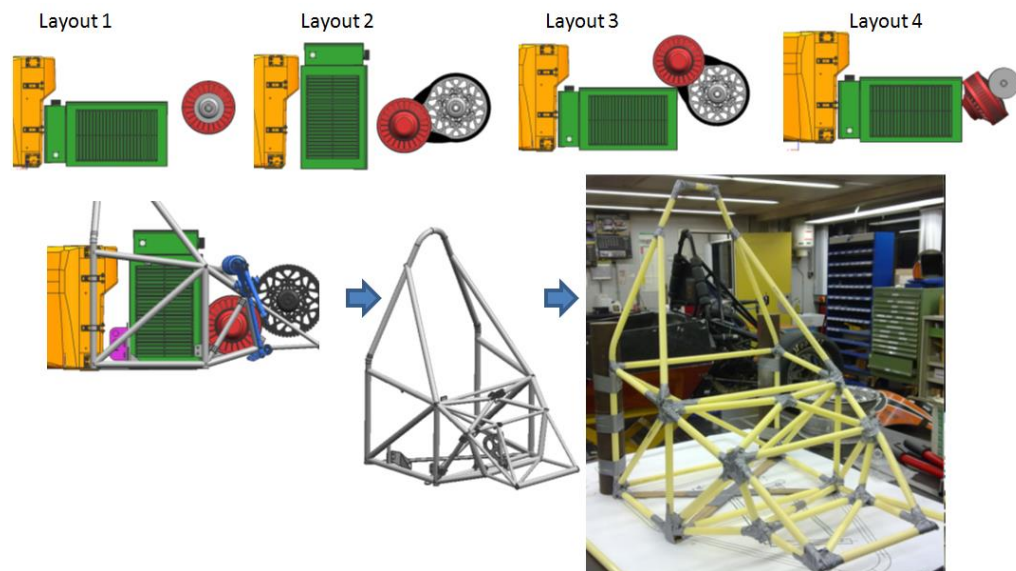
2. The design of the vehicle occupant package always starts at the H-point (The seating reference point). All the hard points of the vehicle are designed taking H-point point as the reference. In industry, the vehicle occupant package is designed taking into consideration 90% of the user population- 5th percentile to 95<sup>th</sup> percentile. For customized car frames for racing events, the frame is designed taking into consideration the dimensions of the driver [20]. Either using a physical; mockup( Figure7) (Figure 8), or using a H point stencil, the posture of the driver is determined. The hard points of the car are decided around the position of the driver. These hard points are given as the input co-ordinates to the CAD software. Thus, the spatial envelope around the driver mankin- the vehicle occupant package is established in the CAD software. The vehicle height is decided by the factors like aerodynamics, ingress-egress, visibility, and comfort. This is a small window of opportunity in product development process to be innovative in vehicle architecture and packaging. However, due to project constrains, this window often closes quickly, and the concepts need to be iterated and communicated clearly to the team in a very short period [16]. [21] [22]



**Figure 9. Ergonomic Analysis Mockup for the finalized design concept**



3. The main objective of package ideation is to study maximum number of system configurations in very short time. Each concept of the layout is sketched out loosely on paper, and evaluated with a cluster of ideas (Figure 10) [23] [20]. Next step is to determine the positioning and packaging of the bulk components of the vehicle like the engine, powertrain, safety equipment, and crash protection systems [24, 23]. Since the occupant package takes up a lot of space, there is a great potential for improvement and innovation at this stage. The approximate dimensions of each of these bulky systems used are known from the vendor. The placement of these components drives the entire vehicle architecture, and affects the proportions of the vehicle. The position of these components is selected, and the hard points for the spatial envelope package around these components are estimated from the layout. As each of the system is added in the layout, the package is iterated to place these components around the occupant package, and the vehicle architecture is finalized.



**Figure 10. Placement of the bulk components for Space Frame Automotive [24]**

4. After vehicle architecture is constructed, a manikin is placed on the seat in a suitable posture (Figure 9) [25]. The vehicle is analyzed for ergonomic requirements. The minimum and maximum reach envelopes are constructed to ensure that the steering wheel, dashboard, and other hard points of the occupant package satisfy the ergonomic requirements. In the industry, since the vehicle is designed for 90% of the population, from 5<sup>th</sup> percentile to 95<sup>th</sup> percentile, the maximum reach envelopes for 5<sup>th</sup> percentile are recorded using the “maximum reach study buck” [23]. Other ergonomic factors such as visibility of the driver, ingress and egress are analyzed at this stage.
5. The location of wheel/axle, and the wheelbase are decided next for the occupant package. It is important to make sure that the center of mass of the vehicle is towards the rear axle. The center of mass should be as low as possible to avoid accidents during high speed.
6. The main aim of this ideation process is to get as maximum ideas, sketched of several layouts with occupants and bulky components, down to paper as quickly as possible [23]. The objective is to visualize the major elements/ components that will affect the size and proportions of the car. The manufacturing and legislation requirements are also taken into consideration to select the most feasible ideas from a pool of ideas. The most feasible looking designs are then tested for the structural requirements.
7. The front end of the vehicle should have a crumple zone to crush at a specific rate to absorb energy [26]. The vehicle occupant package should be very rigid to protect the occupants in case of high speed impact or roll over [26].
8. The Static Structural FEA analysis is conducted for different cases like front impact, rear impact, side impact and roll over (Figure 11) [27, 21]. The approximate force applied on the vehicle in each case can be calculated by knowing the maximum speed of the vehicle, mass of the vehicle and time of impact [28] [27] [29]. The best layout concept will be

selected based on the designs that satisfy all the structural requirements, and have the lightest weight and the lowest center of gravity [28, 29] [26].

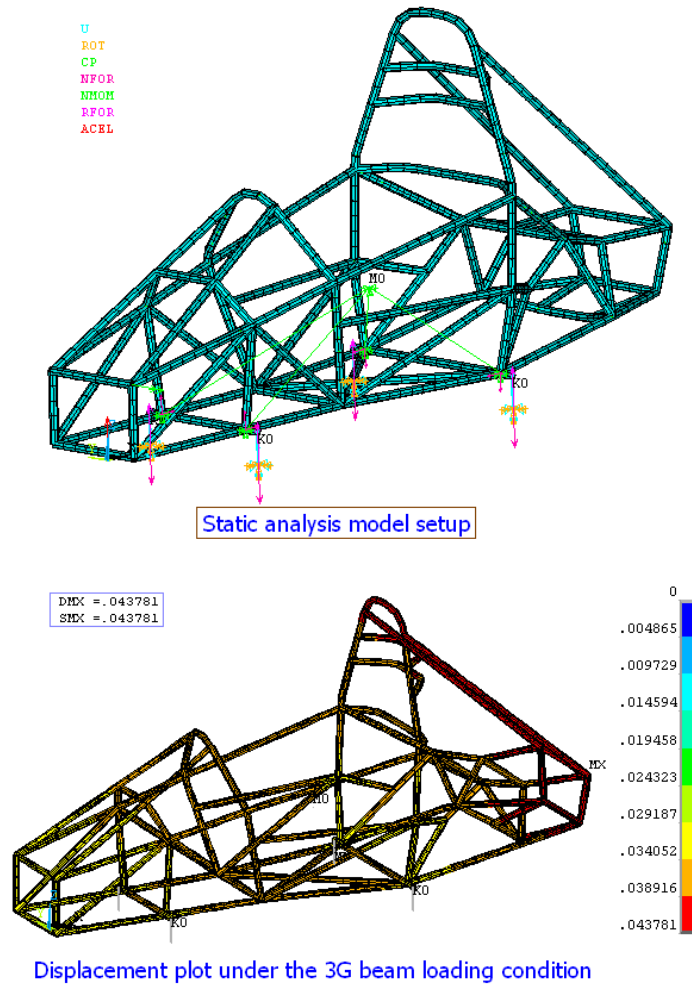


Figure 11. Static Structural Analysis of space frame automotive [28]

9. The final designed is analyzed using crash analysis simulation tool as a sanity check. The mock up of the vehicle is made to ensure that the vehicle satisfies all the ergonomic requirements before the kickoff of the production. The entire design process is iterative, and modeling and iterating different design layouts on a conventional CAD tool can be tedious [25, 29].

## **2.4 Contextual Design**

The task for designing the automotive space frame is complex and iterative process. In order for the new user interface in virtual reality to be user friendly, the mental model followed by VR UI should be similar to the existing process. Contextual design provides tools and methods to capture the work practices in a structured manner. The workflow in the new process should not

The task of designing the automotive space frame is complex and iterative process. In order for the new user interface in virtual reality to be user friendly, the mental model followed by VR UI should be similar to the existing process. Contextual design provides tools and methods to capture the work practices in a structured manner. The workflow in the new process should not drastically change from the conventional methodology. The core intent of contextual design is that the new user interface should support and extend the user's work practice. The contextual design methodology help to understand the user's intents, desires, and drivers while interacting with the user interface [30] [18].

## **2.5 Work Modeling**

Sequence models shows the detail steps performed to accomplish each task while modeling the automotive space frame. The sequence model helps to understand the intent, strategies, and motivation of the designer, and to capture the structure of process followed by the designer.

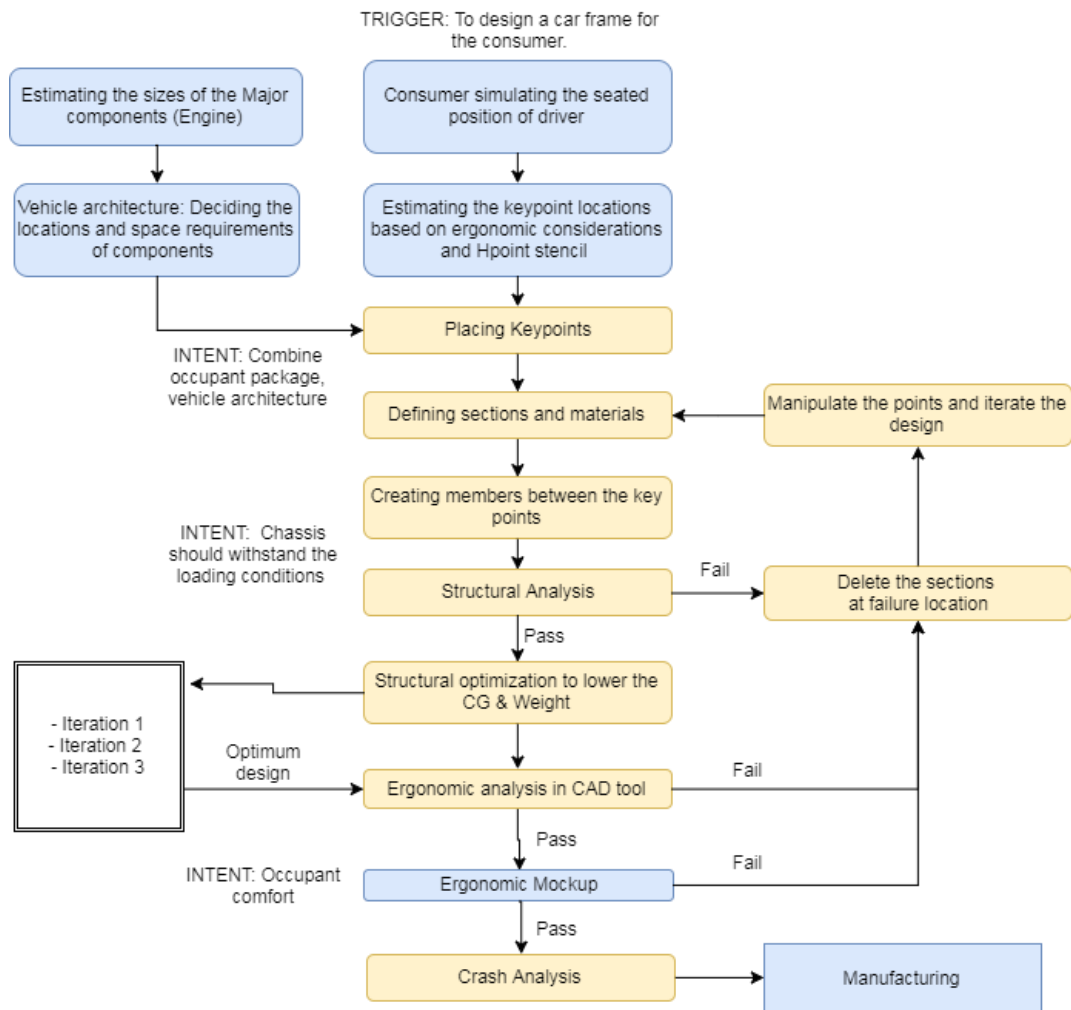


Figure 12. Work Modeling of space frame automotive design process

## 2.6 Requirement Analysis

The requirement analysis table below states the functionalities required for the application without describing the implementation. The requirement analysis describes the capabilities, features and qualities required for the VR user interface. The analysis has decomposed the project into more explicit descriptions for use story goals. These user story goals are different use cases that should be supported by the UI.

**Table 1: Requirement Analysis for modeling space frame**

<b>Definition</b>	<b>Assumptions</b>	<b>Constrains</b>	<b>User story goal</b>
Placing key points around the user for the occupant package	The occupant package is being designed for the user modeling in VR.	Certain key points should be in the same plane	Estimation of the joint positions of the occupant package and the base frame.
Selecting the Cross sections	The cross sections required by user are available in the library	Limited cross sections available based on market availability.	Menu to select cross sections for the members
Create cross sections between the key points	User has defined all the key points required	The user requires 3 points to define the member connecting any 2 key points and the c/s orientation	Creating members between the key points.
Manipulate the sections by dragging the hard points	The space frame is modelled	Manipulation of key points in X,Y and Z directions, XY, YZ and XZ planes. Snapping the points to a certain plane	Manipulating the design with Constraints or “Virtual Fixtures”.

**Table 1: Requirement Analysis for modeling space frame (Continued)**

<b>Definition</b>	<b>Assumptions</b>	<b>Constrains</b>	<b>User story goal</b>
Vehicle packaging for components	The volumetric dimensions of components are known	Only bulky components are considered.	The spatial envelope package around bulky components is analyzed for accessibility for assembly.
Structural Analysis	The space frame chassis is constrained in all directions without any rigid body motion.	Constrain the frame in UX,UY,UZ and apply forces FX, FY, FZ. No rigid body motion.	Constrain, delete the frame in UX,UY,UZ and apply forces FX, FY, FZ. Manipulate and delete the force. Manipulate displacements as the hard points are manipulated.
Ergonomic analysis	The stature of the driver is close to the designer.	Construct a maximum reach envelope.	Construct, delete maximum reach envelope.
Visualizing the centre of mass, weight	The space frame truss, and the bulky components form the major weight of the car	No constrain	Visualize the center of gravity of automotive space frame real time. Update the position of the center of gravity when the space frame is manipulated.

# Chapter 3

## Interaction design

Interaction is the communication between the user and the virtual reality user interface. Interaction in VR- although seems obvious as seen in Hollywood movies, often do not work well with the Hollywood interfaces. Well-designed user interfaces are invisible, and do not make the user to become cautious about the interaction. The various factors considered for designing of virtual reality based prototyping interface are listed in this chapter.

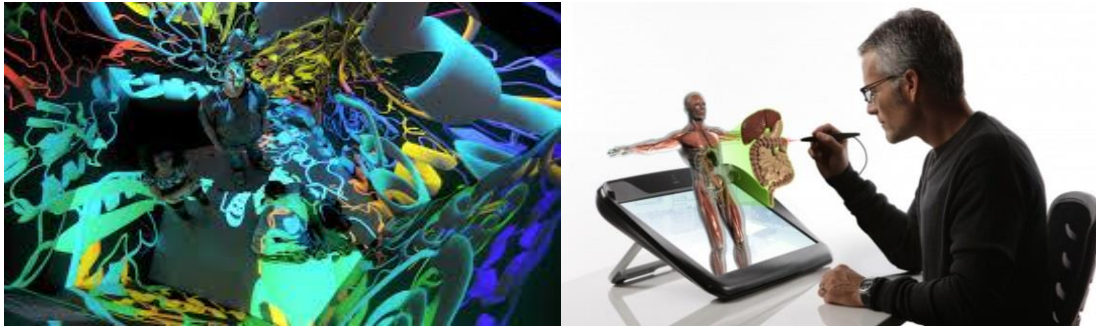
### **3.1 Selection of the Virtual Reality System**

There are various virtual reality systems currently available for commercial use. The VR displays include the 3D visualization caves, the 3D monitors and the VR workbenches. The VR workbench available- zspace would enable the user to design the automotive space frame by sitting at the workstation. However, these workbenches, and 3D monitors will not allow for true scale visualization of the automotive car frame. The user cannot move around and manipulate the car frame using the 3D displays which limit the sense of presence for the user. The StarCave will allow for a true scale visualization of the automotive space frame, but would limit the natural interaction of walking around the car frame and manipulating the space frame design. Hence, owing to the limitations with the 3D displays, the VR devices considered for the scope of this projects were limited to the Head Mounted Displays, and 3D manipulators.

The current popular Head Mounted Displays available in the market include the Oculus Rift, HTC Vive, and the Sony PlaystationVR. The task of modeling and manipulating an



automotive space frame design requires precision. Hence, the best HMD was selected based on a suitable controller. The PlaystationVR controller is tracked by a single camera, and Oculus Rift, HTC vive use two base stations for tracking. In case of PSVR, there might be a situation where one controller is occluded by the other from the camera. In case of oculus, with two cameras positioned in front of the user, the one controller still is occluded from the camera. Occlusion of the controllers might affect the precision required by the user for modeling task. Hence, for the scope of this project, HTC Vive was selected as the VR system with the advantage of roomscale tracking, precise tracking and future scope of including a social aspect for engineering design.

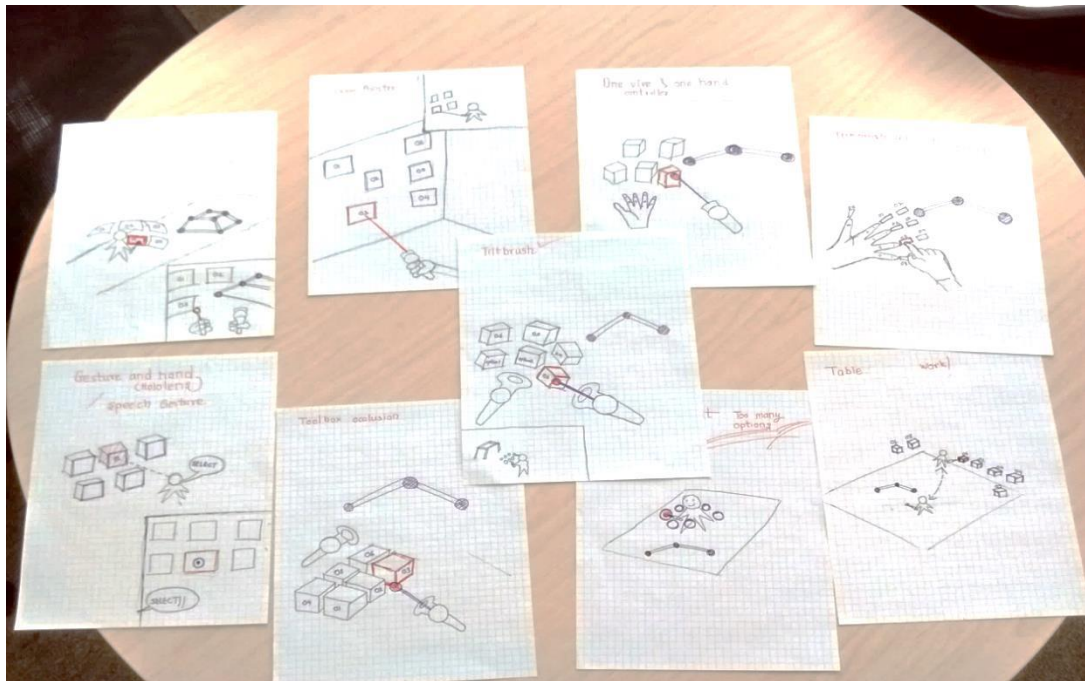


**Figure 13. Starcave @ UCSD (L), Zspace VR Workbenches (R)**

### **3.2 Sketching and Volumetric Layouting**

Various configurations for a 3D User Interface were brainstormed for the HTC Vive. Those include the user interfaces fixed to the wall with laser pointer interaction, gesture and speech based interfaces, interfaces with a controller and a 3D mouse, and 3D mouse in both the hands [31] [32] [30]. Volumetric layouting was conducted to select the feasible options based on minimal effort required during design, ease of use, interaction metaphors, and taking limitations of current technology into consideration.

The best observed configuration was to have the frequently used options in the menu of the controller in the non-dominant hand, and to have the non-frequently used options in the menu on the wall. This menu helps to keep the frequently used options handy in the non dominant hand, as well as keeping the menu uncluttered by segregating the frequently used options from the non-frequent options.



**Figure 14. Sketching and Brainstorming 3D User Interfaces**

### 3.3 Input and Manipulation

The various methods for interaction for the menu are Gestural user interface, Gaze based UI, Virtual control-3D pointer, Laser pointer and Speech recognition [32]. Gestural based user interface are limited by the current tracking technology. Speech based user interfaces will have more cognitive load on the user for memorization of the commands [31]. Gaze based user interface will have low precision, since our neck is not as dexterous as our hands [33]. While

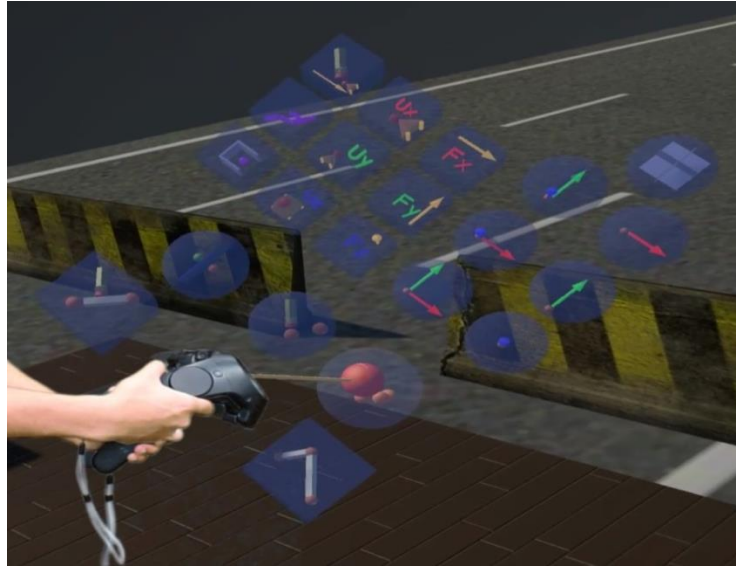
working in VR environments, the user will be manipulating the design somewhere in the room. For a laser based 3D user interface with the menu on the wall, the user has to look at the wall for selecting the option from the menu [33, 30] [34]. However, since the objects in the HMDs are focused just meter away from the user, looking at the wall to select the menu and focusing back and forth causes convergence accommodation conflict [33, 35]. Convergence accommodation conflict is known to cause motion sickness [33]. Hence, we avoided laser manipulators. Hence, based on various factors, the UI manipulation technique selected is inspired from Google Tiltbrush- Virtual cursor with a 3D inhand menu.



**Figure 15. Gaze based UI (MS HoloLens) (Left), Laser pointer UI (Right)**

### 3.4 Layout Size and Shape

The layout of the interface is divided into in hand menu and the menu on the wall. The most common options required to manipulate the design are kept in the in hand menu. The menu options which are used in-frequently, which are used to define the state of the system are placed on the wall. The most commonly used buttons for design and manipulation are placed radially around the controller to enhance the muscle memory [36]. The commonly used buttons in the menu are larger to reduce the time required to interact with the buttons [34] [18] [34].



**Figure 16. Layout for the inhand frequently used options**

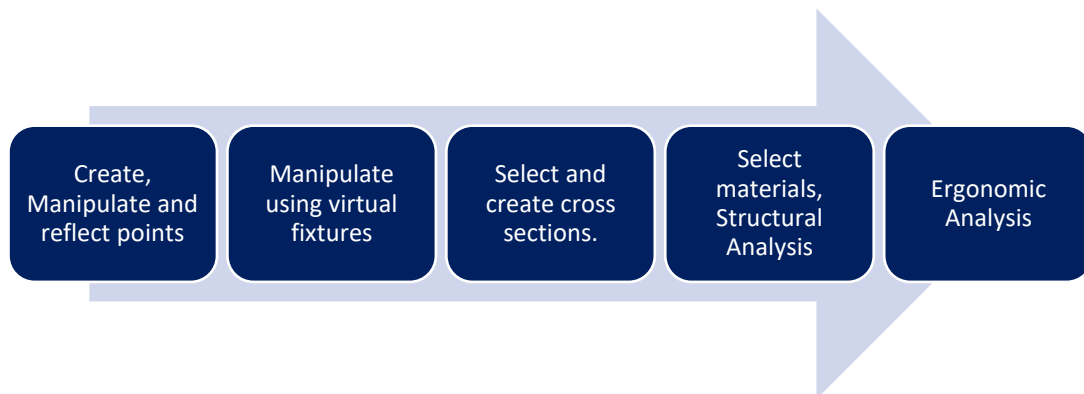


**Figure 17. Layout of the menu use to set the state of the software**

### 3.5 Mental model

A mental model is a simplified representation of a complex user interface. The mental model for a user interface can differ from person to person. A generalized mental model for modeling an automotive space frame using a conventional CAD tool can be simplified as shown in the figure. A mental model which is same as previous use experiences can enable the learning curve of the new user interface to be short, and proves to be an easy to pick up and intuitive interface [37] [36]. The goal of using a familiar mental model is to quickly understood, and accurately predicted user interface [37].

The work flow of the VR user interface extends the user's practice of designing automotive space frame chassis using a conventional CAD tool by following the same mental model. The icons as seen in the user interface are similar 3D versions of the images seen by the user of the conventional CAD software.



**Figure 18. Generalized mental model for the space frame design process**

### 3.6 Virtual Constrains

Virtual constrains allow the user to manipulate the design with precision as described earlier. The user can snap to a reference plane, or a reference line to design the space frame accurately.

### 3.7 User Interface/ Tool Ergonomics

The best tool design for precision is pen shaped. However, considering the bulky shape of the controller, the tool design for precision task are gun shaped as compared to a sword shape. Hence, holding the 3D cursor mimics holding a gun for design and manipulation of the frame.



Figure 19. Tool design inspired from gun shaped power tools for precision tasks

### **3.8 Affordances.**

Affordances help users identify what actions are possible ,and help users predict the interaction behavior [38] [37] [39]. All the fundamental geometry which the users can interact with is designed keeping in mind the affordances [30].

### **3.9 Audio/ Haptic feedback**

The user gets an audio and haptic feedback as he interacts with the buttons. The audio and haptic feedback helps reduce the cognitive load on visual processing, and help improve the user experience [35]. [39] [30]

### **3.10 Navigation**

The navigation method used for the user interface is 1:1 real world mapping. However, in future, if the design of the car is larger than the space for tracking, it is possible to use redirected walking or teleportation [34] [39].

# Chapter 4

## Content Creation

Virtual reality is a relatively new medium, and there are no established standards for the design of VR user interfaces. If the content on a website for a 2D monitor is distracting, the user can still manage by neglecting the distracting organization of website. However, in case of VR, the environment surrounds the 360 degree field of view for the user. Any distracting content/ bad design will cause the user to get out of that VR environment. Hence, it is very important to design pleasing content for VR environments. Other disciplines that have been around longer than VR have some elements in those disciplines that can be applied to VR environments. For content creation, studying fields such as architecture, interior design, industrial design, music, art can add provide great principles, and metaphors to designing environments in VR. Integrating different pieces from different disciplines together can help build a compelling VR experience.

### **4.1 Gestalts principles**

The gestalt principles state that the perception depends upon number of organizing principles using which we perceive objects and the world. The gestalt effect is the capability of our brain to recognize forms visually. The principle involves two aspects: grouping and segregation

Gestalts principles of similarity states that elements of similar properties tend to be perceived as grouped together [40]. The Gestalt principle of proximity states that are close together tend to be perceived as group. The same principle of proximity and similarity are used in



the menu design to group different user interface elements together based on functionality. The buttons in the group on the top left are options used for structural and ergonomic analysis. The buttons in the group on the top right represent options for manipulation. The buttons situated around the controller are commonly used buttons for design and manipulation. Based on the principle of common fate, all the objects that can be manipulated by dragging are represented by a spherical cursor with similar texture [30].

## 4.2 Environment Design

Environment design has 3 aspects: background, contextual geometry and fundamental geometry [38].

**Background:** For the user environments to be immersive, there should be no pixilation visible to the user in the VR headsets. Bright environments make the pixilation of the VR screen prominently visible [35]. Hence, a dark background is used for the VR user interface in order to make it difficult to notice pixilation, and to make the environment more immersive.

**Contextual Geometry:** Contextual geometry includes all objects outside the users interaction zone but which the user can still perceive in 3D [38]. The barriers in the virtual environment afford the movement of the user in the virtual environment. The barriers are placed exactly near the boundary of the tracking space. This eliminates the need of displaying the grid (Chaperone) as user approaches the boundary, and breaking the immersion of the user [38]. The contextual geometry also helps to build a mental model of the environment which helps the user to plan strategies. The geometry acts as the background for the user to compare for the size to the size of the space frame [38] [30].

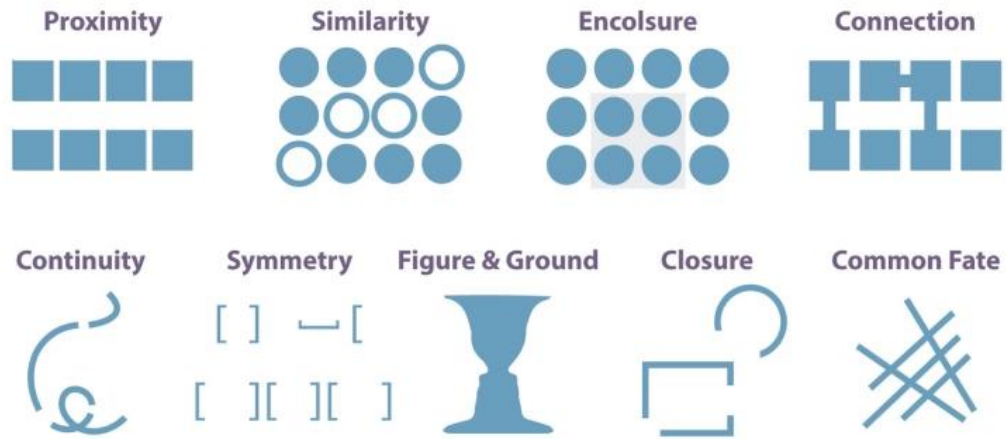


Figure 20. Gestalt's principles

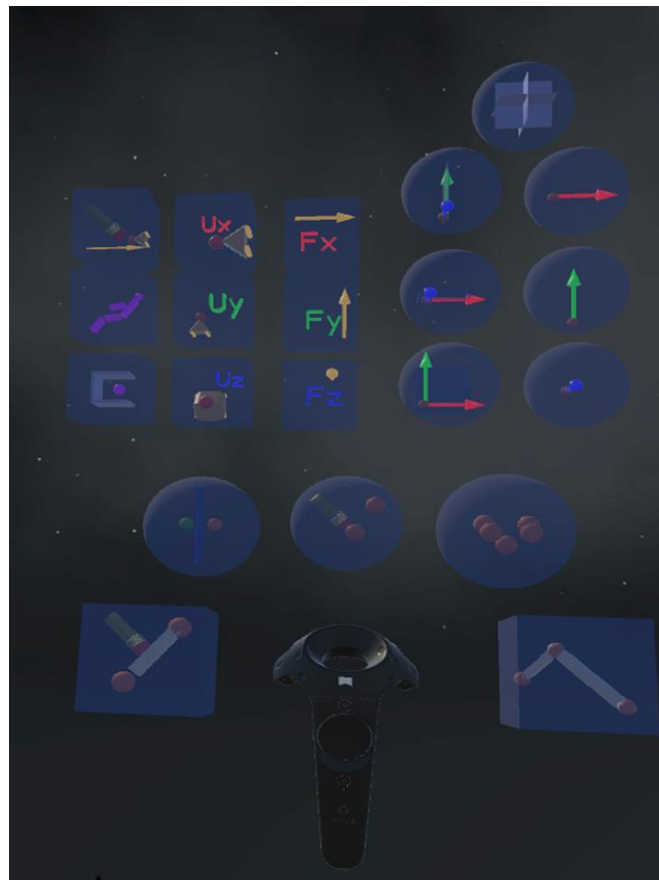
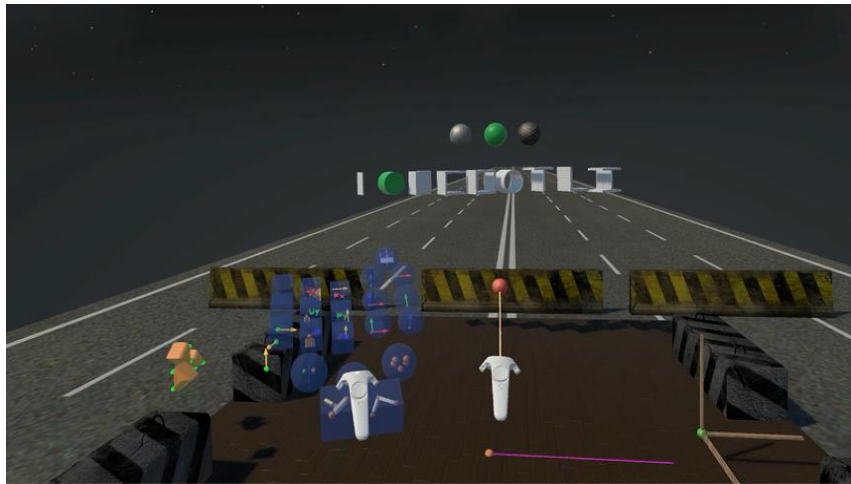
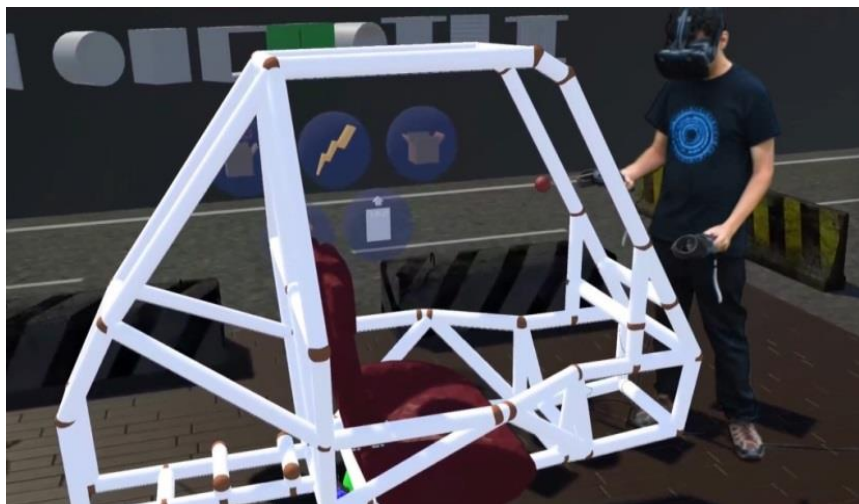


Figure 21. Layout of the inhand menu inspired from Gestalt principles.

**Fundamental Geometry:** Fundamental geometry is the geometry the user can interact with. The fundamental geometry is provided with all kinds of affordance [30]- the geometry have some kind of interaction. For example: Steering, engine, 3D drafter, etc.



**Figure 22. Background and Contextual geometry**



**Figure 23. Fundamental geometry**

### 4.3 Icons and symbols

The icons in the user interface are in 3D objects rather than 2D buttons. The design of icons is based on the principles of contextual design- the symbols used in 3D are similar to the images on icons in a 2D CAD user interface [37]. Contextual design enables then user familiar with 2D interface easily recognize the function of buttons in 3D [37]. Hence, this makes the use of interface easier, and instead of being a cognitive burden for the user, it extends the users practice. There are various metaphors used in icons as symbols [30].



Figure 24. Symbols inspired from existing CAD UI

### 4.4 Interaction aids- Markers

Various interaction aids are provided to draw attention of the user. The trail marks behind the cursor help user guide the cursor and aid in the manipulation of the space frame. [30]

### 4.5 Colors

The colors enable the user to distinguish different objects and perceive the world. Bright colors draw the user's attention. Hence, the main fundamental geometry- including the space frame has a bright color with dark background to capture the attention of the user towards the automotive space frame design and avoid distracting bright backgrounds. Contrasting colors make it easy to perceive the automotive space frame with the background [30]. There is high contrast between elements of modeling and foreground. Similar color pairs are avoided to accommodate color blind users [30].



**Figure 25. Cursor trails aid in manipulation**

# Chapter 5

## Test Case: Modeling an Automotive Chassis

The requirement analysis table describes the specific features as required in the software. Based on the user story goals in the requirement analysis, following use cases / features have been described and developed in the virtual reality user interface. The user interface design was iterative, as described in the following chapters, and a formative user feedback in form of cognitive walkthrough was conducted at every step of the development process. The data structure used for the design process is graph data structure. The class design gives a clearer picture on how the code is implemented.

### **5.1 Create key points using virtual constrains:**

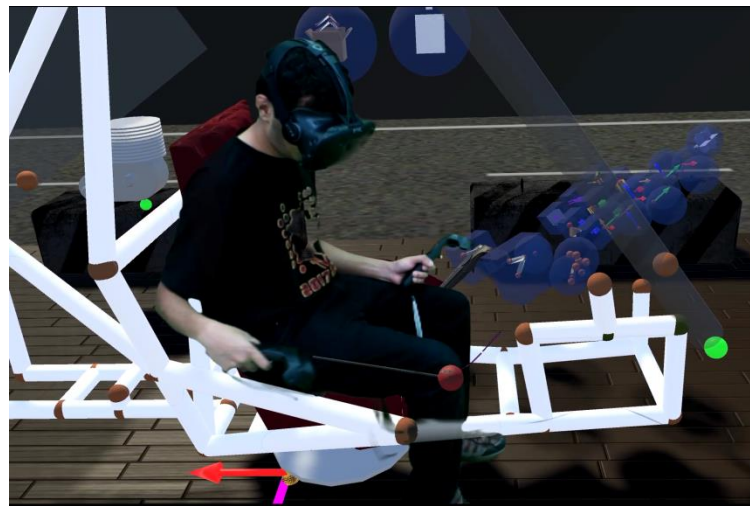
The user can create key points by enabling them “create key points’ option in the radial menu. Since the automotive space frame is more likely to be symmetric, the user can reflect the key points along the XY plane by enabling reflect points. The option to delete points allows the user to undo his actions.

The user might want to create a set of points in a single plane. The user can enable the snap planes perpendicular to X, Y or Z axes; drag the plane to the desired location and create the points close to the planes. Any points created near the plane snap to that plane thus enabling all the points created to be in the same plane. The user can also place

a plane facing an arbitrary direction by 3 reference points. The workflow used to create an arbitrary plane is similar to the workflow in the existing CAD tools.



**Figure 26. Menu for user interface design**



**Figure 27. Modeling the occupant package using virtual constraints**

## 5.2 Select the active section and material.

The user can select the active section, and the default material for modeling operations of space frame using the menu in the work space.



Figure 28. State the active section and material using the menu in the work space

## 5.3 Creating members between the key points.

To define the members between the key points, user needs three key point- two key points define the start and the end of the member, and the third point to define the orientation of the cross section. The “create cross section” option from the menu needs to be enabled each time to create a new cross section. Once the user selects three points- necessary to define the cross section, the member with active cross section can be created between the first two points.



## 5.4 Virtual Constrains and Manipulation.

The space frame structure has to be manipulated, and iterated in a constrained way to minimize the amount of post processing required after concept design stage. The “Virtual Fixtures” for manipulation of the space frame truss help in the manipulation of hard points in a constrained manner.



Figure 29. Virtual reference cylinder to aid in modeling set of collinear points

### 5.4.1 Manipulation in +X,+Y, +Z and XY, YZ XZ plane:

Enabling the manipulate +X,+Y,+Z direction options from the menu help the user to manipulate the design in a single constrained direction irrespective of the motion of the controller. Enabling any two options at a time enable the user to manipulate the points that plane that is XY, YZ or XZ plane.



**Figure 30. Virtual Reference plane to model coplanar points**

#### **5.4.2 Manipulation and snap to plane:**

In some special cases, the user might require for a set of key points to be in the same plane. The snap to the plane tools allows the user to ensure that any points dragged and drop near the plane, always lie in the same plane.

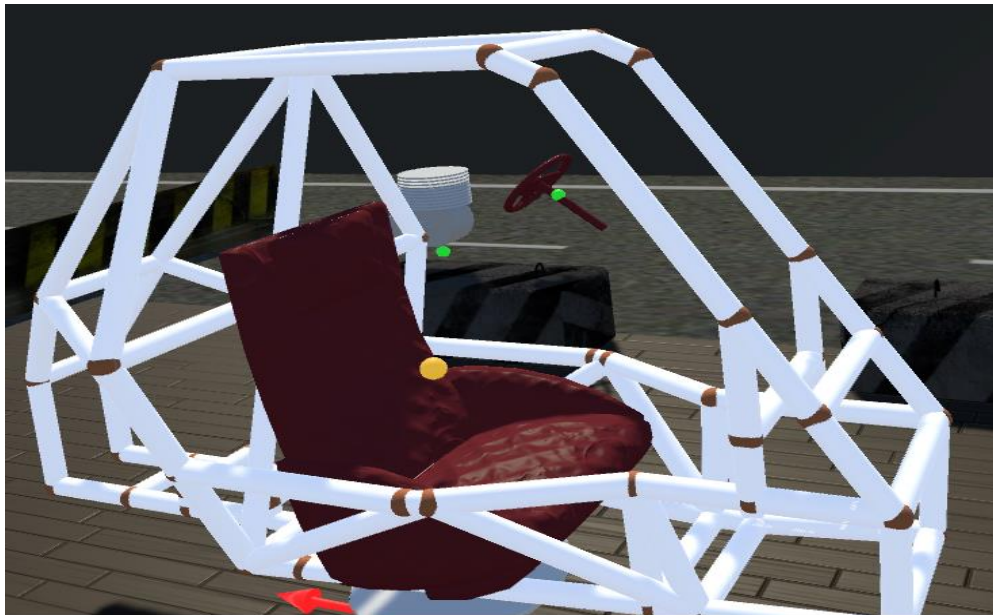
#### **5.4.3 Manipulation and snap to 3D reference line:**

In cases where user needs a set of points to be collinear, the snap to cylinder feature allows the user to ensure that any point lying near the snapping reference cylinder are always collinear with the other points in the cylinder.

#### **5.5 Visualization of center of mass:**

One of the most important parameter during the optimization of the automotive space frame is to lower the center of gravity. In a conventional CAD software, the user

has to check the center of gravity in x,y,z coordinates, and approximately try to visualize the location. In the VR CAD tool, the user can visualize the center of gravity in real time. The user can visualize the effect of each feature manipulated in the VR tool, and this also provides the aid for designing in VR.



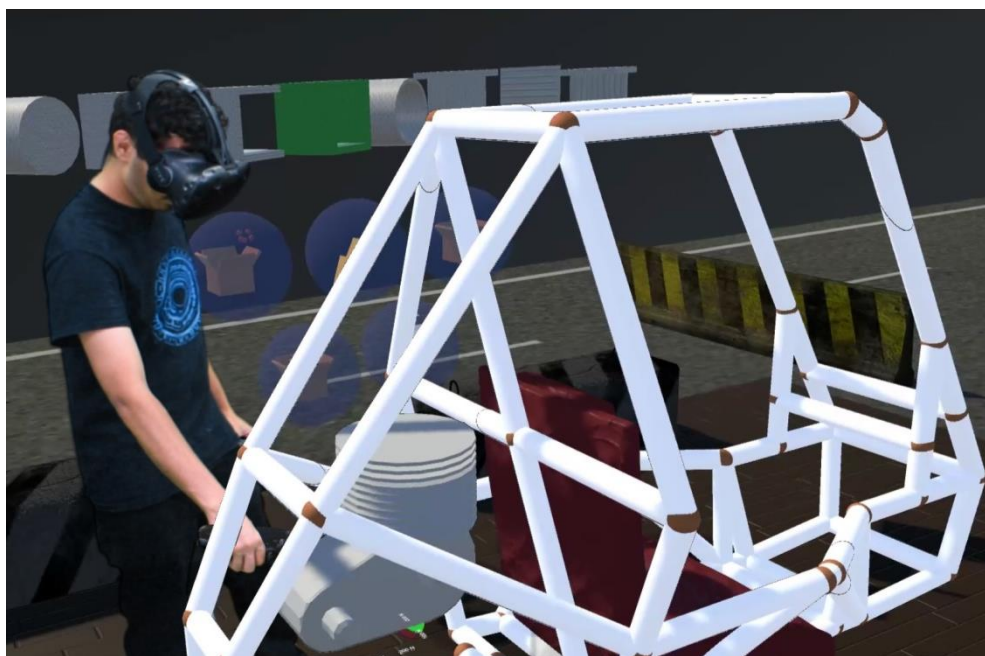
**Figure 31. The center of mass visualization**

## **5.6 Ergonomic analysis**

In a conventional software tool, the user has to manually create the maximum reach envelopes by blending the curves modeled using the data. VR environment enables the user to create the minimum reach envelope around the user in few seconds, and visualize and manipulate the dashboard of the car in 3D.



**Figure 32. Ergonomic analysis of occupant package using maximum reach envelope**



**Figure 33. Vehicle Packaging in VR**

## 5.7 Structural analysis – applying forces and boundary conditions

To get an initial sense and intuition for the design, the user can perform a static structural analysis using the software tool. The created CAD file can be imported to a commercial finite element package- ANSYS Inc., to be analyzed for displacement plots. The user can visualize the displacement of the crumple zone, and the occupant package of the car. The user can select the options from the menu to apply the displacements, and boundary conditions. The software writes an input file for the the ANSYS solver to solve, and then executes the solver. The user is able to visualize the results back in the virtual reality environment.

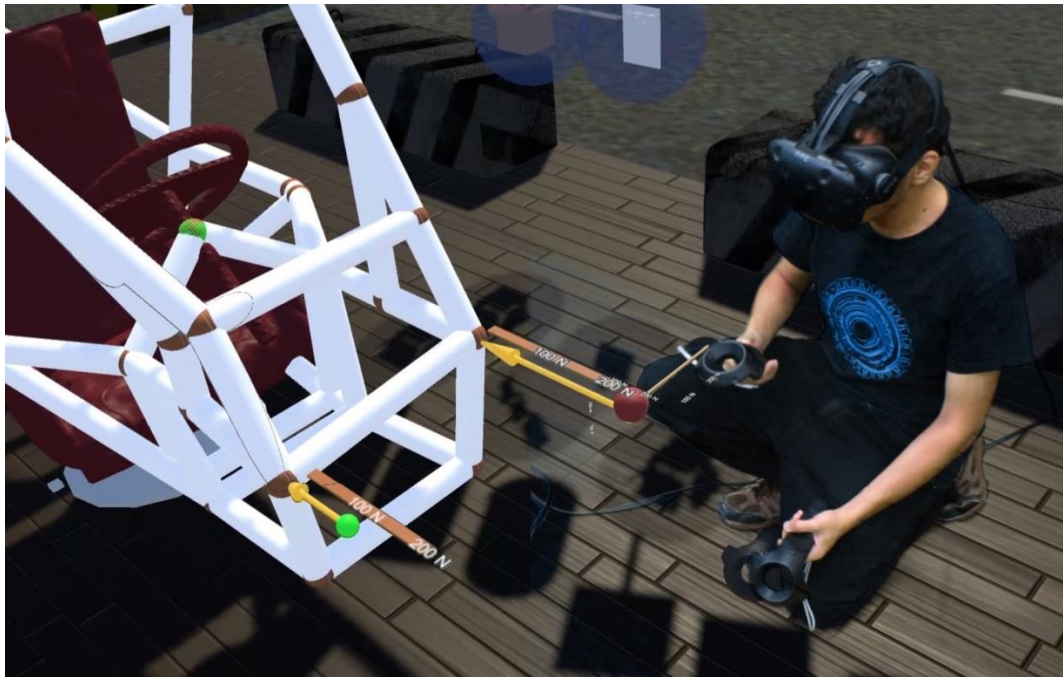
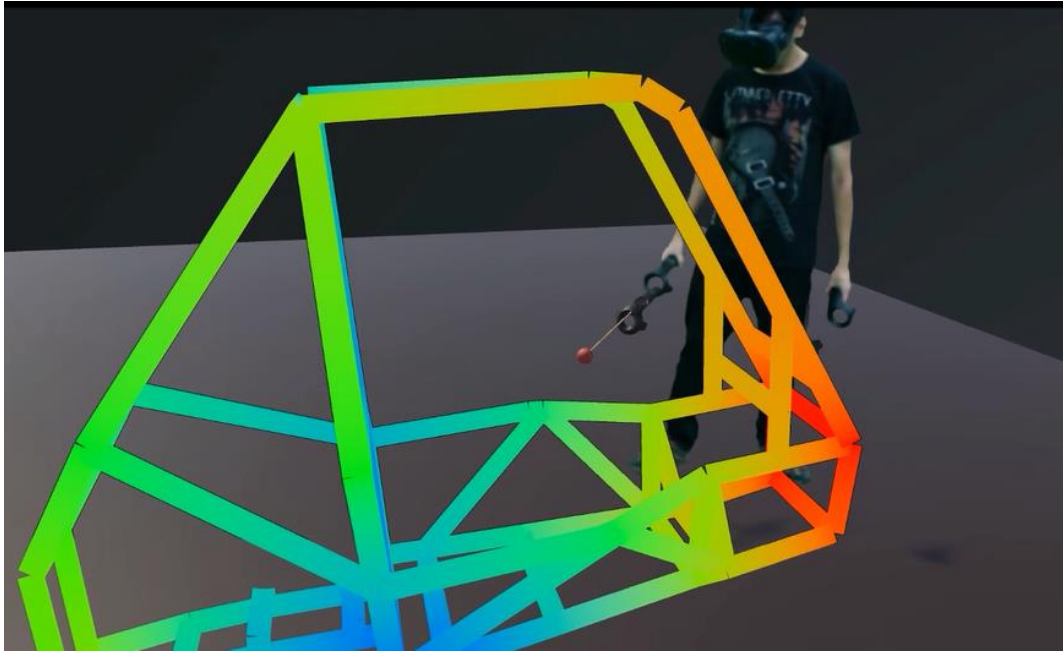
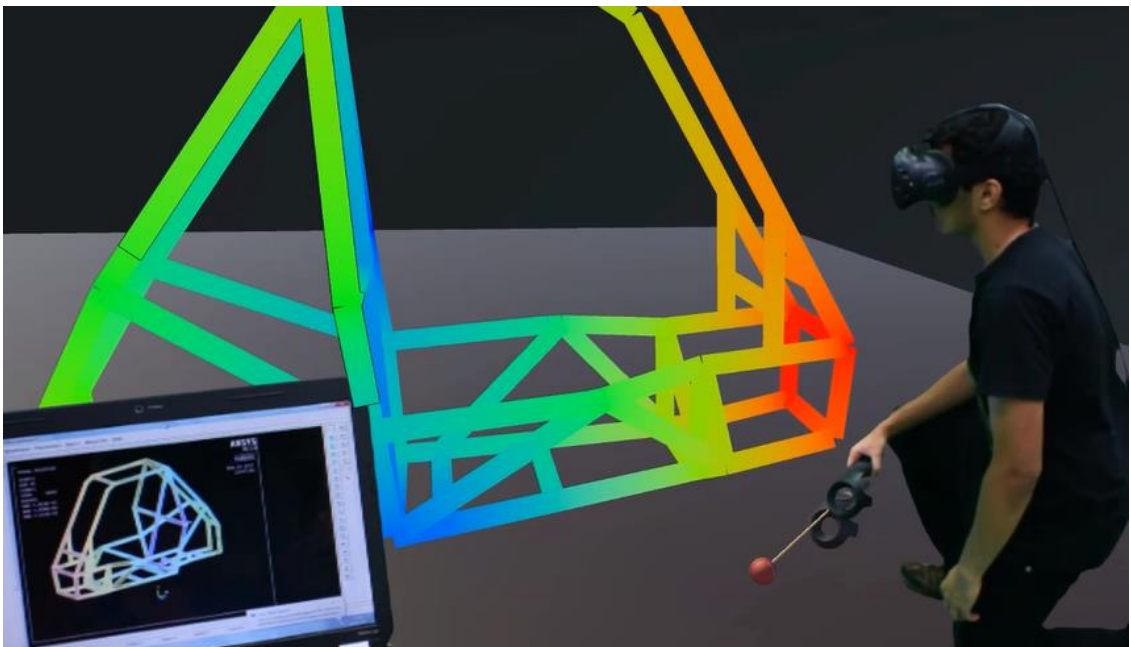


Figure 34. Applying Boundary conditions in VR UI



**Figure 35. The displacement plot for the static structural analysis visualized in VR**



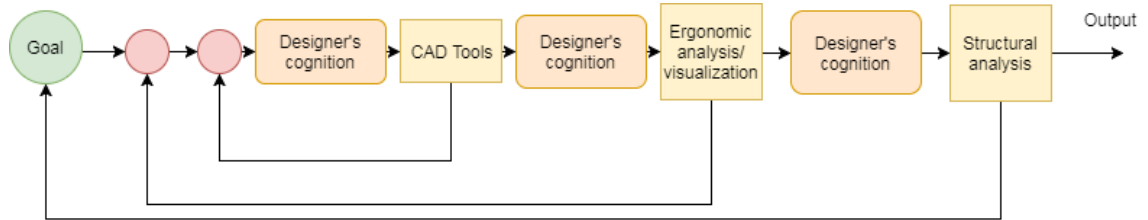
**Figure 36. Visualization of displacement in VR vs visualization in conventional CAD tool**

# Chapter 6

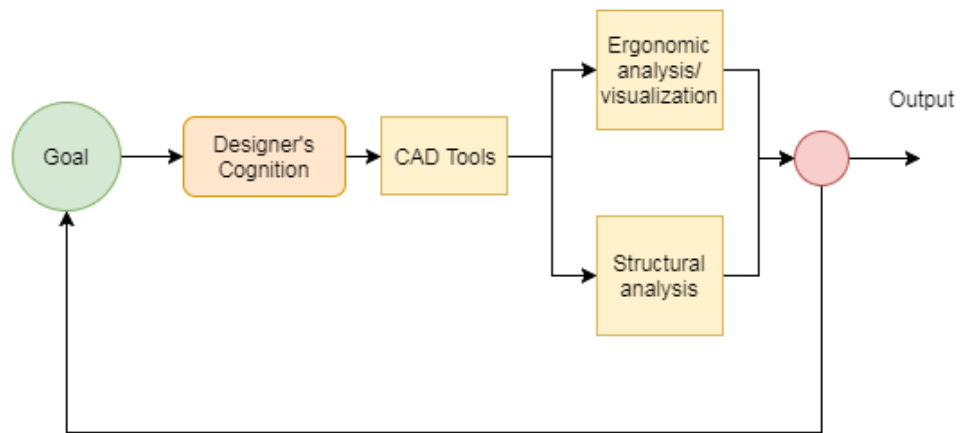
## Evaluation of the User Interface

Black (1990) published a study investigating the impact of two media: paper & pencil, and software on worker's product quality. This research highlighted the limitations of the desktop applications used for creative activity emphasizing the use on natural interfaces like pencil and paper.

Similar observations the comparison between pen and paper, and software user interfaces can be applied to compare Virtual Reality based user interface, and desktop softwares. The preliminary cognitive work analysis illustrates the poor fit between work demands and commands available on desktop tools. Desktop based user interfaces make the conceptual design of the spaceframe cumbersome, and negatively affect the users creativity. Desktop UI need to satisfy the work demands by indirect means like concatenating set of commands in a improvised fashion to achieve goals. This makes the actual path to achieve goals much longer and non-intuitive. VR based UI make the interaction direct, and creativity is only limited by user's imagination/innovation. Vr user interfaces provides minimal workarounds with the ability to design and manipulate in 3D. Actual path to achieve goal is much more intuitive making the design process faster. Figure 37 & 38 represent the process to design an automotive space frame with and without Virtual Reality from controls point of view.



**Figure 37. Goal directed behavior model for CAD on desktop**



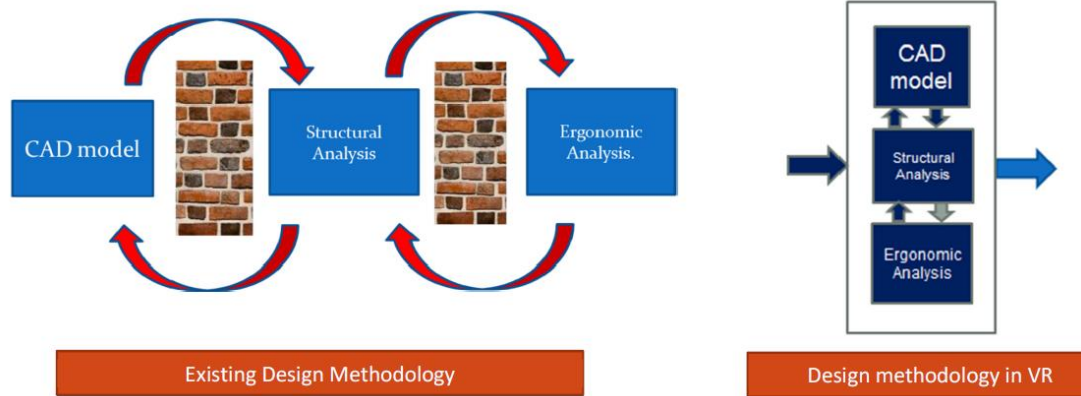
**Figure 38. Goal directed behavior model for CAD in VR**



# Chapter 7

## Conclusion and Discussion

The observations during interaction with the virtual reality user interfaces as compared to computer based CAD interfaces were recorded. The virtual reality based user interface significantly reduces the cognitive load on the user as he designs and manipulates the automotive space frame. The new virtual reality based user interface provides more flexibility in designing the automotive space frame in 3D. The virtual constraints in the VR user interface help the conceptual design to be directly converted into a parametric design without the need of any sort of post processing. The VR user interface can help increase the creativity of the user, by offering more flexibility, and not bothering about the procedure to attain the design imagined by the user. The flexibility allows the user to prototype, and iterates more design concepts in the same time. The analysis tools help aid the concept design process to ensure that the design is not rejected later on in the process due to basic technical shortcomings. The virtual reality based UI provides a technical advantage when the cost of manufacturing demonstration is high which limits the visualization of all possible configurations. The product can be built in 3-dimensions and optically, aesthetically evaluated. The interface provides an economical advantage by allowing rapid product development process and reducing the number of iterations. For multiple users, communication between development team for mutual understanding and workflow can be improved for future applications.



**Figure 39. Proposed benefits of the CAD based UI**

# Chapter 8

## Future Work – Towards more Natural User Interfaces

### 8.1 Introduction

One of the major drawbacks of current limitations of gestural based user interfaces is the lack of haptic feedback while interacting in virtual environments. The user does not get any haptic sensation as the user interacts with the button – presses a key in virtual environment. M.Alger proposed a water textures button for buttons to avoid the feeling of lack of immersion while interacting with VR. However, the feeling of haptic feedback cannot be fully replaced by visual cues. In future applications, where user might need to interact with virtual keyboards/ natural user interfaces to input dimension- haptic feedback is necessary.

### 8.2 Soft Haptic Feedback Glove

We introduce a solution for haptic feedback with soft robotic glove. The glove (Figure 40,41) is capable of providing a haptic feedback to the user as he interacts with the environment. The glove is optically tracked using leap motion, and the glove provides a kinesthetic force feedback as the user interacts with the environment. The glove can be used for haptic feedback for future virtual keyboard applications.

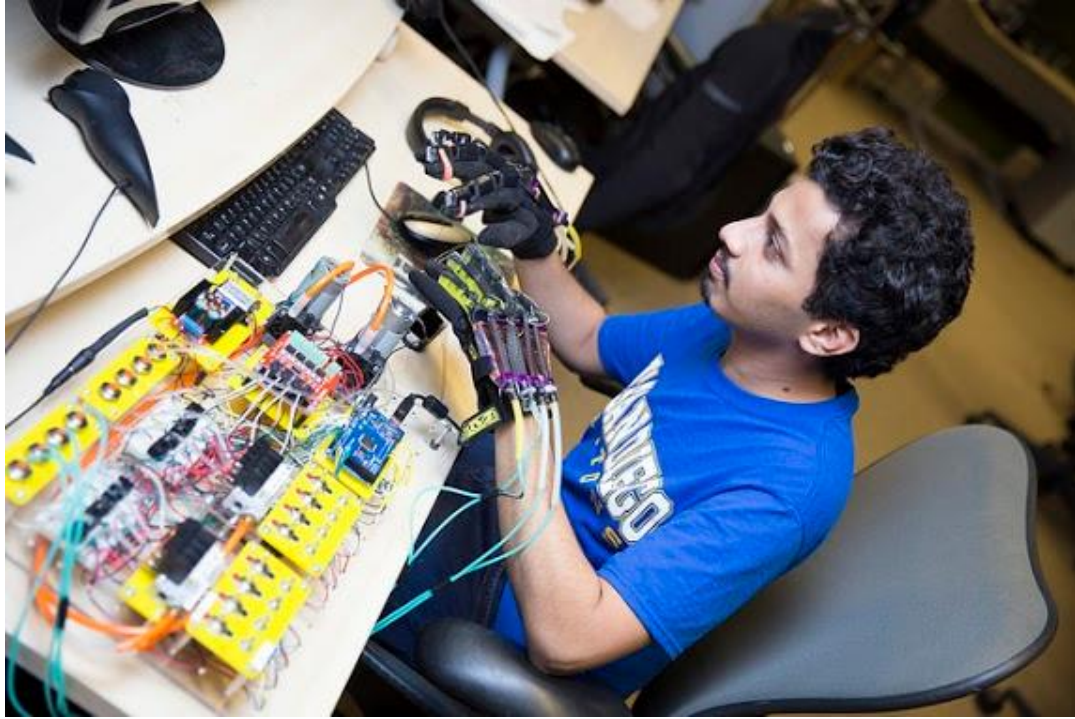


Figure 40. User interacting with the haptic glove user interface

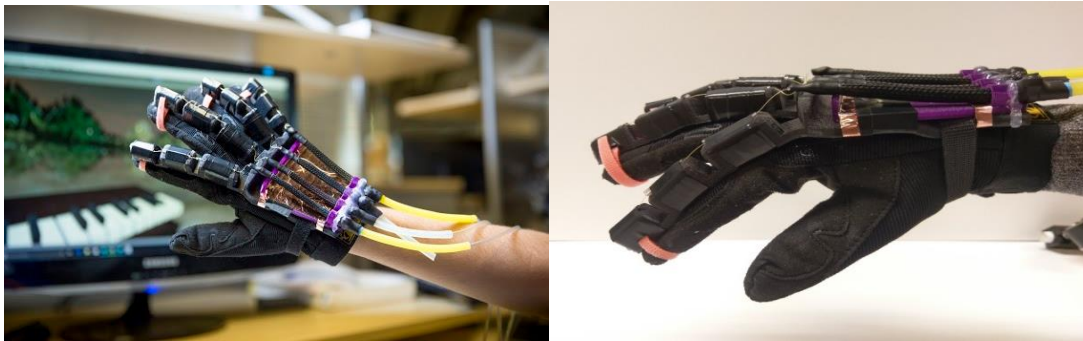


Figure 41. Assembly of the haptic glove

## Bibliography

- [1] Autodesk, "CAD + Augmented & Virtual Reality," San Rafael, CA, USA, 2017.
- [2] Dassault, "CATIA 3D-EXPERIENCE - Immersive Visual Experience HTC Vive Support," Vélizy-Villacoublay, France, 2017.
- [3] Virtualis, "Virtualis," 2017. [Online]. Available: <https://www.virtualis.us/>.
- [4] P. Zimmerman, "Virtual Reality Aided Design: A survey of the use of VR in auto industry.," *Product Engineering: Tools and methods based on Virtual Reality*, pp. 277-296, 2008.
- [5] D. E. Weisberg, "The Engineering Design Revolution," 2017. [Online]. Available: <http://www.cadhistory.net/>. [Accessed 01 09 2017].
- [6] D. Cohn, "Digital News," 2017. [Online]. Available: <http://www.digitaleng.news/de/evolution-of-computer-aided-design/>. [Accessed 07 07 2017].
- [7] N. Wognum, J. Trienikens, "The System of Concurrent Engineering," in *Concurrent Engineering in the 21st Century*, Switzerland, Springer, Cham, 2015.
- [8] B. Gardiner, "DESIGNERS, ARCHITECTS CELEBRATE 25 YEARS OF COMPUTER-AIDED DESIGN," 2017. [Online]. Available: <https://www.wired.com/2007/11/cad-anniversary/>.
- [9] I. E. Sutherland, "Sketchpad: A man-machine graphical," University of Cambridge, Cambridge, UK, 2003.
- [10] A. Amditis, I. Karaseitanidis, I. Mantzouranis, "Virtual Reality Research in Europe: Towards Structuring European Research Area," *Product Engineering: Tools and methods based on Virtual Reality*, pp. 3-20, 2008.
- [11] J. Schulze, C. Hughes, L. Zhang, E. Edelstein, E. Macanngo, "Advanced applications of Virtual Reality," in *Advances in Computers, Vol 82*, Burlington, Academic Press, 2011, pp. 217-260.
- [12] HTC, "HTC Vive," 2017. [Online]. Available: <https://www.vive.com/us/>.
- [13] Oculus, "Oculus," 2017. [Online]. Available: <https://www.oculus.com/rift/>.

- [14] F. Purschke, M. Schulze, P. Zimmerman, "Virtual Reality- New methods for improving and accelerating vehicle development," in *Virtual Reality for Industrial Applications*, Berlin, Heidelberg, Springer, 1998, pp. 105-122.
- [15] M. Jiang, "Virtual reality boosting automotive development," in *Virtual and Augmented Reality in Industry*, Berlin, 2011.
- [16] M.H. Abidi, Mustafa H., Al-Ahmari, El-Tamimi, Abdulaziz M., Darwish, Saied, Ahmad, Ali, "Development and Evaluation of the virtual prototype of the first saudi arabian designed car," *Computers*, 2016.
- [17] E. Varga, "Using hand motions in conceptual shape design: theories and methods," *Product Engineering*, pp. 367-381, 2008.
- [18] I. D. Foundation, "Minimum Viable Product (MVP) and Design - Balancing Risk to Gain Reward," 2017. [Online]. Available: <https://www.interaction-design.org/literature/article/minimum-viable-product-mvp-and-design-balancing-risk-to-gain-reward>.
- [19] A. Tyagi, "Design and Analysis of a Space frame Tubular Chassis for a Formula Student car," *International Journal for Innovative Research in Science, Engineering and Technology*, p. Vol 5, 2016.
- [20] D. Bhise, "Ergonomics in Automotive Design Process," CRC Press, 2011.
- [21] Y. Wang, J. Liu, Y. Li, N. Yang, "Research on Optimization of formula SAE truss frame".
- [22] E.C.Anderson, "Design and Optimization of Carbon Fiber Chassis Panels," Virginia Polytechnic Institute, Blacksburg, Blacksburg, Virginia, 2014.
- [23] S. Macey, "Hpoint: The Fundamentals for Car Design & Packaging," in *Hpoint: The Fundamentals for Car Design & Packaging*, Design studio Press.
- [24] A. Kemna, "Design of a tubular steel space frame for a formula student race car," Eindhoven University of technology, Eindhoven, 2011.
- [25] W. Kinkead, C. Morette, A. Pickering, Z. Sears, "Design and Optimization of a Formula SAE Racecar Chassis and Suspension," Massachusetts Institute of Technology, Boston, MA, 2009.
- [26] B. Biteman, "Baja SAE Frame Design," University of Cincinnati, Cincinnati, 2013.
- [27] Venkatesh S.P., M. Pawar, Maruthi B. H., "Design Optimization and Impact analysis of Chassis system of a Race Car," *International Journal of Enhanced*

*Research in Science, Technology and Engineering*, pp. 377-386, 2014.

- [28] N. Reddy, Vijaykumar S, "Study of different parameters on chassis space frame for sports car using FEA," *IOSR Journal for Mechanical and Civil Engineering Vol 1* , pp. 1-9, 2013.
- [29] A. Reynolds, K. Angeliu, T. Moser, B. Martins, "Design and optimization of a FSAE vehicle," Worcester Polytechnic institute, 2015.
- [30] J. Jerald, *The VR book - Human Centered Design for Virtual Reality*, ACM, Morgan and Claypool, 2016.
- [31] Microsoft, "Designing for VR: Environments and Interactions," [Online]. Available: <https://channel9.msdn.com/blogs/misslivirose/Designing-for-VR-Environments-and-Interactions>. [Accessed 2017].
- [32] F. R. Ortega, F. Abyarjoo, A. Barreto, N. Rishe, M, Adjouadi, *Interaction design for 3D user interfaces : the world of modern input devices for research, applications, and game development*, London, UK: CRC PRes, 2016.
- [33] M. Alger, "VR Interface PreVisualization Methods," [Online]. Available: [mikealger.com](http://mikealger.com). [Accessed 07 07 2017].
- [34] D. Bowman, Kruijff, Laviola J, I. Poupyrev, "3D User Interfaces," 2017. [Online]. Available: <https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/3d-user-interfaces>. [Accessed 007 07 2017].
- [35] P. Fuchs, *Virtual Reality Headsets – A theoretical and pragmatic approach*, London, UK: CRC Press, 2017.
- [36] D. Svanaes, "Philosophy of Interaction," 2016. [Online]. Available: <https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/philosophy-of-interaction>. [Accessed 07 07 2016].
- [37] K. Holtzblatt, "Contextual Design," 2017. [Online]. Available: <https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/contextual-design>. [Accessed 07 07 2017].
- [38] Owlchemy Labs, "The Holodeck is here- Designing for Room Scale VR," [Online]. [Accessed 09 07 2017].
- [39] V. Yasser Malaika, "Interaction Design in VR," 2017. [Online]. Available: [https://www.youtube.com/watch?v=\\_vQo0ApkAtI](https://www.youtube.com/watch?v=_vQo0ApkAtI). [Accessed 07 07 2016].
- [40] J. Carroll, "Human Computer Interaction - Breif Intro," 2017. [Online]. Available: <https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/human-computer-interaction-brief-intro>.

computer-interaction-2nd-ed/human-computer-interaction-brief-intro.

- [41] M. Matjaz, N. Doven, S. Begus , *Virtual Reality Technology and Applications*, Dordrecht: Springer, 2014.
- [42] Interaction Design Foundation, "Interaction Design Foundation," 07 07 2017. [Online]. Available: <https://www.interaction-design.org/literature/book/the-encyclopedia-of-human-computer-interaction-2nd-ed/human-computer-interaction-brief-intro>. [Accessed 07 07 2017].