HiFi: *Hi*de and *Fi*nd Digital Content Associated with Physical Objects via Coded Light

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ABSTRACT

In this paper, we propose the *HiFi* which enables users to interact with surrounding physical objects. It uses coded light to encode the position of user's mobile device in an environment. By attaching a tiny light sensor on a user's mobile device, the user can attach digital information to arbitrary static physical objects or retrieve/modify the attached information as well. With this system, a family member may attach a digital maintenance schedule to a fish tank or indoor plants so that all family members may retrieve that for maintenance reference. In a store, a store manager may use such a system to attach price tag, discount information and multimedia content to any products and customers can get the attached information by moving their phone close to the focused product. Similarly, a museum can use this system to provide extra information of displayed items to visitors. Different from computer vision based systems, HiFi does not depend on object's texture and illumination, etc. Different from regular barcode approaches, HiFi does not require extra physical attachments that may change an object's native appearance. HiFi has much higher spatial resolution for distinguishing close objects or attached parts of the same object. As the HiFi system can track a mobile device at 80 positions per second, it also has much faster response than any above listed system.

Keywords

Coded Light, Mobile Computing, Interactive Space, AR.

1. INTRODUCTION

Physical objects are tangible and can be seen, heard or felt. Many of them also have hidden aspects that cannot be directly sensed such as history, maintenance schedule, users' opinions, etc. The extra information may be important for people to interact with these objects. For example, when a family member feeds fishes in a tank at 8am in the morning, other family members should not feed them again in the morning. If a family member waters a moisture sensitive plant on a certain day, other family members should not water too much or too less after the same day.

We explored the design challenges and requirements of *HiFi*, such as how to present digital content at the right time in a nonintrusive way and how to make the interaction among "hider" and "finder" more enjoyable. We applied them to our system design and created three representative applications: Indoor Plants/Fish Care-giving Assistant, Shopping Assistant and Museum Assistant.

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In order to supply digital content to physical objects ("Hide") and discover them ("Find"), we need to know which object a user interacts with. By attaching physical visual codes (e.g. QR code, special designed visual code [15]) or RFID ([10][13]) on an object, digital content can be associated. Such approaches may change an object's original appearance, and easily distract user's attention as the user has to intentionally look around for the tags. On the other hand, computer vision based object recognition must overcome the variability in textures, lighting conditions, etc, that normally exists in user's environment. To improve recognition and tracking, such systems usually need to instrument the environment heavily [12].

To meet the challenges, we developed a coded light based localization algorithm, which uses a projector to project a sequence of designed gray code images at a very high frequency. By attaching a light sensor on a mobile device and decoding the light sequence, the mobile device location can be inferred.

Our localization technique meets our design requirements well. *First,* it is non-intrusive; no physical tags (e.g. RFID, QR Code) are attached to physical objects. It maintains the physical object's native appearance. *Second*, it has few requirements from users. Only a tiny light sensor is needed to be attached to the user's mobile device. For fast location discovery, an external light sensor is used in our current system (The sample rate is higher than 4k Hz. The embedded light sensor on current mobile phone is too low to meet the fast localization requirement. Typical camera is also insufficient to capture at such high speed). *Third*, it does not distract user's attention. The projecting area is constant light gray to human and merges with the environment quite well. *Lastly*, the location discovery is fast and accurate: 80 positions per second with pixel level accuracy (the size of a pixel depends on the distance between the projector and projection area).

In summary, the contributions of this paper are: *First*, we extensively analyzed the design challenges of the HiFi system. *Second*, we proposed a fast, non-intrusive and easy-to-deploy localization system that fits the HiFi system. *Third*, we designed and implemented three representative applications of the HiFi system that meet different design challenges.

2. HIFI: CHALLENGE & ARCHITECTURE

Various approaches have been explored to extend a physical object's content or interaction interface. By attaching RF and photosensing tags on the physical object, RFIG lamps [13] can track object's location change via projected gray code. Scratch Input [2] used object's surrounding area to extend the interaction surface. SkinIput [3] and SixSense [11] used mobile projector to extend the interaction surfaces into human body and real world. Traditional AR systems [[6], [15]] have explored more about augmenting content on physical world using various visual codes, head-mounted displays for input and output management.

2.1 Design Challenges

We categorize design challenges of HiFi system into five aspects.

Challenge 1: Ideally the performance of HiFi system should be independent of the physical objects' appearances (e.g. color, textures) as well as the environmental lighting condition.

Challenge 2: The digital content associated with physical objects should be easy to update whenever needed.

Challenge 3: Digital content should be presented in a non-intrusive way: They should only show up when users show interests in knowing more about physical objects. They should disappear when users are no longer interested.

Challenge 4: Digital content associated with physical objects might flow in different directions. It is intuitive to understand that digital content flow from "**hider**" (who hides the digital content on the physical objects) to "**viewer**" (who views the content). The flow could also be in the opposite direction, as "viewer" wants to update the content to give feedback to the "hider".

Challenge 5: The way of "hiding" digital content should be intuitive. If necessary, "hiding" more than one physical object should be able to proceed at one place easily.

2.2 HiFi System Architecture

By taking these design challenges into consideration, our final HiFi System architecture is as shown in Figure 1.

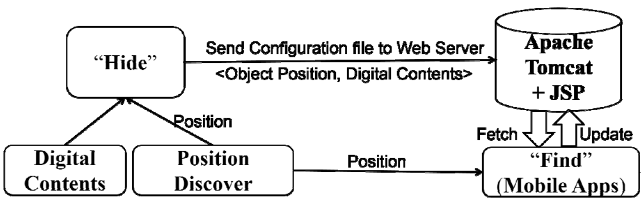

Figure 1. HiFi System Architecture

Two major operations of HiFi system are "Hide" and "Find". "Digital Content" Module provides an interface for "***hider***" to choose content. To meet **Challenge 5**, our three applications use two different hiding ways accordingly: *Mobile Hiding* and *Fixed-Camera based Hiding*. Mobile Hiding is intuitive (like hiding physical objects in real life). Hider stays close to the target physical object, then selects digital content from mobile app's user interface, and finally places the phone close to the physical object to finish hiding (Figure 5). Fixed-Camera based Hiding provides a quick way of hiding content on multiple physical objects in one place. Hider identifies target physical objects' areas through a camera's view and then chooses digital content through a GUI interface (Figure 8). *Position Discover* module discovers real-time position of a mobile device. *Coded Light Localization (Section 3)* is proposed to meet the **Challenge 1**.

Through "hide", the physical object (position) and the digital content are associated together as the environment configuration and maintained by a series of web services (Tomcat + JSP). Any updates made from either hider or viewer will be uploaded to the web server and updated in real time. (**Challenge 2).** It also supports both the hider and viewer to view and modify the digital content associated with the physical objects (**Challenge 4**).

"Find" is done via mobile applications. Only when the viewer stands by the targeted physical object and takes his mobile phone out of the pocket, the hidden digital content will show up on the mobile interface. If any of the two conditions are not satisfied, the hidden content would not show up (**Challenge 3**). In addition, when a user is no longer interested in the content and moves their phone away from the physical object, the digital content will go away immediately. Details of each module in Figure 1 will be elaborated in the rest of the paper.

3. LOCALIZATION VIA CODED LIGHT

Our localization module sets up a coordinate system for a scene (e.g. living room, shop or museum) by coding each position a sequence of temporally binary code, so that each object in the scene can be precisely located. *Coded Light* is a sequence of gray code images (Fig. 2) projected to the environment at a very high frequency (4000 Hz in our system). The light sequence received at each pixel of the projected area has unique coordinate, which is captured by a light sensor and decoded by decoding algorithm. The overall localization rate we achieve is 80 times per second.

Figure 2 shows a sample gray code image sequence used for the localization of an 8x8 pixels projected area. The left three images are used to determine the horizontal coordinates, while the right three images are used to determine the vertical coordinates. Generally, it requires *Ceil (log W) + Ceil (log H)* gray code images to locate every pixel in a W * H projection area.

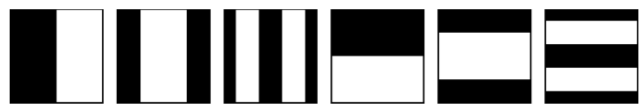

Figure 2. Gray code images for 8*8 projected area.

3.1 Gray Code Location Discovery

Gray code has been explored for location discovery in the HCI community [[5],[7],[8],[9],[13],[14]]. By projecting gray code images onto an arbitrary surface, Lee *et al*. can calibrate the projected content onto it [7]. Lee *et al*. shows a gray code based location tracking technique with 12HZ update [9]. Lee et al. hacked the projector to make both localization and projection at the same time [8]. PICOntrol [14] uses the gray code to locate a light sensor's coordinates inside the projected area so as to identify the activated projected GUI element. IllumiRoom [5] also uses the projected gray code to identify the layout around a TV to provide immersive game experiences. Although these systems demonstrate the successful applications of gray code for location discovery, none of them can achieve a high discovery rate, which limits the practical applicability for real-time applications.

3.2 Hardware Basics

Our localization system consists of a tiny light sensor and DLP projector (Figure 3). The projector periodically projects a sequence of gray code images, and the light sensor reads the light values at a location in the space, which are decoded by a fast, accurate asynchronized decoding algorithm.

3.3 Localization (Decoding) Algorithm

Our DLP projector has a native resolution of 912 * 1140 pixels. Therefore, Ceil (log 912) + Ceil (log 1140) = 21 gray code images are required to locate each pixel of the projected area. In order to decode the coordinates of a location, a sensor is held at that location and reads a sequence of light intensity values. A simple threshold may be used to determine whether each value in the sequence is 1 or 0. This binary gray code sequence is then used to recover the coordinate information.

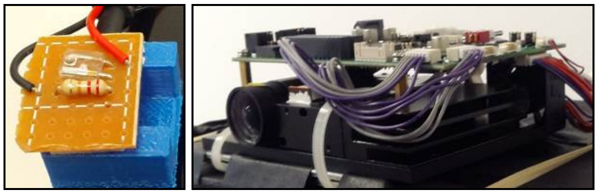

Figure 3. Light Sensor and DLP projector

We adopt a more robust method than simple thresholding. Our method projects a gray code image followed by the projection of its inverse. This doubles the number of gray code images required, making the use of 42 instead of 21 gray code images in our system necessary. However, in this case we determine the binary gray code value based on the difference between a gray code image and its inverse. Since no absolute threshold is required, the method turns out to be very robust to variable ambient lighting conditions.

In addition, in our system the projector and light sensor work asynchronously. Thus, we must embed some "special" images to the gray code image sequence to mark the start and end positions of the sequence. Five all-white and all-black images (representing the start bits "01110") and one all-black image (represent the stop bit "0") are inserted into the beginning and end of the 42 gray code image sequence. The final length of our gray code image sequence is thus 48. As we project gray code images at 4000 Hz, our system can achieve a very high localization speed of 80 Hz.

4. HIDE

"HIDE" is the procedure of associating digital content with physical objects, which is also known as authoring [4]. As mentioned in section 2.2, two ways of hiding are designed.

4.1 Mobile Hiding

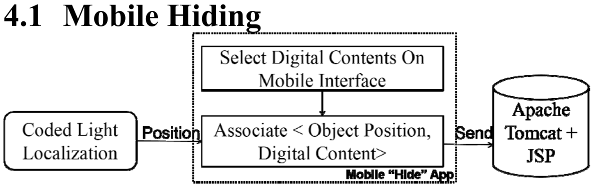

Figure 4. "Hide" digital content through mobile device

The framework is shown in Figure 4. The light sensor attached to the mobile phone reads light intensity values and feeds them to *Coded light based localization* (section 3) to decode the position. Each physical object's location is represented by that decoded position. The mobile user interface allows a user to associate the digital content to that position. Finally the associated pairs are stored as a JSON file and sent to the web server. Figure 5 shows that a family member took care of an indoor plant, and then created a message (about what he did and a picture of the plant) and attached the message to the physical plant, so that other family members can check and adjust their care-giving schedules. *Mobile Hiding* is intuitive as the Hiding happens around the physical object, which is like hiding real objects there. **Note that Camera is NOT needed for the Mobile Hiding.**

4.2 Fixed-Camera based Hiding

It provides a way of hiding digital content on several physical objects in one place. A camera is used to identify physical objects' areas (Figure 6). The flowchart is shown in Figure 7. The left window of the UI in Figure 8 shows the camera's view. The

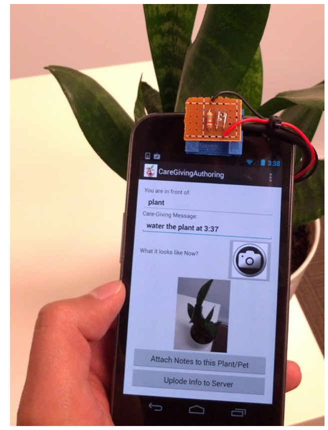

Figure 5. Hiding a care-giving message to an indoor plant for other family members to discover

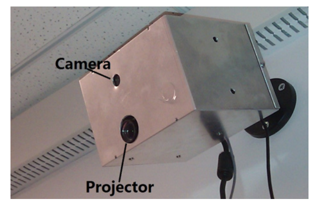

Figure 6. Camera is for identifying physical objects' areas (Note: camera is only needed in Fixed-Camera based Hiding)

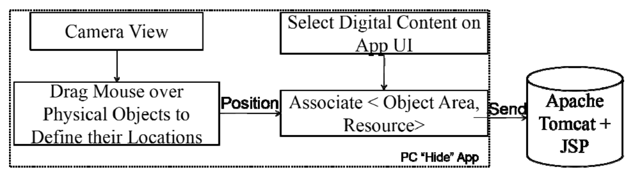

Figure 7. "Hide" through Fixed-Camera View

bright gray light area on the wall is illuminated by the coded light. By dragging the mouse over the physical objects, their location areas can be defined by green rectangles.

The rectangles are represented by the top left corner (TL) and bottom right corner (BR). Initially, all these points' coordinates are in Camera's Coordinate World (CCW). While the coded light based localization system gives the coordinates in Projector's Coordinator World (PCW). A transformation between the two coordinate worlds can be done by calculating the *homography matrix* from CCW to PCW. Given the projector's resolution W * H, the four corners coordinates in PCW (P_{pcw}) are known: (0, 0), (W-1,0), (0,H-1), (W-1,H-1). In this calibration step, the four corners' coordinates in CCW (P_{ccw}) are discovered by asking the user to click on the four corners of the projection area in the Camera View in the GUI (Figure 8). Using these 4 pairs of coordinates (P_{pcw} & P_{ccw}), we calculate the homography matrix H using EmguCV [1]. After that, TL and BR's coordinates in PCW can be estimated by multiplying H. The calibration only needs to be done once, unless the relative position of projector and camera is changed.

5. FIND

Viewer can "FIND" the hidden Digital Content via mobile applications that we designed (Figure 9). The real time position (X_t,Y_t) from the coded light module is used to check with each physical object's position (X_i,Y_i) to decide which physical object is close to the user. If the configuration file is acquired through

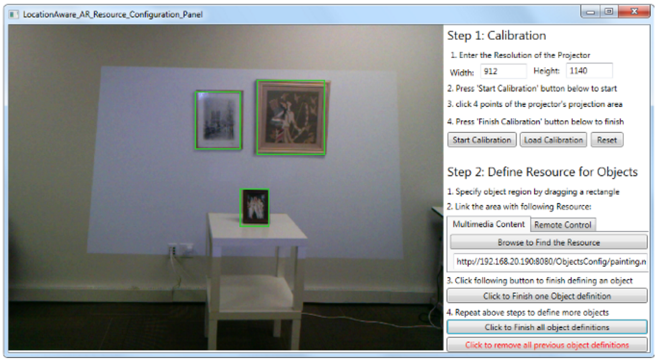

Figure 8. Hiding info on art works via Fixed-Camera View

Mobile Hiding (section 4.1) approach, then each physical object has an effective size (R_i) to represent its actual area. If $\sqrt{(X_t - X_i)^2+(Y_t - Y_i)^2} <= R_i$, then the viewer is close to object *i*. Otherwise, the viewer is not close to any objects. In our current implementations, R_i is a constant. If the configuration file is from *Fixed-Camera based Hiding* (section 4.2), we can simply check (X_t,Y_t) falls into which object's rectangle area. After identifying the physical object viewer is close to, the related digital content will be fetched from web server according the configuration file content and shown on mobile interface.

Figure 9. Flowchart of "Find" hidden digital content

6. APPLICATIONS

We have designed and implemented three HiFi System mobile applications that represent different design challenges.

6.1 Indoor Plants/Fish Care-giving Assistant

Indoor plants/fish need extensive human care. However, it might not be easy for multiple family members to coordinate their care-giving schedules. For example, when a member of a family wants to feed the fish, he might have no idea of when the fish was last fed. Or someone does not have time to water the plant and wants to leave a note on the plant to remind other members to water it.

Indoor plants/fish care-giving represents an application of the HiFi system that requires mutual information exchange between "hider" and "viewer" (*Challenge 4*). All the care-giving behaviors are conducted on the physical objects (e.g. watering the plants / feeding the fish), therefore all the "Hide" and "Find" should physically happen near the physical objects too. Mobile Hiding provides support for "hide", as hider can just type in the message on the phone interface right after he finishes the care-giving activity. Each viewer can retrieval the hidden messages by putting their mobile phone close to the object. Each potential viewer is

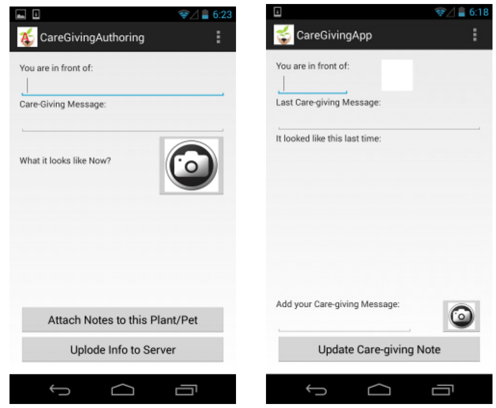

Figure 10. Indoor care-giving app Mobile Interfaces: associating messages with object for the first time (left); viewing and updating messages with the object (right).

also a hider, as they can update the care-giving messages too. So the final mobile applications for "hider" and "viewer' are shown in Figure 10. The left UI is used by the "hider" for associating content with a new plants/fish tank. After initialization, viewer can view and update the content using the right UI. Notice that the last two fields of right UI actually provide the "hide" functionality for the viewer; therefore, the viewer can write down their own care-giving messages and take pictures for other members as well.

Text information (e.g. physical object name, care-giving message) is easy to pack into the JSON format configuration file (Figure 11). However, the pictures taken by users are impossible to pack into the configuration file directly. A two phase transfer strategy is designed to solve this issue. In the *first* round, the metadata of the picture (e.g. file name) is packed with all care-giving text messages into JSON format (Figure 11) and is sent to web server. In the *second* round, the raw image data is sent to a fixed folder on the same web server via http connection. Later on, when another user starts her view app (right in Figure 10), the view app will first send an http request to fetch the JSON format configuration file from the server and then extract the name of the corresponding image, and finally use that name to retrieve the image under that fixed folder in another http request.

{"x": 100, "y": 215, "txt": "plant@watering at 2pm",
"pic":"20130908_140833.bmp"}

Figure 11. Configuration File Format ("@" connects different text fields in the Mobile UI (Figure 10) into one string)

The overall user experience is shown in Figure 5, Figure 12 and 13. Figure 5 shows how to hide digital content through Mobile UI. As Figure 12 shows, after watering the plant, user A types in a message of what he did (1st image) and takes a picture of the plant at that moment (2nd image). He presses the button to associate these content with the plant (3rd image). And finally presses

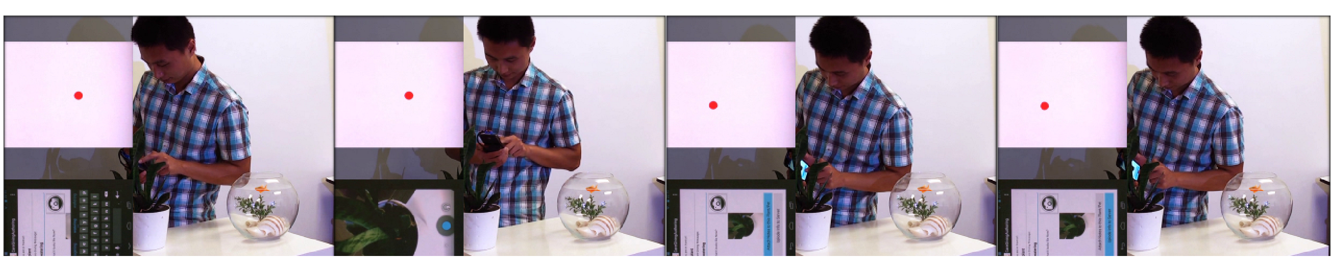

Figure 12. A family member attaches a message to the indoor plant. Red Dot: current position of the mobile in the projection area

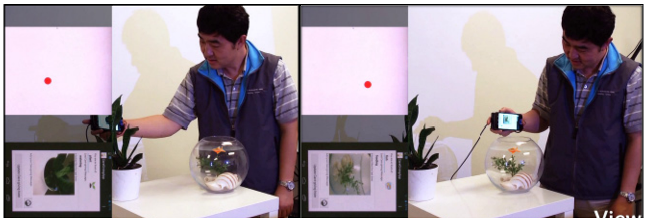

Figure 13. User "finds" the hidden care-giving message by moving his phone close to the plant or fish tank

another button to upload all messages to the server (4th image).

In Figure 13 shows another member B comes later to check the status. When he moves his phone close to the plant first, the message and photo show up (left). Then He moves the phone to fish tank to check related messages (right). Notice that on the UI, he can update (attach) his own care-giving messages to the plant/fish tank so as to notify other members as well.

6.2 Shopping Assistant App

One of the benefits of the HiFi system is the independence of illumination and textures (*Challenge 1*). Computer vision based recognition approaches are usually sensitive to illumination and texture, but our coded light system is not. Taking a clothing shop as an example, the highly similar colors among clothes (e.g. many in black or white) make computer vision recognition barely work. So this app demonstrates how our system meets *Challenge 1*.

Attaching digital content onto the goods in shops (e.g. showing vivid pictures of clothes on models, discount info and price) might positively affect their buying behavior. One important advantage of digital format instead of traditional paper price-tags is that they are easy to update and extend. The new discount/price information can be changed on web server side dynamically and reflected on Mobile UI immediately.

With regard to *Challenge 4*, the digital content mainly flow in one direction (shop manager to the customer). So we have designed two mobile apps for "Hide" and "Find". Mobile Hiding is adopted here for shop staff ("hider") to physically go through each cloth item to attach digital content. The mobile app UIs are shown in Figure 14. All clothes info is stored in the web-server. Shop staff only needs to choose the right brand and style from the drop-down menu list (left), and then the corresponding price, size and picture on a model will be shown up in the UI. As the discount information might change frequently, shop staff can manually type in the "NOTE" field (middle). Content will show up in customer's mobile app UI (right).

The final user experience is shown in Figure 15. Shop staff associates the digital content to each cloth (top images). While shopping, the customer uses a mobile phone to check the hidden information (bottom images). One thing worth pointing out is that this app could also be extended into a platform to support mutual information exchange, so that customers can give comments via mobile app and associate them with the clothes. Other customers can review them to make better purchase decisions and the shop managers can also use them to improve their services.

6.3 Museum Assistant App

While visiting museum or exhibitions, we always see many art works that are not familiar to us. More information about these art works would help understand their meanings. There are several ways of associating extra digital information to the art works. One approach is adding visual codes (e.g. QR code) or RIFD tags on/around them. But the tags change the natural appearance of the

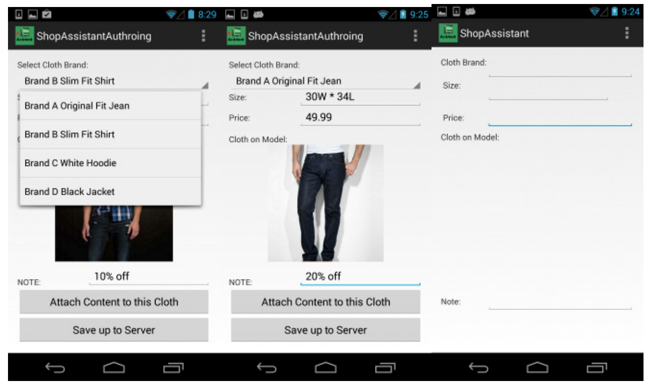

Figure 14. Mobile UI for "hide"(first two) and for "find" (last)

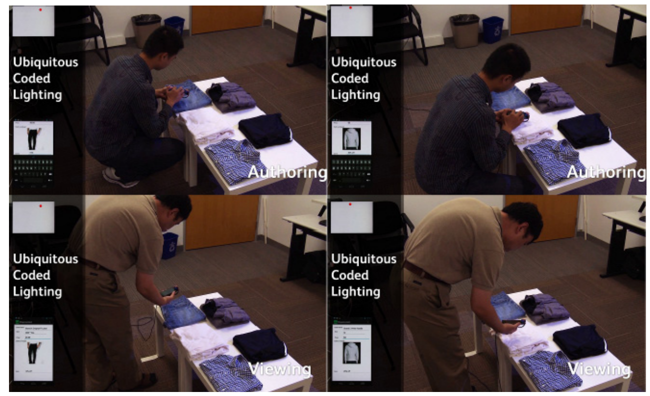

Figure 15. Shop staff "hides" numerous info on each cloth (top) and customer uses mobile app to "find" the hidden content.

art works and also distract attention. Another way is by taking a picture of the art works and then uses computer vision techniques to recognize them to find more information. The recognition accuracy varies depending on the perspective distortion and light conditions. More importantly, most museums/exhibitions do not allow photography. Instead, our Coded Light system can locate each art work in real time without visual distraction.

Unlike the previous two apps, the "hider" actually does not need to be physically close to the art works to hide the information. Meanwhile, "hiding" on many objects in one place is also preferred (*Challenge 5*). Considering these characteristics, we designed the Fixed-Camera based Hiding module (section 4.2). The application's UI is shown in Figure 8.

Two main steps are required to "Hide": *defining an object area* and *associating with a digital resource*. The first step is done by dragging the mouse over the physical object (e.g. green rectangle in Figure 8), which is defined by its top-left and bottom-right corners. Since the object area is defined in Camera Coordinate World but the mobile device's position is calculated in Projector Coordinate World, a calibration step is needed (top-right area of Figure 8). The details are explained in Section 4.2. The second step is done by clicking the *"Browse to Find Resource"* button and choosing the related resource. The object area information and digital content will be linked together as a JSON String. All objects' configurations come together as a JSON Array. The format is shown in Figure 16. It contains the definition of two objects; each one is inside a bracket. "type" means the type of resources: "VIDEO" and "TXT" represent video and text respectively. "tl_x","tl_y","br_x", "br_y" are TL and BR corners' coordinates. "mmurl" contains the URL to the resources.

```
[
{"type":"VIDEO",
"mmurl":"http://192.168.20.190:8080/ObjectsConfig/
NotreDame.mp4", "tl_x":127, "tl_y":44,
"br_x":321, "br_y":166
},
{"type":"TXT",
"mmurl":"http://192.168.20.190:8080/ObjectsConfig/
MulanStory.txt", "tl_x":642, "tl_y":206,
 "br_x":864, "br_y":338
}
]
```

Figure 16. Configuration file for museum assistant app

The coded light is projected towards the art works on the wall. The mobile app checks its current location with each object's area in the config file. If it finds itself in one of the object areas, the corresponding "*mmurl*" is used to fetch the video stream, which will be played immediately on the mobile phone. The user moves the phone out of all art works' areas to indicate he is no longer interested in them, and the video stream will disappear immediately. The fast response in showing and hiding the digital content is due to fast localization of coded light (80 pos/second). In addition, all art works do not have to be in the same plane (an art work is in the front in Figure 8) as long as they do not occlude each other from the projected coded light point of view.

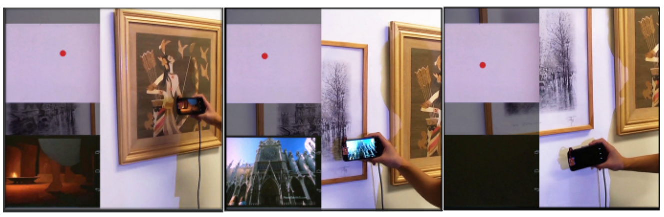

Figure 17. Different video streams are played when the mobile is in different art works areas (right img: stream goes away immediately while the mobile is out of object area.)

7. DISCUSSION & FUTURE WORK

If a physical object's position changes (e.g. room re-arranged), the user needs to apply one of the "hide" approaches to update its new location. Therefore our HiFi system is more suitable in scenarios where objects are not moved often (e.g. furniture showrooms).

The mobile device can be held in different orientations (e.g. landscape, portrait), tilt and rotate within certain angles. However, our system does require a direct light path between the light sensor and the projector light beam.

Although the DLP projector used in our current implementation costs several hundred dollars, a portable mobile projector (typically less than a hundred dollar) can also be used instead which might achieve decent but slightly slower localization speed.

Our HiFi system can track more than one mobile phone at a time, so multi-user collaborative application is one future direction. In addition, our HiFi system is scalable. By assigning different logical coordinate areas to different projectors' projection areas, the system can stitch multiple projectors together to cover a bigger space. The seam of different projection areas need to be handle carefully, as the overlap of two projections might cause inaccuracy in decoding algorithm, which we plan to improve in the future too. Another interesting point is that the multiple projectors do not have to be physically in one place and can be distributed in different geo-locations. So HiFi system can potentially enrich distributed working experience as well. With wearable computers (such as Google Glass and Smart Watches) getting popular recently, the HiFi system can also leverage them for displaying digital information instead of using a mobile phone.

8. CONCLUSION

In this paper, we proposed the HiFi system, which combines coded light localization with mobile applications to "hide" and "find" digital content associated with physical objects. We analyzed design challenges from both user experiences and system robustness points of view. Coded light localization is fast and independent of textures and light condition. It also requires no marks and has almost no visual distraction (illuminated area is constant solid gray to human perception). Three representative applications were designed to explore various challenges of HiFi.

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