Application of a Virtual Environment for Education on the Construction Process of the Colosseum of Rome

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Abstract – **The education of engineering in the classroom has relied on increasingly advanced technologies throughout the years, up to and including modern computer graphics and digital simulation. One of the most valuable innovations for both education and engineering has been the field of virtual environments, which are defined as simulations of data and methods created and presented in a wholly or partially digital space. A virtual environment is an ideal tool for students to observe engineering techniques and concepts with minimal expense and in relative safety. For this research, the project being demonstrated is not a modern construction project, but an ancient one, the Colosseum of Rome.**

For this particular simulation, the virtual environment was rendered using a graphics pipeline representing the components of the structure as individual pieces which could, in theory, be assembled into a complete structure in a specific order based on how the walls, support piers, concrete arches, and floors of each story were in the two decades during which the actual structure was built, starting from ca. 79 AD. From there, these digital assets were compiled in a virtual environment which was presented to a sample student test body via a virtual reality simulation employing a personal computer and the Oculus Rift headset. Each student would navigate through the erection process of the Colosseum, level by level, including infographics describing specific engineering aspects and methodologies used throughout the construction of the monument.

The results of this simulation were graded based on both the historical accuracy of the simulation and the clarity of the presentation, although a more immersive simulation may be possible with improvements to the graphics processing unit (GPU) processing power, framerate, and display resolution. These surveys are a clear demonstration that virtual environments can be a powerful educational tool in terms of instructing students about both construction and computer simulation. It is hoped that virtual environments can be employed for many future simulations in construction engineering, history, and architecture.

I. Introduction

Digital imaging has been used to great effect in the study of history, engineering, and construction; various publications have explored the possibilities that the field has to offer with regards to these subjects and more. In the field of engineering education, 3-D computer modeling and in particular, the simulation technique known as *virtual reality* (VR) can play a significant role in improving understanding of ancient construction and related methods. One topic with the potential for education on multiple subjects which could greatly benefit from virtual simulation is the study of ancient construction and engineering, which involves such fields as history, archaeology, civil engineering, and mechanical engineering. The use of a VR environment in such a scenario can be useful in the education of both history and engineering to a general audience, as well as research in the same fields. This project will present a recreation of the construction process of a monument along with the evaluation process of the completed simulation by a student audience, specifically of one of the most famous ancient monuments: the Colosseum of Rome.

II. Educational Benefits

Digital simulations such as VR would be especially beneficial in a classroom environment, as intended by the product of this research. There are multiple advantages that a digital simulation could bring to this kind of setting, particularly if the technology involved can be easily transplanted and implemented on a large scale to deliver the simulation to as many students as possible. Such advantages could revolutionize the way that students learn about complicated and potentially unsafe topics, especially in the construction and engineering industries.

One of the principal benefits of virtual reality is that it allows users to immerse themselves in an environment and explore it without having to leave the classroom. In the case of the Colosseum simulation, this means there is no need to travel to the monument itself to experience it, and on top of this, students can also explore the structure at its heyday due to the digital nature of the simulation allowing for cost-effective, speculative restoration. The simulation can also save expenses for multiple trips to the site itself, as students could experience the virtual Colosseum regularly and more frequently than with an on-site tour that can only be conducted, for example, during the annual tourist season and only with a limited number of students. The detail and interactivity also has the potential to be more engaging than textbooks and lectures, enabling students from any background to understand the subject matter – which would be especially beneficial to those who would be unable to afford a tour of the actual monument site, be it students or instructors.

Another benefit of a virtual simulation is that without having to venture out of the safety of the classroom, students can also engage in experiences that would be risky if they were implemented physically. This is especially pivotal in the education of construction engineering, where students either tour actual construction sites or construct models related to the topic in question. Actual construction sites present hazards such as falling objects, dangerous heights, or exposure to the elements – all of which are likely present during the construction of modern-day stadiums, for example. While it would be safer to work with reconstructing physical models, such endeavors can either present similar risks to actual construction – such as life-sized restorations of the Colosseum *velarium* (roof awning), the treadwheel cranes used to lift materials for Roman construction, and cage-lifting mechanisms below the arena, all of which have been attempted for documentary purposes – or prone to prohibitive costs as in scale models. On top of reducing both risk to students and expenses paid by institutions, a virtual simulation also means that students do not have to explore the site itself, which can aid in preservation; physical contact by visitors can be detrimental to the conditions of historical remains and may ultimately reduce their value over time, whereas a virtual experience can give students the same experience without such risks.

Finally, students can use the virtual simulation as a starting point for their own explorations into the topics presented. The Colosseum model, for example, can be used as inspiration for the construction of modern stadiums today, since both rely on similar principles and can be seen as different stages in the development of the same type of structure. In addition, the exploration of Roman construction techniques can also be extended to encompass other structures like the Pantheon of Rome, which relied on similar concrete construction methods to the Colosseum, and the techniques used can be applied to other forms of both ancient and modern technology, including infrastructure and green engineering. Virtual reality has great potential in a variety of educational fields, and its application could greatly boost the instructional value for those that have a need for it but have yet to implement it on a large scale.

III. Virtual Environments

For this research, the authors considered two different applications of *virtual environments* (environments simulated in a programming or display application): *augmented reality* (AR) and *virtual reality* (VR). Both of these have been used to great effect in construction, engineering, history, and archaeology; various publications have explored the possibilities that these tools have to offer with regards to these subjects and more. Virtual and augmented reality can play a significant role in improving understanding of ancient construction, providing an element of interactivity which can be put to great use in the understanding of the methods involved; this can also create an effective educational device for showcasing information to a more general audience.

An initial possibility that was considered in this study is the use of *augmented reality* (AR), a digital means of providing extra information for a live video feed which could be used for various applications in engineering, education, commerce, and even medicine [2]. For the Colosseum simulation specifically, augmented reality may present several advantages over virtual reality, such as the involvement of real-world settings and objects (like the Colosseum itself), as well as a wider choice of systems because applications for augmented reality can be implemented on a larger number of devices and less specialized systems. Examples of augmented reality include camera display systems that can see structural components inside walls (e.g. the *opus caementicium* inside the masonry walls), VR glasses that project documents or images of interactive objects, and mobile device applications that provide information in real-time; any of these could be useful for filling in the gaps of the Colosseum as it stands today, via mapping the real-world version and superimposing the digital model over it.

The list of issues and setbacks in AR is quite large compared to VR, meaning that AR would be considerably more difficult to master than VR in the context of the Colosseum project. Kruijff et al. [9] provide a more comprehensive list of possible issues which can be classed into a number of categories: Environment (external perceptual issues), Capturing (problems related to digitizing the environment), Augmentation (issues related to data editing), Display Device (display issues), and User (the client's perception of the final content). Based on the above information, the general consensus would therefore be that if a work of construction, such as the Colosseum, were to be simulated using augmented reality, the result could be one of two different formats. In the context of the project, a method of implementing the AR system would be either a site-specific system that can restore certain areas of the Colosseum into the original state and showcase how each specific part was constructed, or a smaller scale model that can be constructed in real-time on a tabletop or other large, smooth surface.

The second possible alternative for the Colosseum simulation, *virtual reality* (VR), specializes in presenting the subject matter of the simulation in an immersive, wholly digital environment, which can be important for educational purposes such as recreating the construction process of an ancient monument. The computer, software, and equipment render the concept of the simulation, and the student generates the experience, namely learning about the subject matter (the Colosseum in this case), based on feedback from the concept – thereby generating a feedback loop between the interface and the user. Though certain elements of the experience will be invariably lost (in this case, the material texture, weather conditions, and miscellaneous decorative features of the Colosseum), virtual reality cuts these costs to a minimum by creating a unique medium which incorporates as many aspects of the virtual world as theoretically possible.

Because this particular simulation is intended for use in a course on history of ancient engineering, an important question concerns how effective virtual reality would be for presenting a process as large or complex as the construction of the Colosseum, with as effective and fluid graphics as possible while at the same time conserving data for the sake of portability. Real-time visualization, or the presentation of data in an interactive, temporal form, has an advantage of real-time performance and interactivity, which allows for greater potential in client-side exploration, pacing, and comprehension – which may be important for the Colosseum model. Some scholars [13] also suggested a more dynamic exploration of data sets without having to rely purely on the server to change the point of view, resulting in a greater degree of freedom for the client. Virtual reality enables interaction with simulated environments, which may also be constructed from and based off applied data, meaning that VR presents similar advantages. Once environmental sound and deprivation of real-world sensation is included, the result is a heightened sense of immersion which can make the client experience more convincing.

On the other hand, there are several issues to consider when using virtual reality. In several fields of research such as medicine, the immersive experience means that the product must incorporate a degree of user-friendliness, including the avoidance of unwanted symptoms or actions that may preclude advocating the system [14]. However, of more concern to the engineering field would be technical issues, particularly since the specific equipment requires both adaptation of the input devices to the equipment and the specialized technical knowledge on the part of the software engineer to enable such a development. This could lead to a higher long-term cost for image generators and projectors, non-portable equipment, and large display space requirements, as well as environmental clutter that may hinder a sense of realism. Additionally, a large amount of generated information may result in a counterproductive data spike, as the amount of data processed by the client in detailed focus is relatively narrow relative to the amount presented [12].

VR systems from the 1990s were especially problematic in that the primitive headgear fit around the entire head, which could have made for a cumbersome experience. However, this does not mean educational issues should be ruled out. While VR technology was still early in its development as a learning tool, with possible applications in the military, business, and entertainment industries, it was often viewed as being largely ineffective for research and education. Hadipriono et al. [7] sought to prove this wrong by using a VR model for the construction of a highway overpass. This simulation relied on a CyberGlove, synchronized with a virtual hand in the digital environment, to command the program of the simulation using physical gestures, though the Colosseum model will use a simpler keyboard- and mouse-based input and will not require this functionality (making it comparatively easier to use). More advanced VR systems have been developed since then, the technology itself growing in leaps and bounds to address the various issues, both software and hardware, that it was thought to entail during its conception.

The use of virtual reality for the Colosseum simulation involved a conventional head-mounted display, which is generally more compact and less expensive than exhibit-based methods such as projecting the display onto a screen with a completely stationary equipment system. A virtual reality simulation would likely be organized such that a 3D model of the Colosseum is set in an environment in which a camera can move freely. This also means the simulation will be able to present a greater variety of functions as the camera moves through the simulation. This means that the camera is only required to point in the direction of the user's head when synchronized with the VR hardware, and moves primarily within the digital scene with manual user control. Assets that are placed in the virtual environment can be interacted with using manual input from a device such as a VR sensor glove or a keyboard; the latter approach requires a simpler programming scheme and is therefore used for the prototype. This also allows the camera to remain stationary without any movement from the user, so there is less programming required for each frame of the simulation. For this particular course demonstration, students were given a degree of interactivity via keyboard input, which would enable them to freely move through the simulation, as well as shift between construction stages as needed and toggle the popup displays of additional information. The Oculus Rift, one of the most prominent examples of a virtual reality headset, was used to both display the simulation to each student and also monitor their head position, recalibrating the camera rotations accordingly to change the viewing angle within the simulation.

IV. Literature Search

Given the potential of virtual reality in archaeological studies, it is not surprising that multiple publications have focused on its use in the visualization of ancient structures. At least one study concerning reconstruction of geometry based only on historical literature or verbal conditions has shown that this level of reconstructive geometry is well within feasible implementation. As discussed previously, one of the difficulties is rendering the data in three dimensions, particularly with regards to discrepancy between the operator's input and the computation of the simulation. Therefore, three-dimensional acquisition of data and collection of documentation are as important as combining them into a digital model.

The use of virtual reality in a historical simulation is explored by Gaitatzes et al. [5] in a study affiliated with the Foundation of the Hellenic World (FHW), a non-profit association for the preservation and promotion of ancient Greek culture. As opposed to single-person equipment such as helmets and computing gear, a different, much larger method was used for the museum exhibition that implemented the software – an immersive display with walls that double as projection surfaces. For stereo results akin to a VR helmet, shutter glasses provide for the viewers created a three-dimensional effect, and tracking devices can factor in the position of a particular viewer, the "primary" user. The software for the VR components provides a layer between user and hardware, and is usually object-oriented, requiring specialized technology operatives. Tracking head and hand movements determines the position of the user and the direction of his/her gaze, enabling navigation of the 3D world and ultimately interactivity. This framework can be reused and modified to suit specific projects of different kinds, and is constantly updated and extended for greater usability. In light of all these benefits, a number of educational and cultural programs, including the FHW, have taken interest in this method of VR simulation. The premiere program used for the exhibit is "A Journey Through Ancient Miletus", which simulates a journey through the aforementioned city and all its landmarks; the "Temple of

Zeus at Olympia" is similar but on a smaller scale, showcasing the eponymous landmark and its interior. Users can walk, "fly", "dive", and generally explore the various locations throughout the city as they desire, viewing detail, landscape, and infrastructure from multiple perspectives. However, such an advanced process is not without its difficulties. Challenges with regards to this simulation include the use of architectural detail due to the constraints of the techniques involved, and a more optimal performance results in a decrease in detail and interactivity and vice versa. As with the simulation that prefaces the virtual Colosseum construction project, the large amount of data means that different techniques must be implemented to prevent a decrease in performance. Other issues include unintentional environmental "hazards" trapping users, necessitating disabling of collision detection or moving the user elsewhere, and realistic terrain generation and texturing.

Virtual reality can also be used to simulate ancient events, which are even more difficult to simulate due to the lack of physical evidence (and therefore a greater reliance on verbal descriptions alone). A notable example of this was a recreation of the Roman aristocratic funeral of the middle-Republic [8]. This study relied almost entirely on textual accounts as opposed to physical evidence, which varies depending on the sources and often does not focus directly on the scope of the project. It also explored various practical aspects of the Roman Funeral, which was a site-specific event that would have been affected by the physical environment, the experiences of the populace, and the spatial movement of the participants.

An example of digital graphics in ancient Roman archaeology that encompasses a single building, rather than a group of buildings or a whole city, was conducted by Cipriani and Fantini [1] in their study on the octagonal halls of the baths at Hadrian's Villa. This was a study on an architectural archetype rather than the recreation of a building in its entirety; nonetheless, it demonstrates the capability of computer software in the study of specific building topics. The study is intended to explore the ancient designing techniques used for designing new shapes as in the case of Hadrian's architecture, and the specific subject discussed is the octagonal hall and the common features shared by buildings with this type of structure. The analysis included a combination of data acquisition through laser scanning and a hypothetical model generated via NURBS and subdivision surface modeling based on the resultant data, the end result being a hypothetical template that could be used for varying sizes of this type of building plan.

Finally, for the Colosseum itself, Gutierrez et al. [6] experimented with a digital Colosseum model for the simulation of a virtual crowd, which was used to test the efficiency of the *vomitoria*. The structure of the Colosseum was analyzed with the interior passageways in mind – a necessity for the simulation of people moving not only in and out of the structure but also inside as well. The resultant digital model was then analyzed to find the most efficient routes of transport through the monument, as well as potential bottlenecks that could hinder overall crowd progress. Although the construction process of the Colosseum was not taken into consideration, this model could and did serve as a reference for the structure of the interior in the Colosseum simulation created for this paper.

V. Development

The simulation of the Colosseum presented in this research was based on the culmination of a four-year-long research project, which strove to depict the entire construction process from its inception in 79 AD to its final completion eight years later. To recreate the construction process, a "round-robin" (turn-based) sequence of software packages, known as a *graphics pipeline*, was set up using four different programs: Autodesk Inventor (which had been previously used in the modeling of the top-down approach), Google SketchUp (which was considered for the top-down approach and eventually chosen for versatility), Cinema4D (primarily used for texture rendering and object grouping), and Unity Pro (to bring the components together in a virtual environment). Each level was modeled based on a template which defined all of the walls that would have been constructed on a particular level, with the first floor having the most walls due to the seating supports being located further inward than in higher levels. The outer three annular walls are known for the first, second, and third levels of the monument; the fourth story, which was taller and housed the attic, only used the outermost façade wall, with the vaults beneath extending only partway up this level.

Once the stages of the main assembly were completed using Autodesk Inventor, the next stage of the graphics pipeline involved importing them into Google SketchUp (**Fig. 5**), specifically SketchUp Make (the free version, which saves cost and can therefore be used freely in academic circles). This program is designed for flexibility because although the program is not very capable on its own (with limited functionality for creating faces and solids), it is capable of supporting a variety of plugins that allow it to model different kinds of components. In the case of the Colosseum model, the stairways were created and positioned over each of the openings designated by the building plans of the monument, and the various pieces of each level, depending on the material, were grouped together to form a completed part of the final assembly.

Fig. 4: A shaded view of the bottom-up Colosseum assembly. Notice the absence of the seating, which was created separately.

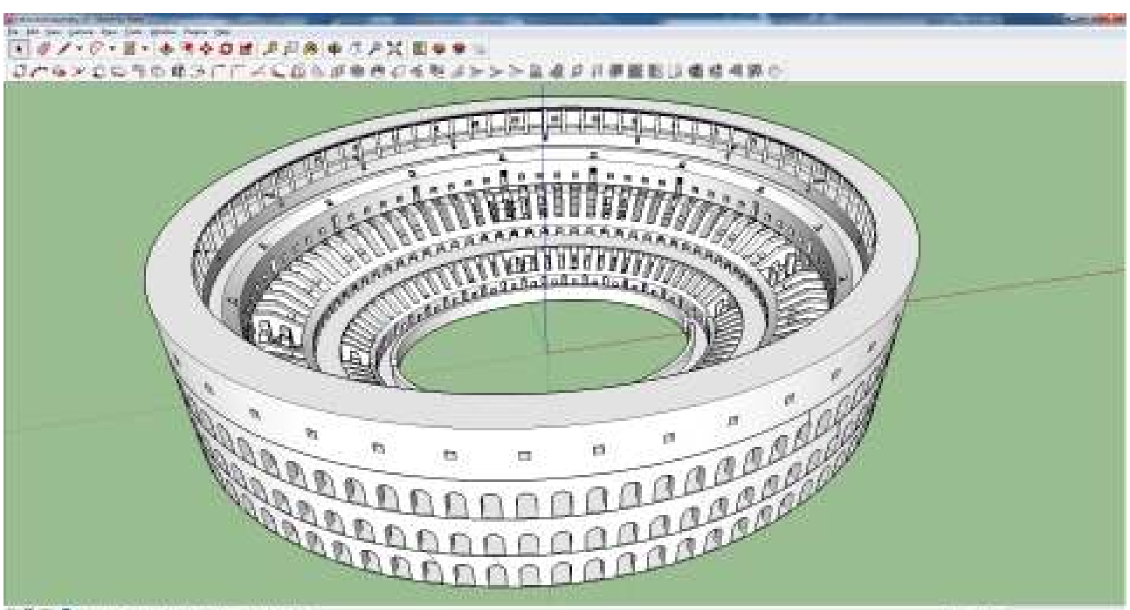

Fig. 5: The bottom-up Colosseum assembly as shown on Google SketchUp.

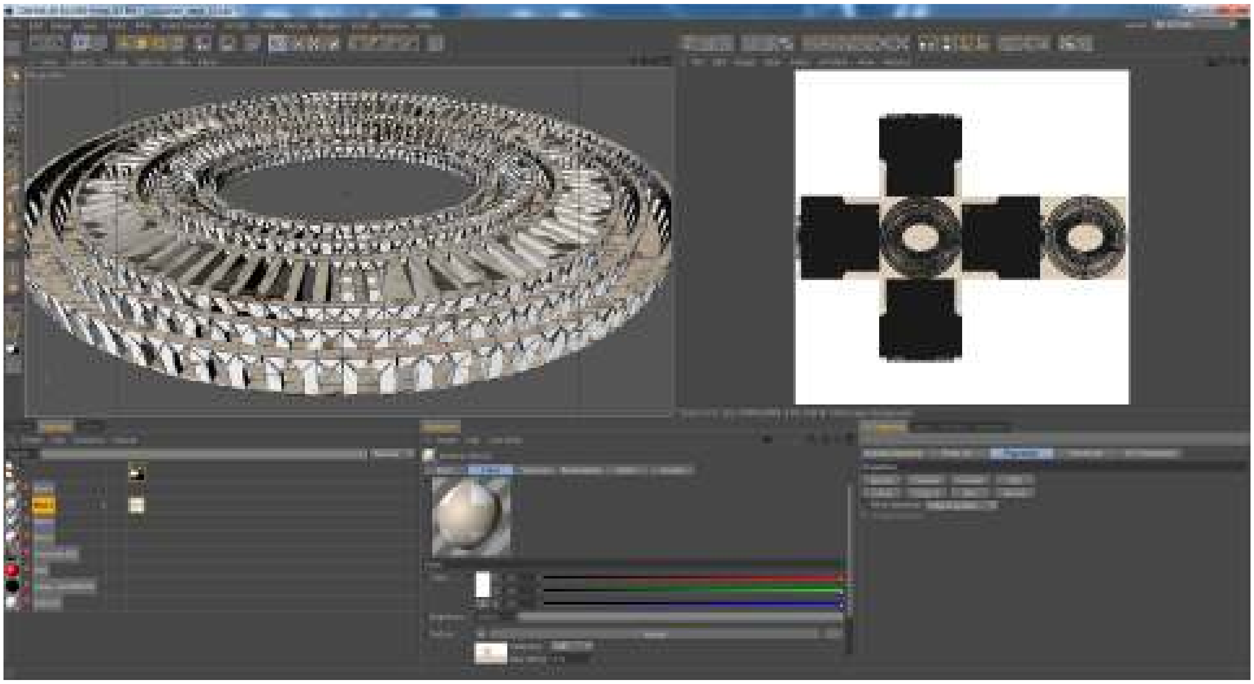

Fig. 6: The rendering stage for the first level, showing the overlap of faces prior to subdividing the geometry.

It is also important to note that the construction process of the Colosseum is not certain, due to the scant literary evidence dedicated to this subject. Any strategy that fits with the mindsets, techniques, and construction safety principles known to the Romans would be viable. As a result, two different digital models were constructed for this project: a *floor-by-floor* method, in which each level is constructed completely and serves as a platform upon which the next floor is built, and a *frame-by-frame* method in which the first two levels are constructed, the seating and second-floor vaults are used as a cover against adverse weather, and the third and fourth floors are placed on top while the first floor vaults are built beneath the seating. Both of these processes rely on the same template pattern used to create each floor, but ultimately resort to different groups of objects. The floor-by-floor method includes the annular walls, radial walls, and annular vaults of each level, and the frame-by-frame method has the annular and radial walls only with the annular vaults being reserved for a separate group.

The third stage in the graphics pipeline, the rendering stage, uses Cinema4D for one important reason: UV mapping (**Fig. 6**). Through the placement of UV coordinates on an image map, Cinema4D can place a texture over the faces of a polygonal mesh. However, while it was originally considered that each level be modeled as a solid piece with all of the components defined via texture, this strategy is not viable because the large amount of data involved results in numerous overlapping faces. A more practical solution would be to divide the level into its individual components, similar to the top-down approach on a smaller scale. This is less likely to produce errors than creating the entire model from the top down, because the interior structure is known beforehand and the components can therefore be divided and textured separately.

The final stage of the graphics pipeline is the assembly of the stages into completed models. This involves importing the completed Cinema4D files into Unity Pro (**Fig. 7**), which parses the projects into groups of components which can then be moved and spaced freely. These components are then put together to form the finished building. In order to recreate the construction sequence in the virtual reality simulation, specific functions are implemented within the frame update routine such that keystroke-based command inputs result in different actions. A global counter and a marker will activate each stage of the sequence, allowing the student to scroll through the entire construction process. Additional functionalities may include pop-ups illustrating specific aspects of the process, including equipment, labor techniques and organization (**Fig. 8**), and a step-by-step construction sequence in detail with a quarter-section of the monument that elaborates on specific erection stages.

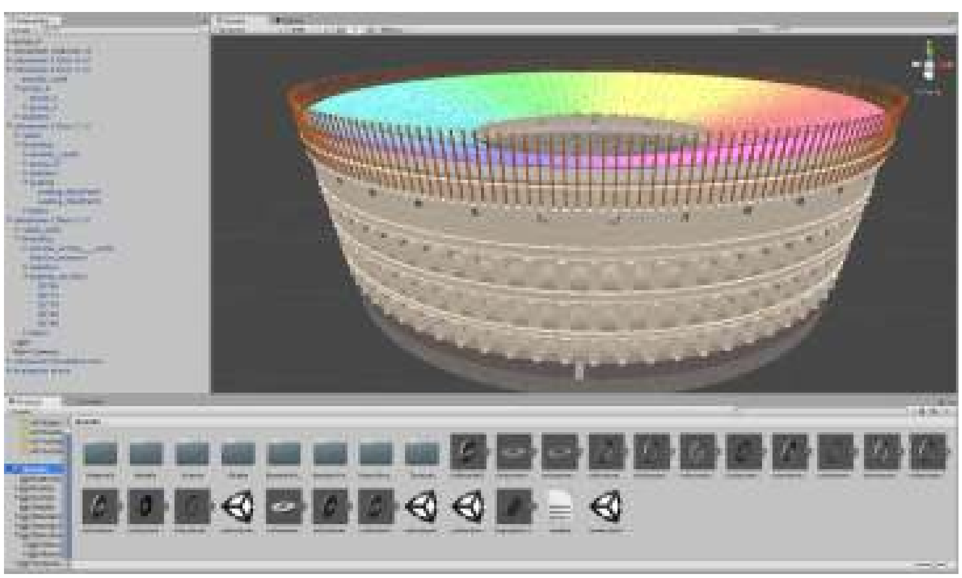

Fig. 7: The Colosseum model in Unity Pro.

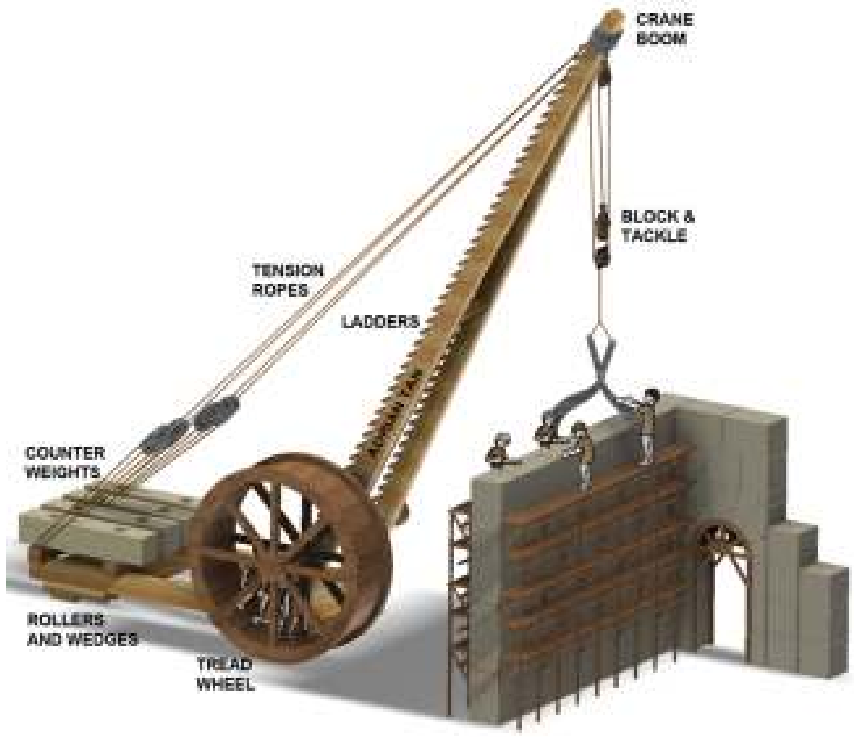

Fig. 8: A diagram of a treadwheel crane, which is used in the simulation to elaborate on specific construction processes.

Because of the importance of the construction equipment, individual models (**Fig. 8**) and explanatory slides (**Fig. 9**) are also constructed, rendered, and made into explanatory infographics for the simulation. Textual explanations are also provided for each of these illustrations as well as the construction sequence stages, explaining what the equipment does, how it works, and how it would have factored into the construction sequence. Additionally, for the construction stages shown for each level, equipment was placed in as needed using imaging software when preparing the sequence images, though this does necessitate the use of still images in the final simulation. Screenshots of the completed simulation are shown in **Figs. 10 through 12**.

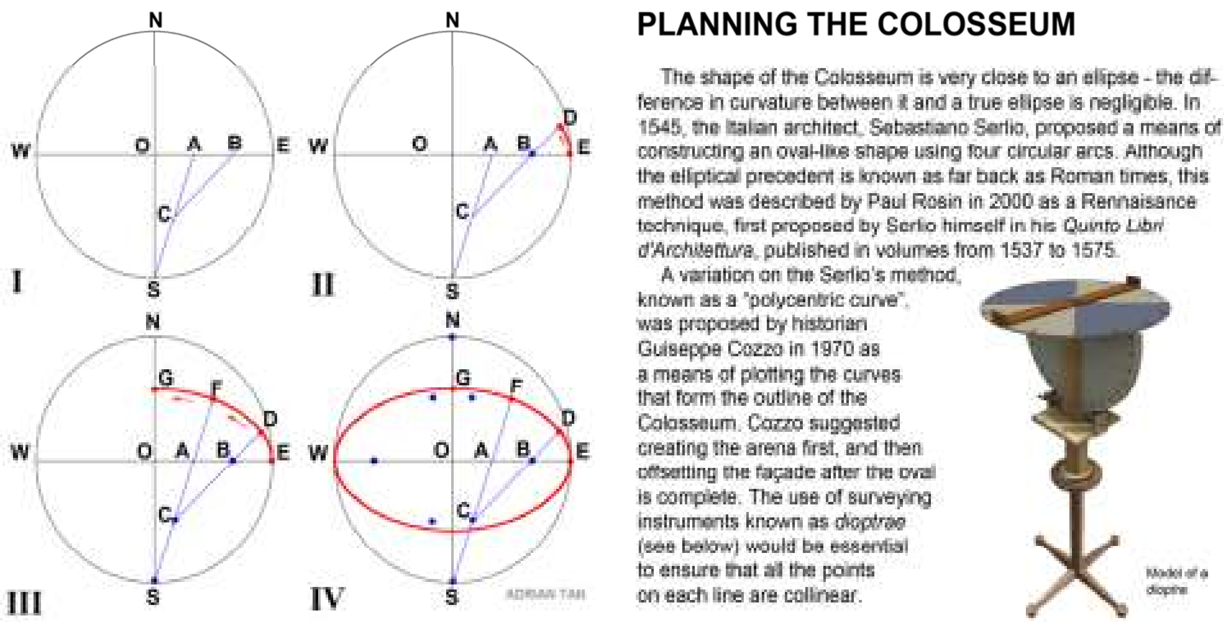

Fig. 9: A sprite used in the simulation, describing the planning process of the arena as derived from Cozzo [3].

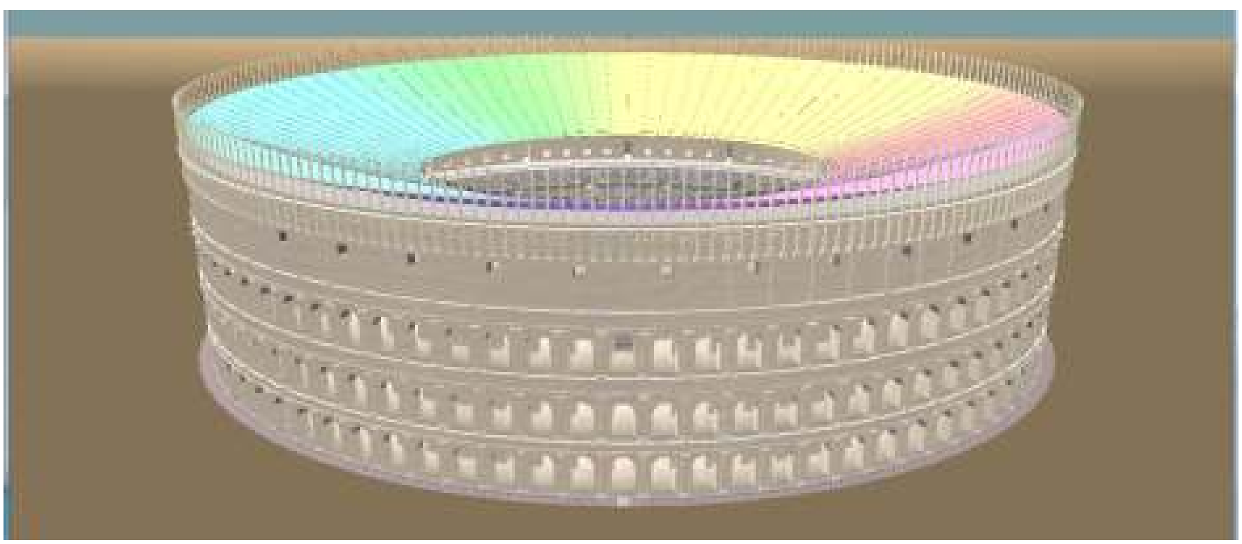

Fig. 10: The final render of the Colosseum model used in the simulation. Note the presence of the *velarium* as an optional feature.

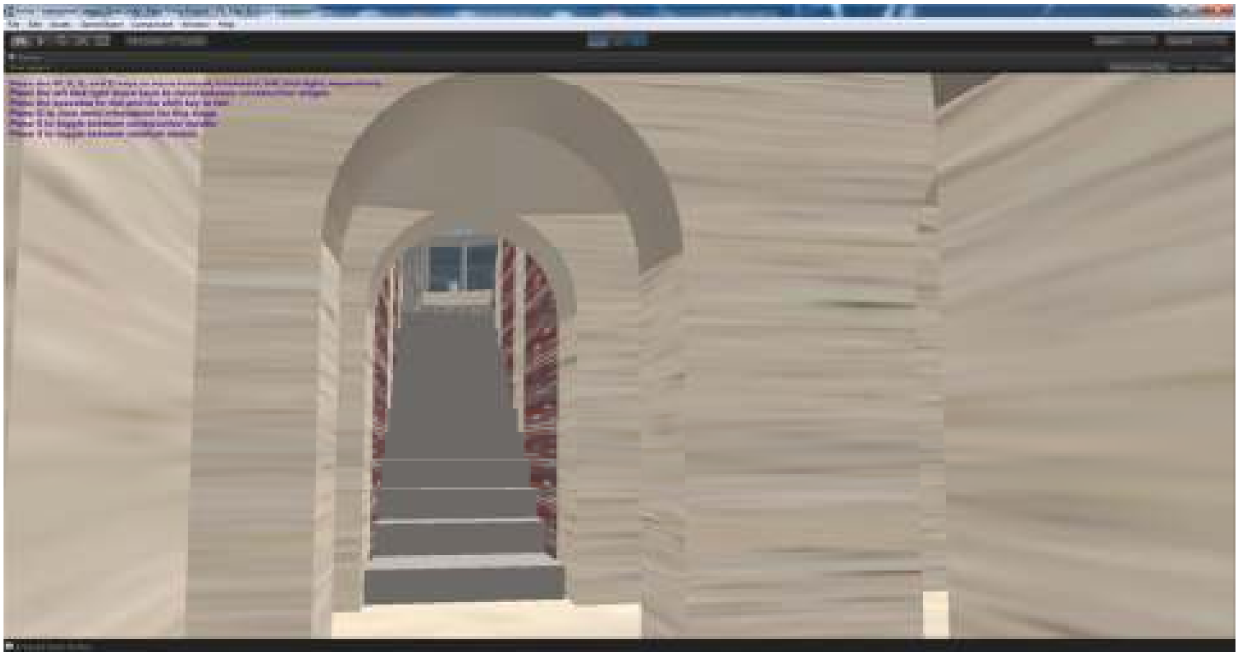

Fig. 11: An interior shot of the Colosseum model.

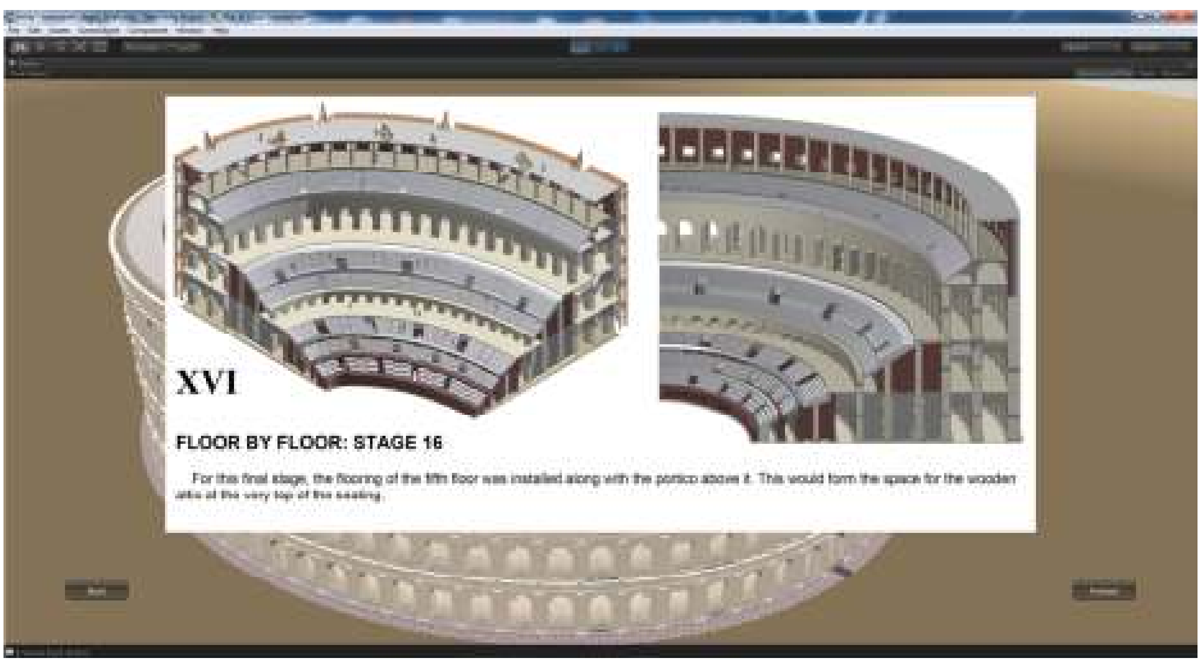

Fig. 12: The user interface of the simulation, showing a stage of the *floor-by-floor* construction process.

VI. Evaluation

The most important portion of the simulation process was to evaluate its performance from the perspective of a layman audience, particularly with students in the fields of history and engineering. This entails a testing process with at least two demographics of this category, along with analysis of the resultant feedback for improvement of the model.

For this paper, the Colosseum simulation project was tested with two different student bodies: an undergraduate course and a graduate course, both on the history of ancient engineering [15]. The concept behind these two testing sessions was that it was to be used as a homework assignment and an evaluation of the use of the program and others like it for educational purposes, as well as integrating it into the course material proper. Because part of the course curriculum material focuses on the greenness and sustainability of ancient monuments and construction processes, the Colosseum and its various innovations in terms of construction economy and resource management were prime candidates for this particular topic, and it was decided early on that the use of a virtual reality simulation to help students understand the various concepts required for said topic would be invaluable for the purpose of both this research and the course itself.

The testing procedure used a prototype for the Oculus Rift, a popular VR head-mounted display [11]. The model used for the evaluation process sported a 7-inch screen, allowing for some overhang for the stereoscopic 3D, mimicking normal vision by allowing for extra viewing area for each eye's respective side. At 90 degrees horizontal, the field of view (FOV) is more than double that of most competitors and completely blocks out the real world to create strong immersion. The current 1000 Hz Adjacent Reality Tracker (a significant improvement over the initial 125 Hz) can sample rates up to 760 Hz which, combined with 3 different sensors for pitch, roll, yaw, and inertia, create the effect of 9 degrees of freedom even though the system technically supports only six degrees of freedom, allowing the system to implement absolute positional tracking without the risk of drifting [10]. It may also be possible for the headset to be adapted for mobile devices running Android [4], which may improve portability and reduce system purchase costs. The Oculus Rift is also compatible with Unity, which was used to create a customized simulation that fit the dual projector screens of the headset.

The Oculus Rift was connected to a Dell Inspiron 620 computer with an Intel® Core™ i5-2310 CPU, 8 GB of memory, and an NVIDIA GeForce 327.23 graphics card with HDMI support. The resolution setup of the monitors involved extending the desktop from the computer monitor to the Oculus Rift, as duplicating the display on both the monitor and the Rift was not fully functional during the time of the testing. This resulted in a problem in which half of the display was shown on one screen on the Rift, and the other half on the other screen, making it difficult to keep track of features on the display. This was likely an artifact of the split-screen functionality used to accommodate the dual-view system of Rift applications. This problem was solved by using a program known as Virtual Desktop, which projects the display to both screens without bisecting it. Additionally, setting the application to send the application directly to the Rift itself allowed both the monitor and the Rift to display the simulation, enabling the evaluation supervisor to guide the user though the simulation without having to remove the device from the user's head (**Fig. 13**).

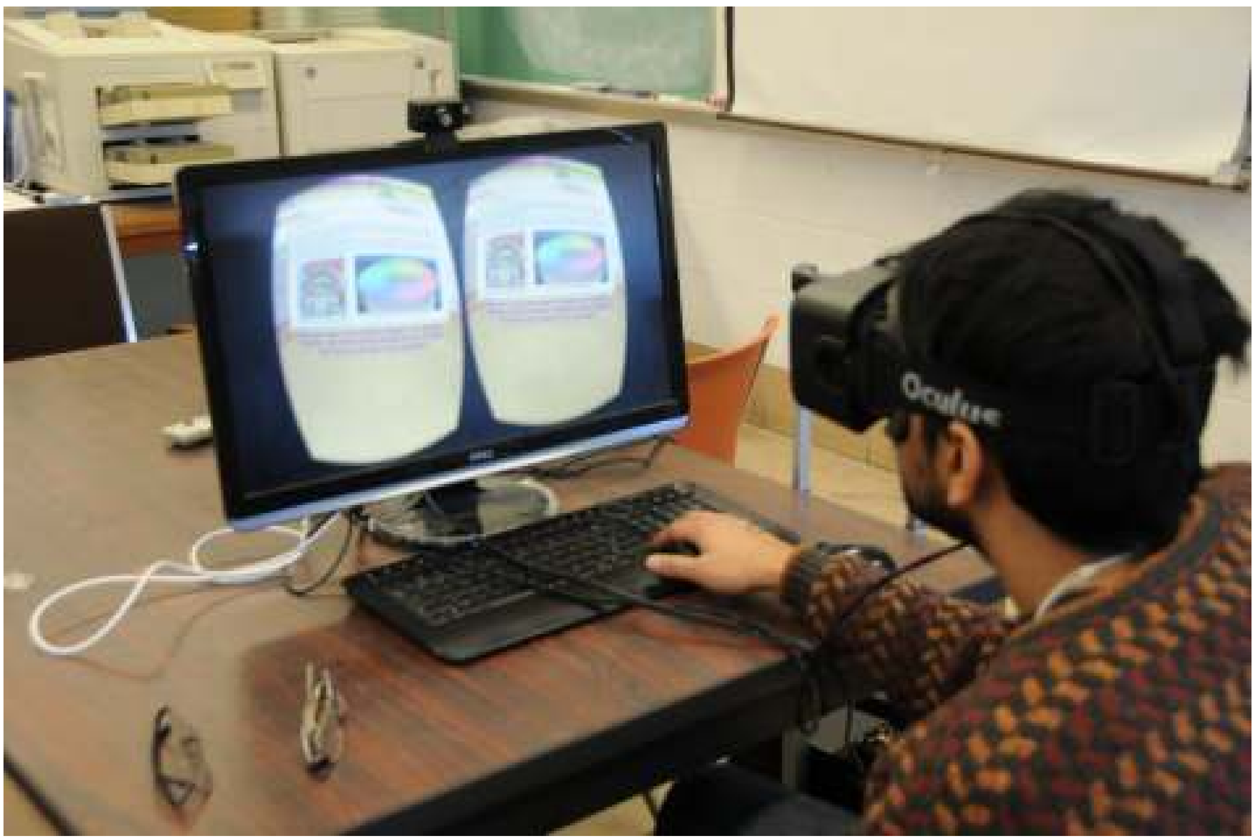

Fig. 13: Demonstration of the virtual reality simulation in a classroom setting. Note that the monitor screen also displays the VR headset view.

In the initial test run, ten graduate students and thirty-two undergraduate students evaluated the program and provided feedback and commentary. Ten survey criteria were presented, with five different numbered opinions ranging from strongly disagreeing with each statement (1) to strongly agreeing with it (5). The results were then anonymously catalogued and averaged, enabling the author of this research to determine which portions of the simulation were strongest and weakest. Aside from providing survey feedback on the simulation, students also used it as a study tool in order to prepare for quizzes and homework assignments for the course pertaining to the construction process of the Colosseum as well as ancient Roman construction methods in general, essentially tying the simulation into the course material in the same manner as a video, essay, or PowerPoint presentation presented as required reading material for a particular class.

The average values of all opinions are shown in **Table 2**, both for undergraduate and graduate students. The most notable characteristic of these results is that the undergraduate averages were generally lower than the graduate averages, with the highest undergraduate averages being 4.1 for Statement #2 ("*A physical recreation of this model would make a good comparison to the actual monument.*") and 4.1 for Statement #5 ("*The educational experience of this simulation overall is effective enough for use in the field.*"). However, all other averages were below 4, both for the educational value and the performance of the simulation. These two aspects are not unrelated, for a better performance in terms of rendering, speed, and detail can make for a more valuable educational experience. Most significantly, the lowest average was 2.5 for Statement #6 ("*This model performs well in terms of render speed (e.g. frame-rate-induced delay is not noticeable).*"), which is consistent with the prediction that a large amount of complex details will result in a reduction in frame rate with the same processing power. Indeed, the commentary from both the undergraduate and graduate students who evaluated the program suggests as such, and also noted that a more powerful processor would be able to produce a faster and more reliable result.

As for why the undergraduate averages were lower than the graduate averages, this may be due to a degree of subjectivity on the part of both parties as to the topics and aspects of focus. Undergraduates would be more likely to focus on graphical aspects such as in video-games and special effects, and their lack of familiarity with the techniques presented by the simulation could add to such a preference. On the flipside, graduate students may have the opposite mentality, and judging from the feedback provided by the graduate class, they may tend to be more focused on the technical aspects of the knowledge base itself rather than the simulation.

Table 2: Evaluation of the Colosseum Simulation.

Number	Education	Undergrad Avg.	Grad Avg.
1	*The user can imagine realistically moving through the model presented in this simulation.*	3.7	4.2
2	*A physical recreation of this model would make a good comparison to the actual monument.*	4.1	4
3	*All of the components of the model can be seen with a virtual walkthrough.*	3.7	4.3
4	*The construction sequences are effective at describing the erection of each stage of the monument.*	3.9	4
5	*The educational experience of this simulation overall is effective enough for use in the field.*	4.1	4.6
	Performance		
6	*This model performs well in terms of render speed (e.g. frame-rate-induced delay is not noticeable).*	2.5	2.7
7	*The textures for this model are accurate compared to the actual building.*	3.4	3.7
8	*The simulation is good at rendering complex geometry (e.g. the details of the model components).*	3.7	3.7
9	*The camera movement in the simulation is precise (e.g. the camera position changes smoothly).*	2.8	3.2
10	*The performance of this simulation overall is effective enough for use in the field.*	3.7	4.2

Given both these preferences and the results of the test, this implies that the techniques presented by the model were modeled and demonstrated effectively, but the resolution and graphical performances were required to catch up. It is likely that the rendering speed in particular would be improved using a faster or stronger processor, or multiple processors working in parallel.

An additional look at the commentary provided by the students indicates that some of the negative results may have been due to extenuating circumstances. The use of glasses or other eyewear, and their removal for use in the Rift due to space issues, may have contributed to the fact that according to some of the students, the text on display looked blurry. Students that have normal vision without the need for eyewear for viewing objects up close were considered the ideal candidates for the evaluation, and those whose opinions were affected by less-than-ideal circumstances were excluded in a second evaluation of the data, as shown in **Table 3**.

The exclusion of outliers from the gathered data results in a slight improvement of the results for the undergraduate group, with the highest average becoming 4.2 for Statement #5. Predictably, however, Statement #6 remains at the lowest average, with only an increase of .1, due to the processing power of the computer remaining largely unaffected. Aside from a more powerful graphics engine, increasing the size of the text shown by the GUI may also be a practical option for improvements on the simulation, to make the information easier to read; however, with limited infographic space, less text can be used at a larger size and therefore less written information about the construction process can be displayed.

Table 3: Evaluation of the Colosseum Simulation (Without Outliers).

Number	Education	Undergrad Avg.	Grad Avg.
1	*The user can imagine realistically moving through the model presented in this simulation.*	3.8	4.2
2	*A physical recreation of this model would make a good comparison to the actual monument.*	4.1	4
3	*All of the components of the model can be seen with a virtual walkthrough.*	3.8	4.3
4	*The construction sequences are effective at describing the erection of each stage of the monument.*	4.0	4
5	*The educational experience of this simulation overall is effective enough for use in the field.*	4.2	4.6
	Performance		
6	*This model performs well in terms of render speed (e.g. frame-rate-induced delay is not noticeable).*	2.6	2.7
7	*The textures for this model are accurate compared to the actual building.*	3.6	3.7
8	*The simulation is good at rendering complex geometry (e.g. the details of the model components).*	3.8	3.7
9	*The camera movement in the simulation is precise (e.g. the camera position changes smoothly).*	2.8	3.2
10	*The performance of this simulation overall is effective enough for use in the field.*	3.8	4.2

The evaluation of the simulation is a straightforward process: have a group of students run the simulation, evaluate their opinions on it, and compile them into a general evaluation on the part of the program. With adequate transportation for a desktop computer, or possibly installation of the software enabling compatibility with the Oculus Rift on an academic server network, it is possible to set up the simulation in a classroom setting. This portability may be enhanced even further with the uploading of the simulation to a public website or server, allowing it to be accessed at any time for use with appropriate hardware purchased by users themselves.

The overall reception of the program based on the review results is average to positive, with the feedback favoring the spatial details of the model as well as the relative accuracy compared with the monument itself. The processing power of the hardware, which was the major setback as far as the reviews were concerned, can be theoretically remedied via upgrading the operating system, as it affects both the rendering speed and the camera movement precision, framerate, and sensitivity compared with the input control system.

VII. Conclusions

The general idea of this simulation is to evaluate the practicality of a multimedia virtual reality system that covers the construction of an ancient monument. In this respect, the information that is presented is based on years of research and development to ensure that the data is as accurate as possible, which provides a solid base for the program to work upon. The program also presents all of the information gathered in a comprehensible manner, which would be useful for education of a variety of audiences as well as broaching the subject of ancient construction to different fields. The virtual reality application that results from this strategy is both comprehensive and flexible, allowing a student to look at multiple different scopes of the project. Test results have shown that this simulation is a powerful tool for teaching both history and engineering in the classroom and can be used to further research into the topics it demonstrates.

These same test results also show that the simulation has several aspects that can be further improved upon. Notably, the processing hardware has only a limited capability of handling the amount of data provided by the simulation, which resulted in mentions of reduced resolution and framerate during the testing process. Additionally, in the fields of engineering and archaeology, the data constantly changes with new discoveries or further analysis, which often calls for changing the knowledge base of the simulation. Any changes which are made on the structural level will need to be run through the graphics pipeline and the component replaced wholesale, although the automatic recalculation of a change in the model can speed up the process.

Future studies on this project may focus primarily on improving the resolution of the simulation as well as simulating more realistic environments and aesthetic details. Representations of monuments and buildings in most media are highly detailed but model largely complete structures without attention to the construction process; it is possible that an improved simulation may have to address both the increase of more aesthetic elements and the optimization of data handling. To this end, more powerful hardware systems may be tested in the future to determine the optimum software, hardware, and complexity thresholds which can be used for the simulation, with emphasis on portability and usability in a classroom setting.

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References

[1] Cipriani, Luca and Fantini, Filippo. 2014. "The Geometry Behind the Octagonal Hall of Small Thermal Baths at Hadrian's Villa." Proceedings of the 16th International Conference on Geometry and Graphics, Innsbruck, Austria.

[2] Cline, Mychilo. 2009. *Virtual Reality: a Catalyst for Social and Economic Change.* University Village Press, pp. 58-9.

[3] Cozzo, Giuseppe. 1971. *The Colosseum: The Flavian Amphitheatre, Architecture, Building Techniques, History of the Construction, Plan of Works.* Fratelli Palombi, pp. 16-7.

[4] Fincher, John. 2013. "Virtual reality set to go mobile as Oculus announces Android compatibility for Rift". Gizmag.com. Sourced from: http://www.gizmag.com/oculus-rift-for-android/29592/

[5] Gaitatzes, A., Christopoulos, D., and Roussou, M. 2001. "Reviving the past: Cultural Heritage meets Virtual Reality." Source: http://www.peachbit.org/sites/peachbit.org/files/VAST01_vr_final_p103.pdf

[6] Gutierrez, D. et al. "Virtual Crowds in a Digital Colosseum." Virtual Retrospect 2005. Proceedings of the Conference, Biarritz (France), November 8th-9th-10th 2005. Source: http://giga.cps.unizar.es/affectivelab/publications/VIRTUAL_RETROSPECT.pdf

[7] Hadipriono, Fabian C., Richard E. Larew, and Tsung-chieh Tsay. 1996. "Interactive and Immersive Training in a Virtual Environment for Construction Students." Proceedings of the 103rd ASEE Annual Conference, Washington, DC.

[8] Johanson, Christopher John. 2008. *Spectacle in the Forum: Visualizing the Roman Aristocratic Funeral of the Middle Republic* (Doctoral dissertation). University of California, Los Angeles.

[9] Kruijff, Ernst, J. Edward Swan II, and Steven Feiner. 2010. "Perceptual Issues in Augmented Reality Revisited." Proceedings at the IEEE International Symposium on Mixed and Augmented Reality 2010. Source: http://www.cse.msstate.edu/~swan/publications/papers/2010_Kruijff-etal_Perceptual-Issues_ISMAR.pdf

[10] Lang, Ben. 2012. "Former Apple Talent Developing Oculus Rift Headtracker, "9 DOF" and 760Hz Gyro Sampling". Roadtovr.com. Sourced from: http://www.roadtovr.com/oculus-rift-headtracker-adjacent-reality/

[11] Scaleform. 2013. "Oculus Rift Developers Get Extra Boost of Support from Unity Technologies." Source: http://www.oculusvr.com/press/oculus-rift-developers-get-extra-boost-of-support-from-unity-technologies/

[12] Seidel, Robert J. and Paul R Chatelier. 1997. *Virtual Reality, Training's Future? Perspectives on Virtual Reality and Related Emerging Technologies*. Springer, p. 20.

[13] Sherman, William R. and Alan B. Craig. 2003. *Understanding Virtual Reality: Interface, Application, and Design, Volume 2.* Morgan Kaufmann, pp. 14, 131, 383.

[14] Stein, Joel (Contributor). 2009. *Stroke Recovery and Rehabilitation.* Demos Medical Publishing, p. 318.

[15] Tan, Fabian and Adrian Tan. 2015. "A Course in the History of Ancient Engineering." Proceedings of the ASEE's 122nd Annual Conference and Exposition. American Society of Engineering Education, June 14 – 17, Seattle, Washington.