Exploring Immersive Simulation based Design Frameworks in Support of the Moon Mission

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Abstract—This paper discusses the adoption of Virtual Reality (VR) based immersive design frameworks to support the study of habitat design and assembly related to the Moon mission. Simulation based design approaches have been explored to propose and compare the design of Deep Space Habitats for the astronauts to live and work along with robotic assembly of habitat components. These approaches have been implemented using the Immersive Vive VR platforms to support this design activity. The simulation framework will allow engineers to collaborate and design deep space habitats as well as to propose/study alternate ways to assemble them using robots and other automated resources.

I. INTRODUCTION

Simulation based design approaches involving VR based approaches are being adopted rapidly in various domains ranging from manufacturing to medical surgical training [1-7]. Such VR based approaches involve the use of Virtual Prototypes (VPs) which can be described as 3D VR based models seeking to simulate a real or imagined target environment and which are capable of supporting immersive interactions with users. The process of developing a 3D digital mockup or VP is known as Virtual Prototyping [1].

Virtual Environments (or Digital Mockups) involve the use of Virtual /Augmented/Mixed Reality technologies in creating a 3 dimensional artificial or synthetic environment which enables users to perform ‘what if’ analysis, understand a target problem as well as compare solution alternatives for a wide range of domains. Such Virtual Environments (or VPs) are widely used in space systems and engineering domains to help support concurrent engineering principles including cross functional design analysis and reducing overall time to design and build such systems. Virtual Reality (VR) based 3D dimensional (3D) environments enable users to interact at various levels of immersion: none, semi and full immersion. Immersion refers to the ability of a user to ‘go inside a virtual environment’ and touch, navigate, interact and explore more interactively. Augmented Reality (AR) and Mixed Reality (MR) environments allow users to interact with simulated and real world environments; for example, the Microsoft HoloLens platform enables the creation of such MR environments. There are several benefits of using VR/MR/AR environments in process design tasks; these include easier customization, lower cost, reduction in number of design changes, ability to support concurrent engineering principles, and reduction in need to use physical prototype among others.

The process design activities including design of the Deep Space Habitats as well as study of manufacturing automation issues outlined in this paper deal with NASA’s moon mission. NASA has started planning and preliminary engineering activities related to sending humans to the Moon again [2]; this is intended to serve also as a design/planning/implementation launch pad for a mission to Mars as part of other Deep Space Missions in the future. The simulation based design process discussed in this paper emphasizes the creation of advanced 3D simulation models to support cross functional analysis while reducing the lead time to design and build target products, components or complex systems. In this context, such VPs and training environments can play an important role in providing a cross functional platform for engineers and scientists from different disciplines to identify problems, propose solutions and analyze alternatives in such simulation based design environments.

Fig. 1 Role of Simulation based Design principles for Habitat Design and Assembly
In this paper, the foci is on two related aspects: (a) exploring the role of such immersive VR environments to support habitat design (b) investigate the design of a manufacturing automation tasks such as those involving assembly of habitat modules on the Lunar surface. Both these thrusts are part of a long term goal to design and build automated capabilities and framework in support of the Moon mission (figure 1).

II. DEVELOPMENT OF THE SIMULATION ENVIRONMENTS

The VR based simulation environments were built using C#, JavaScript and the Unity 3D game engine for the Windows platform. Immersion refers to the ability to support users to ‘immerse’ themselves inside a target simulation environment using 3D eye-wear, trackers and other sensors. The immersive environments were built using the HTC Vive™ VR platform [10]. The simulation environments will be built using the Unity 3D™ game development engine in a Windows platform. Languages such as C# and JavaScript were used for programming the various simulation modules.

Solidworks™ has been used to build the CAD models for the simulation environments. HTC Vive™ has been used to create the VR/AR simulation environments. The CAD models were created using Sketchup and Solidworks; the robot models (such as Robonaut model discussed later in this paper) were obtained from the official NASA 3D resources website [9].

The Vive comprises of a fully immersive VR headset providing a 110° field of view, and equipped with two wireless hand held controllers [10] which can be used to navigate, explore and interact with target simulated environments. The hand held controllers enable users to pick up objects, manipulate tools and perform other tasks relevant to assembly and service contexts. The simulation environments discussed in this paper were created using Unity 3D engine, Steam VR tool kit and a third party Photon VR toolkit.

A. Simulation Environment for design of the Lunar Habitats

VR based simulation environments were created to propose and analyze alternate lunar habitats for the astronauts to live and work (along with storage facilities for SEVs, robots and other equipment). One of the core activities involved creating a 3D based simulation environment which can be used by distributor teams of Engineers to collaborate and propose various habitat design ideas and assess them in a cross-functional manner using multiple criteria (cost, time, energy consumption, among others). Using this VR based environment, modular alternatives for the construction of surface habitats were explored. Two initial designs which were explored were dome shaped and box shaped habitats using modular components (shown in Fig. 3 and 4). The design and analysis focused on using assembly robots to build these habitats using the modular components transported to the moon before the astronauts reach the lunar surface. Using the simulation environments, the project team was able to explore process design issues relating to assembling of such habitats.

The Robonaut class of robots (is an earlier robot design developed by NASA and discussed in section B) can used to perform an assortment of tasks such as assembly, service, and other fastening operations. In general, it will be useful to have multiple classes of robots performing mundane and more sophisticated tasks (of increasing complexity); this is essential to ensure that the more expensive, versatile robots are not used for the mundane less complex routine tasks. For example, the Valkyrie robot is designed to be a humanoid robot capable of operating in degraded or damaged human-engineered environments [8].
The assembly robot will require additional functionalities including the following:

- **Tool changing:**
  The modified Robonaut will be able to change tools according to the assembly or other task requirements. This will enable it to be more versatile to perform various assembly and manipulation tasks including tool handling for obtaining lunar and other samples as part of experimental activities (fig 5).

- **Reachability:**
  The Robonaut can be supported by a scissor lift mechanism which allows it to move up and down increasing its reach and manipulation capabilities which will be useful for assembly of habitat modules (the scissor lift can be seen in Fig. 5).

The various tool changer process layout alternatives as well as the design of the scissor lift were studied using the immersive simulation environments. Candidate designs were proposed and compared interactively. A tool pallet for such tasks was incorporated as shown in Fig. 5.

The proposed Lunar Habitat was segmented into modules for sleeping, working and fitness. An overview of these modules is provided in the following sub-sections.

1. **Sleeping Pod Design**
   A design for a sleeping pod which can also be used for a personal workstation was proposed. This pod is a semi-cylindrical dome consisting of a sleeping bag, a workstation, computer display, storage units and bags for storage. LED lights were incorporated which could be adjusted by astronauts for relaxation and comfort. A view of the sleeping pod is shown in Fig. 6.

2. **Fitness modules**
   The reduced gravity on the lunar surface can impact the health of the astronauts. Reduced bone density
can lead to health issues, including being susceptible to fractures [13]. For these reasons, regular fitness routines and exercises are necessary; the design of fitness areas and modules along with an array of compact exercise equipment was studied in the VR environments. A partial view of one of these segments is shown in Fig. 7.

In our proposed assembly context, the Robonaut class of robots can also work collaboratively with other robots such as the Valkyrie robots to build parts or modules of these space habitats. As part of this framework, automated methods can be adopted to generate assembly and path plans to support such assembly tasks. The position of modular parts and feeders can be among the data inputs for the generation of the assembly planning sequences. Genetic Algorithm (GA) and Insertion algorithm based approaches can be used to determine the near optimal collaborating sequence underlying the assembly tasks involving the building of such modular components of the habitats. Using a GA based approach, the shortest travelling sequences during the assembly tasks can be studied; a near optimal solution can be generated. In general, the GA is an evolutionary algorithm which derives its behavior from a metaphor of the processes of evolution in nature [11]. It generates each individual sequence from some encoded form known as a "chromosome" or "genome"[12]. The assembly sequence can be viewed as chromosome (also sometimes called a genotype). In this GA based approach, the chromosome is represented as a linked list of target positions that the assembly robot must reach to complete a given assembly task. Based on habitat design data (based on the positions of the feeders, location of fasteners and tools, and the positions of the robots), a near optimal sequence and path can be determined; assembly plans can be compared and studied based on assembly time, risks and savings in energy consumption. A pseudocode of the main steps of such a GA based approach involving one assembly robot is shown in Fig. 9. In certain assembly contexts, the path followed by the robotic manipulator may not be a straight line (because of the presence of obstacles between a start point and a destination); for such situations, the presence of collision free paths can be used to determine the actual distance; such collision free path planning can be accomplished by A* algorithms [14, 15].
GENETIC ALGORITHM

1: \(i\leftarrow 1, j\leftarrow 1, \text{NumParts}=9, \text{NumFeeders}=2, \text{Chromosomes}=50, \text{newFitness}=0, \text{generationsWithoutImprovement}=0\)  

\(\text{//select number of parts, feeders, chromosomes}\)

2: \text{Initial 50 population randomly}  

\(\text{//Randomly initiate population}\)

3: \(\text{While generationsWithoutImprovement < 10000}\)  

\(\text{//Algorithm termination criteria}\)

4: \(\text{Begin}\)

1: \(\text{Compute Fitness}(j)\)  

\(\text{//Compute the fitness of the jth chromosome in generation i}\)

2: \(\text{Perform Selection Operation}\)  

\(\text{//Use the roulette wheel to select random population}\)

1: Set \(j=1\)

1: For \(j\leftarrow 1\) to 50

2: Do

1: \(\text{Compute Fitness}(j)\)

5: End

2: Set \(\text{Sum}=0, j=1\)

1: For \(j\leftarrow 1\) to 50

2: Begin

3: \(\text{Compute Sum} = \text{Sum} + \text{Fitness}(j)\)

4: \(j=j+1\)

5: End

3: Generate a random \(c\) from the interval \((0, \text{Sum})\)

4: set \(j=1, P=0;\)

1: While \(j < 50\)

2: Begin

3: Compute \(P = P + \text{Fitness}(j)\)

4: If \(P>c\)

5: Then select the \(C_i\)

6: End If

7: \(j=j+1\)

8: End

3: \(\text{Perform Crossover Operation}\)

\(\text{//Perform Crossover operation}\)

1: Assuming \(C_0, C_{n-1}\) are selected from population for crossover operation

2: Generate a random \(P\) from the interval \((0, 1)\)

3: If \(P>c\text{(crossoverProbability)}\)

4: Then Copy the chromosome \(C_m\) and \(C_{n-1}\) directly into new population

5: Else

1: Generate a random \(K\) from the interval \((1, 9)\)

2: Do Cross over \((C_i, C_{i+1})\) from cutting point \(K\)

3: Generate two new individuals \((\text{Child}_i, \text{Child}_{i+1})\)

9: End If

4: \(\text{Perform Mutation Operation}\)

\(\text{//Perform Mutation operation}\)

1: Generate a random \(P_n\) from the interval \((0, 1)\)

2: If \(P_n>c\text{(mutationProbability)}\)

3: Then Copy the chromosome directly into new population

4: Else

1: Generate random \(r_1, r_2\) from the interval \((1, 9)\)

2: While \(r_1 = r_2\)

3: Begin

4: Generate a random \(r_2\) from the interval \((1, 9)\)

5: End

6: \(\text{tmp} = \text{chromosome}[r_1]\)

7: \(\text{chromosome}[r_1] = \text{chromosome}[r_2]\)

8: \(\text{chromosome}[r_2] = \text{tmp}\)

5: End If

5: \(\text{Compute BestFitness}(i)\)

\(\text{//Calculate the best chromosome in each generation}\)

1: \(\rightarrow\)

2: If \(\text{newFitness} < \text{bestFitness}(i)\)

\(\text{//Search for better fitness than incumbent one}\)

3: Then

1: \(\text{newFitness} = \text{bestFitness}(i)\)

2: \(\text{bestChromosome} = \text{bestChromosome}(i)\)

3: \(\text{generationsWithoutImprovement} = 0;\)

4: Else

1: \(\rightarrow\) generationsWithoutImprovement;

5: End If

Fig.9. Overview of the key steps in the proposed Genetic Algorithm based assembly sequencing approach
III. CONCLUSION

This paper discussed the adoption of immersive Simulation based design approaches and environments to support the design of habitat related elements as well as some elements of the process design involving assembly of habitat modules in the context of Moon mission. Simulation of assembly tasks can play a key role in comparing process design alternatives; the automated generation of assembly sequences for assembly of habitat can be studied using Genetic, Insertion and other algorithms. Based on these process designs, a manufacturing automation framework can be implemented in support of these activities. These simulation environments can also be used to obtain feedback and input from astronauts early in the design cycle; it can later be used to train them as well in preparation for the Moon mission.

ACKNOWLEDGMENT

We would like to acknowledge the background and contextual information provided by engineers from the NASA Johnson Space Center (Houston), which enabled the conceptualization of the overall framework and approach outlined in this paper. Some of the students participating in these research activities were provided funding through a NSF REU Site grant (grant number 1359297). Some of the habitat design activities were accomplished as part of project activities (funded by NSF through two grants, 1547156 and 1748091) and were part of a new senior level / graduate elective course on Modeling of Cyber Physical Systems at Oklahoma State University.

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