Paper

Automatic Sub-pixel Projector Calibration

Supporting Improved Calibration for Projected Environments

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Abstract This paper presents a new hardware and software calibration technology to improve the process of automatic multiple projector calibration using photo detectors to support Spatial Augmented Reality. This research builds on existing calibration methods that employ point-based photo detectors by advancing the hardware with a larger surface area photo detector to locate sub-pixel position with structured light. This data is used to expand the Gray-coding algorithm with an additional step that improves the measurement. The novel hardware allows a sub-pixel position to be calculated and leveraged to improve alignment of multiple-projector environments. The results show the new approach improves position measurement from pixel accuracy using a point photo detector with Gray-code by an order of magnitude providing sub-pixel accuracy by leveraging the planar photo detector and additional algorithm steps.

Key words: Calibration, Spatial Augmented Reality, Structured Light, Gray-coding, Photo Detector.

1. Introduction

This paper describes a novel approach to perform automatic sub-pixel projector calibration to improve the accuracy of alignment of multiple projector systems over existing methods. While this solution is appropriate for multiprojector display walls[1], the main goal of this paper is for an automatic calibration solution to support multi-projector Spatial Augmented Reality (SAR) systems[2][3]. SAR employs projected light to present perspective corrected computer graphics that directly illuminate physical objects to enhance their appearance[4]. To achieve this illumination, a simple substrate is constructed with the desired shape. For example, the appearance of the white physical control panel prototypes (shown in **Fig.** 1) is enhanced by the SAR system.

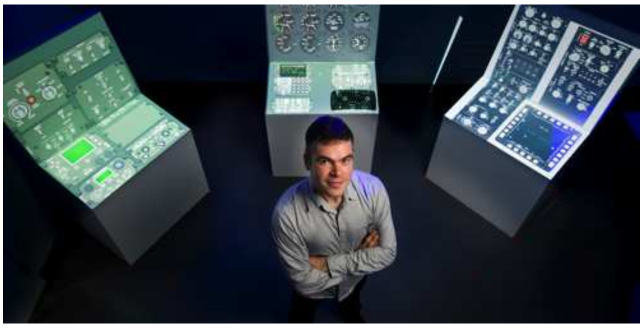

Fig. 1 Three mock-up control panels employing SAR to enhance their appearance.

Succinctly, this paper describes a novel approach to finding projector calibration parameters that are relative to physical points associated with the projection substrate[21]. Four goals have motivated us for this problem as a means to improve the usability of multi-projector systems in settings such as commercial, research and entertainment, and these goals are as follows:

(1) The system can calibrate a set of projectors to a known volume of space.

(2) The calibration performs at sub-pixel measurement to optimize alignment.

(3) The calibration system must be generic, easy to deploy and operate on arbitrary object shapes.

(4) The calibration may run continuously to detect and correct small changes to the projector alignment.

We present the following scenario to illustrate how we envision the calibration process operating. Consider a team designing a control-room, such as those used on submarines, with three workstations. The team employs SAR to visualize different control features on each physical prototype and different physical placements of the workstations, as depicted in **Fig.** 1. The team attaches a set of calibration cubes to known locations on the three physical prototypes. The system performs automatic projector calibrations for each of the physical prototypes. As the team moves, bumps, and adjusts

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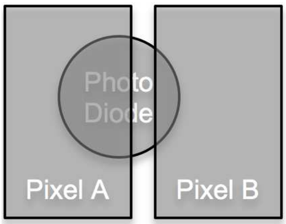
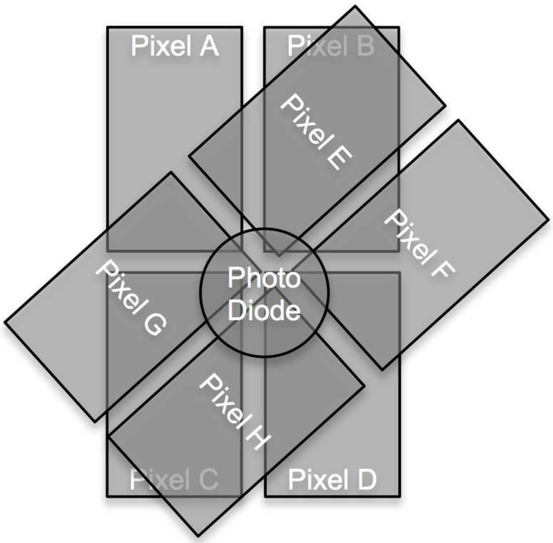


(a)



(b)

Fig. 2 Projected pixels on photo detector. (a) Overlapping of two projected pixels on a point sized photo detector. (b) Overlapping of eight projected pixels from two projectors.

the physical prototypes, the calibration system is able to make fine adjustments (at a finer resolution than tracking sensor system) to correct the appearance in real-time. Multiple projectors are employed as a means to reduce shadows while the team interacts with the system.

Current systems[5)] provide key functionality to support such scenarios. However, there are limitations that prevent the flexibility and performance we are aiming for. We have found that current point based photo detectors locate a position with no better than a whole pixel accuracy (not sub-pixel). A reason for this occurring is that in practice when projected Gray-coding is performed two pixels may overlap the photo detector (depicted in **Fig.** 2(a)). In this example it is clear that pixel A has a greater overlap, but during standard Gray-coding operations both pixels will be determined to be in this position. For this reason current algorithms employing Gray-coding do not render down to single pixel lines. We would like to determine sub-pixel location with respect to the photo detector.

Fig. 2(b) depicts the case of two overlapping projectors. Pixels (A, B, C, and D) from projector one overlap the pixels (E, F, G, and H) from projector two. All eight pixels will be registered with the photo detector. Sub-pixel accuracy would allow the best alignment of pixels to the photo detectors position. Additionally we can assign particular pixel pairs from the two projectors. In the case of our example, we could define pixels C and G to overlapping along with H and D.

This paper presents four scientific contributions to photo detector calibration methods for Spatial Augmented Reality: 1) A new hardware approach using a planar photo detector with a large surface area in place of a point sized photo detector as used on previous systems. 2) An algorithm that extends Gray-coding with sub-region based exposure on the planar photo detector to find a sub-pixel position. 3) An evaluation to quantify the results between a point sized photo detector and Gray-code calibration system with our planar photo detector and sub-pixel algorithm. 4) A generic hardware design with detached photo detectors allowing arbitrary models to be calibrated by placing photo detector nodes on key points of a physical model.

2. Background

Projector calibration methods are a well-researched area; a common method of projector calibration is to employ a calibrated camera[6)]. These projector-camera systems allow for real-time image adjustment that enable images to be displayed onto surfaces that are not traditionally designed for projections, such as non-planar geometry and textured surfaces[7)8)].

Zollmann et al.[9)] proposed a projector and camera calibration method that uses coded projection patterns to align coordinate systems between the projector and camera. Zollmann and Bimber[10)] later developed a projector camera system that allowed for a multiple step technique providing imperceptible cues for geometry and radiometry calibration. Their technique was extended to display geometry and color corrected images on surfaces with irregular geometries and non-white surfaces during runtime[7)]. These techniques are similar to the camera calibration method described by Zhang et al.[11)].

Fiala[12)] employed a digital camera and computer vision technique to calibrate a set of projectors with the assistance of self-identifying patterns. He employed an array of ARTag markers as the self-identifying patterns as a means of precise locations to be identified. Griesser and Gool[13] extended this concept for projector calibration environments with an arbitrary number of projectors and cameras.

A second method of projector calibration employs photo detectors to find projector alignment. Several research projects proposed projector based position detection employing photo detectors in a projection volume. Summet et al.[14]developed a projector based position detection system for a hand held device with a binary scanning method.

The measurement results with photo detectors allow a direct mapping between the real environments and projection information without consideration of a camera coordinate system. Based on this concept, Lee et al.[5] proposed a movable projection screen tracking system with a high frame-rate. Their system allowed for realtime calculations of homographies between the projector and the movable projection screen[15]. They also calibrated an augmented environment with a car model that used embedded fiber optics attached to photo detectors[16].

Kojima et al.[17] developed an augmented reality environment with moving robots by using a projector based position and rotation tracking method. The tracking system employed a planar array of single point sensors on the robots with gradient patterns projected onto the planar array[18]. Their method allowed the position of the robot to be determined to sub pixel accuracy. However, a large pixel count is also required to maintain a correct gradient pattern. On the other hand, our current method is able to measure sub-pixel position by having at least two partial pixels on a planer sensor. Furthermore, in this paper, we propose to apply sub-pixel measurement results to improve the calibration of a multi-projector SAR environment. To date photo detector based detection methods use point light-sensors with binary projection patterns for projector calibration. In this paper, we explore a possibility of sub-pixel accuracy calibration systems by using a planer photo detector and a binary scanning pattern.

Rasker et al.[19] proposed a wireless photo detector tracking system with a RF communication and Gray-code. They demonstrated how the addition of a photo detector to a wireless tag allowed for geometric operation of finding the 3D position of a tag. The combination of sensors and projector (camera and orientation) with radio communications to an RF tag contained a photo detector that allows for 3D correspondence to be calculated between the projector and the wireless tag.

Raskar et al.[20] also developed a method of spatio-temporal coded projection of light to label 2D or 3D spaces. They employ a set passive binary spatial masks each in front of optical transmitters (LEDs) a in defined configuration that exploits epipolar constraint results for the receiver photo detector. The optical transmitters are placed in predefined calibrated locations to spatio-temporally encode the working region. Photo detectors are placed on locations, and they decoded optical signals from the different transmitters for pose information (location and orientation).

3. Photo Detector Calibration in SAR

This section describes an overview of a common photo detector calibration process and introduces the challenges that we address to explore a sub-pixel photo detector calibration algorithm for multiple projector alignment.

3. 1 Common Process

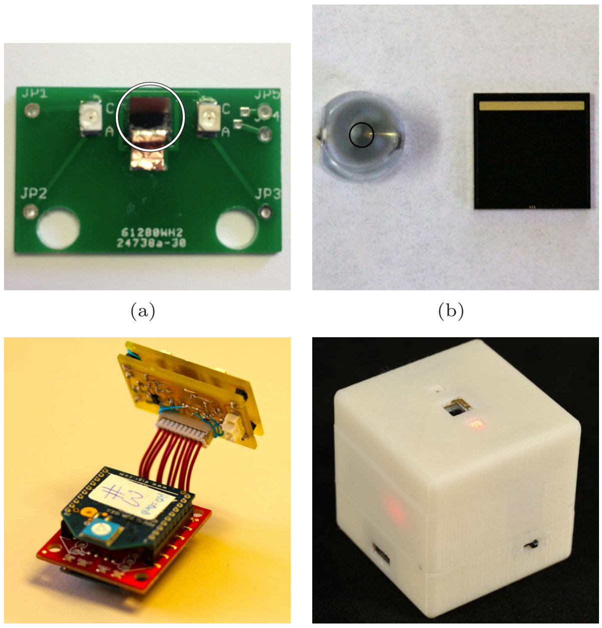
SAR uses projectors to provide a 3D volume for projecting graphics geometrically aligned with physical objects in the environment. A calibration process is required to calculate both the intrinsic parameters of the projector, such as the horizontal and vertical field of view , and the extrinsic parameters, such as the projectors position and orientation relative to the world. This is commonly accomplished by matching projector pixels with known 3D points in the world, such as features on a physical object.

These correspondences can be found manually to pixel accuracy with a projected crosshair visually displayed on the physical object and then using a keyboard or mouse to adjust the crosshair's position on the image plane. This is the technique employed in the Shader Lamps[4] system. This manual process can be automated with projector camera pairs, as demonstrated by Koller et al.[8]. Alternatively, the process can be automated using photo detectors at known locations in the physical environment, such as in the work by Lee et al.[16]. Here Gray-coding is used, which uses a sequence of projected images to find the pixel locations of the photo detectors. Once the projector-world correspondences are found, the calibration parameters for the projector can be calculated. The algorithm for calculating these parameters is described in detail by Bimber and Raskar[6].

3. 2 Hardware Challenges

One aspect of current photo detector calibration systems that can be explored further is the selection of the light sensitive element employed to support projected Gray-coding calibration. Existing projector calibration implementations employ point sized photo detectors that use a spherical lens above a photo element. We refer to this design as a point sized detector. A limitation of this approach when capturing projected light is the hardware is unable to capture the details of an entire pixel clearly. One reason for this is the photo detectors lens may capture projected light information from multiple pixels (shown in **Fig.** 2(a)). Additionally the gap between the two pixels, called the screen door, is also incorporated into the combined light intensity measurement.

Another aspect of current photo detector calibration systems that can be explored further is the form factor of the physical sensing hardware. Current systems employ photo detectors that are permanently fixed to objects and are not designed to be generically applied to arbitrary objects. For example, Lee et al.[16] attach photo detectors to the four corners of a planar cardboard display area using custom electronics and fixed wiring. This design requires that electronics and wiring are adapted for each object that requires registration with the projector system.



(a) (b) (c) (d)

Fig. 3 Hardware Components. (a) Close up view of planar photo detector shown in white circle. (b) left - Top view of point size detector with lens, sensing element is shown with black circle. right - Planar photo detector. (c) Electronic components including Arduino Pro Mini, Xbee wireless, amplified planar photo detector. (d) Generic photo detector node in 3D printed case.

4. Sub-pixel Calibration Extension

This section addresses two challenges, developing new photo detector hardware and a novel algorithm to perform calculations for the sub-pixel accurate system.

4.1 Photo Detector Hardware

To overcome the limited surface area of the point sized photo detector (shown in **Fig.** 3(b)), we selected a planar photodiode with a larger surface area allowing an entire pixel to fit on the photodiodes surface. In our current projected environments the pixels have an approximate size of 1.5mm x 1.5mm when projected from a distance of 4000mm. There are instances of different pixel sizes, and our planar photodiode can support these different sized pixels. Our design employs a planar photodiode (Silonex SLCD-61N2 shown in **Fig.** 3(a)) with a 21.4sq.mm sensitive area (5.1mm x 5.1mm minus the solderable contact area). This allows at least one pixel and the surrounding screen door information to be captured in most common cases. The planar photo detector response is amplified with an opamp (Microchip MCP601) configured to a ten times gain. The resulting signal is measured using the internal 10bit ADC of a microprocessor (Atmel 328P). The measured light value is transmitted over a wireless communications channel (Xbee 1mW 802.15.4 stack) to a host PC. A 110mA hour LiPo battery with a basic charge circuit using USB power is used to power each calibration node. Two CREE LEDs were also placed near the photo detector for future camera calibration support. The internal electronic components can be seen combined in **Fig.** 3(c). All electrical components are enclosed in a 40mm x 40mm x 40mm 3D printed ABS plastic cube depicted in **Fig.** 3(d).

4.2 Algorithm

This section describes how we extended the existing photo detector based projector calibration process to provide a sub-pixel pixel accurate calibration. Following the standard Gray-coding process[16], there are two additional steps we developed that leverage the planar photo detector functionality to measure sub-pixel position. Equation 1 provides a mathematical description of the calculation for the sub-pixel position by measuring a ratio of a scan line as it passes over the photo detector; **Fig.** 4 depicts the photo detector with a single scan line projected onto its surface.

The resulting solution is presented in a pixel to photo detector coordinate system, two floating point values describes the X and Y position of the photo detector.

Whole number values are the centers of the projected pixels. The algorithm returns position of the centre of the photo detector in the pixel coordinate system.

We also assume the pixel area is no larger than the photo detector area. The following steps describe the position algorithm:

(1) *Obtain the coarse X and Y position.* Determine a coarse position to the apparent size of the sensor, within three pixels, using a Gray-code image sequence in both X and Y axis.

(2) *Obtain the precise X position.* This is performed by scanning a one pixel vertical line left to right across the photo diode measuring the light level at each step. The scan starts from beyond the left edge of the photo diode and extends beyond the right edge of the photo diode. The X pixel position of the mean center of the measured received light starts once the scan line enters the photo detector, this position is calculated as follows:

$$mpp = \frac{\sum_{i=1}^{steps} p_i \cdot l_i}{\sum_{i=1}^{steps} l_i}$$
$$mpp = measured\ pixel\ position$$
$$p_i = step\ pixel\ position$$
$$l_i = measured\ light\ level(above\ ambient\ light)$$

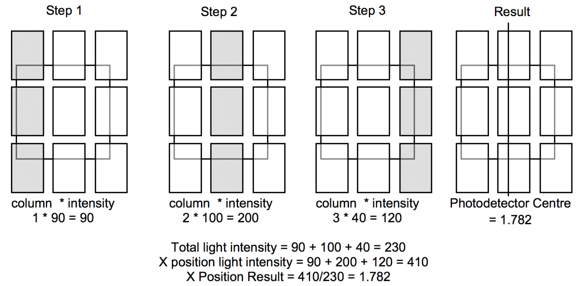
Post condition:

$$\#\ of\ steps \cdot pixel\ area\ is \geqq sensor\ area \tag{1}$$

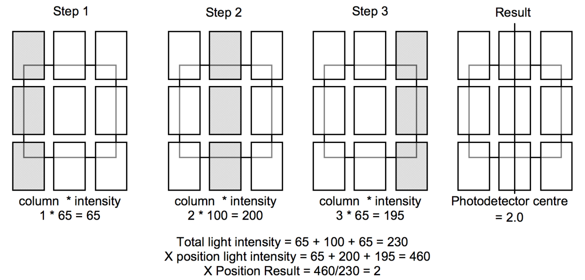
(3) *Obtain the precise Y position.* Similar to the X position, the scanning is performed on a one pixel horizontal line top to bottom across the photo measuring the light level at each step. The scanning also starts from beyond the top edge of the photo diode and extends to beyond the bottom edge of the photo diode. The Y pixel position of the average center of the measured received light is calculated using the same equation as for the X pixel position in step 2.

The calculation is analogous to finding the position of the center of masses. Where the centre of mass calculates from the distribution of measured mass, our scan line algorithm calculates intensity values of light. Center of mass R with continuous mass density p(r) is given with Equation 2.

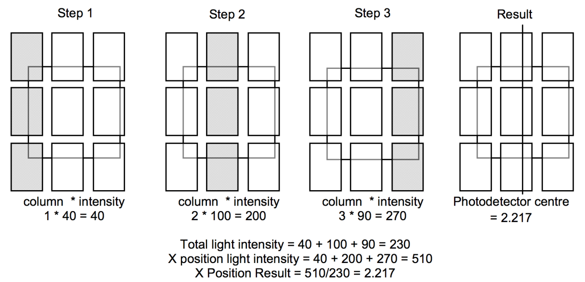
$$R = \frac{1}{M}\int p(r) r dV \tag{2}$$



(a) Light intensity calculation with left biased weight on the X axis



(b) Light intensity calculation with center biased weight on the X axis



(c) Light intensity calculation with right biased weight on the X axis

Fig. 4 Three examples of the sub-pixel algorithm demonstrating left bias, center and right biased.

Equation 3 is the discrete case M total mass m_i is the mass at one point and r_i is the position. The similarity can be seen between Equation 1 and 3.

$$R = \frac{1}{M}\sum m_i r_i \tag{3}$$

To further describe the steps in the sub-pixel calculation, **Fig.** 4 visually depicts three examples of the X position calculation with the photo-diode biased to the left, center and right position. The scan lines representing illuminated pixels are depicted with the small gray rectangles on the planar photo detectors surface (the large square). We present three illumination examples to describe the algorithms operation, for each example a vertical bar is swept over the surface of the photodetector. The algorithm begins once the first group of pixels illuminates the photo detector. **Fig.** 4(a) demonstrates a sub-pixel calculation with the photo detector biased to the left of the pixels. **Fig.** 4(b) presents an example with the photo detector centered relative to the pixels and **Fig.** 4(c) provides a right biased example. For each example only the X position is depicted.

5. Evaluation

This section compares the performance of a point size photo detector using the Gray-coding algorithm to our planar photo detector that employs Gray-coding and the sub-pixel algorithm extension. The evaluation was setup with following experimental parameters: the physical environment, light intensity parameters of projected pixels, the procedure and the performance results.

5.1 Physical Environment

To provide a suitable physical testing environment we prepared a projected volume with a computer controlled rotary table (Sherline P/N 870) to precisely move and measure the photo detector nodes' positions. The Sherline rotary table provides 28800 step positions per revolution or 0.0125 degrees per step. **Fig.** 5 shows the apparatus consisting of a precise computer controlled rotary table and photo detector nodes attached to the rotary table, and both these items are placed in the projected volume. The goal is to move each photo detector node in a circular motion and record the known location with the detected location. The photo detector nodes were placed in a relative position to each other on the rotary table. With this motion, each photo detector path presents all angles to the projected pixels on the X and Y axes as it is rotated. We employed a NEC NP510W projector with a 4 meter projection distance; in this configuration the pixels are approximately 1.5mm wide.

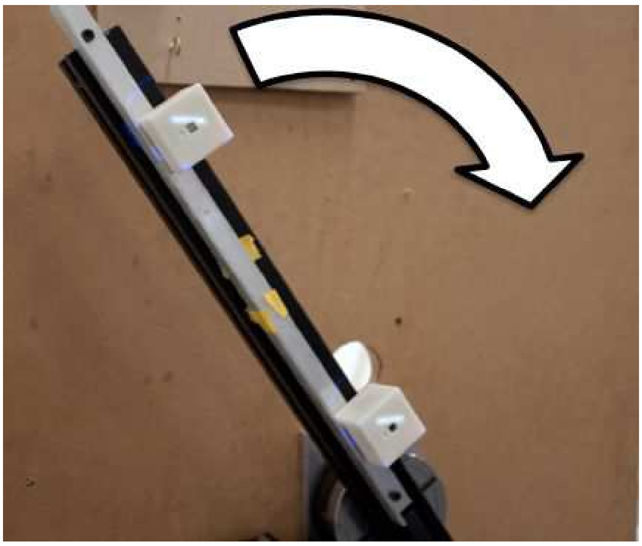


Fig. 5 Computer controlled rotating arm for precise movement.

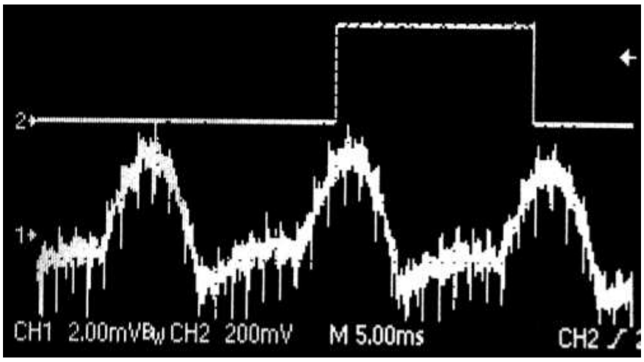


Fig. 6 Intrinsic short-term light output variation of the NEC NP510W Projector

5.2 Projected Pixel Light Intensity Considerations and Parameters

The implementation of the sub-pixel measurement requires a moving horizontal and vertical line to be projected on the photo detector; we refer to this process as a scan line. An ideal set of scan lines would not overlap or have gaps. However as previously mentioned, common natural light projectors display small pixel regions with a gap between each neighboring pixel that is not illuminated. This is commonly called the screen door effect and contributes to a reduced light level measured on photo detectors.

The sub-pixel algorithm also makes the assumption that the light levels of the projected pixels are constant over time, making the algorithm sensitive to short term intrinsic light level variations. In preparation for the evaluation, we measured the response of the photo detector under projected light to capture the internal characteristics of the projector (Trace 1). **Fig.** 6 shows an oscilloscope trace of the output level of the photo detector. The ripple in the signal was measured to show a 60Hz frequency. We used this parameter to synchronize the measurement with an interval of approximately 16.6mS (Trace 2) to optimize the sub-pixel location calculation.

5.3 Procedure

The following process was performed with the two photo detector hardware systems, a point sized photo detector and our planar photo detector. With the detectors installed on the rotating apparatus, the position was repeatedly recorded while moving the detectors in a circular motion. The following steps were performed 360 times (one revolution) to gather the data for the performance analysis. The Gray-coding algorithm was used for both photo detector systems and we applied the sub-pixel algorithm to the planar photo detector following this step.

(1) Perform Gray-code to locate photo detectors with an approximate position.

(2) Perform sub-pixel calibration algorithm with horizontal and vertical scan lines.

(3) Record position of photo detector relative to pixels.

(4) Rotate the photo detector in a circular motion by 1 degree on the computer controlled arm.

(5) Return to step 2 and repeat.

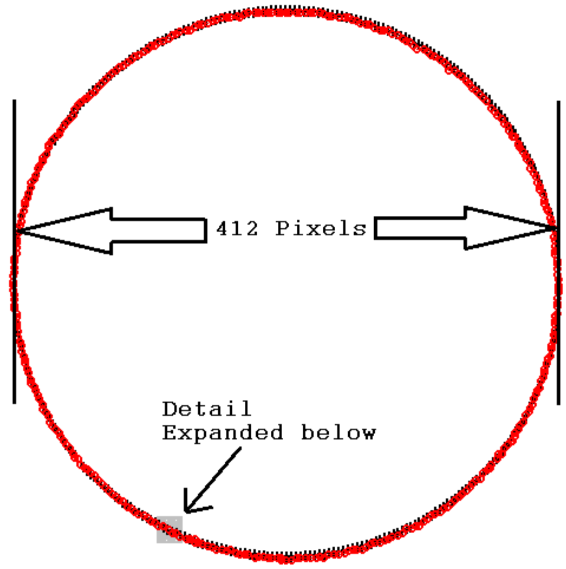
5.4 Performance Results

All of results are reported in pixel coordinates, as this is what is being measured by the photo detectors. The data gathered from both the point sized and planar photo detectors is shown on the graph in **Fig.** 7(a). To clearly identify the performance we provide a zoomed in section of the graph (with the grid lines spaced at one pixel) for both the point and planar photo detectors in **Fig.** 7(b). This zoomed in portion of the graph displays both the ideal path and the measured path using a point sized photo detector. As expected the stair stepped line of the measured path demonstrates the pixel level accuracy (X SD=0.667 Y SD=0.818). **Fig.** 7(c) depicts with the same zoom factor both the ideal path and the measured path using a planar photo detector. The increased accuracy can be identified visually and is demonstrated with an order of magnitude improvement comparing the standard deviation (X SD=0.029 Y SD=0.037), this is indicated with an additional zoomed in region on the graph with an order of magnitude increase.

The data recorded during the evaluation procedure was further analysed to find the error term between the actual position and the measured position in pixels. **Fig.** 8(a) shows a scatter plot of the error term that was calculated of both the point size and planar photo detectors on the one graph. The planar photo detector series are clustered in the center of the plot while the point photo detector measurements show a greater deviation from the actual position. **Fig.** 8(b) shows only the planar photo detector error term on the scatter plot with the scale adjusted to emphasis the fact these error terms are only fractions of a pixel.

5.5 Applied SAR Results

The previous section has shown the results of calculating the pixel location for each photo detector. By placing the sensors at known locations on the object, a projector calibration can be completed. The goal is to provide better projector alignment with multiprojector systems that would not be possible with point photo



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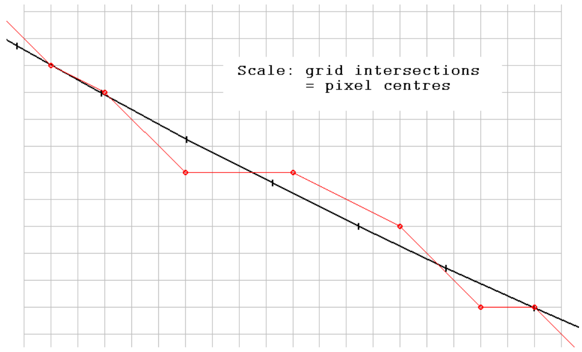

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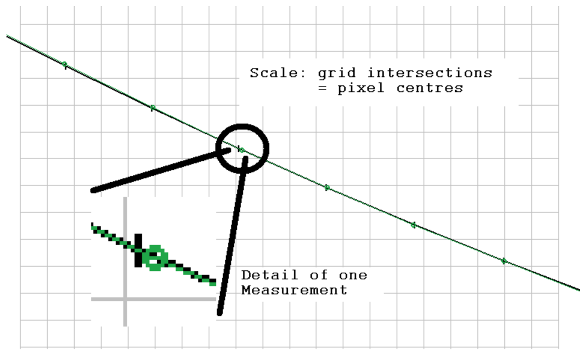
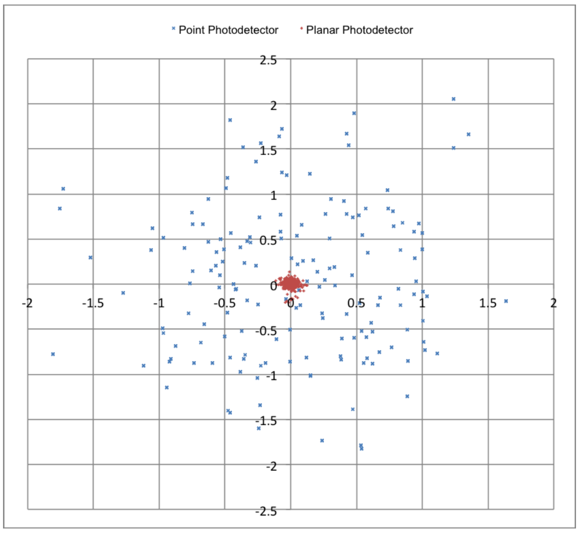


(c)

Fig. 7 (a) Evaluation data shows circular plot recorded. (b) Point photo detector and ideal line shown with zoom at pixel level. (c) Planar photo detector and ideal line shown with zoom at pixel level.

detectors.

The first step to the applied use of this calibration process is to place the photo detector nodes at known locations on the object to be illuminated with SAR (shown in **Fig.** 9(a)). Using projection targets as a reference is a good approach, because CAD models for these objects already exist. This makes finding suitable positions easier, as the coordinates can be taken from



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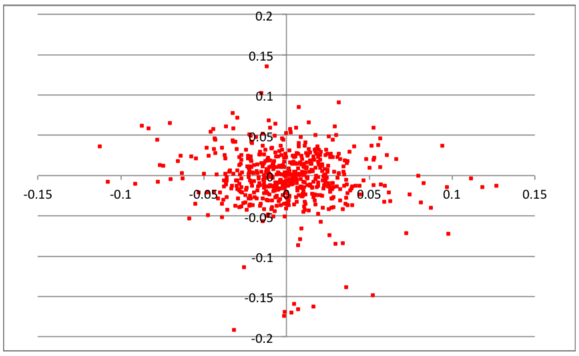


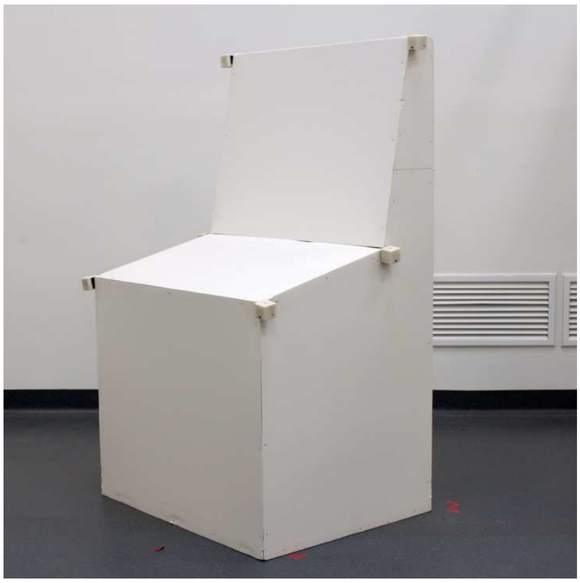
(b)

Fig. 8 (a) Scatter plot showing both the point sized and planar photo detector error term. The sub-pixel measurements from the planar photo detector are clustered in the graphs center. (b) Zoomed scatter plot showing the error term with only sub-pixel measurement.

CAD, rather than performing manual measurements of the environment. The photo detectors are placed onto the object.

The accuracy of photo detector placement affects the quality of the registration between the object and projected appearance, and the engineering of a suitable attachment mechanism is currently under investigation and outside the scope of this paper. However, the calibration for multiple projector alignment is not affected by placement. For example, a slightly mis-placed sensor will leave an unprojected white seam on the edge of an object but this will not create a shadowing affect of two mis-aligned projectors. During testing, we measured the final placement of the sensors, and updated the coordinates to optimise the appearance.

Once the sensors have been placed, the calibration algorithm can be performed. The algorithm described in Section 4.2 finds the projector locations for each sensor. These locations are paired with the 3D locations taken from CAD data of the object, and the projector calibration is calculated and performed. This process can be repeated for any number of projectors. **Fig.** 9(c & d) shows the calibration results with two projectors.



(a)

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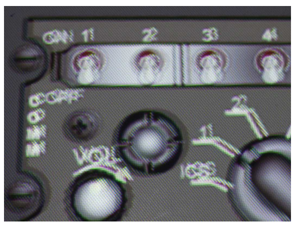

(c)

(d)

Fig. 9 (a) White console mock-up with photo detector nodes attached. (b) Calibrated projector system providing appearance details. (c) Calibration of two projectors showing the coarse calibration step. (d) Calibrated two projectors with sub-pixel calibration.

Fig. 9(c) is with two projectors after the Gray-coding calibration step. At this stage the two projected images are poorly aligned, with the two projected images forming a ghosting effect on the objects surface with a pixel mis-alignment of up to 3 pixels. **Fig.** 9(d) shows the results after the fine calibration step has been completed. Here, the projected images are much more closely aligned and no ghosting is noticeable. This demonstrates the level of alignment between that can be achieved with the new calibration process.

We demonstrate of our SAR design application of a command and control workstation on a regular basis. We noticed the physical projection substrate would move slightly when people are pretending to press the controls on the simulated workstation. We developed a real-time calibration system to adjust for small changes, that are smaller than traditional 6DOF (Degrees of Freedom) tracking systems can accurately sense. Therefore once the projectors are calibrated, we placed our new calibration system into a real-time updating mode. This entails the system to perform continuous scan line detection operations. This real-time updating allows for the system to correct for small movements of the physical object, in our case the workstation model. This requires the movements to be small enough to keep the photo detectors within the region of the scan lines. If the move is too great, the system performs a complete re-calibration. This re-calibration feature can be turned off if required. Our new calibrations system may be employed with or without a traditional 6DOF tracking system.

6. Limitations

There are a number of limitation to both the hardware and the algorithm that we have identified. Firstly, the maximum pixel size is limited to the area of the photo detector. In our current implementation the photo detector has a 21.4 sq.mm area, however this could easily be reduced or increased to match smaller and larger projected pixels respectively. The achievable resolution is limited by the pixel light level behaviour of the projector and will vary with different brands. Variations in pixel characteristics also change over time. For example, the temperature of the projectors internal components stabilize over tens of minutes and the performance increases.

The Large Area Photo detector position measuring algorithm described by this paper measures variation in light levels, received by the sensor as the scanning algorithm progresses. The algorithm is therefore sensitive to other sources of light level variations. The algorithm is sensitive to short term ambient light level fluctuations such as the 100Hz that will be present from incandescent light globes (50Hz mains cycle assumed). This source of measurement noise may be controlled by reducing ambient lighting, by averaging measurements over an interval that matches the fundamental frequency of the noise source, or by synchronising measurements to the source of the noise.

7. Conclusion

This paper has described the design of a novel photo detector projector calibration system that provides subpixel measurement. The technique has demonstrated an order of magnitude improvement in resolution of pixel measurement over that achieved using a point sized photo detector and the traditional Gray-code projection sequence. This technique may be used to better measure the alignment of overlapping images of multiple projectors in order to achieve higher quality cross calibration of multiple projectors used for a 3D projected environment. This technique will assist with real world measurement accuracy by enabling the intrinsic and extrinsic characteristic of projectors to be measured with higher accuracy.

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