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Exploring the role of Simulation-Based Design principles in support of transportation and material handling activities for the Lunar Mission

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***Abstract*— Simulation-Based Design (SBD) approaches can help conceptualize engineering plans and design activities with the adoption of Virtual / Augmented Reality based digital mockup techniques and technologies. This paper outlines preliminary activities based on SBD principles aimed at supporting some of the material transport activities for NASA's Lunar Mission. Immersive Virtual Reality (VR) based simulation environments were created to support some of the simulation based design activities. The engineering design activities included (i) planning and conceptualizing an autonomous system for transporting payloads from the Gateway to the Lunar surface, (ii) exploring design of cable-based robotic system for transporting parts from one location to another on the surface of the Moon and (iii) studying path planning approaches to transport materials on the Lunar surface. The initial conceptualization of design ideas for these three thrusts are presented along with a discussion of the SBD implementation using the Unity engine on the immersive Vive platform.**

I. INTRODUCTION

This paper presents a Simulation-Based Design approach supporting certain elements of design and analysis pertaining to three thrusts in the context of the Moon Mission. They include exploring (i) the design of an autonomous system for transporting the payload containing parts from the Gateway to the Lunar surface, (ii) a cable robot based system for transporting parts from one location to another on the surface of the Moon and (iii) path planning approach to transport materials on the Lunar surface.

In general, Simulation-Based Design (SBD) refers to the creation and adoption of Virtual Prototypes in various fields and application contexts. In general, Virtual Prototypes (VPs) refer to 3D engineering models designed to support both product and process design while being capable of supporting immersion by users [16]. Such VPs or digital mockups have been created for a range of engineering [17, 23] and medical applications [18, 19, 20]. More recently, research initiatives have explored the role of such VPs as a link between cyber and physical activities as part of broader Internet-of-Things (IoT) based frameworks [21, 22]. In this paper, such a Simulation-Based Design (SBD) approach is discussed which involves the design of such Virtual Prototypes (VPs) to support preliminary designs proposed by engineering student

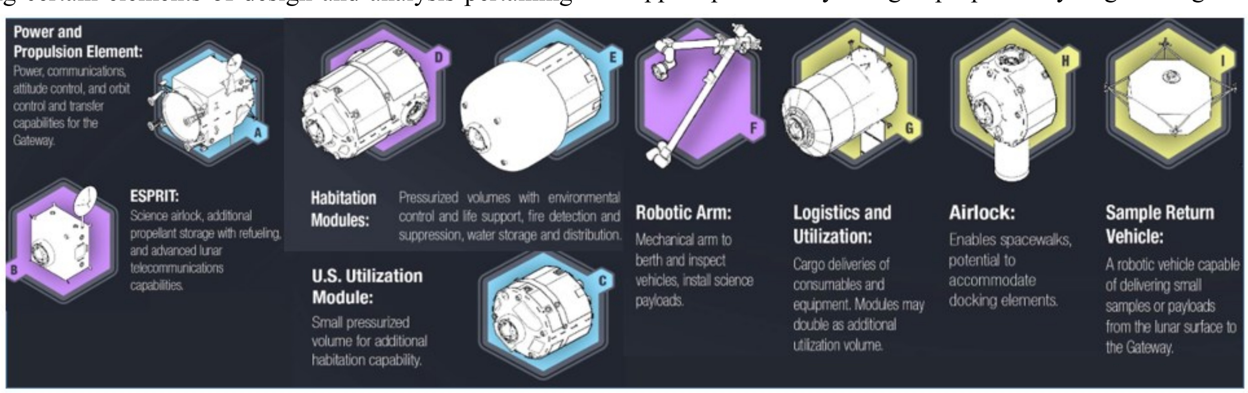

Fig. 1. Overview of the various modules of the Gateway [4]

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teams to address the three identified thrusts.

The adoption of SBD based principles enables the reduction of lead time to design and build specific components and systems in a variety of engineering activities including the three thrust areas discussed in this paper. Such a SBD framework can provide a platform to identify problems, propose solutions and analyze alternatives. In [5, 14], a SBD based approach was discussed focusing on the assembly and design of habitats for astronauts to live and work on the Moon. The SBD related research related to the Moon mission presented in this current paper is a continuation of these prior research activities.

An Information Centric Systems Engineering (ICSE) approach [15] was adopted to support the design of the simulation environments for the Moon mission. In general, Systems Engineering (SE) underscores an interdisciplinary process [2] to ensure that stakeholders needs are satisfied throughout a system's entire life cycle [3]. The Systems Engineering (SE) perspective adopted in developing this SBD approach provided a structured foundation to help understand core phases and their relationships involving planning, building and validating the simulation environments for the Lunar mission. The ICSE approach involves the creation of information-centric process models to plan, build and validate the simulators developed. In such information centric modeling context, the emphasis is on modeling various attributes for each functional task including functional and temporal relationships of key activities within a target process or life-cycle activity [6].

NASA's Gateway (Fig. 1), which is being designed to support the Moon mission, seeks to establish an autonomous platform to refine and mature short- and long-duration deep space exploration capabilities through the next decade [1]. It is expected to be assembled in a Lunar orbit where it can be used as a staging point for missions to the Moon and other destinations in deep space. In general, this Gateway can evolve for different mission needs (involving exploration, science, commercial and international partners).

The contribution of the research outlined in this paper is to provide a foundational basis to address identified engineering elements for the Moon mission using the SBD approach. This paper summarizes some of the preliminary outcomes including the development of 3D immersive Virtual Reality based environments (shown in Fig. 2) in the context of the 3 identified thrusts which include:

1. Proposing plans and design ideas to support an automated Lunar landing system from Gateway to the Moon to transport supplies equipment and other robotic components.
2. Exploring the Design of a Cable robot-based system for transporting supplies and automation components between locations on the surface of the Moon.
3. Investigating path planning approaches to transport materials on the Lunar surface.

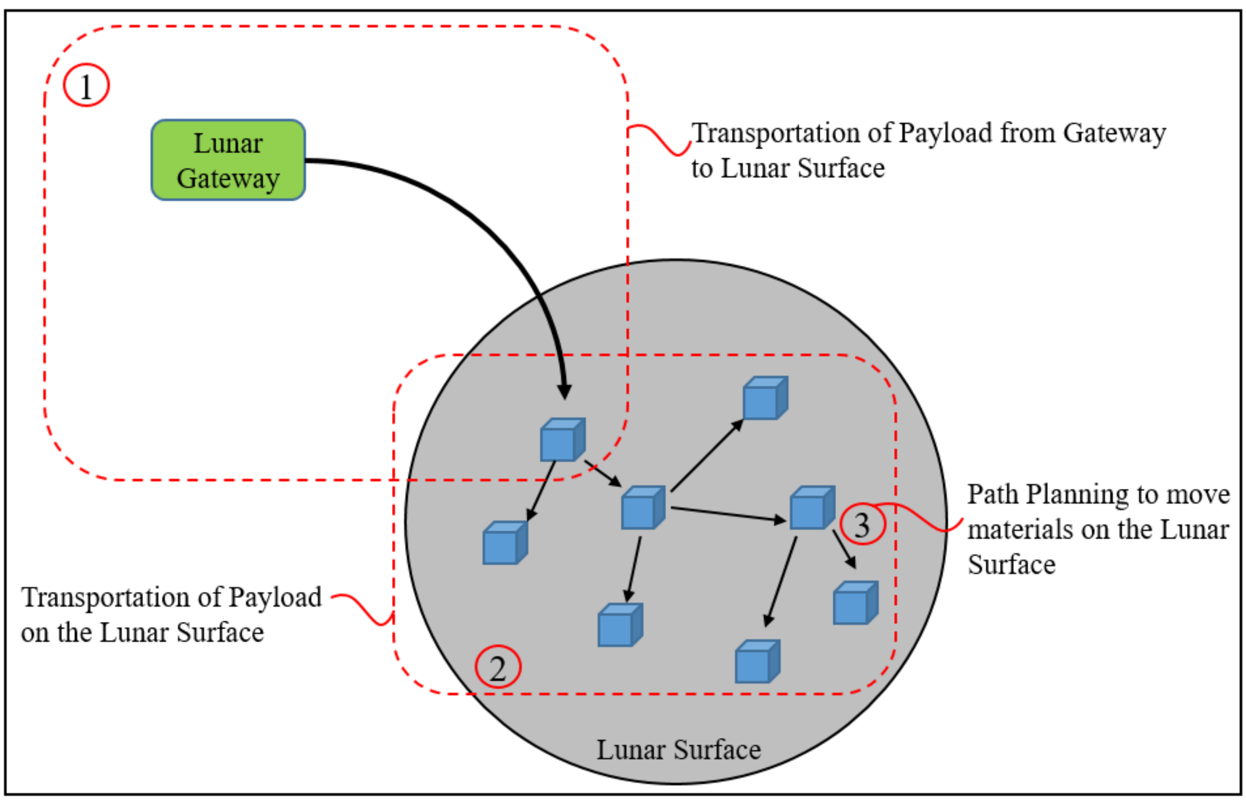

Fig. 2. The three thrust areas discussed in this paper in the context of the Moon mission

II. Development of the Simulation Environments

The VR based simulation environments were built using C#, JavaScript and the Unity game engine for the Windows platform. Immersion refers to the ability to support users to 'immerse' themselves inside a target simulation environment using 3D eyewear, trackers and other sensors. The immersive environments were built using the HTC Vive VR platform. The CAD models were created using Sketchup and Solidworks™.

Vive is a fully immersive virtual reality platform (Fig. 3) which consists of a VR headset providing a 110˚ field of view and wireless handheld controllers providing intuitive controls [8] Steam VR tool kit and a third party Photon VR toolkit were also used for the development of these simulation environments.

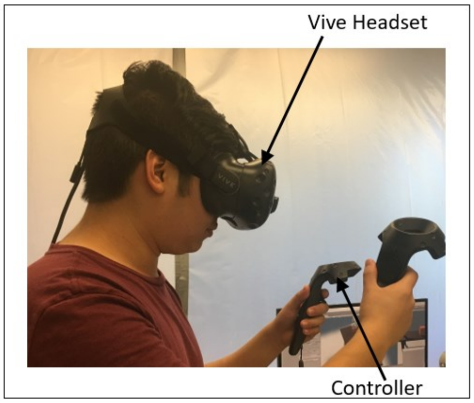

Fig. 3. User Interacting with the virtual training environment using the Vive

A. *Designing an autonomous system for transporting payloads from the Gateway to Lunar surface*

In this first thrust area, the focus was to explore and propose design alternatives for the transportation of payloads from the Gateway to the Lunar surface. An autonomous transportation system was proposed which could dock to the storage station operating in the Lunar orbit. The transportation system would pick up the payload from the storage station and undock. Subsequently, the autonomous system would head to the Lunar surface. Once it is near the Lunar surface, it would fire the thrusters to hover above the surface. Using a Skycrane maneuver [11], this system can lower the payload to the Lunar surface. Once the payload touches the surface, the transportation system would return to the storage station to dock, refuel, and connect to another payload.

The design of the autonomous transportation system consisted of a protected enclosure consisting of onboard computers and electronics. The frame of the system held the protected enclosure, the fuel tank and the vectored thrusters (shown in Fig. 4). It also consisted of a cable system to lower the payload on the Lunar surface.

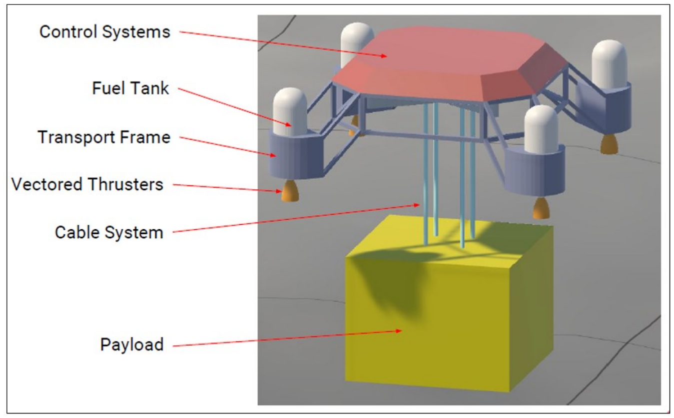

Fig. 4. Components of the autonomous transportation system

The autonomous system was designed to carry the estimated payload mass of the NASA Multi-Mission Space Exploration Vehicle (3000 kg) [12]. Fuel constituted a majority of the mass. A view of the simulation environment developed to study the autonomous transportation system is shown in Fig. 5.

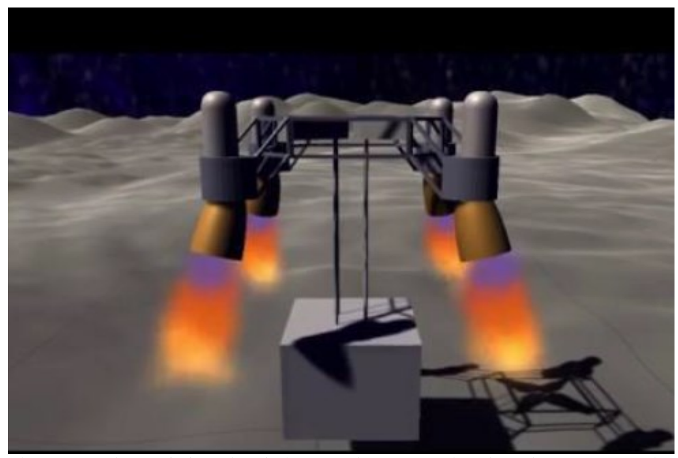

Fig. 5. A view of the Simulation Environment showing the transportation moving closer to the Lunar surface to drop the payload

B. *Exploring the design of a cable based robot system to transport parts on the Lunar surface*

The emphasis in this second thrust area was to design a cable robotic system for the transportation of payloads from one location to another on the Lunar surface. An additional capability was to support manipulation and positioning tasks. The cable robotic system proposed involved 4 robotic cranes which can work in coordination to pick up and manipulate target payloads (equipment, supplies in containers, etc.); they would also be capable of transporting payloads from one location to another on the Lunar surface.

A 4 mobile crane based system was proposed which would allow the workspace (between them) to be modified to accommodate a range of transportation functions. The design consisted of a system of 4 networked mobile cranes that roughly resemble the columns of a cable-driven parallel robot operating space. Each robot has a hexagonal body that sits on

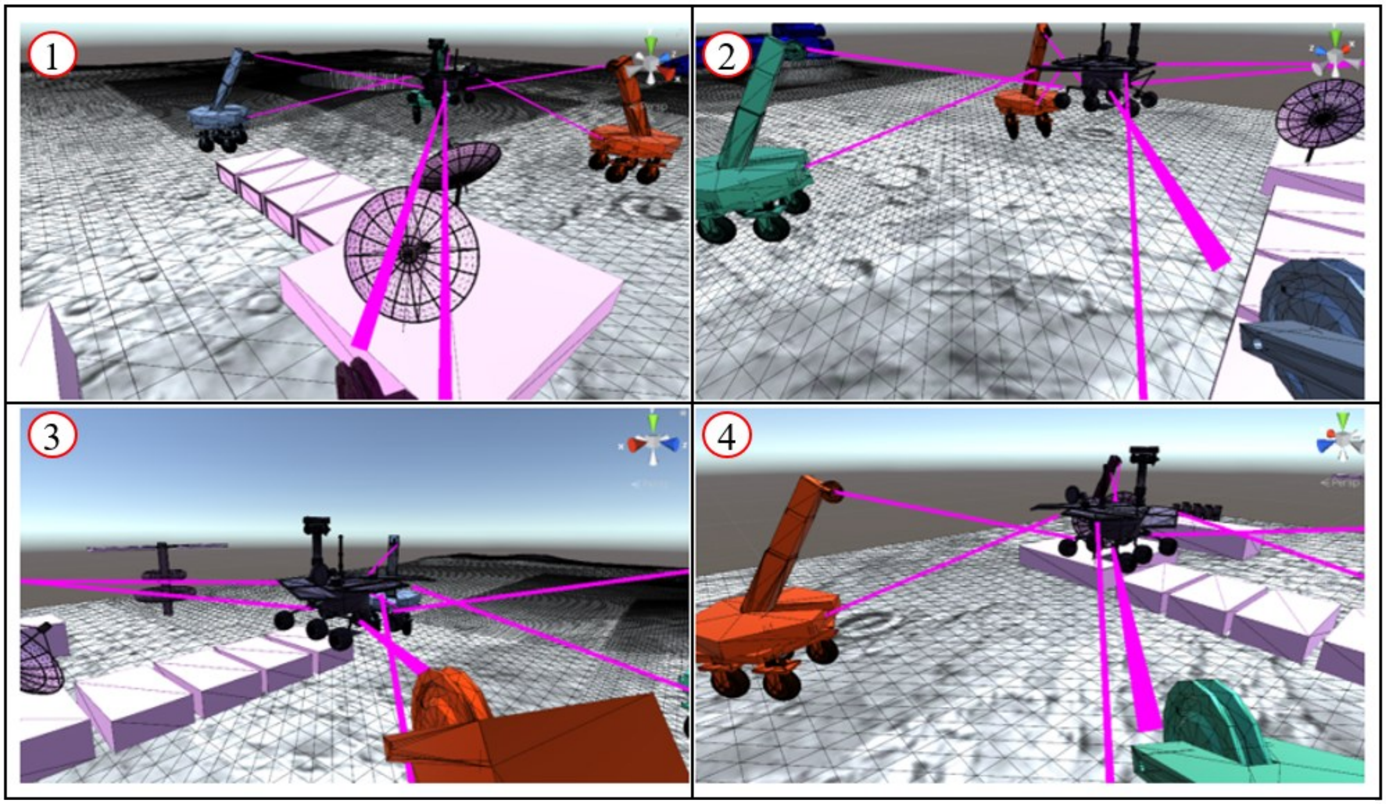
Fig. 6. Simulation scenes involving the four-cranes based robotic system to transport materials from one location to another on the Lunar surface

top of a Nomad chassis, as seen on the Nomad Rover [9]. The body top can swivel 360 degrees clockwise and counterclockwise. The robot has a telescoping (extending) boom centered on body top which houses internal winch and pulley systems (upper and lower). The Swivel and extension ability of the robot allow for payload maneuvering and obstacle avoidance. The Bottom winch can also raise and lower to avoid obstacles within workspace. The views of the simulation scenes showing the 4 crane based robotic system transporting materials from one location to another on the Lunar surface are shown in Fig. 6.

There is a LIDAR sensor [10] mounted on top of the boom and camera embedded in the body of each crane. Data is sent to a predetermined "host" crane that maps out the virtual workspace and calculates the lowest cost path with the A* algorithm. Instructions are then sent from the host (server) to other client cranes. Any of the cranes could be a host or client crane. As part of the design activities, several issues of importance were identified including the material properties of the cables in this robotic material handling system. The cables in this design needed to self-regulate its temperature. The end effector (Fig. 7) was interchangeable using hooks or electronic claw which would be powered by cable. The supporting cables needed to withstand both temperature extremes of the Moon, flexible enough to wind and unwind with precision, and durable enough to last through frequent use over time.

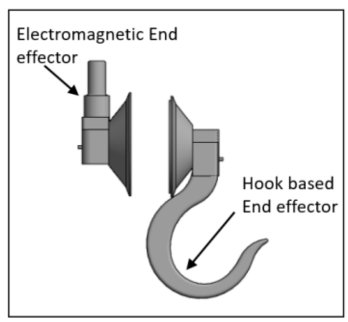

Fig. 7. End effectors for the cable robots

An ionizing mesh was needed around the electronic components in order to repel dust from the surface of the cable.

Several crane based designs were proposed and explored using the SBD approach. A VR based environment was created using the Unity 3D engine and the Vive platform; this allowed team members to conceptualize ideas, compare alternatives and propose modifications. It also supported systems engineering principles by allowing NASA engineers to interact with these immersive environments and provide feedback on the initial designs.

C. Path Traversal during transportation on the Lunar Surface

There is a need to determine collision-free paths for the transportation of the payloads and materials on the Lunar surface by other transportation vehicles (dedicated to moving equipment, materials and supplies between a landing site and habitats or other sites. A collision-free path planning approach using the A Star (A*) algorithm [13] was explored. The Lunar surface (or target region) can be divided into a grid consisting of n cells (Fig. 8). A* requires mapping the parts' coordinates to cells in the grid which is achieved by rounding coordinates points to the nearest cell. This algorithm takes an input of the originating cell and destination cell to return a path that contains no obstacles. The three cost variables (g, h, f) are used to calculate the collision-free path. **g cost** is the cost of movement from starting point to a given cell on the grid. **h cost** is the estimated cost from the given cell to the destination cell and **f cost** is the sum of g and h.

These variables are used to calculate and track a trace leading to the destination with the least cost possible. Fig. 9 uses a grid of 5 x 5 cells to illustrate this A* based approach. The start point (or cell) is colored blue with an index of 3 and the destination colored red with an index 17. The gray cells in the grid represent the obstacles. The goal is to start at the blue cell and find the path that is the lowest cost to the red cell while avoiding the gray cells. In this case, the orthogonal distance between two cells is set to 10. Fig. 9 represents the calculation that the A* outputs to reach its destination. Calculations are shown for g cost, h cost and f cost for neighboring cells of origin cell.

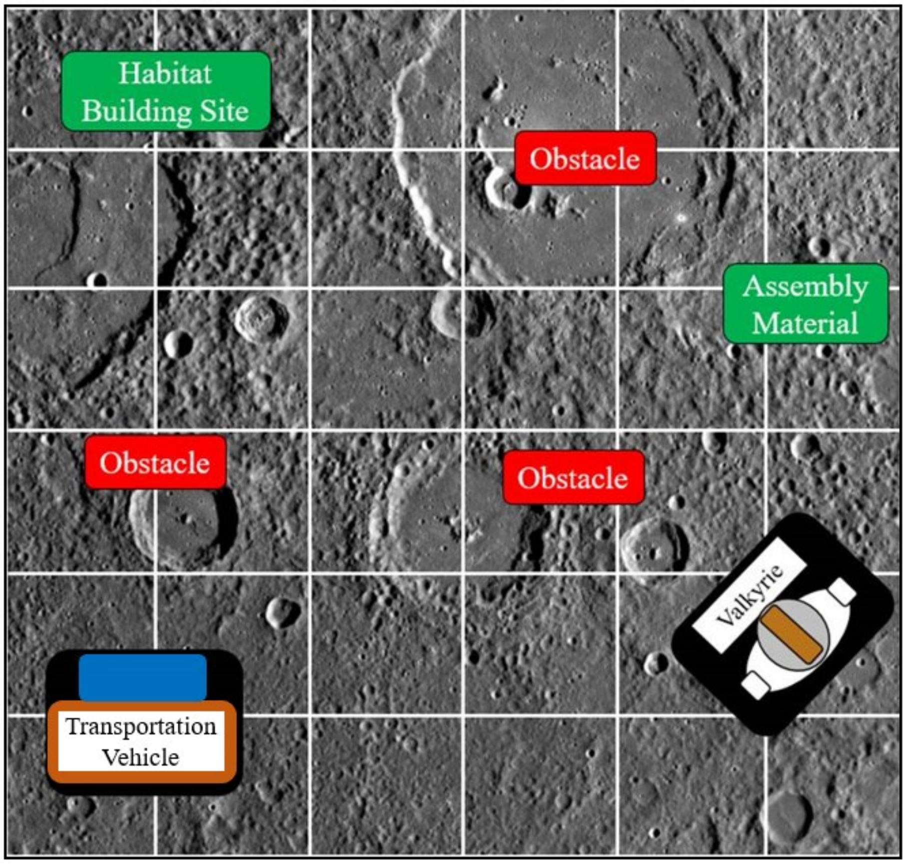

Fig. 8. A top view of the Lunar surface (divided into a grid for the A* implementation), the obstacles and the transportation vehicles

Comparing the f costs, cells 2 and 8 have the lowest cost; the A* algorithm can pick any of these two choices. If cell 2 is selected, it has no option but to progress to cell 1 beyond which it cannot proceed any further due to the presence of obstacles. In that case, our approach uses backtracking and goes back to the start (origin) cell 1 and picks the second choice (cell 8) and proceeds from it to the destination. The calculation of f costs for the surrounding of cell 8 is carried out to determine the next cell to be traversed until the destination cell is reached.

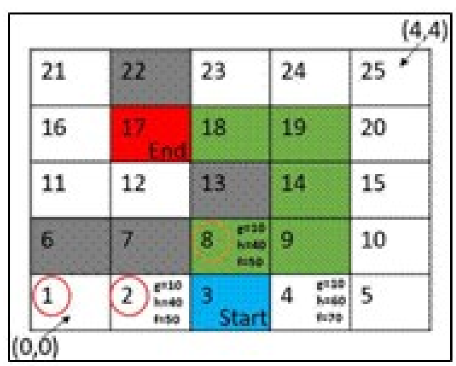

Fig. 9. Calculations for g, h and f costs

Fig. 9 shows one step calculation of the shortest collision-free path; the movements are modified to prevent diagonal movement. Using such an A* based approach, the generation of collision-free paths can be accomplished for tasks involving transporting equipment from one location to another on the Lunar surface.

III. Conclusion

This paper discussed the adoption of Simulation-Based Design principles to support addressing three thrusts in the context of the Moon mission. These three thrusts included (i) design of an autonomous system for transporting the payload containing parts from a Lunar orbit to the Lunar surface, (ii) designing cable robots based system for transporting parts from one location to another on the Lunar surface and (ii) exploring path planning approaches for transporting materials on the Lunar surface. Based on Simulation-Based Design principles, VR based environments were created using the Unity 3D engine implemented on the Vive platform.

Several simulation environments were created to support the study of various design alternatives relevant to the three thrusts. The SBD activities were accomplished by student teams, who proposed and compared various design ideas using the VR based environments. They also interacted with NASA engineers (on a bi-weekly basis), who provided feedback to the conceptual designs. The VR based environments allowed the teams to propose various initial ideas and consider cross-functional issues. The teams were composed of electrical engineering, mechanical engineering and computer science students. The SBD based approach enabled the adoption of concurrent engineering based principles, which also enhanced the communication among the cross-functional team members.

An Information Centric Systems Engineering approach (ICSE) was adopted to support the design of the simulation environments. This supported an interdisciplinary process while enabling a structured foundation to design and build these simulation environments.

Additional design and analysis activities related to these thrust areas are continuing.

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