COMP4801
FINAL YEAR PROJECT
FINAL REPORT
FYP16042 - Mixed Reality Art Gallery Modeling with HoloLens and Google Tango

Supervisor:
Dr. Loretta Yi-King Choi

Prepared by:
Wang Shi Sheng (3035085865)

Other Group Member:
Ng Koon Hang, Gary (3035101554)

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Abstract

The rise of virtual reality and augmented reality provides brand new way of interaction with digital information. However, virtual reality immerses the users in simulated world with scarce connection with the real one. Augmented reality merely overlays virtual objects over real ones with no specific concern about the interaction in between. By understanding the environment, mixed reality is capable of blending the virtual objects with the real world. This project proposes a mixed reality system with multiplayer engagement based on Microsoft HoloLens and Google Tango tablet. Several innovative applications for creation works, such as painting in 3-dimensional space and 3D reconstruction, are introduced to appreciate the interaction and collaboration with the concept of mixed reality. In terms of technical objectives, the main focus will be put on the implementation of spatial mapping, Gaze-Gesture-Voice (GGV) input. Up to this point, all the mixed reality applications on both HoloLens and Tango have been implemented and tested. The cross-platform multiplayer is also finished and the whole system is now ready for demonstration.
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List of Abbreviations

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<th>Abbreviations</th>
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<tr>
<td>MR</td>
<td>Mixed Reality</td>
</tr>
<tr>
<td>VR</td>
<td>Virtual Reality</td>
</tr>
<tr>
<td>AR</td>
<td>Augmented Reality</td>
</tr>
<tr>
<td>GGV</td>
<td>Gaze-Gesture-Voice</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
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<td>PUN</td>
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1. Introduction

Since the year of 2013, a collection of virtual reality (VR) headsets including Oculus Rift and HTC Vive have been introduced to the public. The common point of VR headsets is that they display the software-generated images to replicate a virtual world setting. Although such synthetic environments may possess the properties of the real ones, there can also be no connection between the physical and virtual world. For example, the basic physical laws may no longer hold.

On the other hand, the concept of augmented reality (AR) introduces a real-time view of the physical world with supplemented elements generated by the computer. For instance, the mobile game Pokémon GO by Nintendo enable players to catch pocket monsters that do not really exist. Nevertheless, most implementations of augmented reality simply overlay the images and information on the physical world. This makes it more stiff and less interactive if a virtual object and a real one overlap unnaturally.
Mixed reality (MR) shares the same characteristic with augmented reality. Both the virtual and physical objects are combined. However, in mixed reality, the spatial mapping of the real environment is perceptible by the computer. Then the objects, including the real and virtual ones, can have interactions at a level of visual verisimilitude (see Figure 1). Thus there is enhanced illusion of having both aspects in the same reality.

![Image of mixed reality](image)

**Figure 1.** Virtual objects are displayed as if they are placed on table or projected on wall with the correct perspective in real world. This makes the combination of two environments true to life. (image source: Microsoft)

Thanks to the introduction of HoloLens by Microsoft in 2015, developers can implement more immersive and interactive mixed reality applications. Applications targeted for this device such as HoloBlocks and HoloAnatomy can now be downloaded from Windows Store. However, most of them exhibit limited functionalities and no multiplayer support. For example, HoloBlocks has the sole functionality of generating and placing objects (i.e. cubes and spheres) on detected surfaces. In this project, a mixed reality system with multiplayer engagement will be built with HoloLens and other hardwares. Several innovative scenarios including interior design and 3D painting will be implemented to demonstrate a more natural way to create and collaborate.
2. Objective

The objective of the project is to build a workable demo of mixed reality. The demo should have the capability of observing the spatial mapping. In other words, this system is able to recognizing the surface of ceiling, walls, table and floor. In addition, the demo is planned to take the Gaze-Gesture-Voice (GGV) input as controlling methods. Multiple users can interact with both the physical and virtual environment and also collaborate with each other. The scenarios for creation works as well as their main technical focus include but not limited to:

- Setting up an art gallery — spatial mapping
- Designing the interior setting (painting viewer) — spatial mapping; GGV (particularly gaze input); spatial sound
- Drawing in three-dimensional space — GGV (particularly manipulation gesture)
- 3D reconstruction (object scanning) — surface observer; computer vision
- Viewing and interacting with objects — GGV (particularly navigation gesture)
- Complementary application (focus point stabilizer) — GGV (particularly gaze input)
- Cross-platform multiplayer synchronization — coordinate calibration

All the works above are projected at the same place of the physical world. Therefore users may have better experience in collaboration. With the HoloLens, anyone can easily participate in this process and realize his or her own design in a more natural and interactive way than the approach of augmented reality. In the meantime, the work done is shared among all the other users in real-time.
3. System Details

In this section, the infrastructure of the whole mixed reality system will be introduced. Reasons will be provided for the choices of hardware and software platforms. In the second subsection, the scope of the project will follow. The 5-stage approach for building the system will be explained as the last part of this section.

Infrastructure

The hardware for the mixed reality system includes two kinds of devices, Microsoft HoloLens and Google Tango tablets. HoloLens is a head-mounted display (see Figure 2a) equipped with an inertial measurement unit (IMU), four environment understanding sensors and a depth camera. It can map the surroundings in a short time with relatively high precision. This provides users with the most interactive demonstration of the mixed reality and thus makes HoloLens our first choice.

![Figure 2a](image source: Microsoft)

![Figure 2b](image source: Google)
However, the number of HoloLens is limited due to the high price (US$3000). Since we want more users to get involved, the more affordable Google Tango tablets (US$512) are used as supplementary devices. They are Android based devices with a touchscreen, cameras for motion tracking and depth sensing (see Figure 2b). No extra setup is necessary for new users to participate in the collaboration. However, the other smart devices such as tablets and mobile phones with ordinary touchscreen and cameras are ruled out as complex calibration is necessary before they can be used. All the devices within the mixed reality system are connected via LAN/WiFi so that the status of the demo can be shared.

The scenarios and features will be implemented with the Unity 3D game development platform. This is a generally free-to-use software kit for developing games and demos. It has a well written documentation and an active supporting community. In addition, Unity supports multiple platforms so that little works are needed to build applications for different devices. Moreover, Photon Unity 3D Networking Framework SDK is used for realization of multiplayer support. These are the general practices in individual gaming development and thus we will adopt them over other choices.
Scope
One of aims of this project is to demonstrate the advantages of mixed reality over augmented reality and virtual reality in terms of interactiveness in creative works. Therefore, more attention are paid to the innovation of various demos within the system. In other words, the system is supposed to include a collection of innovative scenarios such as painting in three-dimensional space featuring mixed reality, namely spatial mapping and GGV input. The complexity of a particular functionality is not within scope. As an example, the implementation of 3D drawing should not focus on the diversity of pen tools. Although the details will be refined, this will never be comparable to professional software for digital painting. The accuracy and level of details of 3D reconstruction will be subject to the actual performance of the devices. In building this system, an uninterrupted user experience is preferred over finer details with less consistent performance.

Approach
Figure 3 shows the main flow for building the mixed reality system. Basically five steps are involved in the procedure.

![Figure 3](image-url)
I. **Review on hardwares and softwares to be used within this project.**

For the first stage, research works has been done on the developing platforms including hardwares and softwares. As most of them are still under beta testing and not finalized yet, there may be unforeseen bugs and disfunction. Furthermore, the limitation of the hardware have been found so that unrealizable functionalities can be eliminated from the project scope at the early stage.

II. **Implementation of prototypes for the mixed reality system.**

Prototypes of scenarios will be implemented within this stage. Possible ones include building of a scaled virtual city, designing of interior setting, interacting with virtual models placed in physical world, painting using gestures in three-dimensional space and 3D reconstruction using stereo vision. More scenarios may be added to the system as long as they demonstrate the innovative usage of mixed reality.

III. **Integration of multiplayer support.**

Works will be done on support for multiplayer engagement. We will try to share the spatial mapping and the coordinates among different devices. The origin of world coordinate is supposed to be calibrated using Vuforia Augmented Reality SDK and cross-platform synchronization is to be archived utilizing Photon Unity Networking framework. In this way, multiple users can see others’ works at the same location of the physical environment so that they can collaborate in a natural manner.
IV. Refinement of functionalities.

The details of each scenario built in previous stages is to be refined. Possible refinement includes enhancing stability of user input. For example, the precision of hand tracking can be improved. Rendering performance can be improved by optimizing the number of triangles used for representing the spatial mapping. Complementary applications for graphics stabilization is to be implemented to archive consistent visual experience.

V. Testing and modification.

The system as a whole will be setup in an indoor environment for robustness testing. Further modifications will be carried out to improve the performance under unexpected situations. For example, simplification of spatial mapping may be applied if the environment is more complicated than what the hardware can handle.

The mixed reality system proposed in the project is supposed to be a experimental and developmental implementation of mixed reality. As stated in previous section, the objective is to build a system to demonstrate the possible application of mixed reality. We will regard a working demonstration in a simplified space as the baseline for this project. The space setup will be limited to 3-meter by 3-meter with no complicated structure, subject to further changes. Each scenario of a workable demo should have appropriate integration of spatial mapping and GGV input respectively. Graphic performance will also be considered as part of the pass-fail criteria. Lags in rendering virtual objects will have negative effect on user experience. A system with unfavorable performance should not be qualified for successful implementation. From the users’ prospective, positive feedback in terms of interaction and collaboration will be regarded as the indication of pass for the project.
4. Project Status

Results — HoloLens Platform

At this time, I have finished all the prototypes of scenarios as stated in previous sections as well as the complementary parts for the mixed reality system. The applications are implemented based on the review of the developing platforms including hardwares and softwares. I have take into consideration of the recommendations on hologram stabilization and performance by Microsoft in the course of application design. Furthermore, a number of preliminary testings based on these prototypes were done to help make clear of the hardware capability. Certain refinements and adjustments have been carried out to make the system work with satisfying performance.

I. Setup of art gallery

There are six main scenarios of the HoloLens part of the mixed reality system. The first one is setup of the art gallery with spatial mapping. The raw information of spatial mapping is stored as meshes and is to be used in the following applications. Surface meshes are categorized into major groups such as walls, floors and ceilings. Equipped with a depth camera, Microsoft HoloLens is capable of perceiving the geometry of the surroundings within about 3.1 meters. With the mesh caching strategy, the device can store, update and discard the information of spatial surfaces for a whole room. There was no significant decline in performance of mapping surroundings when around 2500 square foot area and over 500,000 triangles were cached. This suggests that if the dimensional scale of the system is restricted to indoor level, the application should have no pitfall for performance. Nevertheless, because of limitation on the density of mesh triangles, only the simple surface like tables, walls and shelves were detected. The device showed no capability of processing complicated surfaces such as creased fabric. It is unlikely that we should consider such condition for building the system.
II. Interior design

The second scenario is designing the interior setting, namely the painting viewer (see Figure 4). The prototype utilizing the spatial mapping and gaze-gesture-voice input was implemented. The user is able to choose from the loaded paintings and posters and stick to a suitable surface. In addition, the description using spatial sound can be played as user’s need. This can serve as the guidance in the art gallery.

![Figure 4. The prototype of poster viewer for interior design was implemented. The user can stick, move and delete a chosen poster. The application mainly utilizes spatial mapping and GGV input.](image-url)
III. 3D painting with gestures

The third scenario is drawing in three-dimensional space. This application enables the user to paint 3D space with hands. The user input is called manipulation gesture, which keeps track of the position of hands. This is used as mock handwriting procedure. However, there is a known issue that hands to be tracked need to be within the field of view (FOV) of the integrated cameras. Since the FOV of cameras is limited, the user wearing the device is required to focus on the hand holding the virtual paint brush.

The rendering capability of HoloLens is around 80,000 triangles at more than 30 frames per second. As it is a mobile head-mounted display with limited computational power compared to desktop PCs, two rendering techniques were introduced to increase performance and reduce latency while maintaining acceptable quality of graphics.

The pen strokes are represented by segments consisting of pairs of lines and dots. One trivial way of assembling the segments is to use Unity primitive objects. One cylinder (88 vertices, 80 triangles) is to be used as the line and one sphere (515 vertices, 768 triangles) is to be used as the dot. However, as the number of segments needed for a single pen stroke will be normally at the level of around $10^2$, this will result in low frame rate and cause discomfort for users. Therefore I adopted the usage of quads with billboard rendering. Each pair is made up of one quad (4 vertices, 2 triangles) as rectangle and another one as circle. Both quads will reorient the rotation to face the user if the threshold of user movement is reached. This radically decreases the number of vertices and triangles to be rendered.
The other feature is GPU instancing recommended by Unity. The adoption of a instanced shader and texture atlas (see Figure 5) can reduce the draw calls and then the overhead for the CPU. There are still other choices of advanced rendering such as static batching and dynamic batching. The combination of the two techniques above demonstrated good graphics quality and acceptable frame rate in the tests.

Figure 5. The quad for line and the quad for dot are combined as a whole to utilize the feature of texture atlas and GPU instancing.
IV. 3D reconstruction

The fourth scenario is 3D reconstruction. This application is capable of scanning the real objects placed on surfaces such as floors, walls and ceilings and making virtual replicates. It is also a mock stamping procedure using mixed reality. This prototype was implemented with surface observer, the Unity API portal for spatial mapping functionality. This is originally used for understanding the surroundings and thus the observation volume can not be set to a small value to tightly fit the object to be scanned. The results of testing during the implementation showed that a value less than 1 by 1 by 1 cubic meter will cause unexpected exceptions and system halt. Then there will be fallback that the whole room is to be scanned before the necessary part of mesh is picked.

The reconstruction procedure includes three steps. First, three or more landmarks are picked for setting up the normal vector, origin plane and clipping volume. Then the surface observer starts scanning. Finally the object mesh within the clipping volume will be taken via a multi-threaded post-processing step.

In order to achieve a well balanced performance between latency and quality, the scanning parameters is set to a medium preset. The precision is 1500 triangles per cubic meter against the ordinary 500 triangles/m³ used for spatial mapping. The theoretic maximum value is 6000 triangles/m³ but a test has shown that there will be no notable increase in scanning quality beyond 1500 triangles/m³. The time interval between mapping updates is 0.5 second. Smaller interval caused exceptions in the same test.
Another optimization is the usage of wireframe in rendering the object meshes (see Figure 6). The main reason is that the meshes got from surface observer API has no uv information for applying complex textures. On the other hand, the wireframe is a good-cheap-fast alternative for simple demonstration like the one in this mixed reality system.

![Figure 6. The ball is scanned by the 3D reconstruction application and wireframe is used to render the mesh for a balance between latency and quality.](image)

One originally planned feature of the 3D reconstruction function is the usage of render texture. In other words, HoloLens does not only reconstruct the shape of objects but also takes pictures of the real objects during the scanning procedure. The set of pictures captured is fit to the mesh of the object with the help of camera calibration matrices so that they can be used as textures in replacement of the wireframe material. However, the operating memory (RAM) for applications on HoloLens is bounded to no more than 800 megabytes so that the number of pictures is also limited. In addition, the fitting process is compute-bounded since the shader needs to fit the texture coordinates for every vertices of the object mesh. In the preliminary tests, this plan resulted in unfavorable graphics performance and even occasional system crash. Therefore, I took the wireframe as the fallback option.
V. Interaction with objects

The next scenario is about interaction with objects in scene including paintings, posters, drawings, reconstructed 3D objects as well as other objects in the future implementations. At this stage, preliminary interactions such as initialization, movement and deletion has been implemented. All of these use the integrated user input of HoloLens. Two main input for HoloLens are voice input and gesture input. HoloLens showed capability of recognizing voice commands almost instantly when we tried out the demos. This is also mentioned by the documentation that processing voice input is hardware accelerated. Therefore, since I have followed the guidelines of creating concise commands, voice will be a handy input method. The core interaction includes press, release and bloom (see Figure 7a and 7b). Moreover, HoloLens can track the movement of user’s hand. Then complex gestures such as holding, manipulation (1:1 movement) and navigation (like joystick) can be recognized by combining individual presses and releases.

**Figure 7a.** Flexing the index finger down (press) and then back up (release) makes an air-tap for selection. (image source: Microsoft)

**Figure 7b.** Bloom is to hold out the hand, palm up, with fingertips together and then open the hand. This gesture is reserved for HoloLens system and thus can not be used for our own application. (image source: Microsoft)
In the prototype application, three basic gestures were well recognized. Holding and navigation worked with high accuracy as well. However, the manipulation gesture performed below expectation. The virtual object was moved only for a short distance before the gesture source was lost. It is likely that HoloLens has a rather limited area for gesture recognition unlike VR devices with external cameras (see Figure 8). One of our proposed scenarios, painting in three-dimensional, requires such gestures (see Figure 8). The unexpected performance indicate that there can be difficulties in implementing this functionality. Overall, the user input offered by this mixed reality system is handy and lightweight. It is supposed to be extensible for future usage but diversity of gestures is still limited if no external controllers like Leap Motion is to be officially supported in the near future.

Figure 8. Tilt Brush by Google makes use of HTC Vive. This virtual reality device has two ‘Lighthouse’ external sensors and is thus able to capture extensive movements. However, the recognition area is limited for HoloLens and it is more difficult to develop such painting application.
VI. Graphics stabilization

The last application is a complementary one to achieve better hologram stabilization and graphics quality. Among all the quality metrics mentioned in the official guideline by Microsoft, jitters and color separation are the two which were identified during the preliminary tests. Jitter is high frequency shaking of virtual objects and it is generally caused by low frame rate and bad sensor tuning. Color separation is the rainbow effect where graphics is separated into red-green-blue-green patterns. Both problems will have a negative effect on user experience and are supposed to be reduced to a minimum level.

HoloLens has its default choices of stabilization plane. All the virtual objects passing through the plane will have best rendering quality (see Figure 9). However in this mixed reality system, there is a variety of virtual objects attached to different surfaces in the same 3D space. The choice of focused object will also be different in various scenarios. For example, the user will probably want to focus on the pen strokes when drawing. The last application, namely the focus point manager, was implemented with a custom strategy of choice. A focus point along with a normal vector is chosen to set up the stabilization plane. At the same time it has a cache strategy which checks the cached objects to increase efficiency. With the help of focus point manager, hologram stabilization and user experience are improved to an acceptable level even if there is a low frame rate.

Figure 9. The objects passing through the stabilization plane will have minimum number of jitters, color separation and other graphics problems. The focus point manager is a complementary application to assist the HoloLens to choose a suitable plane in various scenes.
Results — Cross-Platform Multiplayer

In order to archive the cross-platform multiplayer feature between HoloLens and Tango tablets, two external development frameworks are used, namely Photon Unity Network (PUN) framework and Vuforia AR SDK.

I. Vuforia Augmented Reality SDK

Due to the different definition of world coordinate on HoloLens and Tango, location of the origin point, orientation and scale of coordinate system require to be calibrated before the holograms can be projected at the identical physical location.

Fortunately, both HoloLens and Tango take the unit length in Unity editor as one meter in real. Then the only calibration work that remains is location of origin point and orientation. Since the origin is defined as the spawning point of the devices, there is possibility that a physical calibration can be archived by matching the origin and forward vector of HoloLens and Tango when launching the applications. However, this option is rejected since it may cause inconvenience that conflicts with a favorable user experience.

For the reason above, we embraced the Vuforia SDK for coordinate calibration. In general, it is an multi-platform library that can recognize specific images, objects and markers. One image is printed and prepared at a fixed location for each instance of the mixed reality system. In this way, both HoloLens and Tango are capable of figure out the origin location and orientation. In the tests, Vuforia demonstrated satisfying recognition speed and accuracy and precision of coordinate calibration was better than the physical method in real-life usage.
II. Photon Unity Network framework

PUN is a free-to-use Unity package for multiplayer games on all platforms. It offers a plug-and-play solution for creating cross-platform system like our case. PUN makes use of Photon Cloud, a cloud service provided by Exit Games and requires no master server setup. The location and orientation of game objects instantiated with Photon will be automatically synchronized at the frequency of 10 times per second. PUN has been adopted by a wide range of developers from indies to AAA studios. In addition, there is a well maintained documentation and therefore we decided to take it as the major option for multiplayer support.
Limitations

The main limitations encountered is due to the specification and characteristics of the hardware. First, the limited number of mesh triangles makes it impossible to deal with complicated surface. It is likely to be avoided if the precision is still acceptable and we focus on innovation rather than the complexity of the demos. Second, HoloLens sacrifices the tracking range in order to get extra portability. Extensive movements can not be captured without external sensor. Therefore we find it difficult to implement the painter application for HoloLens. This will possibly have a negative on the user experience but it is likely that this will be enough in terms of a demonstration instead of a product for marketing.

Another limitation comes from the fact that we are still trying to exploit creative usage of mixed reality other than those specified in this report. Such scenarios should also be realizable under the restrictions of the current developing platform. Although we have already had a few ideas of utilizing mixed reality, it will always be better if we can come up with more innovation applications.

Finally, the project faces the difficulty of lack of official multi-platform support. Microsoft has published an open source package called HoloToolkit to simplify the developing procedure within Unity. The latest release included the updated APIs for recognizing user input as well as sharing coordinates among HoloLens devices. It is likely that multiplayer support between HoloLens can be integrated with less effort. However, the collaborative work using both HoloLens and Tango tablets receives no official support. We have adopted Vuforia to calibrate the coordinate system between different devices and then Photon PUN to archive cross-platform synchronization. However, it still breaks our original design principle of building a “join and play” mixed reality system in any physical environment without additional setup.
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**Future Works**

The single player functionalities for the proposed scenarios have been implemented and multiplayer and multi-platform support have been finished as well. Based on the result of the previous stages, we have finished the refinements and testing correspondingly. More refining work and adjustments are to be planned if necessary. For the future maintenance and development, we will pay more attention to possible applications that demonstrate better human-commuter interactions. At the same time, we will keep exploring the characteristics of the hardwares and try to come up with novel ideas of innovative usage of mixed reality. In that case, we will try to combine the new works done on both devices and verify the feasibility of cross platform interactions. The table 1 below provides a overview of the current schedule of the project.

<table>
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<th>Stage</th>
<th>Milestone</th>
<th>Deadline</th>
<th>Status</th>
<th>Remark</th>
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<tr>
<td>1</td>
<td>Review on platforms</td>
<td>mid-October 2016</td>
<td>finished</td>
<td>hardware: HoloLens as main platform; Tango tablet as complement software: Unity3D, Photon, Vuforia</td>
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<td>2</td>
<td>Interior design</td>
<td>December 2016</td>
<td>finished</td>
<td>prototype of painting viewer finished; uses spatial sounds as description</td>
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<tr>
<td></td>
<td>Drawing in 3D space</td>
<td>same as above</td>
<td>finished</td>
<td>uses manipulation gesture</td>
</tr>
<tr>
<td></td>
<td>3D reconstruction</td>
<td>January 2017</td>
<td>finished</td>
<td>uses surface observer and wireframe; has limitation but satisfies need for demo</td>
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<tr>
<td></td>
<td>Interactive objects</td>
<td>same as above</td>
<td>finished</td>
<td>includes drawings, scanned objects</td>
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<tr>
<td></td>
<td>Focus point manager</td>
<td>same as above</td>
<td>finished</td>
<td>complementary app for stabilization</td>
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<td>3</td>
<td>Multiplayer support</td>
<td>February 2017</td>
<td>finished</td>
<td>multi-platform planned</td>
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<td>4</td>
<td>Refinements of details</td>
<td>March 2017</td>
<td>finished</td>
<td>e.g. hand tracking precision; rendering performance optimization</td>
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<tr>
<td>5</td>
<td>Testing &amp; modification</td>
<td>April 2017 onwards</td>
<td>finished</td>
<td>more work if necessary e.g. robustness testing; spatial mapping simplification</td>
</tr>
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**Table 1.** Project schedule showing the five stages approach and the current status.
5. Conclusion

This project proposes a real-time demonstration of a mixed reality system with multiplayer engagement. The objective is to deliver various interactive and innovative applications for creation works utilizing the mixed reality devices.

We have implemented the mixed reality application for creation works on both HoloLens and Tango tablets with consideration of the capability of corresponding devices. Furthermore, cross-platform multiplayer support is integrated into the mixed reality system so that users can collaborate on the same piece of work with minimum effort for beforehand setup. The final product demonstrates the possibility of real-life usage for such mixed reality system.

The limitations in hardware specifications may negatively affect the user experience for the time being even though much effort have been made to optimize and refine this system. However, this does not eliminate the future development since we have a belief that the mixed reality system will have a more satisfying performance and portability if the devices keep receiving updates. At the same time, we should keep on exploring other innovative workable applications to demonstrate the necessity of mixed reality for creative works.
References


