Generating a Multiresolution Display by Integrating Multiple Projectors

Yu-Pao Tsai[1,3], Yen-Nien Wu[2], and Yi-Ping Hung[1,2]
[1]Institute of Information Science, Academia Sinica, Taiwan, R.O.C.
[2]Department of Computer Science and Information Engineering, National Taiwan University, Taiwan, R.O.C.
[3]Department of Computer and Information Science, National Chiao Tung University, Taiwan, R.O.C.
Tel: +886-2-23625336 ext 433, Email: hung@csie.ntu.edu.tw

Abstract

Research on creating a large, high-resolution, low-cost display system has become increasingly important due to the growing desire in many fields for bigger and better displays. In order to get a better balance between cost and resolution, we propose a multiresolution approach that projects the foveal view in higher resolution and the peripheral view in lower resolution. The major difficulty is how to eliminate the noticeable seams between different projections by geometric calibration and photometric uniformity. In this paper, we develop a semi-automatic approach to accomplish this task using a video camera. As opposed to previous works, our method for geometric calibration allows the display screen to be either planar or non-planar. It does not require highly accurate camera calibration, nor does it require 3D geometric estimation of the screen surface. Instead of using a spectroradiometer, an expensive device previously used for color calibration, we use a low-cost video camera and still result in acceptable performance in our experiments.

1. Introduction

Research in building large, low-cost displays [3][5][8] has become increasingly popular due to the growing desire for bigger and better displays in the entertainment, industrial, and scientific worlds. An approach utilizing multiple projectors has attracted a great deal of interest. This research aims to create large, high-resolution displays by presenting improved methods of creating a "projector mosaic" [8] which is a collection of projected images combined to form one large display. Most methods use many projectors to provide high-resolution through out the entire display area. However, the audience only focuses on a part of the projected area, so only this area requires higher resolution. In this paper, we propose a multi-resolution approach that balances the cost and the resolution quality of a large display system.

In our experiments, two projectors are used to build a two-level display. We can easily extend to a multiple-level display by using more projectors. Illustrated in Figure 1, one projector is used for the large, general view, the other for the target view. Assuming the user always looks at the center of the display, the region labeled as *H* in the center of Figure 1 shows the region to be displayed in high resolution. We identify this region as the *Fovea Region*. The other region, labeled *L*, only provides the user an overview of the displayed content, and thus only requires lower resolution. We identify this region as the *Peripheral Region*.

In order to build a wall-size, multiresolution display, we must overcome two hurdles: (1) geometric calibration and (2) photometric uniformity. Geometric calibration obtains the transformation matrices between projectors and the display screen. To reduce human labor, a camera is used to develop fully or semi-automatic methods for geometric calibration. Many researchers have investigated this problem based on the assumption that the surface of the display screen is planar [1][2][3][8][11]. However, the display screen is not always ideally planar. If the content mosaic is projected onto a surface with some non-planar areas, the projection will be distorted. In a previous method [7], non-planar calibration required a calibrated stereo camera in order to estimate the geometry of the entire display surface. Our project performs non-planar calibration using an un-calibrated camera. An image projected onto any display screen will appear undistorted and normal.

Photometric uniformity eliminates color variation between fovea region and peripheral region. A previous work used an expensive device, the spectroradiometer, to deal with color variation [6]. This device characterizes the photometric properties of various projectors. Using information obtained form this device, they match the photometric characteristics of different projectors using per channel color look up tables. In our research, we achieve the same results with a commercially purchased video camera. Each projector projects three color channels (red, green, blue) individually, and then increases the intensity of each color by a given interval. The camera captures the images and uses the information to calibrate the colors between the multiple projectors to achieve color uniformity across the display.

The major contents of each part of this paper are as follows. Section 2 will give a system overview that briefly describes each stage of this project. The two parts of system calibration, geometric calibration and photometric uniformity, are given in Section 3 and 4, respectively. In section 5, the experimental results will be given and a conclusion will be drawn in section 6. Finally, a brief description of possible future works will be provided in section 7.

2. System Overview

The process of building a seamless, multi-resolution display system can be divided into two steps. In the first step, we deal with the geometric calibration which includes lens distortion calibration, homography estimation, and refinement for non-planar screen. Lens distortion calibration is used to correct the distortion made by camera lens. If the screen onto which we will project is planar, we can calculate homography which is the transformation between the screen and the projectors. If a screen is not perfectly planar, our method can be used to refine the transformations so that the displayed image will be undistorted and normal. The second step of our system deals with photometric uniformity which includes color calibration and intensity blending. Color must be calibrated because the color response is different for each projector. Color calibration is split up into three main components: non-linearity correction, luminance matching and chrominance matching[6]. Non-linearity correction finds a mapping function which is used to linearize the input-output responses for each projector. This mapping function provides the necessary input to generate the desired output, see subsection 5.1. Luminance matching finds the common luminance range among all the projectors by finding the brightest black and the dimmest white. In chrominance matching, we adjust the input-output responses by minimizing color difference between projectors. After color calibration, we compute intensity weight for the overlapped region so that projections in the overlapped region are blended and appear uniform with non-overlapped regions.

3. Geometric Calibration

3.1 Lens Distortion Calibration

The system in this project consists of one camera and n projectors. The goal of this project is to stitch n images from n projectors together to create one seamless display. A camera is used to obtain the relationship among the projectors, camera, and the display surface. Since any image captured by a camera is subject to lens distortion, the distorted image must be calibrated before processing the captured images. In order to calibrate the distorted image, we use the formula

$$\begin{aligned} u &= (v - v_C)(1 + \kappa d^2) \\ d &= \| v - v_C \| \end{aligned} \tag{1}$$

where v is the point on the image before calibration, u is the point on the image after calibration and v_c is the image center.

3.2 Estimation of homography

Assuming that the screen surface is planar, a structured pattern is projected onto the screen for each projector. Then a camera is used to capture the projection, and the pattern is detected from the captured images to compute homography between camera and projector. For each projector, a pattern point of 5x5 solid circles is used instead of a grid or checkerboard because solid circles are easier to detect and can be just as precise. In Figure 2, the white dots are the pattern points and the quadrilateral enclosing the dots is the estimated display region. The pattern point locations are used to calculate a 3x3 homography $H_C^{P_i}$ between the camera C and projector P_i. Given a point m_{P_i}, the location of the point on the camera image, m_c, can be determined using the following

$$m_C = H_C^{P_i} m_{P_i} \quad ; i = 1,2,..., N \tag{2}$$

Before appointing the area that the final image will be projected on, the *display area*, the relationship between the camera and the screen is first calculated. The display area on the screen can be located after appointing it on the camera image. Assuming the screen is predominantly planar, only the coordinates of the screen's four corners on the camera image are needed to calculate the homography H_C^S between the camera and the screen. Next, the display area is identified by selecting the following two coordinates on the camera image: the top-left corner and the bottom-right corner. Assuming that the screen area is a rectangle, the homography between the camera and the screen can be used to calculate the rectangular display area by using those two coordinates. This homography between the screen and the camera needs to be derived in order to identify which projectors are projecting which pixels on the display area. Since the homography between the camera and the screen has already been calculated, as is the relationship between the projector and the camera, the relationship $H_{P_i}^S$ between the projector and the screen can be calculated. That relationship is defined as

$$H_{P_i}^S = (H_C^{P_i})^{-1} H_C^S \tag{3}$$

In Figure 3, the display area is shown as the shaded region. The outer quadrilateral is the screen surface. Now, knowing which projectors are projecting which pixels, this information can be used to calculate the weight intensity necessary for each pixel from each projector.

3.3 Refinement for Non-Planar Screen

If a display screen is non-planar, the projected image will be slightly distorted. To deal with this situation, we apply an image warping method based on the radial basis function to calibrate this distorted image. Previously, an estimated homography between the pattern points and the detected points was obtained. A pattern of 5x5 points were projected, and widely spread so that the minor distortions due to the non-planar surface are not taken into account when calculating the homography. It is assumed that these non-planar regions are proportionally small in size and rare in number. To detect where the non-planar areas are, a larger number of pattern points is projected onto the display screen and the locations of these points are detected. With the estimated homography, the ideal locations of these points can be calculated and can be thus called the ideal pattern points. If the display surface is planar, then ideal pattern points and detected pattern points should match. However, if there are non-planar regions on the display screen, then there will be discrepancies between the ideal pattern points and the detected pattern points. Thus these areas are calibrated by warping the source pattern image so that the detected pattern points matches that of the ideal pattern points.

For better understanding of this non-planar calibration method, Figure 4 is used for demonstration. According to Figure 4, point P_1 on the projector image will be projected onto the screen and then captured as point P_2 on the camera image. The inverse homography relationship between the camera and projector is used to calculate the projector point P_3 from camera point P_2. Had the display surface been planar, then the projector point P_3 would have projected the point P_2 captured by the camera image. However, since the surface is not planar, point P_1 projected the camera point instead of P_3. Thus projector point P_3 needs to be warped to point P_1 to account for the non-planar surface. As a result, the region surrounding P_3 in the source image is warped in the same manner that P_3 was warped to P_1. In this paper, the radial basis function is adopted to perform the image warping [9].

4. Photometric Uniformity

5.1 Color Calibration

A successfully blended projector mosaic is not complete without color calibration because the color intensity is not uniform from projector to projector. Thus an algorithm that consists of three parts is applied: non-linearity correction, luminance matching, and chrominance matching [6]. Instead of using a spectroradiometer as in previous methods, we use a commercially purchased video camera to calibrate colors. Each of the three independent color channels, *r*, *g* and *b* is mapped. This saves the time spent on calibrating every combination of the three colors channels. Colors need to be mapped so that the colors projected by the superposition of the independent color maps for each channel match.

To begin the algorithm, the three color channels, *r*, *g*, and *b* are first transformed into a luminance and chrominance form. For example, the *r*, *g*, and *b* are transformed into the CIE-XYZ form [12]. This CIE-XYZ form is used to separate the luminance and chrominance components. In non-linearity correction, the problem is that the input and output response of each color channel is not linear. Ideally, when given a certain input, a certain output is expected. However, that is not the case and thus it is necessary to apply the non-linearity correction method, that generates a mapping table to linearize the input-output response. In Figure 5, the luminance level for every input intensity is shown. The ideal input and output responses of each channel is represented by l_p but the actual response is represented by f_p. This graph reveals the correct input level necessary for the desired output luminance level. The desired luminance level can be obtained by finding the correct input level necessary. The next step in this algorithm is luminance matching. In luminance matching, a common luminance range is found for all different projectors. This is necessary because each projector has a different intensity range. Therefore, in order to project a color-uniform image, the luminance range must be the same for all projectors. Thus, the highest and lowest intensity levels are obtained for each projector. With this information, according to Figure 6, the common range amongst the projectors is the brightest black and the dimmest white. Lastly, the final step of the algorithm is the chrominance matching. For chrominance matching, a reference projector is chosen and the other projectors are mapped to match that projector. A difference in color is obtained between the reference projector and the other projectors. This difference is represented as a distance metric E_{94} [4] and the distance must be minimized in order achieve color uniformity across the projectors.

5.2 Intensity Blending

When two projections overlap, the overlapped region has twice the intensity as the non-overlapped regions. This overlapped region is very noticeable obvious and can thus distract an audience from watching the picture, and instead attract their attention towards this bright region. The audience will tend to focus their attention on this one flaw in the projector mosaic. Thus, in order to seamlessly merge the images without any obvious overlapped region, an intensity blending technique is used to smoothly combine the images into one large picture. This technique, known as feathering or cross-fading, calculates an intensity weight for each pixel of the projector image. The intensity weights of the two images in the overlapped regions add up to the same intensity as the non-overlapped region. The assignment of intensity weights to each pixel is also called a mask.

Before the blending process, we let the user to select a region R_H, where is displayed in higher resolution. The shaded region in Figure 7 shows an example of a selected R_H. Once the R_H is selected, the projection region which is overlapped by two projections and is outside the R_H will be blended to obtain a smooth transition. We denote the projector used to display the foveal region to P_H, and the other projector to P_L.

For a pixel $\boldsymbol{u}=(s,t,1)$ on the image which is displayed by the projector P_H, we transform it to the screen coordinates. If it is inside the R_H, its alpha value is assigned 1. Otherwise, its alpha value can be calculated by

$$\alpha_{P_H}(\mathbf{u}) = e^{-d} \qquad (4)$$

where d is the distance to the nearest edge of R_H.

For a pixel $\boldsymbol{u}=(s,t,1)$ on the image which is displayed by the projector P_L, we transform it to the screen coordinates. If it is inside the R_H, its alpha value is to be 0. If it is outside the available projection of projector P_H, its alpha value is assigned 1. Otherwise, its alpha value can be calculated by

$$\alpha_{P_L}(\mathbf{u}) = 1 - e^{-d} \qquad (5)$$

where d is the distance to the nearest edge of R_H.

6. Experimental Results

In this experiment, two NEC LT157 LCD projectors and a commercial video camera was used. The resolution of the captured image on the video camera is 640 x 480 pixels. We apply our method to display three high-resolution images: the map image, the satellite image, and the circuit image. The resolution of the map image and the circuit image are 3Kx2K, and the satellite image is 3Kx1.7K. The original map image is shown in Figure 8(a). Figures 8(b) and 8(c) show the generated images for the foveal and the peripheral views. The projection result is captured by a camera, and the whole picture captured is shown in Figure 8(d). To see the details, the area marked black in Figure 8(d) is enlarged in Figure 8(e), where the right part is clearer and has higher resolution than the left part. Figures 8(f), 8(g), 8(h), 8(i) show another example of projection after shifting the viewing position to a new one. Figures 9 and Figure 10 show the projection results of the satellite image and the circuit image. Figures 9(a) and 10(a) are the original images, and Figures 9(b) and 10(b) show the projection results. Figure 9(c) and 10(c) show the comparison between different resolutions.

7. Conclusion

We proposed a multiresolution approach to constructing a large, low-cost display by integrating multiple projectors. In this paper, we construct a two-level resolution display system using two projectors in our experiments to demonstrate our method; it can be eaily extended to a multiple-level display by using more projectors. The idea of our multiresolution system is motivated to the foveal/peripheral vision of the human retina. The foveal region where the user wants to inspect the detail is displayed in higher resolution, while the peripheral region is displayed by the other projector to provide an overview of the content in lower resolution.

The major advantage of the proposed method is a substantial cost reduction in building large, high-resolution displays and without losing resolution in the interested region. Another advantage of this method is that, even when the display screen is non-planar, our method can provide undistorted projection without requiring 3D geometric estimation of the non-planar screen surface.

8. Future Works

In this paper, a single camera was used for the geometry calibration. Some researchers [1][2] used multiple views for a more refined geometric calibration. In the future, we will use a pan-tilt-zoom camera to improve the accuracy of geometric calibration. In addition, this research plans to adjust the radial attenuation of brightness from the center to the edges of the projector’s field of view so as to allow a more uniform display since the projector’s color is not uniform even within its own field of view. The next phase of this research is to divide the projector image up into n blocks and then calibrate each block individually to match a reference. Since there will be a gap between the blocks, the block center will be used to interpolate and smooth the gap across the blocks.

Acknowledgements

This work is supported in part by the National Science Council, Taiwan, under the grant NSC-92-2622-E-002-027-CC3.

Reference

[1] H. Chen, R. Sukthankar, G. Wallace, T.-J. Cham, "Calibrating Scalable Multi-Projector Displays Using Camera Homography Trees," *CVPR Technical Sketch*, 2001.

[2] Y. Chen, D. W. Clark, A. Finkelstein, T. C. Housel, and K. Li, "Automatic Alignment of High-Resolution Multi-Projector Displays Using An Un-Calibrated Camera," *Proc. of IEEE Visualization*, 2000, pp. 125-130.

[3] M. Hereld, I. Judson, and R. Stevens, "Introduction to Building Projection-based Tiled Display Systems," *IEEE Computer Graphics and Applications*, July/August 2000, pp. 22-28.

[4] N. Katoh, S. Ohno, “Three-dimensional Gamut Mapping Using Various Color Difference Formulae and Color Spaces,” Journal of Electronic Imaging, 8(4), 1999, pp. 226-250.

[5] K. Li, H. Chen, Y. Chen, D. W. Clark, P. Cook, S.

Damianakis, G. Essl, A. Finkelstein, T. Funkhouser, T. Housel, A. Klein, Z.Liu, E. Praum, R. Samanta, B. Shedd, J. P. Singh, G. Tzanetakis, and J. Zheng, "Building and Using a Scalable Display Wall System," *IEEE Computer Graphics and Applications*, July/August 2000, pp. 29-37.

[6] A. Majumder, Z. He, H. Towles, and G. Welch, “Achieving Color Uniformity Across Multi-Projector Displays”, *Proc. of IEEE Visualization*, 2000, pp. 117-124.

[7] R. Raskar, M. S. Brown, R. Yang, W.-C. Chen, G. Welch, H. Towles, B. Seales, and H. Fuch, “Multi-Projector Displays Using Camera-Based Registration,” *Proc. of IEEE Visualization*, 1999, pp. 161-68.

[8] R. Raskar, J. V. Baar, and J. X. Chai, "A Low-Cost Project Mosaic with Fast Registration", *Proc. of Asian Conference on Computer Vision* (ACCV2002), 2002.

[9] D. Ruprecht, and H. Muller, “Image warping with scattered data interpolation,” *IEEE Computer Graphics and Applications*, March 1995, pp. 37-43.

[10] M. Stone, “Color Balancing Experimental Projection Displays,” *Proceedings of the 9th Color Imaging Conference: Color Science, Systems, and Applications*, 2001, pp. 342-347.

[11] R. Sukthankar, R. G. Stockton, and M. D. Mullin, “Smarter Presentations: Exploiting Homography in Camera-Projector Systems,” Proc. of ICCV 2001, 2001, pp.

[12] G. Wyszecki, W.S. Stiles, “Color Science: Concepts and Methods, Quantitative Data and Formulae,” Second Edition, Wiley, 1982.

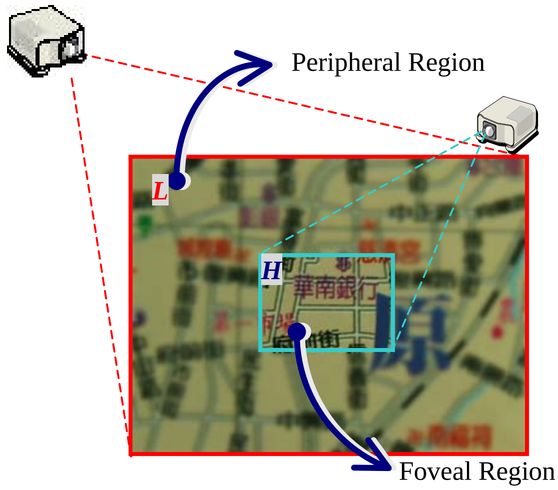


Figure 1. Illustration of multiresolution display generated by using multiple projectors.

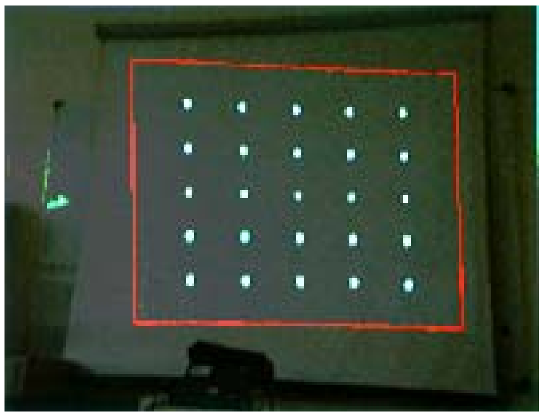


Figure 2. The detected pattern points and the estimated display region.

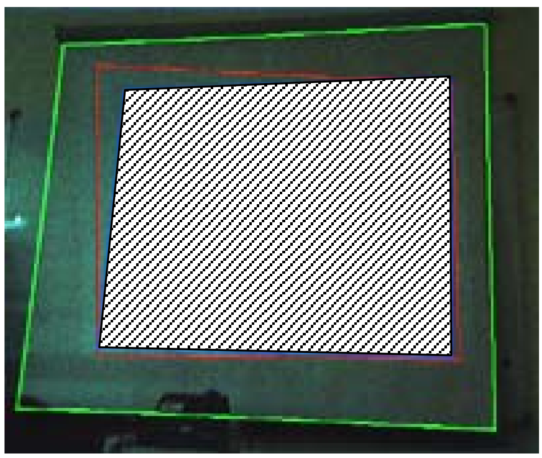


Figure 3. The display area is selected as the shaded region. The outer quadrilateral is the screen surface.

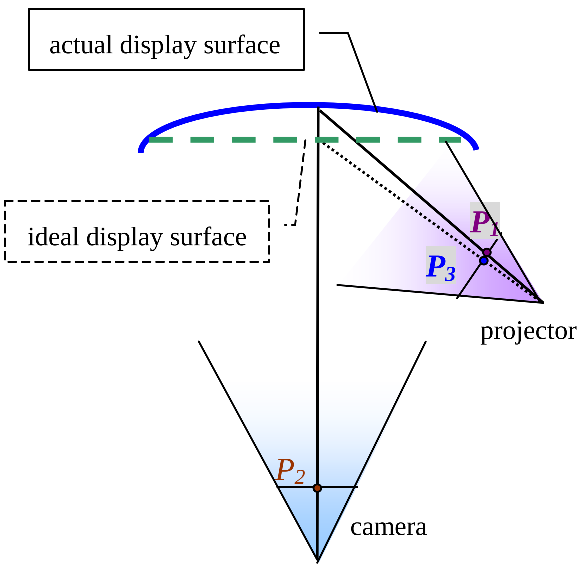


Figure 4: Illustration of non-planar calibration.

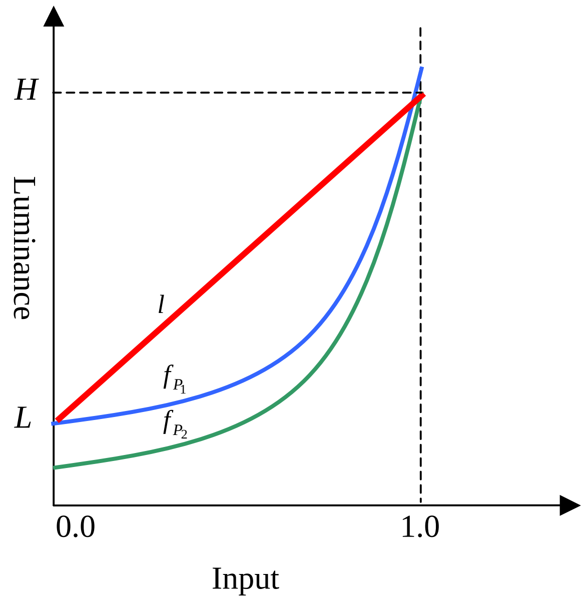


Figure 6: This graph shows the darkest white L, and the lightest black H, between two projectors. *l* is the common intensity range between the two projectors.

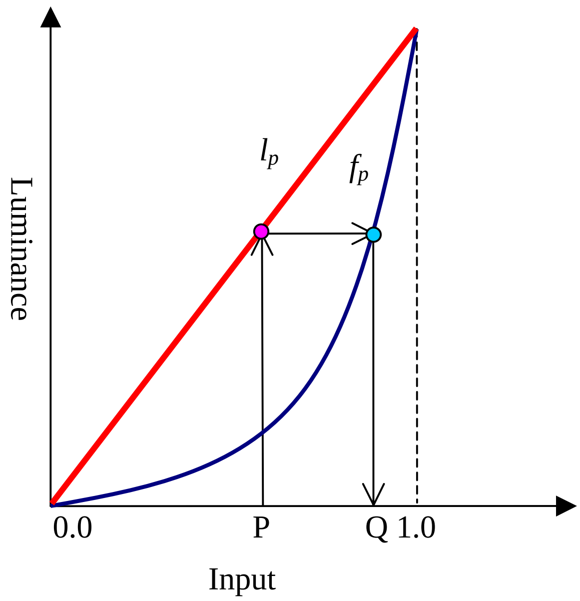


Figure 5: The ideal input and output response of each channel is represented by l_p; the actual response is represented by f_p. This graph reveals the correct input level necessary for the desired luminance output level.

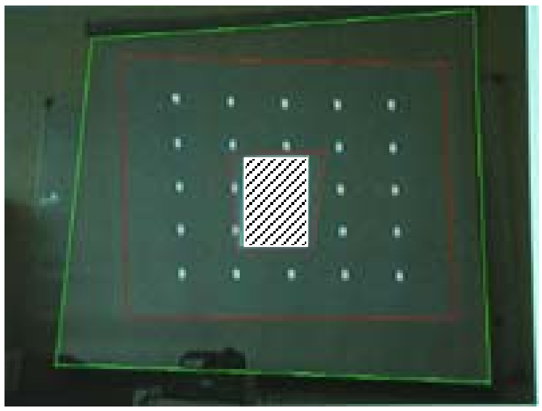
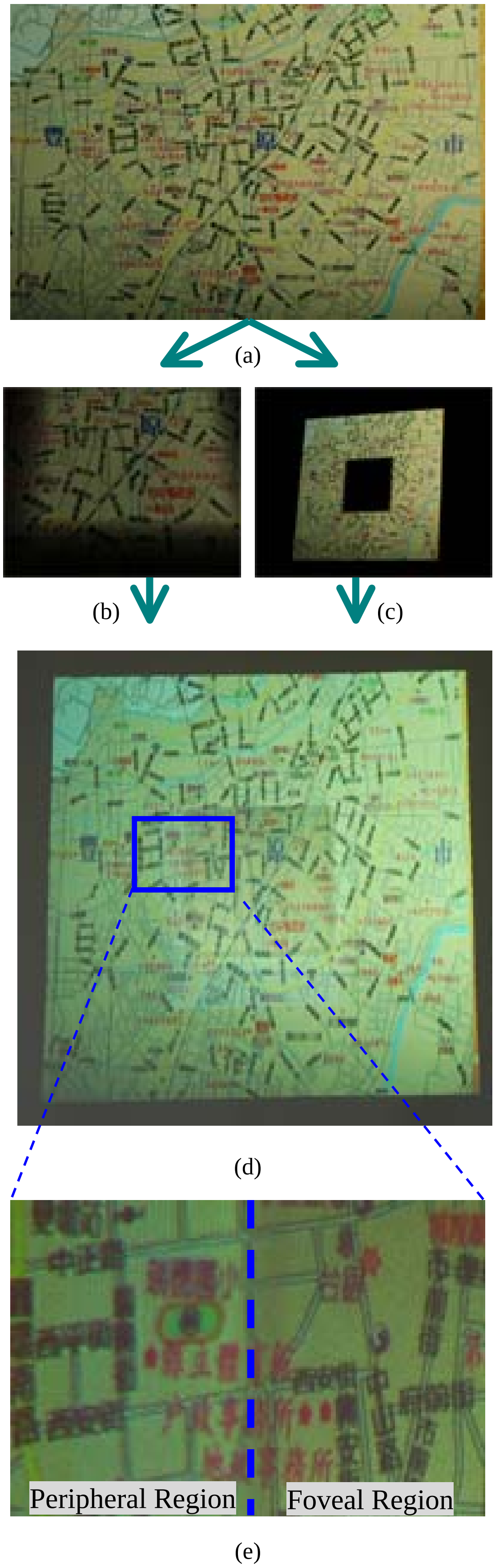


Figure 7. The user selects the shaded region manually to indicate the area on where the higher resolution image is projected.



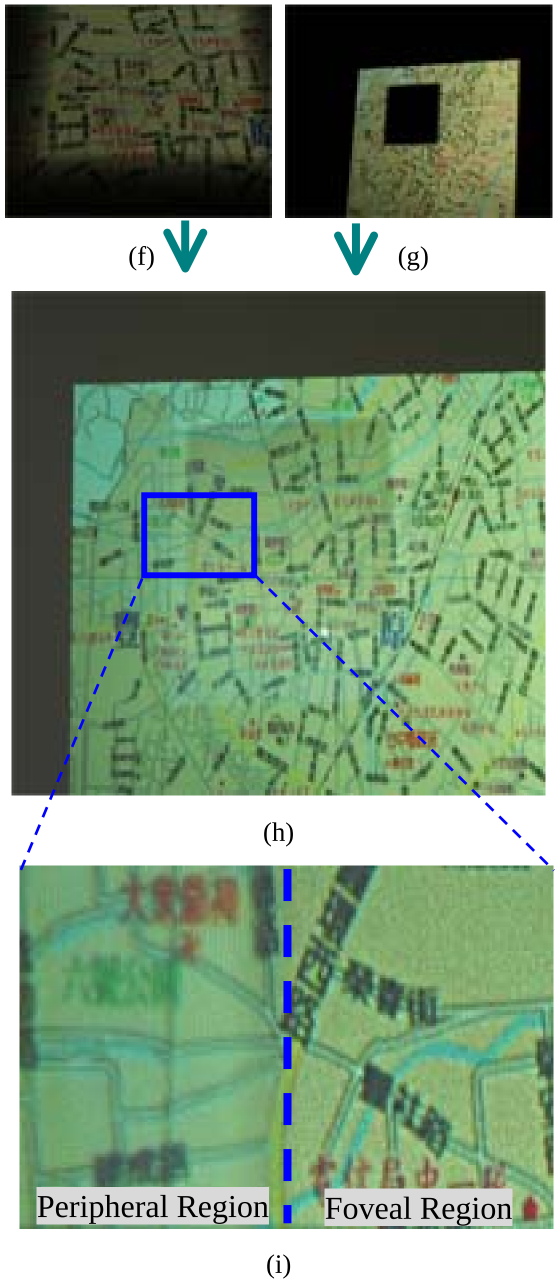


Figure 8. Multi-resolution projection of the map image.

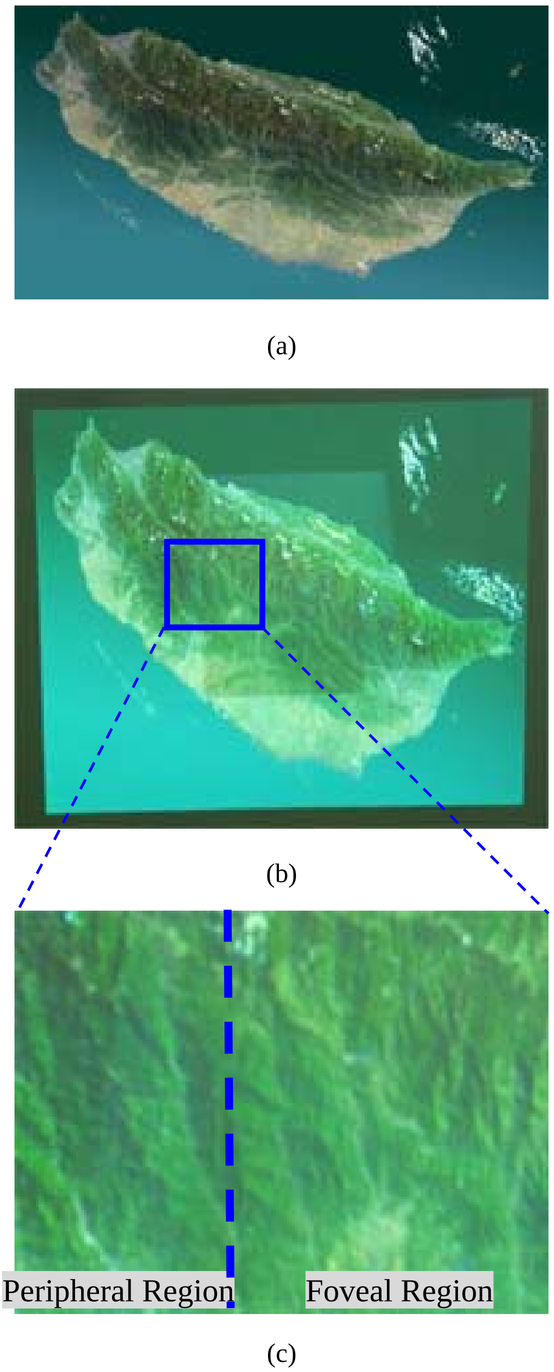


Figure 9. Multi-resolution projection of the satellite image.

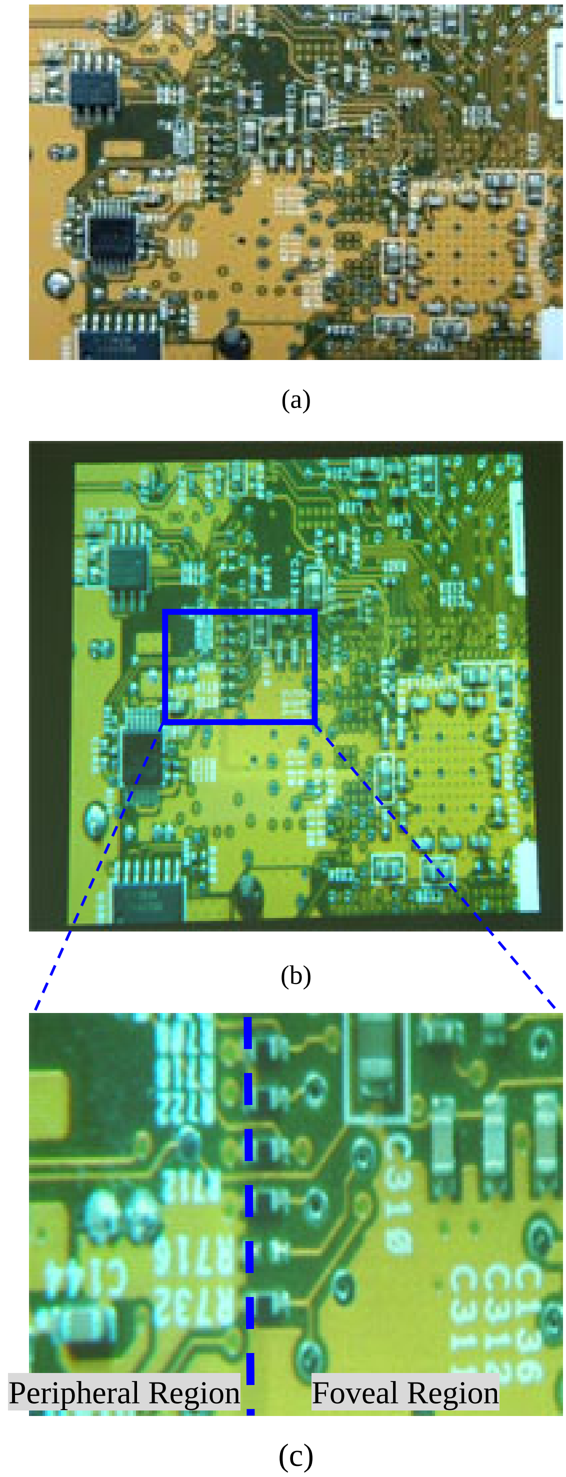


Figure 10. Multi-resolution projection of the circuit image.