Product Requirements Document:
Digital Cloaking Instrument
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Faculty Advisor: John Howell
Senior design team: Johana Escudero, Xi Zhou, Shenghan Gao

Rev	Description	Date
D	PRD Final Draft	12-16-2016

Team Dynamics
Johana Escudero - Project Coordinator, Customer Liason
Xi Zhou - Document Organizer
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1. General Information

Our customer wants to cloak a transportation system so the scenery behind it is conserved. The idea is to have multiple, stationary, 1m x 1m screens that can be joined together to an appropriate size (large enough to cloak the transportation system). Our work will involve creating a smaller prototype of a 1m^2 block using a small display such as a cell phone screen. The final cloaking screen needs to work at viewing distances of 50 feet or further, outdoors (day and night), and it has to maintain an angular resolution close to the resolution of the human eye. These requirements, especially the resolution requirements, are to make the cloaking effect believable. The composite image should contain enough views to cover ±15 degrees horizontally, and the views must update every ~15 minutes or faster. Obtaining an image close to real time is desired, but not required. We are responsible for creating a lenslet array, finding an image acquiring procedure to obtain images for the final composite image, and optimizing the image processing routine. We will also help with preparing a demo in December that Dr. Curtis and Prof. Howell will use to seek additional funding for this project. Our PRD includes specifications for the demo in December and specifications for our senior design prototype next semester.

The digital integral cloak consists of three main subsystems:

1) Image capturing system: An array of CCD cameras to capture the scene behind the cloaked region from many perspectives.

2) Image processing: The images are processed to create a composite image.

3) Display: A custom display is made from an extremely high-resolution optical display covered by a lenticular array.
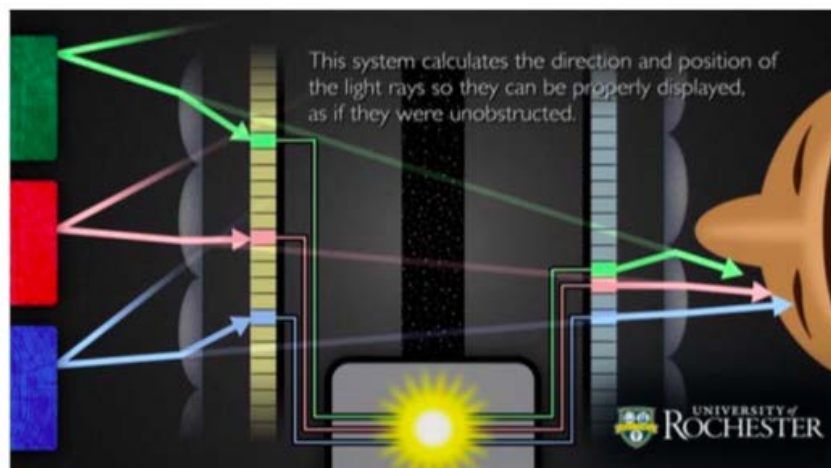

Figure 1. Digital cloaking architecture. Left to right: image capturing system, image processing, and a display covered by a lenticular array. The lenslet array makes it appear like the rays from the object have passed the obtrusion (screen) undeviated. Image credit: Frame taken from University promotional video produced by Matt Mann.

To make the scene look "real" (change with a viewer's perspective), a lenslets array is placed in front of the display (that is displaying a composite image) to send different images

to different viewing angles. The display is placed at the focal plane of the lenslet array, thus the light from each pixel will be approximately collimated and look to be the size of one lenslet. Each lenslet then becomes a new "pixel" called a superpixel.
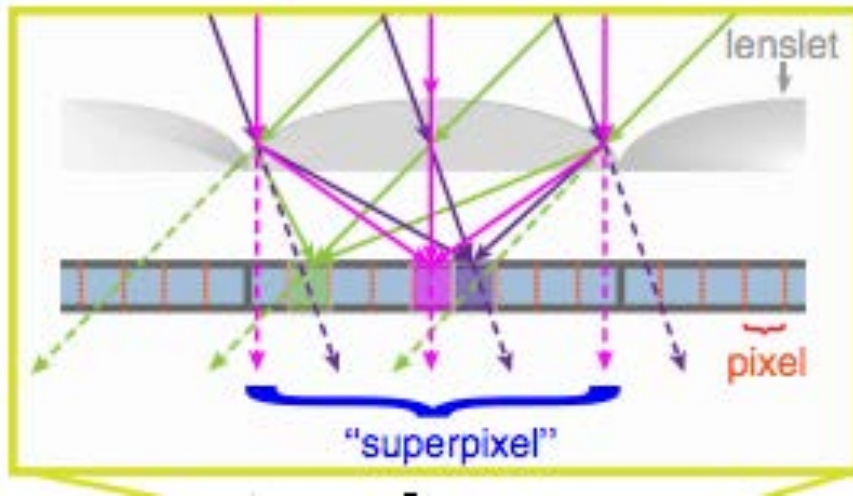

Figure 2. Detailed view of the detector array using a lenslet-based detector.
Reference: Joseph S. Choi and John C. Howell, "Digital integral cloaking,"
Optica 3, 536-540 (2016)

2. Specifications for Senior Design Project

Our customer, faculty advisor and team are all aware the following specifications can and likely will change during the spring semester. It is easy to adjust to changes since we have done an initial analysis using different parameter such as: lpi (lens per inch), viewing distance, number of desired views, and different types of interlacing. This means that even if a parameter changes, we will be able to adjust accordingly.

2.1 December Demo

The prototype will be to show a committee the possibilities of a cloaking display. The prototype will be a board with rectangular cell-phone-sized holes. Most of the holes will be empty, showing a scene in the background, but one of the hole will have a Z5 phone that is covered with a 20 lpi lenslet array. Our goal is to trick people into not seeing a phone is behind one of the holes.

Specifications:
- 20 lpi = 1.27 mm/lens
- Viewing distance: 20 lpi is good for 4.37 m away
- Angular range: ± 15 degrees
- Number of views: Since we are going to use the 20 lpi lenslet array from Prof. John Howell to proof concept, the number of view we will get from the lenslet array will be 245 views:

$$\frac{(806\ ppi)\left(\sqrt{37}\right)(3\ pixle/rows)(2\ rows)}{(6\ rows)(20\ lpi)} \approx 245\ views$$

- Superpixels: with the 20 lpi lenslet array, the number of superpixels is equal to 787

        super pixels/m.
- Interlacing: Interlacing on Mathematica code

2. 2 Senior Design Prototype

Specifications
- 6 lpi: From 50 feet away this corresponds to a spot size of 4.43 mm, meaning each lenslet (super pixel) should be ~ 4.43 mm (equivalent to 6 lpi).
- Viewing distance: 50 feet away
- Angular range: Undecided
- The number of views required for near perfect cloaking is:

$$\frac{90 \ degrees}{1/60 \ degrees} = 5400 \ views$$

Which is not possible to obtain with current display technology. The number of views will instead depend on our display, which is the highest density 4K display available on the market. The maximum number of views we can get from the Z5 screen is:

$$\frac{(806 \ ppi \ )(\sqrt{37})(3 \ pixel/rows)(2 \ rows)}{(6 \ rows) \ (6 \ lpi)} \approx 817 \ views$$

- Superpixels: using 6 lpi lenslet array, the number of superpixels is equal to 236 super pixel/m
- Interlacing: Improved code on Matlab
- Screen control: Customer would like to be able to control multiple Z5 screens simultaneously, to meet the desired 1m by 1m screen.

3. Considerations

3.1 Environment
Since the cloaking display will be outdoors we will need to consider the following:

- Brightness: We need a display screen bright enough in the day, but also adaptable to nighttime use
- Weatherproofing: Making sure CCD cameras and cloaking display is safe outdoors during different seasons (over a range of temperature degrees) and regular weather conditions (water proof)

3.2 Power supply
Similar energy consumption as a commercially available typical Samsung screen for the same area.

3.3 Resolution
Based on human eye angular resolution: 1 arcmin.

3.4 Super Pixels

A super pixel is a single lens in a lenslet array under which many smaller pixels collimate light out in different directions. Each super pixel images a specific angular view of one scene. The number of pixels under the lenslet relates to the number of views available, so for more views (which is desired, since we need it to work over a wide angular range) we need lenslets (super pixels) large enough to collimate the output of a high number of pixels.

3.5 RGB Re-grouping

The display's RGB pixels are horizontally aligned, but to increase the horizontal resolution we will regroup the RGB pixels diagonally. Regrouping the RGB pixels allows us to increase the horizontal ppi by a factor of six by trading off six times the vertical ppi. Regrouping RGB pixels involves some coding to reprogram the image being displayed. This is done by rearranging the composite image's array, which can be done on Matlab (or Mathematica).

Figure 3. Pixel arrangement of Xperia Z5 Screen. This layout is not an accurate representation of the RGB pixel distribution.

*Note: We need the screen to work for ± 15 degrees horizontally, but only ± 3 degrees vertically. So it would be okay to improve the horizontal resolution while trading off vertical resolution.

However, after checking the screen with a microscope we found the pixel alignment actually looks like the drawing below.
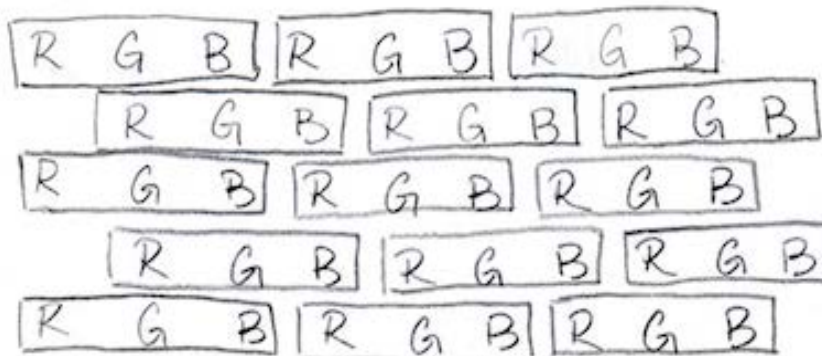

Figure 4. RGB pixels alignment of the Z5 screen. Drawing is not to scale. The actual RGB pixels are square not triangular.

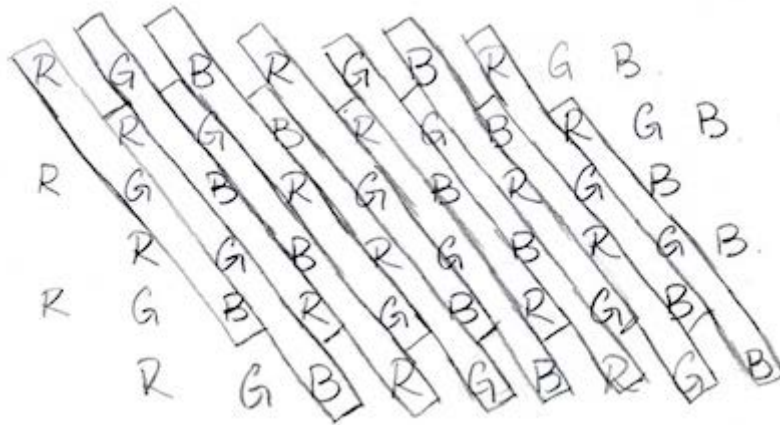With regrouping, the RGB grouping is the following.

Figure 5. Regrouped pixels alignment. Drawing is not to scale.

After regrouping, the horizontal pixel density of the screen will increase about 6 times (by a factor of $\sqrt{37}$). This factor of six comes from a combination of a 3X increase from the sub RGB pixels combined in rows 1, 3, 5, and another 3X increase from the sub RGB pixels combined in rows 2, 4, 6. This also means the vertical pixel density of the screen will decrease by about 6 times.

Note: The horizontal and vertical pixel density is a rough estimation, since the pixels are actually aligned at a 9.46-degree angle counterclockwise to the vertical direction.

The steps we are taking for regrouping are:

1. Figuring out how to write a function which takes a video and integer i as input and spits out the i-th frame of the video.

2. Write a function with determines how many frames are in a video.

3. Write a function which takes an integer N and calculates M integers which are all separated by the same integer m and roughly centered around N/2. For example, N = 1024, M = 6, m=3 gives solution 500, 504, 508, 512, 516, 520 as a satisfactory solution. This will be used to determine which frames to pull from the N frames of the video given M views and frame spacing of m frames.

4. Additional steps will be added as specified by the client.

4. Current Difficulties

1. Consulting with people in the ECE department on the possibility of controlling multiple Z5 screens simultaneously to display a 1m by 1m image.

2. Merging 420 views into one composite image.

3. Looking into a commercial lenslet array that meets (or is close to) our specification for our senior design prototype.

4. Re-grouping RGB pixels by Matlab or Mathematica.

5. Non-senior Design Responsibilities

We are not responsible for the following:

1. Weatherproofing to, for example, changes in temperature and seasons

2. Image capturing, which involves a mechanical setup for holding/sliding camera(s)

3. December Demo - Our group will be helping the customer complete the UR Venture Proposal demo, but we are not responsible for the completion of the proposal or demonstration.

4. Updating image every 15 mins, which involves improving the code for creating a composite photo out of multiple views.

6. Timeline and Things to do Spring 2017

January
-   Coding for Composite Image:
    -   Using a scanned video of a scene, our goal is to generate code that exports one frame every 5 frames, and then composites those exported frames into a single composite image. The desired result is to have the composite image automatically save right after the scan process is done. We want to process to be quick so the image updates at least every 15 minutes.

February
-   Connecting Multiple Screens
    -   Consult with experts from the ECE department on how to have multiple screens connected simultaneously.
-   Remote Control of the Display
    -   Research on controlling the whole screen (multiple connected screens) with a PC.

March
-   Applying lenslets array on display
    -   Cut acrylic board to the size of the screen
    -   Cut the lenslets to the angle of the pixel alignment (9.5 degrees).
    -   Adhere the lenslet to the acrylic board dust and air bubbles free.
    -   Estimate the lenslet focal length and set up the screen to the focal plane of the lenslet.

April
-   Testing Design
    -   Once we have a working screen, we will let our customer decide how he wants to display the technology. We have had a few brainstorm sessions to decide where we will put the display. A few ideas we have talked about are: in a hallway, on a door, and in a cell array (like what is being done for the December demo). Once we find a good idea that works with our setup for the

display, we will showcase it during senior design.

7. Appendix

7.1 December Prototype Progress

<u>Johana</u>
- Framing: We sent a CAD design of our board design to someone at UR Ventures. The board will be made out of wood and painted matte black.
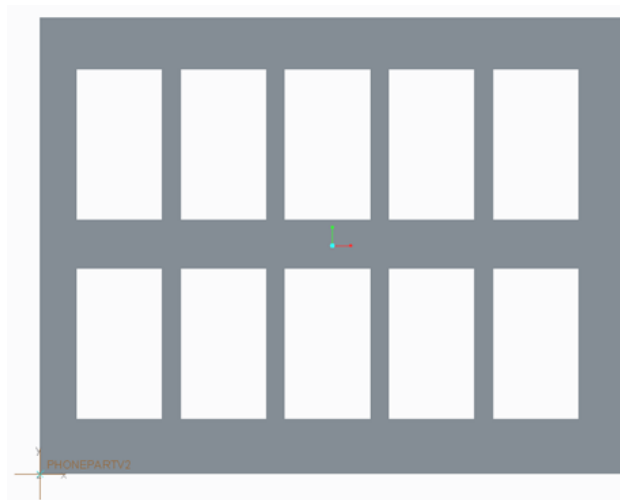

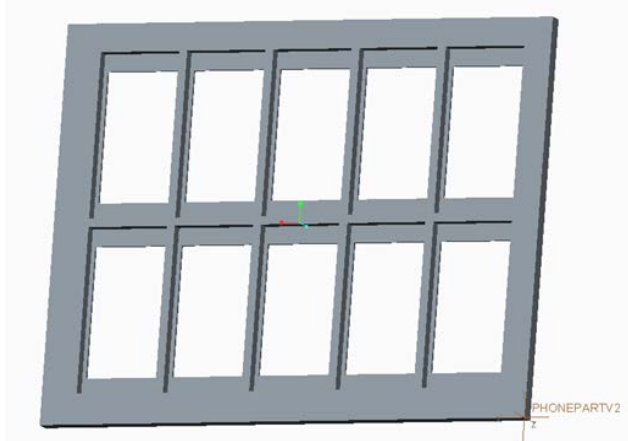Figure 6. Snapshot of CAD file showing the front view of the framing.

Figure 7. Snapshot of the CAD file showing the back view of the frame. Each hole is cut to fit a cell-phone, but only one of the holes will contain a cloaked phone display.

- Interlacing processing: Interlacing means taking a composite image and modifying its array to how you would like the phone to display the image. By rearranging the array, you can change which pixels are showing specific parts of the image, meaning the pixels get "regrouped" to function vertically rather than horizontally. My contribution will be taking the work done on Mathematica and translating it to MATLAB (so the image processing is quicker) and making modifications/updates for the code to work with our specific RGB display.

Shenghan
- PC phone interface: After the lenslet is aligned to the display, it would be tedious to take the lenslets off just to be able to swipe on the phone screen (to change an image, change phone settings, etc.). That would mean realigning the lenslet to the screen every time we need to use the phone screen. It would be much more convenient (and time efficient) to remote control the display phone with another device. Currently we are using an application called TeamViewer. Installing this application on two separate phones gives us the ability to control one phone (with lenslets attached) with another. It will be like the two phones are sharing a screen; the phone without a lenslet array will be used to change settings on the phone being used as a display.

Xi

- Lenslet array: The lenslets array is cut to the size of the phone screen and then adhered onto an acrylic board that is also the size of the screen. The acrylic's purpose is to protect the phone display. To correctly place the lenslet array (adhered on the acrylic) one focal length from the display pixels, we would need to know the exact location of the pixels and the focal length of the lenslets. Since we do not know these parameters, we can only estimate by putting the lenslet at various distances from the display (using small pieces of stacked paper as spacers) and finding the best resolved image. Previously with the iPad mini, the distance was about 8 pieces of paper. Due to this display being different the thickness of the screen (from pixels to the cover) will be different. So we will work from the 8 pieces of paper to find the best spacing.

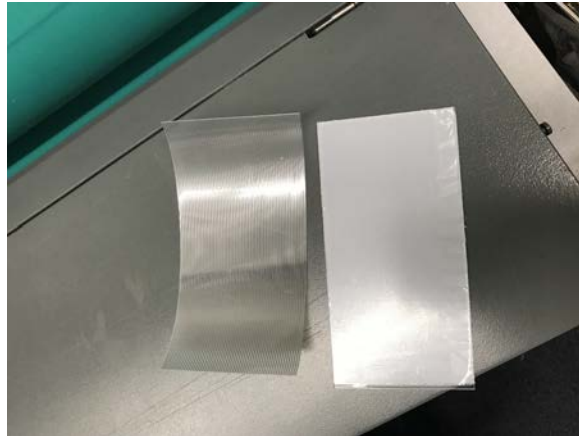Figure 8. Lenslet array sheet.

Figure 9. Cut lenslet array (left) and acrylic board (right).

Figure 10. Adhering a lenslet array to an acrylic board using a roller.

7.2 Display (Xperia Z5) Specifications

Since we need multiple views, where the number of views corresponds to how many pixels we can fit under a lenslet, we need a display with a high pixel density. A higher density gives us more pixels to create views with in a given area (lenslet size). Even though the Xperia screen has a display that is beyond the resolution of the human eye, only a few of its pixels are used per view making all of the pixels in the display important. In the end each view will be at/close to the spot size resolution of the human eye.

Figure 11. Picture of Xperia Z5 phone screen

- Display model: Xperia Z5 cell phone screen.
- Dimension: 5.5 inches (diagonal)
- Pixel Pitch:806 pixels per inch (ppi).
- Resolution: 2160 x 3840
- Resolution with regrouping:

  Super pixel (resolution of one image of the composite image): 53 x 631

  Sub pixel: 13138 x 631

Where the horizontal Super pixel resolution is calculated by:

$$\frac{(2160)(\sqrt{37})}{246 \ views} = 53 \ Super \ pixels$$

This is a rough estimation, since the pixels are actually aligned at a 9.5-degree angle counterclockwise to the vertical direction. The $\sqrt{37}$ comes from the phone screen rations, which was previously discussed in section 3.5.

7.3 20 LPI Specifications

Size:
20 LPI means 20 lens per inch.

Focal length estimation:
1. Start with the image of a single RGB pixel line (with a black background) on the display screen. The line should be in the lenslet orientation.

2. Place the lenslet above the line, where the line should be approximately in the middle of one lenslet.

3. The focal length should be about 8 layers of paper, so start to test the spacing with 5 pieces of paper, and add one layer at a time.

4. When the lenslet is a focal length away, only one lenslet will show the pixel line while all the other lenslet stay dark. Even when changing the viewing angle, only the particular lenslet will be illuminated. If the distance between the display and lenslet is shorter than the focal length, there will be more than one illuminated lenslet. If the distance between the display and the lenslet is longer than the focal length, there will be one lenslet partially illuminated.

Angle of the lenslet placed on the screen:
The lenslet is expected to be about 9.46° counter clockwise to the vertical direction of the screen.

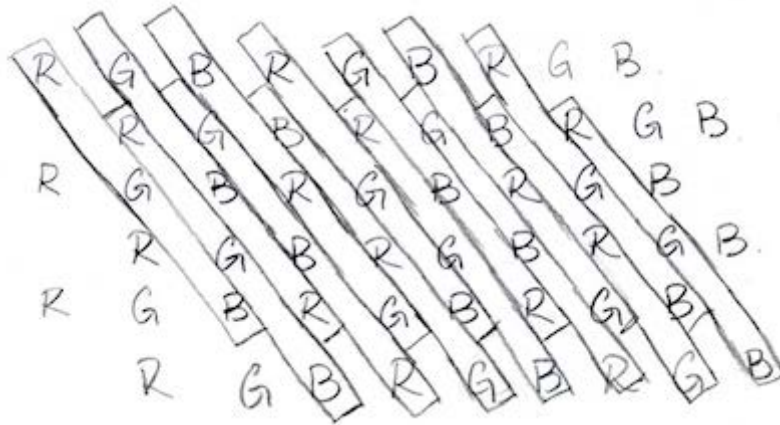The angle the same as the regrouped pixel alignment.

Figure 12. Regrouped pixel layout. The pixel sizes are not to scale. The ratio of the length of one horizontal RGB to its height is 1:1 (the horizontal RGB is a square).

The angle of the regrouped pixel can be calculated by

$$arctan\left(\frac{1\ pixel}{6\ lines}\right) = 9.46°$$