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Title: Cost-Effective Computer Vision Interfaces for Educational Virtual Reality Games

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Category	**Min**	**Max**	**Chosen**
Requirement Analysis and Design	0	20	10
Theoretical Analysis	0	25	0
Experiment Design and Execution	0	20	10
System Development and Implementation	0	20	20
Results, Findings and Conclusions	10	20	10
Aim Formulation and Background Work	10	15	10
Quality of Paper Writing and Presentation	10		10
Quality of Deliverables	10		10
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Cost-Effective Computer Vision Interfaces for Educational Virtual Reality Games

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ABSTRACT

The benefits and motivations of using virtual reality systems in education have been widely studied and are well accepted. The implementation of virtual reality as an educational tool creates increased access to information, increased details and enables distance learning and the opportunity to experience things that were previously inaccessible. While the motivations for the use of virtual reality in education are widely accepted, these systems have still not seen a widespread adoption in educational environments. Several barriers to entry, including the high cost associated with virtual reality equipment, are responsible for the current lack of implementation of virtual reality systems in educational environments. The development and implementation of cost-effective computer vision interfaces could result in a widespread adoption of virtual reality as an educational tool.

KEYWORDS

Virtual Reality, Education, Serious Games, Virtual Reality Games

1 Introduction

The use of Virtual Reality (VR) for education provides multiple benefits. VR systems provide increased access to information, increased details, the opportunity for distance learning and the possibility to experience environments and simulations that were previously inaccessible. Attending a physical art exhibition is generally a one-dimensional experience. The information directly available to the viewer is limited, usually in the form of a placard with the artworks title, dimensions and medium. ArtEx is a virtual reality art exhibition that allows the user to access additional information about the artist and the artwork that they have created. Serious games provide satisfaction that is beneficial to the learning outcomes of the user. The enjoyment of learning through an educational game, results in an increase on the time spent learning, and deeper learning and retention of the information [1, 7, 8]. These factors provide reasoning for the implementation of virtual reality systems in educational environments. However, the high cost associated with virtual reality systems has hindered the possible widespread adoption of this technology.

This is a research project, aimed at determining whether alternative cost-effective Virtual Reality interfaces, can provide the same level of immersion as a standard system. The development of a virtual reality environment and a cost-effective, marker-based interface was used when conducting this research. The Samsung GearVR is the headset of choice for this project and uses a Samsung S10 smartphone as display and as a processing element. While the smartphone is positioned in the head mounted display (HMD), the camera can still be used to detect and track Vuforia image marker objects. This technology allows the position and orientation of a purpose designed controller to be tracked and replicated in the virtual environment in real time. A heuristic evaluation was done on the environment, to determine the advantages of the marker-based system, in comparison with a standardized Samsung controller. When comparing the interfaces, it is important to place focus on the level of immersion experienced when using each interface, and the efficiency in terms of the functionality of each system.

2 Related Work

2.1 Virtual Reality

Immersion has been described as a person's desire to continue working on a task [4]. Research focused on immersive and non-immersive VR environments, suggested that fully immersive VR environments are more efficient, as an educational tool, than non-immersive desktop-based VR [3]. Immersive environments provide multiple benefits over non-immersive alternatives. These include an increased sense of presence and motivation, which results in increased retention of information [8]. The implementation of virtual reality in educational environments, provides multiple benefits over traditional methods. These benefits are frequently mentioned in research based on virtual reality as an educational tool. These results show that VR systems provide users with increased detail [9, 10], increased access to information [8, 10] and allow users to experience previously inaccessible simulations and environments [10, 11, 12].
Virtual reality systems are evaluated using several measures; interaction, immersion, motivation, performance, retention and satisfaction. A VR system that improves these measures will provide users with several positive learning outcomes. Users of a functional VR system will spend more time on a task and will also experience deeper learning due to the interaction and immersion within a VR environment [1, 4, 8, 13].

Measure	No. Papers
Interaction	13
Immersion	9
Motivation	7
Performance	8
Retention	5
Satisfaction	12

2.2 VR Interfaces

During development of a virtual environment, it is important that the selected interface is suitable to that environment. The level of immersion experienced by a user is influenced by the chosen interface. The development and implementation of a suitable interface will increase the level of immersion within the environment [7]. The cost of a high-end VR system is generally high, making more complex systems and their suitable interfaces less applicable for implementation in educational environments. The development of cost-effective interfaces would increase the possibility of widespread application of VR systems as an educational tool. Cost-effective 1st and 2nd tier systems, such as Google Cardboard and Samsung Gear VR, have been developed and are available worldwide. These systems use a smartphone-based head-mounted display (HMD). A smartphone is attached to the HMD, and functions as the display and processing element of the system. The main form of input on smartphone devices is the touch screen, however with the smartphone placed in the HMD the touchscreen is inaccessible. This is the biggest issue with 1st and 2nd tier VR systems. Alternate cost-effective interfaces must be developed to provide a form of input for the user. The Samsung controller designed for the Samsung Gear VR is cost-effective and can be used as an effective interface. The Samsung controller consists of a touchpad, a back button, a home button and a trigger. While the controller can be implemented in most VR environments, specific functionality is difficult to implement due to the limited forms of input provided by the controller. The tracking of the Samsung controller is limited by three degrees of freedom. The rotation of the controller is tracked as rotation around a point and the exact orientation of the controller is therefore not tracked in real-time. An alternative form of interface uses marker-based feature detection. With the smartphone positioned in the HMD, marker-based feature detection simultaneously uses the smartphone's camera to detect and track image marker objects that are placed on the controller. The position and orientation of the image marker is tracked in real time, allowing a model of the controller to be positioned in the virtual environment. Research done into marker-based feature detection suggested that the built-in object detection capability of marker-based tracking remains unchanged [14]. Additionally, reliability is mentioned as the primary benefit of this technology.

3 Methodology

3.1 Interface Design

The development of the virtual art gallery and interface was done using a User Centered Design (UCD) approach. The 3D modelling of the controller was completed over three iterations of design and printing. The first iteration resulted in a low-quality controller. While the controller was a working example, the functionality of this interface was low due to the design of markers, which were too small. This design flaw made the detection of the markers unreliable. The second iteration of design included larger sections for the markers that were placed behind the slider object. The resulting controller was of a higher printing quality, and the changes in design removed the issues of functionality.

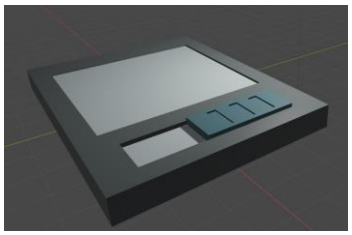

Figure 1: Controller Model

3.2 Educational Environment Design

The design of the environment was done after the first iteration of interface design and was completed over four iterations. The first iteration of development involved the creation of a basic environment and the implementation of the controller in this environment with complete functionality. A recording of the environment and the controller functionality was reviewed in a demo. Feedback provided was based on the functionality of the interface and was positive. The second iteration was focused fully on the design of the environment. During this iteration, one of the three artists was changed, due to frame rate problems caused by too many vertices existing in the sculpture objects. The sculpture exhibition was replaced with Gerald Chukwuma's work, in the form of paintings on top of carved wooden paneling. The third iteration of environment design included branding of the virtual art gallery, the creation of a main menu scene and the addition of editing placed on artworks such as kinetic elements and enhanced colour when viewed through the controller interface. During this iteration, the functionality of the Samsung controller was implemented in order to provide a benchmark interface for comparison. This version of the environment was submitted with the final version of the controller and all required equipment for testing the environment.

4 Features

4.1 Interface

The controller consists of two identical sides. Each side contains a large square window and a rectangular indent beneath the window where the slider is positioned. An image marker object is placed on each window (Front Side: Marker A, Back Side: Marker D), and two smaller markers are placed beneath the slider (Front Side: Markers B and C, Back Side: Markers E and F). The environment consists of an art gallery, which is duplicated to provide the functionality of the controller. The player object is positioned in the main gallery, with the main camera attached to it. A second player object is positioned in the duplicate gallery, with a secondary AR camera attached to it. The section titles, main artworks and artist descriptions are placed in the main gallery. All additional information is positioned in the duplicate environment. Marker A is rendered as the view from the secondary camera. This provides the functionality of the controller interface, where the window can

be used to view the additional information that is placed in the secondary environment.

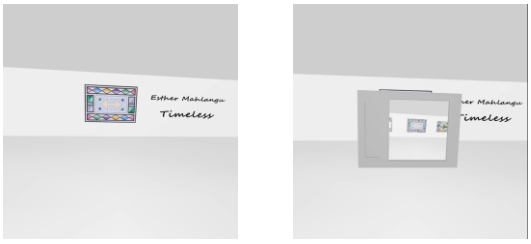

Figure 2: Representation of Controller Functionality

The interface can be used to move the user around the gallery. A black "X" is used as a crosshair and is shown in the center of the window. When the slider moves the change in pattern is detected. The change in marker visibility calls the PlayerMovement script. The movement is handled with ray casting, positioned on the reticle and casted in the direction of the reticle's forward vector. If the ray collides with a floor object, the player is moved to that location, and the secondary player is moved to the corresponding location in the duplicate gallery. This functionality ensures that the location shown on the window of the controller, is the same as where the player is positioned.

The marker placed in the window on the back side of the controller, Marker D, is rendered as a map (Figure 2) of the exhibition. The map shows three blue circles, each representing one of the artist's exhibitions. The reticle is rendered on top of the map, when the reticle collides with a circle the circle is highlighted with a thin ring around it to show which location is currently selected. When the slider is moved, the change in pattern is detected and the PlayerMovement script is called. Since Marker D is visible, the back side of the controller is visible and so the MapMove() method is called. This method teleports the player to the selected location. This functionality provides an alternative form of navigation, that is slower to activate but allows the player to easily move larger distances.

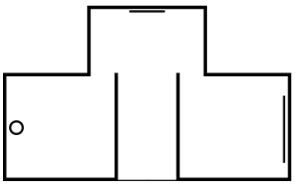

Figure 3: Map of Exhibition

4.2 Virtual Environment

The virtual art exhibition consists of three rooms, with a description of the artist and a single artwork displayed in each. Each section contains the work created by three artists, using different techniques and mediums. The sections demonstrate how paintings, photographs and other types of artwork can be displayed in a VR environment, and the unique effects that can be added to each type of work when displayed in a virtual art gallery. The implementation of ArtEx in a commercial environment, would require all artwork to be displayed in each section. With each artwork having its own added effects and additional information when viewed through the controller. Due to time constraints, a single artwork is displayed in each section, this artwork describes the entire collection of work and the user must use the controller interface to access the additional information. When the player enters a section of the gallery for the first time, a voiceover is played providing additional information on the artist and their collection of work.

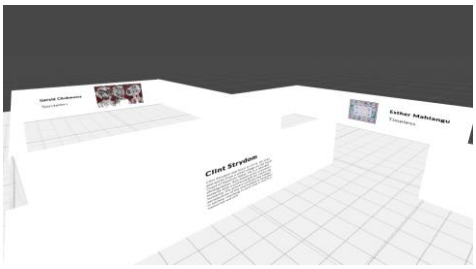

Figure 4: Virtual Art Exhibition

The first section "Timeless" was created by Dr Esther Mahlangu. Her Ndebele abstract artworks are created with acrylic on canvas. When viewed through the window on the controller, the user will be shown alternating images of the artists other works from the collection, and alternating images of Esther Mahlangu creating the works. This functionality demonstrates how the technological advantages of a virtual environment can be used to display multiple artworks on a single canvas, allowing users to experience a much larger body of work than they would in a physical art gallery.

Figure 5: Esther Mahlangu "Ndebele Abstract"

Gerald Chukwuma's section, "Storytellers", is described by the single work titled "The Storytellers". Chukwuma creates abstract artwork by carving into wooden panels, and painting on top of them. "The Storytellers" is made up of 17 carved wooden panels, which rotate individually when viewed using the controller interface. This shows how kinetic elements and animations can be used to add to the user's experience. Several other artworks are visible in this section, when viewed through the window of the controller.

Figure 6: Gerald Chukwuma "The Storytellers"

The third collection is “Visions” by Clint Strydom. This collection of work is described by the landscape photograph “Painted Skies over Isandlwana”. The photograph is the artist’s attempt to portray the Battle of Isandlwana from a South African perspective. The landscape is edited with red markings, when viewed using the controller, to symbolize the bloodshed experienced during the battle. The markings were included to demonstrate how visual effects can be added, to provide additional information on the meaning of the artwork. Two additional works are also visible in Strydom’s section when looked at through the controller.

Figure 7: Clint Strydom "Painted Skies over Isandlwana"

5 Development

The development of the environment and interface was conducted using a variety of software.

5.1 Software Tools

The virtual environment was developed using Unity 3D, with Vuforia, GearVR and Oculus packages as imports. The Vuforia package provided basic functionality for detection and tracking of image marker objects. Vuforia uses key point detection to identify whether a detected image matches one of the image markers that are stored in a database. The exact process used by Vuforia is not publicly available. However, the tracking of image markers most likely uses keypoint detection in ORB. This algorithm looks at a 16-pixel ring around each pixel P of an image. If 8 of the pixels are brighter or darker than pixel P, then P is a keypoint [5]. The key points of a tracked image are compared to the key points of the stored image markers. If there is a match the image is detected as an image marker and is then tracked by the Vuforia package. GearVR provided the necessary software to allow for the development of a virtual reality environment, rather than a standard 3D environment developed using Unity. Oculus 17.0 was used to access basic models and functionality, that were necessary for implementing the functionality of the standardized Samsung controller within the environment. Adobe Photoshop was used for all editing of assets, including changes to artworks, creation of all textual assets and the ArtEx logo.

5.2 Interface Development

The interface is made up of two sides each containing a large square window and a rectangular space beneath the window where the slider is positioned, an inner layer that acts as the surface on which the markers are placed, two sliders and two surfaces with raised outer edges that provide room for the slider to move freely (Figure 9). Development of the controller was done using Blender for modelling and Ulitmaker Cura for 3D printing. The modelling of the controller was done over three iterations. Two separate controller objects were modelled. The first involved the development of a paper prototype (Figure 7), which was used to demonstrate the functionality of the controller. The image marker objects, responsible for the functionality of the slider, were placed on folded paper flaps. That could be opened or closed to represent the slider being moved. The prototype was evaluated using a video that demonstrated the controller functionality within the environment.

Figure 8: Paper Prototype

Figure 9: Interface Concept

The second iteration was conceptual, a single sided controller object showing the design of the controller (Figure 1). This model was imported into Unity and used as the controller object in the environment. The second model included all necessary adjustments that are responsible for the slider functionality of the controller. Cylindrical rods and indents were added to support the assembly of the controller, raised indents and grooves were added to provide room for the wings of the slider allowing the slider to move freely (Figure 5). Testing of the second iteration highlighted an issue with the detection of the markers placed behind the slider. The third iteration was designed with larger sliders and a larger area around the slider, to make increasing the size of the markers possible.

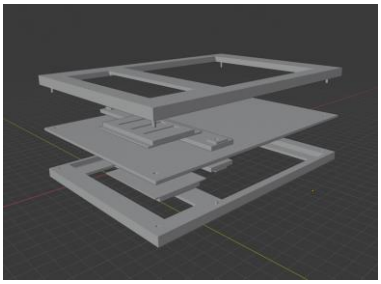

Figure 10: Interface Components

6 Testing

Due to the pandemic, recruitment of participants for user testing was not viable. A heuristic evaluation approach was used instead. While user testing would have been beneficial to this research, heuristic evaluation conducted through testing by experts can result in major and minor usability problems being identified [5]. The heuristic evaluation process followed was adapted for virtual reality environments, using Nielsen’s usability heuristic evaluation [2, 6]. Two experts in the field of virtual reality tested the interface and the environment. The users conducted a heuristic evaluation and answered several additional questions focused on the design and

functionality of the system. The usability of the purpose designed controller and the Samsung controller, and the level of immersion experienced when using either controller, were compared. An acceptance test was performed by both users, to determine if the system meets several requirements.

6.1 Heuristic Evaluation

Usability testing was conducted by two users. Each user was given the HMD, the controller, the Samsung controller and the smartphone containing the latest build of the project. No instructions were given to the users in terms of tasks that needed to be completed. Through exploration of the virtual art gallery, using both controllers, the users identified any issues with the design and functionality of the system. The users were asked to identify any problems with the interface or environment, provide additional information on the issue and potential solutions, identify which heuristic was contravened and assign a severity rating (low, medium or high) which indicates how large an impact the issue has on the overall quality and usability of the system. The additional questions asked focused on the design of the environment and the usability of the controllers withing the environment. The questions asked were the following:

- Do you like the look of the environment? Do you have any suggestions on things that should be changed?
- Did you experience any problems when using the 3D printed controller? Was the controller easy to use?
- Did you experience any problems when using the Samsung controller? Was the controller easy to use?
- Advantages of the 3D printed controller
- Advantages of the Samsung controller
- Do you have any suggestions on ways to improve the functionality of the system?
- Do you have any suggestions on ways to increase the level of immersion?

The answers to the additional questions provided all necessary information needed for the evaluation of the design of the environment, usability of the controllers, advantages of either controller in comparison with the alternative interface, the functionality of the system and the level of immersion experienced when using the system.

6.2 Acceptance Test

An acceptance test was conducted during testing. The users were asked questions to determine if several requirements were met. The questions asked are the following:

- Does the game meet all requirements to be considered an educational game?
- Does the interface meet the requirements to be considered a low-cost interface?
- Does the controller interface work correctly?
- Is the level of immersion higher than when using a standardized controller?

The answers to the questions asked during this phase of testing, would identify if any severe problems exist in terms of the general concept of the virtual environment and the purpose designed controller.

7 Results and Discussion

The results from the heuristic evaluation identified a large amount of usability issues (Table 1). The heuristics that were violated - by the identified issues - were control mapping, consistency, immersion, realism, feedback, support for learning, compatibility with user's task and domain and navigation and orientation support. The issues identified were recorded and fixed in a final iteration of environment and interface development. Issues with high severity were focused on first, several issues mentioned were problems with the user's understanding rather than the usability of the system and therefore no changes were needed. Each issue shown in Table 1 has an associated ID value, which is used to make evaluation and discussion of the results easier to follow.

7.1 High Severity Problems

This section focuses on the high severity problems displayed in Table 1. The problems identified with high severity were (1), (2), (6), (9), (14) and (18). Issue (1) was a control mapping problem which impacted the usability of the Samsung controller withing the VR environment. This problem was easily solved with remapping of the controls, such that the touchpad is used for alternating the view rather than the back button. Issue (2) identified a problem with the purpose designed controller. The view of the extra view window is related to the orientation of the player's head rather than the controller. The window on the front side of the controller, is rendered as the view from a separate camera object – placed within the duplicate art gallery - that follows the rotation of the main camera in the scene. The functionality works this way to ensure that the extra view window displays the respective area within the alternate gallery. Fixing this issue was impossible as aligning the extra view window to the orientation of the controller, would require redesigning the entire system. Issue (6) identified that two separate voiceovers would play if a user moved into a new room without listening to the entire audio clip. This issue was fixed by disabling the audio player when the user moves outside of a minimum range. Issue (9) suggested that frames should be added to the artworks. However, in a physical exhibition these artworks are never displayed in frames and therefore no changes were made. Issue (14) was a problem with the user's understanding of the controller functionality and not a problem with the usability of the system, this issue was therefore disregarded. Issue (18) identified a problem with the map displayed on the backside of the controller. The user's current location was not shown on the map, this issue was fixed by changing the colour of the circle on the map that represents the room that the user is currently in. The identification of major issues of the environment and the interface, and the changes made to remove those issues resulted in a large improvement to the usability of the system.

7.2 Medium Severity Problems

The issues identified with medium severity were (3), (4), (5), (11), (15) and (17). These problems were mainly visual issues which

negatively impacted the user's experience. Issue (3) suggested that that the extra view window should rotate to adapt to the orientation of the controller. The correct orientation of the interface places the slider on the left side of the controller. This design decision was made to place the slider image marker objects closer to the smartphone's camera. Holding the controller in another rotation positioned the image markers further from the camera, which resulted in less reliable tracking of the slider's position. Therefore, issue (3) was disregarded. Issues (4) and (15) identified that the crosshair clips the view of the map displayed on the backside of the controller. This issue was fixed using ray casting, where the crosshair was placed on a vector that ended slightly closer to the main camera, rather than the vector that collides with the controller window. Issue (5) was a suggestion to increase the value of the extra view window, by placing additional information in 3D space rather than just on other parts of the wall. All artworks in the exhibition are displayed on canvas or wooden paneling. These artworks are flat and the inclusion of additional information in 3D space is not applicable. The inclusion of sculptures in the exhibition would allow for additional information to be displayed in 3D space, however sculptures were removed from the environment due to frame rate issues caused by the objects containing too many vertices. Issue (11) suggested that the user's view should be aligned with a point of interest when using the map to teleport to a new location. This issue was fixed by changing the rotation of the player's transform to face the main work displayed in each room, which was previously set to the player's rotation before teleporting. Issue (17) suggested that the design of the environment was bland, and the user felt that it made the environment feel antiseptic. The ArtEx exhibition is intentionally contemporary in design. This design decision was made to create a simple, modern art exhibition which does not distract the user's attention from the artwork. This issue was the user's personal preference and not a major design flaw and was therefore disregarded. The identification and fixing of these issues resulted in a more immersive environment, with smoother navigation and transitions between the different rooms.

7.3 Low Severity Problems

The low severity issues identified were (7), (8), (10), (12), (13) and (16). These issues were all based on visual and audio aspects of the environment. Issues (7), (8) and (10) all suggested visual changes that could increase the separation between the main exhibition and the exhibition displayed on the extra view window. These issues were the user's personal preferences in terms of the design of the environment. Issue (8) suggested that the additional information from other rooms should not be visible to the user from their location. This issue was fixed by adding extra walls in the extra view environment, blocking the additional information contained in other rooms from the user's view. Issue (7) and (10) were suggestions based on the user's personal preference in terms of the design of the environment and were therefore disregarded. Issue (12) suggested that a narration should be added to welcome the user when they first enter the gallery. While an audio narration would improve the user's experience, this was not added due to time constraints. Issue (13) identified spelling and grammar errors within the text displayed in the environment. Changes were made to remove these errors. Issue (16) was based on localized audio volume. The voiceovers are played as 3D sound rather than 2D, this results in a change in volume based on the user's position and rotation. This issue was impossible to fix. With the AudioClip spatial setting set to 2D, the sound is still played from an AudioSource which is position on a game object placed within the 3D environment. Once the audio clip has started to play it is impossible to update its position in real time, resulting in localized audio volume. This issue is caused by using Unity 2017, as it is the only version compatible with the Virtual Reality packages used and still contains recorded errors in terms of handling 2D sound within a 3D environment.

7.4 Additional Question

Several additional questions (Table 2) were formulated to determine any issues and positive feedback in terms of the general design and functionality of the system. These questions focused on specific aspects of the system including environment design, usability of both the purpose designed and the Samsung controller, general functionality of the system and the level of immersion experienced by the user. The answers to these questions provided important feedback that was used to improve the overall design of the system. The feedback gained from this section was mainly positive. The main issues drawn from this feedback were usability issues with the Samsung controller within the environment. These problems were identified in Table 1 and each having a high severity rating. The last iteration of development focused on solving all high priority issues, and the negative feedback - based on the usability of the Samsung controller - from Table 2 no longer applies to the current system. The positive feedback from this section described high functionality of the purpose designed controller, high visual quality of the artwork, a high level of immersion within the environment and advantages of the purpose designed controller in terms of position and orientation tracking that is not achievable with the Samsung controller. The feedback gained from these additional questions, shows that the general design and usability of environment and the controller interface are of a high quality. The changes made based on the identified issues in Table 1, solved the mentioned issues in the negative feedback shown in Table 2.

7.5 Acceptance Test

The acceptance test consisted of research questions constructed to identified if several requirements were met by the system. These questions and the answers to the questions are shown in Table 3 and Table 4.

The first question aims to determine if the VR system meets all requirements to be considered an educational game. The responses to this question differed, with both users agreeing that the system is entertaining and educational. User 1 stated that the system can be considered an educational game, as the virtual reality element provides entertainment and the information displayed in the environment educates the user. User 2 described the system as an educational experience rather than an educational game. The

reasoning for this categorization is based on the lack of specific game elements such as a winning condition. However, the inclusion of a winning condition is not an imperative criterion for a system to be considered a game. Many successful games, such as Minecraft, have no specific goals or winning conditions. This reasoning is sufficient for ArtEx to be considered an educational game.

The second question was formulated to determine if the purpose designed marker-based controller meets all requirements to be considered a low-cost interface. Both users agreed that the requirements are met, and the controller can therefore be considered a low-cost interface. The cost of 3D printing the controller and printing the image markers onto paper is negligible. The cost of developing the controller is less than the cost of the Samsung controller which is considered a low-cost interface. The main issues in terms of the cost of the controller are access to a 3D printer and time. 3D printers are an expensive form of equipment, with long periods of time required for printing a single object. These issues could make this type of interface inapplicable in specific low-resourced environments. However, purchasing a 3D printer would not be necessary as the printing of the controller can be done through outsourcing.

The third question was based on the usability of the purpose designed controller. Both users stated that the functionality of the controller is high. User 1 suggested that changes could be made to further improve on the functionality of the controller. User 2 specifically mentioned better functionality with the purpose designed controller in comparison to the Samsung controller. The existing issues with the functionality of the Samsung controller before testing, made the comparison between the controllers unfair. The system should be tested again with these issues fixed before determining which controller has higher usability.

The fourth question aimed to determine if the purpose designed controller increased the level of immersion experienced by the user, when compared to the Samsung controller. Both users described the level of immersion experienced with each controller as comparable. User 1 suggested that fixing issue (3) shown in Table 1, would result in the purpose designed controller increasing the level of immersion. The suggested change was impossible to apply to the system, as it would require redesigning the entire functionality of the interface. User 2 stated that while the level of immersion experienced when using either controller is similar, the usability of the marker-based controller was higher than that of the Samsung controller. Several high severity issues were identified in terms of the functionality of the Samsung controller during testing. The system should be retested, for the comparison of the usability of the controllers to be fair.

7.6 Evaluation of the Testing Process

User testing would have provided valuable feedback to the research conducted on cost-effective computer vision interfaces for virtual reality environments. Due to the pandemic recruitment of users for testing was not viable. The use of a heuristic evaluation provides important and valuable feedback, the value gained when using heuristic evaluation is increased when conducted using experts in the field that is being researched [6]. The results gained from testing identified many issues, with different severities, in terms of the design and functionality of the system. The evaluation of the feedback and the implementation of solutions to the identified issues, resulted in a higher quality system with better functionality. Given the constraints that resulted from the global pandemic, the process followed during testing was the most effective possible form of evaluation. The testing process would have provided more value if additional users were included. The results gained from a heuristic evaluation, using experts in virtual reality, would have been more useful if 3-5 participants were used instead. However, the feedback provided by the two users identified the main issues of the system, with several issues being mentioned by both users. The inclusion of more participants would have resulted in more issues being identified. However, all high severity problems were identified with only two participants.

8 Conclusions

The development of cost-effective computer vision interfaces for virtual reality environments could result in educational virtual reality games being widely adopted as an educational tool. The testing of the serious game showed that alternative interfaces with high usability can be developed for a low cost. Low-cost interfaces can be implemented within virtual reality systems and still provide high functionality and immersion. These systems are more applicable in an educational setting than current high-quality VR systems. The testing of the marker-based controller described the level of immersion as comparable to that experienced when using the benchmark Samsung controller. Specific changes to design and functionality of the interface could result in a level of immersion that precedes that of the benchmark interface. The results from testing show that it is possible to develop an alternative cost-effective interface with better functionality than currently accessible low-cost interfaces. This type of interface can be designed to add to the users experience within a virtual environment, as the functionality of that interface can be designed specifically for the environment with additional functionality that is impossible to achieve on a standard controller. Marker-based feature detection is an effective, low-cost technology that provides real-time position and orientation tracking of objects, which can be used to develop high quality computer vision interfaces for virtual reality environments.

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Appendix

Table 1: Heuristic Evaluation

Heuristic Evaluation: User 1				
ID	**Problem**	**Heuristic**	**Severity**	**Extra Notes**
Samsung Controller				
1	Using the back button to dismiss the extra view makes the controls feel clunky.	Control Mapping	High	Could resolve by using the touch pad to do the same functionality as the back button.
Computer Vision Controller				
2	The view of the extra info view should be related to its orientation rather than the player's head orientation.	Consistency	High	To see what I mean, try tilting the extra view controller up or down while looking at it - Its view doesn't change.
3	The extra view window should rotate to adapt to the way the user holds it. I preferred holding the controller in portrait view.	Consistency	Medium	Would also solve the issue of the controller favouring right-handed users.
4	The crosshair in the teleportation window clips the view.	Consistency	Medium	This changes its shape which might confuse users.
Educational Game				
5	Consider putting extra info in 3D space rather than just other parts of the wall. This would help to increase the value added by the extra view.	Immersion	Medium	Right now, the extra view is only really serving to reduce the clutter in the main world by essentially moving extra artwork to the extra view. You could explore the usefulness of the extra view further.
6	Two sound clips play at once if I am listening to one clip and I teleport to the other room.	Consistency	High	
7	The white theme looks good for the main world but consider experimenting with colour in the extra view world to further differentiate it.	Immersion	Low	
8	The extra view information for artworks should not be visible from other rooms (e.g. I can see the centre rooms extra information by looking through the hallway.	Immersion	Low	This would make the extra view more special. It would be fine to have each artwork in a separate room in the alternate view.
9	Consider adding frames to the artworks to give them a greater 3D presence.	Immersion	High	Right now, they feel like images plastered on the walls.
10	Consider altering the floor materials in the different rooms to make them more distinct from one another.	Realism	Low	
11	Teleporting to a room does not automatically align the user towards something of interest	Feedback	Medium	Could be resolved by adding particle effects or information on the floor to help signal to the user what has happened.
12	Consider having a narration to welcome the user when they enter the gallery.	Consistency	Low	
Heuristic Evaluation: User 2				
ID	**Problem**	**Heuristic**	**Severity**	**Extra Notes**
13	Spelling and Grammar in text	Support for learning	Low	Some of the text has spelling errors, which are distracting.

14	Panel occlusion with Samsung Controller	Compatibility with user's task and domain	High	The panel occludes the centre of the view making it almost impossible to use the main view (e.g., for reading text). It would be better if the Samsung controller pointer could be used to move it aside. Currently this makes the alternative interface almost unusable.
15	Selection crosshair visibility	Navigation and orientation support	Medium	The selection crosshair is sometimes only partially visible. It should also be in a contrasting colour.
16	Localised audio volume		Low	
17	Antiseptic environment		Medium	
18	Current location not shown on map		High	
Additional Comments: User 1				
19	Point and click for the Samsung controller works really well.			
20	Slide to move in the computer vision controller works well and the white slider was a good form of feedback.			
Additional Comments: User 2				
21	It is good idea to have two forms of navigation through the space: a slower one to activate but which takes you further, and a more immediate mechanism for local movement.			
22	Generally, the scene is displayed at a good resolution and the artworks can easily be appreciated. This is a more difficult balance than it might at first appear.			
23	I didn't have a lot of criticisms because you have taken a lot of care to make the interface usable. In particular, I think the decision to increase the button size was a good one.			

Table 2: Additional Questions

Additional Questions		
Question	**Description**	**Answer**
Environment Design	Do you like the look of the environment? Do you have any suggestions on things that should be changed?	In general, the artwork displays very well. I found the art gallery itself rather bland. I think you could work on this a bit.
Marker Based Controller Issues	Did you experience any problems when using the 3D printed controller? Was the controller easy to use?	I sometimes had slight difficulty getting the slider buttons to register. However, I would say this worked on the first attempt about 80% of the time and I was always successful on the second attempt. I think you fix for the button size was a good one because I did not have to bring the controller too close for the slider button to register. In general, the usability of this interface is high.
Samsung Controller Issues	Did you experience any problems when using the Samsung controller? Was the controller easy to use?	I found it very difficult to use the environment with the Samsung controller successfully because the central panel obscured the view. I think this needs to be configured so that it can be moved or perhaps raise / lowered with a button click. This interface needs reworking to be roughly comparable.

Marker Based Controller Advantages	Advantages of the 3D printed controller	The 3D tracking for maps and alternate views is a definite advantage. It is difficult to achieve something even vaguely comparable with the controller.
Samsung Controller Advantages	Advantages of the Samsung controller	Button presses are easier to achieve in that they are picked up 100% of the time.
Functionality	Do you have any suggestions on ways to improve the functionality of the system?	I felt like my finger might have occasionally obscured the controller button area.
Immersion	Do you have any suggestions on ways to increase the level of immersion?	Perhaps some work on the environment. Although, I found the environment generally immersive. The trick is to enhance the display of the artwork and not detract from it.

Table 3: Acceptance Test, User 1

Acceptance Test: User 1	
Question	**Answer**
Does the game meet all requirements to be considered an educational game?	Yes, educational games aim to both entertain and educate. The virtual reality parts of the experience entertain and the information on the artwork educates. My feedback mostly surrounds how to enhance the entertainment aspects of the experience.
Does the interface meet the requirements to be considered a low-cost interface?	Yes, in comparison to the Samsung controller it is a lower cost interface approach.
Does the controller interface work correctly?	Yes, but there are some additional features that could be added to make it more usable.
Is the level of immersion higher than when using a standardized controller?	At the moment, it is comparable but fixing the issue mentioned above relating to which orientation the extra view follows may tip the immersion levels towards the computer vision controller. Also, the Samsung controller's controls should be improved to make it a fairer comparison.

Table 4: Acceptance Test, User 2

Acceptance Test: User 2	
Question	**Answer**
Does the game meet all requirements to be considered an educational game?	This meets the requirements of an educational experience rather than an educational game per se. While it informs the user effectively about the art on show and the necessary context, it lacks many game elements, such as a winning condition.
Does the interface meet the requirements to be considered a low-cost interface?	Yes, the additional cost incurred through 3D printing and paper printing is relatively negligible. It does, however, require access to a 3D printer and sufficient time. This may be an issue in particularly low resourced environments.
Does the controller interface work correctly?	Yes, it does. I found the ability to move the printed controller in 3D particularly effective as opposed to the Samsung controller.
Is the level of immersion higher than when using a standardized controller?	I don't think there is much difference in immersion. The shape and feel of the controller as a tool matches the virtual representation more closely in terms of haptics, which does add a little to immersion. More important, however, is the increased usability.