AUGMENTED REALITY PERSISTENT ANNOTATION

BY

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THESIS

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ABSTRACT

We present a novel augmented reality annotation system that can create persistent annotation in any environment. The environment is either meshed in real time or loaded from previously scanned model. The model remains invisible while providing reference to real world geometry. Annotations are persistent across multiple sessions and devices. Annotations can also be color-coded and filtered. Our interface has annotation indicators and a radar map to help users quickly locate annotations. Multiple devices can work under a synchronized network to facilitate collaborative annotation tasks.

We also conducted a user study to evaluate our system. Results have shown both quantitatively and qualitatively that our system improves productivity for annotation tasks.
To my parents and June, for their love and support.
I would like to thank my advisor, David Forsyth, for his guidance, advice, and support for my thesis research project. He has advised many inspiring ideas and provided many insightful suggestions. Without his assistance and guidance, this project and thesis would not have been made possible.

I would also like to thank Qiuhua Ding, my friend and colleague who helped me on my research project. Qiuhua contributed to the annotation save and load feature as well as the networking module. He also assisted in conducting the user study. Therefore, I would like to thank him for his contribution and assistance.
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CHAPTER 1

INTRODUCTION

We present a persistent annotation system implemented on the Project Tango tablet device. The system can create augmented reality (AR) annotations bounded by real world environment without any prior knowledge of the environment. The environment is either modeled in real-time by integrated depth sensor or loaded and localized from previously scanned model. The model is not rendered but provides reference to real world geometry. Real world environment is displayed through a live video stream overlay from the forward facing camera. Augmented annotations are created by a simple touch on the tablet’s touch screen display. Then the annotation is augmented on the display screen matching real world locations. These annotations behave similarly to real annotations. They can be dragged around and will be occluded by the surrounding physical environment. As virtual objects, they can also be color-coded and filtered dynamically based on tag color. The annotations are registered to the model of the environment. Thus they will show up consistently in the registered location. Annotations are also synced simultaneously across devices as they are being created, moved or deleted, allowing multiple users to collaborate in the same environment. The system
also has indicators showing nearby off-screen annotations and a radar map to guide users in finding both nearby and distanced annotations.
CHAPTER 2

BENEFITS OF THE SYSTEM

2.1 Efficiency and Productivity

The annotation act not only as alternative to their real world counterparts, but also as a novel way of placing persistent information. Information attached to the annotations is more accurate and updates more quickly compared to other physical media. Annotations can be easily located with the aid of our navigation interface. With these advantages of our system, we can drastically improve work efficiency and productivity. We also verify these advantages in our user study.

Our system is more accurate in locating annotations. As annotations are registered to the model representing the environment, they appear precisely where they were placed. For example, consider an air-conditioning vent cover that needs to be replaced in a warehouse. Compared to a text note or a map describing the location of the vent cover, our system will guide the user to exactly where the issue is located and display an augmented marker on top of the vent.
The annotations are updated synchronously across devices in the same network. If multiple users are annotating the same environment, any modification will show up simultaneously for all users. Users no longer need to centralize information. This process is done automatically across all networked devices. For example, multiple workers are verifying inventory stock in a warehouse. With our system, the warehouse can be divided up into sections. Each worker can annotate his/her section when the verification is completed. The manager can immediately attend to a section if a worker reports an issue and can monitor completion progress as it is being updated.

Our system can help users quickly navigate through an unvisited environment and locate an annotation. The indicator interface acts as peripheral vision to help users find nearby off-screen annotations. The radar map provides general direction to distanced annotations and displays a bird’s eye view of nearby environment and annotations. Different than physical maps, the radar map reorients itself as the user turns. The user’s forward direction always coincides with the map’s north direction. This feature is especially helpful for users who have difficulty reading maps.
2.2 Privacy

As one participant pointed out in Table A.4 Quote 28, the annotations on our system are privatized. The system can control what annotations are being displayed for each user. Thus privacy can be protected for sensitive annotated information.

2.3 Long-term Impacts

The digitalized information can be further explored through data analysis. The annotations can take on many different forms. Depending on the use of the annotations, they may carry more useful information when viewed collectively. For example, when used for construction inspection, annotation heat map can reveal potential structural weakness in a building. The system can also be used to place augmented reality advertisements. Imagining holding up a tablet at Times Square, all the billboards become augmented objects advertising different products. Tapping on a billboard will expand more detailed information regarding the product, along with a button to place an order. E-commerce would have a brand new sales platform.
CHAPTER 3

USER EXPERIENCE

Our system is easy to understand and operate. The main interface of the system is illustrated in Figure 3.1. When users hold up the device, a live video stream from the forward facing camera is rendered. Invisible meshes overlay on top of the video stream as the environment is being scanned. As shown in Figure 3.2, users can choose to render the meshes using a button on the top left screen. Then they can see the mesh of the room being created as they navigate through the area. When the system operates in an unvisited environment, it would construct a mesh of the environment using its depth perception modules. However, if the environment has been visited, the system imports the mesh of the previously learned environment. Then the system localizes with respect to the mesh. Once the mesh has been created, the system can use it as a spatial reference to place virtual annotations.

Creating a virtual annotation is done through a simple tap on the tablet screen. An augmented annotation will appear at the indicated location as if placed in real world. The annotation can be dragged around and will move along meshed surfaces before finalizing at a desired location. The same drag-
Figure 3.1: Main interface

Figure 3.2: Mesh overlay rendered (left); invisible mesh using subtractive shader (right)

ging operation can be done on existing annotations. Tapping on existing annotations will change its color. Annotations with different colors can be filtered using a button on the top left screen. Double tapping an annotation brings up a remove button to remove the annotation. When an annotation is occluded by the environment, e.g. a wall, it disappears as if it is actually occluded.
A radar map appears on the bottom right corner of the screen. Annotations will appear as dots on the radar, with corresponding color to the actual annotations. The center mini-map shows a bird’s eye view of the meshed environment and virtual annotations. The outer radar grid indicates general directions of the distanced annotations. As shown in Figure 3.3, each dot on the radar map correspond to one actual annotation. Arrow indicators will appear on edges of the screen to indicate off-screen annotations that are not occluded. These interfaces help users quickly identify locations of the virtual annotations.

Figure 3.3: Each dot on the radar map corresponds to one annotation.

The system can be used individually or collaboratively with other devices. When used collaboratively, any modification to the annotations will be synchronized between all devices on the same network. Thus annotation
information can be shared efficiently and effectively among all users.
We conducted a user study to compare our AR annotation method with conventional sticky note method. The results verified that our system improves efficiency and productivity for annotation tasks. 12 participants were partnered up into groups of two. Each group completed two experiments on each of the two test sites. Our system is used on one of the test sites, while sticky note is used on the other. The number of groups in each assignment configuration is shown in Table 4.1. With this arrangement, we can cross validate the performance of each annotation method on each test site.

Table 4.1: Group assignment configuration, e.g. 3 groups using our system on test site 3124

<table>
<thead>
<tr>
<th></th>
<th>Test Site 3124</th>
<th>Test Site 3102</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our System</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Sticky Note</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

4.1 Test Site

The two test sites are similar in geometry but different in area size. As shown in Figure 4.1, test site 3102 is slightly larger in size then 3124. They
are located in an academic building; each includes two hallways and a common area. Highly distinguishable locations such as door tag, wall corners, billboard, and sofa chair are used to place markers. While markers on wide flat surfaces are easy to find, harder locations such as the back of a sofa chair increase the difficulty to find a marker.

![Test Sites](image)

**Figure 4.1:** Test Sites

### 4.2 Experiments

The experiments consist of a series of goal driven tasks to simulate a construction inspection scenario. Two inspectors, aka the participants, are
inspecting and fixing issues annotated on the test site. Some issues are already detected and marked in the area. But new issues may be discovered and can only be solved with their partner’s expertise. Their task was to locate and resolve all the annotated issues assigned to them.

Each participant was instructed to retrieve 5 markers, which adds up to 10 markers in total for each test site. Marker locations are different for each participant, but are determined prior to the test and are the same for each group of participants. 3 of the 5 markers would be initially placed on the test site; 2 others will be placed by the participant’s partner, i.e. participant A will place 2 markers for participant B, vice versa. Each participant will be accompanied by a researcher, who will provide instructions on where to place new markers during the test. Depending on the system being used, the markers would be either virtual for our system or physical when using sticky notes. For each annotation method, the tasks are slightly different.

4.2.1 Sticky Note Method

For the control experiment, sticky notes are used as method of annotation. A map of the test site is given to assist finding the markers. Participants are given a printed map of the test site at the beginning of the test. Locations of the 3 existing markers are indicated on the map. The task is to find
each of the markers, draw a cross on it, and retrieve it. The reason to draw a cross is to mimic the double tap gesture for removing a marker on our system. If the participant is nearby a pre-determined location for new markers, he/she will be instructed to place a new marker for his partner. The participants are told to communicate and inform their partner if a new marker has been created. They are also asked to mark the location of the new markers on their map. This is to simulate the need to keep record of the resolved issues. The experiment ends when each participant has retrieved all 5 markers.

4.2.2 AR Annotation Method

For the test experiment, virtual markers displayed on our system are used. The radar map and off-screen indicator interface act as alternative to the printed map. Different from the sticky note method, locations of the 3 existing markers are shown on the radar map. Prior to the experiment, participants had to wait for the researchers to localize the system. This process allows the device to recognize and load previously scanned model of the test site. The 3 existing markers are also loaded during localization. The task, identical to the sticky note method, is to locate each of the markers and remove it. Participants are also instructed to create new markers. However, as the system is synchronized simultaneously, the marker locations show up simultaneously on the other participant’s device. Thus there is no need for
verbal coordination between the participants. Though we still encourage communication if the marker location doesn’t seem clear on the radar map. The tasks are completed when all of the markers are found and removed.

4.3 Data Collection

We keep track of the time it took for each group to complete each experiment. The measurement starts when participants receive either the physical map or the Project Tango tablet. And the timing stops when all 10 markers have been retrieved and removed. This measurement can provide a quantitative analysis over performance of the two annotation methods.

At the end of the user study, participants are asked to complete an anonymous questionnaire without the presence of the researcher. Completed questionnaires are mixed with other questionnaires and put into an envelope by the participants to avoid interviewer bias. A copy of the questionnaire is attached at Section A.1. The questions serve as a qualitative measurement of the user experience.

We have also attached the IRB approval form and informed consent form in Section A.2. Raw data from the user study is attached in Section A.3.
4.4 Results

As mentioned above, for each annotation method, there were 3 groups tested on each of the two test sites. We averaged the time used for the 3 groups and present the recorded time in Table 4.2. Completion time raw data are listed in Table A.1

Table 4.2: Average completion time for each annotation method at the two test sites. Bolded time is better.

<table>
<thead>
<tr>
<th></th>
<th>Test Site 3124</th>
<th>Test Site 3102</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our System</td>
<td>02mins 40secs</td>
<td>02mins 55secs</td>
</tr>
<tr>
<td>Sticky Notes</td>
<td>02mins 47secs</td>
<td>04mins 30secs</td>
</tr>
</tbody>
</table>

Compared to the physical sticky notes method, our system had shorter completion times on both test sites. We found that performance in the larger test site 3102 had a greater time difference. Although we cannot conclude the linear relationship between performance and annotation area size, we did notice a few interesting observations. Due to the relative small area of test site 3124, participants could easily see their partner placing a new marker for them. Participants also yelled across the hallway to notify the location of the new markers. One participant replied in Table A.3 Quote 8: “It does not beat yelling out the positions of physical sticky notes to my partner.” These collaborative behaviors greatly reduced the time it took for participants to synchronize new information. Thus the advantage of network-synchronized system was lowered. Moreover, usability issues with removing virtual mark-
ers also delayed completion time for our system. Details are discussed with other limitations.

The questionnaire and averaged rating for each question are shown in Table A.2. We summarize the findings as follows. As shown in Figure 4.2, participants found it easier to find virtual annotations than sticky notes. This is true for both existing markers and new markers created by the participant’s partner.

![Figure 4.2: From left to right, questions correspond to search difficulty of (a) find sticky notes on printed map; (b) find sticky notes created by partner; (c) find virtual notes on radar map; (d) find virtual notes created by partner](image)

Short answers also showed positive comments on the ease to locate virtual markers. For example, in Table A.4 Quote 25: “Easy to read the locale of the annotations, both pre-created and created by my partner.”

From Figure 4.3, we can see that the average attitude towards the system is “neutral”. The majority of participants found it neutral or easy to
learn how to use the system. As one participant pointed out in Table A.4 Quote 18: “very easy to be used even I’m a very new user.” Only two of the participants reported minor difficulty when using the system. The wait for localization did affect user experience greatly, which we will discuss in Section 4.5.

Figure 4.3: From left to right, questions correspond to attitude towards (a) the system in general; (b) user-friendliness of the system; (c) wait for localization

When asked for preference between the two annotation methods, average rating in Figure 4.4 indicated participants prefer our system to sticky notes. Preference for collaborating use was much higher than individual use. In the short answers, 75% of the participants thought our system would be useful. The negative comments suggested a more stable system and user interface updates.
Figure 4.4: From left to right, questions correspond to preference for (a) individual use; (b) collaborative use

4.5 Limitations

Through questionnaire report and observations, we found two issues with our system. First of all, many participants reported difficulty when removing annotations. For example, one participant reported in Table A.4 Quote 26: "too easy to accidentally create a new annotation or change the color." The double tapping gesture often resulted in creation of many new annotations. This could be caused by the system registering multiple double taps as a series of single taps. As users accidentally create new markers, the natural response was to double tap on those markers in order to remove them. However, this created even more markers. This usability issue added a lot of time variance on the virtual annotation experiment.

As shown in Figure 4.3 Q11 and also numerous short answer feedbacks, the majority of participants reported frustration over the long localization
process. The process is when the device tries to find its location in the loaded environment. On average it took about 2-3 minutes, with one extreme case, which took up to 10 minutes. The localization problem is a nuisance, but will be improved in upcoming Project Tango API updates.
CHAPTER 5

BACKGROUND

There has been various work using augmented reality to create virtual annotations. Previous work has laid down the guidelines for the design space of our system.

Wither[1] introduced an annotation taxonomy, which included two annotation methods: model based annotation and measurement based annotation. The most prevalent method among existing implementations is the model based annotation, in which an existing model of the environment is required. Placing a virtual note is done using localization and ray casting [2]. Reitmayr [3] presented a collaborative outdoor AR system using existing large geographic 3D models. Schall’s [4] augmented underground infrastructure system also relied on existing geographic information systems (GIS). However, not all locations have an existing model, especially for indoor areas. The measurement based annotation uses depth measurement to detect the location to place the virtual object. Chekhlov [5] used visual SLAM to locate flat surfaces. Wither [6] annotated surfaces using a laser range finder.
Based on positioning, the display technologies can be categorized into Head-mounted displays (HMD) and Hand-held displays (HHD) [7]. Products such as Google Glass, Microsoft Holo Lens, Facebook Oculus Rift, and HTC Vive use the same display component, which directly projects visual stimuli onto the user’s visual field. As for Hand-held displays, it is common to see an AR application on a mobile device. These applications are often used in combination with ARTag [8] that function as location reference for augmented objects.

From the display technique perspective, the displays can also be categorized into video see-through and optical see-through [9]. Video see-through renders a live video overlay as a substitute of the real world, and then virtual objects are rendered on top of the video overlay. And optical see-through keeps the real world as is through a see-through glass, then renders AR content as overlays on the glass or lenses.

Tracking for AR applications is done with either outside-in or inside-out method. [10] Outside-in camera arrangement refers to using stationary camera to measure moving markers on the device. Inside-out camera arrangement refers to the camera mounted on the device, which then measures tracking features on the surrounding environment.
CHAPTER 6
APPROACH

Our approach falls under the model based annotation method proposed by Wither [1]. Creation of annotations relies on a model of the environment, either newly scanned or loaded from existing model. We have chosen to implement our system on the Project Tango Development Kit tablet.

6.1 Design Choice

The computational problem we are trying to solve is essentially a simultaneous localization and mapping (SLAM) problem, where we need to construct a map of an unknown environment while keeping track of our orientation and position within this space. We chose Project Tango over other platforms due to its advantages in these three factors:

- Video see-through display
- Inside-out tracking and area learning
- Depth perception
6.1.1 Video see-through display

Project Tango is equipped with a 7-inch touch screen display, thus it will take the video see-through approach to render augmented objects. It relays its camera video to the background while rendering virtual objects on top. The video see-through method offers few advantages over the optical see-through. It is easier to manipulate real world scene because real objects are rendered through the same graphics pipeline as virtual objects. We can arbitrarily decide which part of the scene to be rendered or occluded by controlling the rendering sequence of the cameras. Optical see-through display does not support full occlusion due to the transparency of the display glass. Moreover, most prevalent optical see-through devices such as Microsoft Hololens aren’t available for our purposes.

6.1.2 Inside-out tracking and area learning

Project Tango uses its inertial measurement unit (IMU) in combination with a wide-angle fisheye camera to perform tracking and area learning. One immediate advantage of this tracking method is that the device is not tethered. Compared to outside-in tracking devices such as Oculus Rift and HTC Vive, Project Tango is a portable tablet device. This means it can be used in any environment and still perform tracking without any prior set up. Moreover, the device only has the form factor of a 7-inch tablet. Although inside-out tracking may be subject to large drift due to a lack of visual fea-
tures in some cases, portability is a priority for our system design.

As Project Tango tracks itself, it also generates an area description file (ADF) using visual features from the fisheye camera. The ADF can then be used to localize the device when the system visits a previously learned area. ADF enables persistent annotation to be loaded and localized.

6.1.3 Depth Perception

Project Tango uses infrared projector and sensors to actively scan the environment and provide a depth map of the scene in front of the device. The depth map is then used to generate a mesh model of the environment. Ray casting to the mesh model determines locations for the annotations. Compared to other depth sensors, Project Tango is designed with depth perception in mind and thus better integrated.

One concern we had with the depth sensors is power consumption. In combination with its NVIDIA Tegra GPU, the depth sensor may cause battery life limitations if used extensively. We did not run into any battery limitations during our tests and user studies; however, we anticipate power consumption would be a bottleneck on usage time for the Project Tango device.
6.2 Interface

We initially designed our system to have a head mounted display (HMD) interface. Using a third party head mount, we were able to render stereoscopic view for the display. However, due to the camera’s narrow field of view and display rendering latency, we discarded the HMD approach. Our final implementation used a hand-held display (HHD) interface.

6.2.1 Hand-held Display

One advantage of the HHD interface over the HMD interface is people’s familiarity with the interface. Smart phones and tablets are ubiquitous nowadays, which means the majority of the population is used to hold up a touch screen device and interact with it. Interaction through this interface would be identical to using any other mobile applications. Furthermore, issues with the HMD interface no longer pose significant hindrance to usability of the system. First of all, the narrow field of view will not create discomfort when the device is held at a distance from the user. The experience would not be too different than making video recordings with a tablet. Latency may still be noticeable. However, removing the need for stereoscopic view rendering reduces computation use by half. Thus the HHD interface mitigated issues from the HMD interface. One downside of this interface is that users would have to carry the device by hand while operating the system.
6.2.2 Stereoscopic View

Although our attempt to use the HMD interface failed due to hardware limits, we thought it is still noteworthy to explain how we rendered stereoscopic view on the Project Tango device.

To achieve binocular vision on a single display with a single camera live feed, we need to consider two parts: rendering the virtual scene and the real world scene. Rendering the virtual scene with stereoscopy is simple. We simply initialize two cameras and separate them by the interpupillary distance (IDP) in virtual space. As for the real world scene, we came up with a solution after receiving inspiration from Oculus’ rendering technique. We shifted the video stream to create stereoscopic view. Because the tablet screen is split in two halves for binocular vision, we only have half of the original screen width to render each of the views. We selected the center 50% pixels of the video stream and shifted the view left and right by half of the IPD to form views for each eyes.
7.1 Occlusion

Occlusion is a necessity in realistic rendering of virtual objects under AR setting. As one of the depth cues in visual perception, occlusion contains information regarding relative location between objects. Without occlusion, users will be able to see virtual annotations in another room. It may seem convenient for finding annotations, but it also creates confusion regarding the actual location of the annotation. The annotation could be in the adjacent room, or in a room further away. We choose the video-see through display method to occlude virtual objects by setting the rendering sequence of pixels. But the question is, how do we determine if a virtual object should be occluded by the video pass through?

We utilized the properties of a subtractive shader to occlude the virtual objects. The video stream of real would is rendered as background and does not contain any depth information. Thus all the virtual markers are rendered by default so there is no occlusion. If we render the underlying mesh of the
environment, occlusion is achieved. But the mesh would be rendered on top of the video stream. The solution is to write a custom shader, which turns off rendering to all color channels but keeps the object depth in the z-buffer. We applied the shader shown in Figure 7.1 to the mesh objects, making them invisible but still occlude virtual annotations. Thus annotations will appear to be occluded by the physical environment of the video pass through, as shown in Figure 7.2.

```glsl
Shader "SubtractiveShader" {
    Properties {
        _Color ("Color", Color) = (1,1,1,1)
        _MainTex ("Albedo (RGB)", 2D) = "white" {}
        _Glossiness ("Smoothness", Range(0,1)) = 0.5
        _Metallic ("Metallic", Range(0,1)) = 0.0
    }
    SubShader {
        Tags { "RenderType"="Opaque" }
        Pass {
            // use a pixel blend, so that it takes
            // from the color from the buffer
            Blend SrcAlpha OneMinusSrcAlpha
            // pixel blending only works with lighting
            Lighting On
            // make sure the depth gets written in
            ZWrite On
            ZTest Less
            // turns off rendering to all color channels
            ColorMask 0
        }
    }
}
```

Figure 7.1: Subtractive shader used for occlusion

Our initial attempt that failed relies on the point cloud depth data. The idea was compare virtual objects within the camera’s view frustum to the
Figure 7.2: As user moves from left view to right view, annotations are occluded by the invisible mesh of the corner walls.

point cloud. If a virtual object has greater depth value than the point cloud along the camera’s viewing direction, then this virtual object is occluded. Due to the uncertainty of the IR readings (reflective surfaces such as glass; depth out of range), occlusion using this method often resulted in flickering annotations.

7.2 Virtual Annotations

When the user taps at a screen location, a ray is casted into the screen at the location. If the first intersection is with a mesh surface, then a new marker prefab is instantiated. The marker uses the 3D location of the intersection as its position and the mesh surface normal as its orientation. If the ray intersects with an existing marker, then the marker behaves differently depending on the touch gesture. With a single touch, the marker changes its filter color. Double touch initiates the remove button, shown in Figure 7.3;
tapping on the remove button removes the annotation. The double tapping gesture is recognized by measuring time interval between consecutive taps. We used 0.5 seconds as the threshold to recognize a double tap event. A dragging operation activates consecutive ray casts against underlying mesh as touch location changes. The selected marker’s location then gets updated with the new intersection location.

Figure 7.3: Double touch initiates a remove button.

7.3 Indicators

Although discomforting effects caused by the camera’s narrow field of view was alleviated when we selected the handheld display interface over the HMD interface, the issue with limited field of view (FOV) persists. The lim-
ited FOV causes the user to loss their peripheral vision in the virtual world. Users will only be able to see virtual objects within the visual field of the camera; they won’t be able to locate a nearby virtual annotation if the annotation is off-screen. Drawing inspiration from first person shooter games, we came up with the idea of marker indicators. Similar to how damage indicators show direction of enemy engagement, we used arrow indicators to show nearby off-screen markers. When a marker is off-screen but visible from user’s current location (not occluded by any obstacles), an arrow indicator with matching color to the marker will appear on the edge of the screen to show direction towards the marker. Moving the screen of the tablet towards the indicated direction and the indicated marker would eventually show up on the screen display. With the indicators acting as peripheral vision for the user in the virtual environment, locating nearby annotations is no longer hindered by the camera’s limited FOV.

7.4 Color Coding and Filtering Annotations

Annotation filtering was also an improvement we made to enhance usability of our system. As the number of annotations increases, the amount of matching indicators also increases. With normal usage, the edge of the screen still gets crowded with too many indicators. When a group of annotations are from the same direction, their indicators tend to cluster at the edge of the
screen. Thus the clustered indicators will be hard to distinguish. Grouping annotations allow users to focus on a subset of the annotations. This feature would improve work efficiency because users can ignore the annotations that don’t matter and are potential distractions. We made it possible by labeling annotation with color tags. For experimental purposes we chose three colors (Red, Green, Magenta). By selecting corresponding filters, only annotations with the selected color will be shown. As shown in Figure 7.4, this feature helps users to find the annotations that matter the most.

Figure 7.4: Annotations being filtered by colors
7.5 Radar Map

One disadvantage of our AR system is that it lacks situational awareness. Since the video overlay camera on the Project Tango only has a 38 degrees field of view, the user’s attention is easily confined to what is visible. Although finding nearby un-occluded annotations are made easy by the marker indicators, locating occluded annotations or annotations in the distance may still be troublesome. Thus we’ve implemented a radar map to assist users in finding annotations. The radar map was merged from two initial designs, as shown in Figure 7.6. The final design, as shown in Figure 7.5, consists of a round mini-map in the center and a peripheral radar grid.

Figure 7.5: Radar map with mini-map in the center and radar grid on the outer rim
In the mini-map, user will see small dot indicators with corresponding colors to the markers being indicated. The location of the indicators is proportional to the distance between the user and the marker. Meshes are rendered to show geometry of the surrounding environment. Users can easily interpret their location and the relative locations of nearby markers. We used a separate observer camera hovering above the user’s virtual location to render the bird’s eye view of the mini-map. In order to render the invisible mesh, we used a replacement shader to swap the subtractive shader with the standard shader. Thus the mesh may be invisible in the video overlay view but still show up on the mini-map.

As markers gain distance from the user, they will gradually move to the edge of the mini-map and seamlessly turn into slightly larger dot indicators on the outer radar map. In the radar grids, distances are shown disproportional as they are remapped using a sigmoid function, as shown in Figure 7.7.
Relative orientations are still maintained to indicate general directions of the
distanced markers. The combination design of the mini-map and radar grid
maximizes information utility on the radar.

\[
\left( \frac{2}{1 + e^{-x^2}} - 1 \right) \times 250
\]

Figure 7.7: The sigmoid function compresses marker distances into ranges from
0 to 1. Then the result is scaled up by the radius of the radar (250 pixels).

We also differentiated vertical surfaces in the mini-map. During our
initial tests, we found that if a scene is densely mapped, it can be very
difficult to distinguish walls and floors in the bird’s eye view of the mini-
map. Thus we used the user’s height as a reference to segment the walls
from the meshes. We colored the mesh with a different color if its height is
above user height. As shown in Figure 7.8, contours of the walls will show up
as a different color than the floors, thus distinguishing the vertical surfaces.
The contours drastically improved usability, as the users will now be able to
interpret room boundaries even if multiple rooms are adjacent to each other.
7.6 Networking Module

Multi-user networking is an essential part of our system. It enables annotations to be synchronized across multiple devices. We used Photon Unity Network framework to establish communication between devices. When a device creates a room, it exports its area description file, mesh and annotations. Then all subsequent devices will import these data and localize with respect to the area description file. This ensures all devices are in the same coordinate system. The Photon SDK allows one device to initiate function calls on all other devices in the network. Thus when a new annotation is created, modified or removed, the equivalent functions are called on all networked devices. We did not implement synchronized meshing due to drift issues. Thus all devices will load the same mesh for each environment.
CHAPTER 8
FUTURE WORK

Some of the next steps include increasing stability and scalability of our system. Mesh maintenance will allow users to update mesh either individually or collaboratively. Cloud data services can be used to store modeled environments. Then users can query a new area using area description files and retrieve annotations from the cloud. Annotation filtering can be further developed to help users retrieve more sophisticated annotations. Virtual annotations can be developed to support multi-media. Hardware modification to angle the forward facing camera can prevent users holding up the tablet for extensive time, thus reducing user fatigue.
REFERENCES


APPENDIX A

A.1 User Study Questionnaire
For each question, circle the number on the scale or write short answers.

1. How easy is it to find sticky note annotations marked on the printed map?
   

2. How easy is it to find sticky note annotations created by your partner?


3. How easy is it to find virtual note annotations marked on the radar map?


4. How easy is it to find virtual note annotations created by your partner?


5. How much do you like using the application?


6. How would you evaluate the user-friendliness of our annotation system?

   [-2] I can never figure it out  [-1] Neutral  [0] As easy as picking up any applications

7. What’s your preference between the two methods for individual use?

   [-2] Sticky note  [-1] either one is good  [0] Virtual note

8. What’s your preference between the two methods for collaborative use?

   [-2] Sticky note  [-1] either one is good  [0] Virtual note
9. How inconvenient is the localization process, when researchers had to wave around the tablet and wait for the application to localize to the learned model?

-2  -1  0  1  2
I can't stand it  The wait is troublesome  Neutral  It's okay  I don't mind at all

10. What do you liked about the system?

11. What do you disliked about the system?

12. Do you think this system will be useful, why?
A.2 IRB Approval Letter and Informed Consent Form
February 26, 2016

David Forsyth
Department of Computer Science
1332 Siebel Center
201 North Goodwin Avenue
Urbana, IL 61801

RE: Evaluating AR annotation system for virtual note creation and retrieval tasks: A comparison with conventional annotation methods
IRB Protocol Number: 16557

Dear Dr. Forsyth:

This letter authorizes the use of human subjects in your continuing project entitled Evaluating AR annotation system for virtual note creation and retrieval tasks: A comparison with conventional annotation methods. The University of Illinois at Urbana-Champaign Institutional Review Board (IRB) approved the protocol as described in your IRB application, by expedited continuing review. The expiration date for this protocol, IRB number 16557, is 02/25/2017. The risk designation applied to your project is no more than minimal risk. A Certificate of Assurance is available upon request.

Copies of the attached date-stamped consent form(s) must be used in obtaining informed consent. If there is a need to revise or alter the consent form(s), please submit the revised form(s) for IRB review, approval, and date-stamping prior to use.

Under applicable regulations, no changes to procedures involving human subjects may be made without prior IRB review and approval. The regulations also require that you promptly notify the IRB of any problems involving human subjects, including unanticipated side effects, adverse reactions, and any injuries or complications that arise during the project.

If you have any questions about the IRB process, or if you need assistance at any time, please feel free to contact me at the OPRS office, or visit our Web site at http://oprs.research.illinois.edu.

Sincerely,

LeaAnn Carson, MS
Human Subjects Research Specialist, Office for the Protection of Research Subjects

Attachment(s): Written informed consent document
c: Sida Li
University of Illinois at Urbana–Champaign
Research Information and Consent for Participation in Social Behavioral Research Evaluating AR annotation system for virtual note creation and retrieval tasks: A comparison with conventional annotation methods

You are being asked to participate in a research study. Researchers are required to provide a consent form such as this one to tell you about the research, to explain that taking part is voluntary, to describe the risks and benefits of participation, and to help you to make an informed decision. You should feel free to ask the researchers any questions you may have.

Principal Investigator Name and Title: David Forsyth
Co-investigators: Sida Li, Qihua Ding
Department and Institution: Computer Science Department, College of Engineering
Address and Contact Information: 201 N Goodwin Ave. Urbana, IL 217-265-6851

Your participation in this research is voluntary. Your decision to participate, decline, or withdraw from participation will have no effect on your grades at, status at, or future relations with the University of Illinois. If you decide to participate, you are free to withdraw at any time without affecting that relationship. Approximately 20 subjects may be involved in this research at UIUC. The purpose of this research is to evaluate an augmented reality annotation system for tasks involving placing and retrieving virtual and real annotations. This research will be performed at Thomas M. Siebel Center for Computer Science. Subjects will be given a series of tasks using our system or existing annotation methods. This study is not designed to benefit you directly. This study is designed to evaluate our augmented reality annotation system. The study results may be used to help other people in the future.

In this study, you will be asked to perform a series of tasks using an augmented reality app we have developed on a tablet device. Tasks will involve placing and retrieving virtual notes and real sticky notes in the Siebel building. You will have a partner to perform cooperative goals in these tasks. The completion time and your walk path during the study will be recorded anonymously. Then you will complete an anonymous short questionnaire to provide feedback on your experience.

To the best of our knowledge, the things you will be doing have no more risk of harm than you would experience in everyday life. The University of Illinois does not provide medical or hospitalization insurance coverage for participants in this research study nor will the University of Illinois provide compensation for any injury sustained as a result of participation in this research study, except as required by law.

Your study-related information may be kept confidential, but not always. In general, we will not tell anyone any information about you. When this research is discussed or published, no one will know that you were in the study. However, laws and university rules might require us to disclose information about you. For example, if required by laws or University Policy, study information which identifies you and the consent form signed by you may be seen or copied by the following people or groups:

- The university committee and office that reviews and approves research studies, the Institutional Review Board (IRB) and Office for Protection of Research Subjects;
University and state auditors, and Departments of the university responsible for oversight of research;
Federal government regulatory agencies such as the Office of Human Research Protections in the Department of Health and Human Services;

When the results of the research are published or discussed in conferences, no information will be included that would reveal your identity.

There are no costs to you for participating in this research.

You will receive $5 cash for completing this study. If you do not finish the study, you will not be compensated for this visit. If you complete the study, you will receive a total of $5. You will receive your payment immediately in person. If you decide to participate, you are free to withdraw your consent and discontinue participation at any time.

The Researchers also have the right to stop your participation in this study without your consent if:
→ They believe it is in your best interests;
→ You were to object to any future changes that may be made in the study plan;

Contact the researcher Sida Li at email address: sidali2@illinois.edu

• if you have any questions about this study or your part in it,
• if you have questions, concerns or complaints about the research.

If you feel you have not been treated according to the descriptions in this form, or if you have any questions about your rights as a research subject, including questions, concerns, complaints, or to offer input, you may call the Office for the Protection of Research Subjects (OPRS) at 217-333-2670 or email OPRS at irb@illinois.edu

I have read (or someone has read to me) the above information. I have been given an opportunity to ask questions and my questions have been answered to my satisfaction. I agree to participate in this research. I am 18 years of age or older. I will be given a copy of this signed and dated form.

_________________________________________  ____________________________
Signature                                               Date

_________________________________________  __________________________
Printed Name                                            Date

_________________________________________  __________________________
Signature of Person Obtaining Consent                      Date (must be same as subject’s)

_________________________________________  __________________________
Printed Name of Person Obtaining Consent

Short Study title or IRB Protocol Number, Version #, [date], Page # of #
A.3 Measurement Raw Data

Completion Time

Table A.1: Task completion time for each group at each test site using different annotation methods

<table>
<thead>
<tr>
<th>Group #</th>
<th>Test Site</th>
<th>Annotation Method</th>
<th>Completion Time (min:sec.mil sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3102</td>
<td>Our System</td>
<td>03:54.66</td>
</tr>
<tr>
<td>1</td>
<td>3124</td>
<td>Sticky Note</td>
<td>04:59.51</td>
</tr>
<tr>
<td>2</td>
<td>3102</td>
<td>Our System</td>
<td>03:13.65</td>
</tr>
<tr>
<td>2</td>
<td>3124</td>
<td>Sticky Note</td>
<td>01:59.07</td>
</tr>
<tr>
<td>3</td>
<td>3102</td>
<td>Our System</td>
<td>02:12.55</td>
</tr>
<tr>
<td>3</td>
<td>3124</td>
<td>Sticky Note</td>
<td>03:43.34</td>
</tr>
<tr>
<td>4</td>
<td>3102</td>
<td>Our System</td>
<td>03:16.97</td>
</tr>
<tr>
<td>4</td>
<td>3124</td>
<td>Sticky Note</td>
<td>02:49.06</td>
</tr>
<tr>
<td>5</td>
<td>3102</td>
<td>Our System</td>
<td>01:53.18</td>
</tr>
<tr>
<td>5</td>
<td>3124</td>
<td>Sticky Note</td>
<td>04:45.91</td>
</tr>
<tr>
<td>6</td>
<td>3102</td>
<td>Our System</td>
<td>02:13.67</td>
</tr>
<tr>
<td>6</td>
<td>3124</td>
<td>Sticky Note</td>
<td>03:35.27</td>
</tr>
</tbody>
</table>

A.3.1 Questionnaire Feedback (Multiple Choice)

Table A.2: User selection for question 1-9 of the questionnaire. Each column records selection for one participant. Each row records selection for one question.

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>P6</th>
<th>P7</th>
<th>P8</th>
<th>P9</th>
<th>P10</th>
<th>P11</th>
<th>P12</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td>Q2</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>Q3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td></td>
<td>1.416666667</td>
</tr>
<tr>
<td>Q4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td></td>
<td>1.333333333</td>
</tr>
<tr>
<td>Q5</td>
<td>1</td>
<td>-1</td>
<td>-1</td>
<td>-2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>1</td>
<td>2</td>
<td></td>
<td>0.166666667</td>
</tr>
<tr>
<td>Q6</td>
<td>0</td>
<td>-1</td>
<td>-1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td></td>
<td>0.583333333</td>
</tr>
<tr>
<td>Q7</td>
<td>1</td>
<td>-2</td>
<td>-2</td>
<td>-2</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>2</td>
<td>-1</td>
<td></td>
<td>0.25</td>
</tr>
<tr>
<td>Q8</td>
<td>2</td>
<td>-1</td>
<td>-1</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
<td>1.083333333</td>
</tr>
<tr>
<td>Q9</td>
<td>-1</td>
<td>-1</td>
<td>-2</td>
<td>-2</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-1</td>
<td>-2</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
<td>-1.166666667</td>
</tr>
</tbody>
</table>
### A.3.2 Questionnaire Feedback (Short Answers)

Table A.3: User feedback for short answer questions from questionnaire. Second column indicates user and question, e.g. P1,Q10 is participant 1’s answer for question 10.

<table>
<thead>
<tr>
<th>Quote</th>
<th>User</th>
<th>Question</th>
<th>Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quote 1</td>
<td>P1, Q10</td>
<td>The visuals are intuitive, positive for the collaboration.</td>
<td></td>
</tr>
<tr>
<td>Quote 2</td>
<td>P1, Q11</td>
<td>Recognition/Location is still immature. Lagging is still far too significant.</td>
<td></td>
</tr>
<tr>
<td>Quote 3</td>
<td>P1, Q12</td>
<td>For researcher/lab use: fine. In real life: no.</td>
<td></td>
</tr>
<tr>
<td>Quote 4</td>
<td>P2, Q10</td>
<td>There is collaboration between the two tablet, connected by wifi, which probably gonna have future use.</td>
<td></td>
</tr>
<tr>
<td>Quote 5</td>
<td>P2, Q11</td>
<td>The sticky notes just go through the wall. The locations are really in accurate.</td>
<td></td>
</tr>
<tr>
<td>Quote 6</td>
<td>P2, Q12</td>
<td>For multi-player game, probably.</td>
<td></td>
</tr>
<tr>
<td>Quote 7</td>
<td>P3, Q10</td>
<td>It would be cool for notes left my partner isn’t here</td>
<td></td>
</tr>
<tr>
<td>Quote 8</td>
<td>P3, Q11</td>
<td>It does not beat yelling out the positions of physical sticky notes to my partner. Also holding up a tablet is more annoying than using my eyes.</td>
<td></td>
</tr>
<tr>
<td>Quote 9</td>
<td>P3, Q12</td>
<td>If my partner had added virtual notes earlier without me seeing them then the radar map would be very useful.</td>
<td></td>
</tr>
<tr>
<td>Quote 10</td>
<td>P4, Q10</td>
<td>Not much.</td>
<td></td>
</tr>
<tr>
<td>Quote 11</td>
<td>P4, Q11</td>
<td>Need to hold a tablet up, keeping one arm always busy. Also, drift is really annoying.</td>
<td></td>
</tr>
<tr>
<td>Quote 12</td>
<td>P4, Q12</td>
<td>Once some of the smaller issues like localization and drift are improved upon. Also, this system serves better as a wearable (like the Hololens) as opposed to something held by the user.</td>
<td></td>
</tr>
<tr>
<td>Quote 13</td>
<td>P5, Q10</td>
<td>It was very easy to use and to locate the sticky notes [meant virtual notes] quickly.</td>
<td></td>
</tr>
<tr>
<td>Quote 14</td>
<td>P5, Q11</td>
<td>It was too easy to accidentally create sticky notes [meant virtual notes]. It let the sticky notes [meant virtual notes] move a little bit along surfaces. If it got too close to an object (maybe 2 feet from a door), it didn’t know where it was.</td>
<td></td>
</tr>
</tbody>
</table>
Table A.4: User feedback for short answer questions from questionnaire continued.

<table>
<thead>
<tr>
<th>Quote</th>
<th>P5, Q12</th>
<th>Yes because it takes a lot of subjectivity out of positioning.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quote</td>
<td>P6, Q10</td>
<td>Virtual note are very easy to be used. And it is very helpful to find the virtual stickers.</td>
</tr>
<tr>
<td>Quote</td>
<td>P6, Q11</td>
<td>Double-tab function is sometime troublesome. And it takes a little long to be localized.</td>
</tr>
<tr>
<td>Quote</td>
<td>P6, Q12</td>
<td>Yes. It can easily help me to find targets. And very easy to be used even I’m a very new user.</td>
</tr>
<tr>
<td>Quote</td>
<td>P7, Q10</td>
<td>? has mini-map.</td>
</tr>
<tr>
<td>Quote</td>
<td>P7, Q11</td>
<td>Too slow. Fails too many times.</td>
</tr>
<tr>
<td>Quote</td>
<td>P7, Q12</td>
<td>Yes, but not for me. The mini map is my savior. The system needs updating.</td>
</tr>
<tr>
<td>Quote</td>
<td>P8, Q10</td>
<td>Tablet form factor Motion tracking</td>
</tr>
<tr>
<td>Quote</td>
<td>P8, Q11</td>
<td>Localization</td>
</tr>
<tr>
<td>Quote</td>
<td>P8, Q12</td>
<td>Yes, in a few years when the sensor is more robust, better depth camera, better tolerance to environmental condition.Useful for construction, architecture, etc.</td>
</tr>
<tr>
<td>Quote</td>
<td>P9, Q10</td>
<td>Easy to read the locale of the annotations, both pre-created and created by my partner.</td>
</tr>
<tr>
<td>Quote</td>
<td>P9, Q11</td>
<td>Was too finicky - too easy to accidentally create a new annotation or change the color. I’d recommend long-press instead of double-tap to remove.</td>
</tr>
<tr>
<td>Quote</td>
<td>P9, Q12</td>
<td>Yes because it is relatively accurate, easy to use, and makes the annotations easy to keep track of.</td>
</tr>
<tr>
<td>Quote</td>
<td>P10, Q10</td>
<td>The system is a very innovative marking system, as it is very easy to find every marker, your, or your partners. I also liked that every inch of space is assessable, even the ceiling, which is somewhere you would not be able to put a sticky note on. I also like that it is privatized, so other than you and your partner, no one else can see the marker.</td>
</tr>
<tr>
<td>Quote</td>
<td>P10, Q11</td>
<td>The one dislike is the “localization” process, as it seemed like a very glitch process currently, and for daily use, might be very inconvenient. Another dislike is that holding up the tablet may be tiresome for scenarios with many markers.</td>
</tr>
</tbody>
</table>
Table A.5: User feedback for short answer questions from questionnaire continued.

<table>
<thead>
<tr>
<th>Quote</th>
<th>P10, Q12</th>
<th>P11, Q10</th>
<th>P11, Q11</th>
<th>P11, Q12</th>
<th>P12, Q10</th>
<th>P12, Q11</th>
<th>P12, Q12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quote 30</td>
<td>P10, Q12</td>
<td>Yes, because it is a clean and efficient marking system, and I can see it being used for business or commercial purposes.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quote 31</td>
<td>P11, Q10</td>
<td>Very interesting to play with, but maybe a bit hard to use, especially the removing note part. The best part may be the ease of spotting/finding.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quote 32</td>
<td>P11, Q11</td>
<td>A bit unstable, somewhat slow.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quote 33</td>
<td>P11, Q12</td>
<td>It can be useful when multiple people need to annotate the same area. It makes the communication about notes very easy.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quote 34</td>
<td>P12, Q10</td>
<td>That it can point the direction of the targets and update on the run.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quote 35</td>
<td>P12, Q11</td>
<td>Selecting the points was a bit of problem. I kept making new targets when I tried to either remove or change into different color.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quote 36</td>
<td>P12, Q12</td>
<td>Yes, direction guiding and syncing was really helpful.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>