Self-Calibrated Structured Light 3D Scanner Using Color Edge Pattern

Samuel Kosolapov
Department of Electrical Engineering
Braude Academic College of Engineering
Karmiel 21982, Israel
e-mail: ksamuel@braude.ac.il (Samuel Kosolapov)

Abstract—**A prototype of general-purpose fast and inexpensive non-laser structured light self-calibrated 3D scanner using a unique color edge pattern was designed, built and tested. The main elements of the 3D scanner are non-laser slide projector and inexpensive WEB camera. The pattern projected to the colored 3D object in test consists of a plurality of a pairs of color strips, white strips and black strips. In the simplest implementation, three basic complimentary colors {M, Y, C} were used, effectively creating at least 6 unique color edges. The addition of black and white delimiter strips enables the creation of a pattern containing 32 easily recognized edges in the simplest implementation and 153 color edges in case six colors {R, G, B, M, Y, C} are used. Color edges can be easily (and unambiguously) detected on the true-color 2D images of the 3D object in-test (grabbed by WEB camera) which enable the reconstruction of the 3D shape from a single 2D frame. Optional mechanical translation of the pattern enables the increase in the number of edges and, after applying a sequence of image processing algorithms, the building of a true color 3D model of the scanned 3D object. In order to lessen pure acquisition time (when 3D object in test must not move), special auto-calibration elements were integrated into scanner mechanical construction so that auto-calibration and 3D reconstruction steps are executed after acquisition is finished. Scanner prototype was tailored to scan 3D shape of human foot with a 3D accuracy of about 0.5 mm in less than 2 sec, which is adequate for the selected exemplary application: individual insoles design and production.**

Keywords-image processing; 3D scanner; structured light; color edge detector

I. INTRODUCTION

"Structure light technique" - the illumination of 3D objects by specially designed pattern in order to create 3D models of real 3D objects from set of relevant 2D images is well known [1][2]. A number of techniques to solve the "ambiguity problem" resulting from the usage of monochrome and color structure light patterns are known [1][2][3]. In the frames of previous research [4][5], a number of 3D scanner prototypes were build. Generally, the operation of a 3D scanner requires a time-consuming calibration step. The goal of this research was to evaluate the "post-acquisition calibration" concept. The re-designed prototype contains calibration elements (calibration bars and calibration markers), which are an integral part of the scanner mechanical construction. By using these auto-calibration elements, required calibration information can be extracted after image acquisition is finished. Post-calibration may be especially useful in the field condition or in medical devices, when usage of "standard" time-consuming calibration procedure may be problematic. Following parts of this article describes main elements of the exemplary design of the 3D scanner, color edge pattern used, main blocks of the reconstruction software and results of 3D Scanner operation.

II. SCANNER DESIGN AND OPERATION

The exemplary design and operation of 3D Scanner using a unique color edge pattern (see Figure 1 and Figure 2) was described in [3]. The main elements of the software used to reconstruct 3D image were described in [3][4][5]. In this research, additional auto-calibration elements (see Figure 3) were included in the scanner design. Additionally, electromechanical means were modified to enable micro-movements of the slide.

Figure 3 presents a number of original, intermediate, and processed 2D images obtained during reconstruction steps. Callout 1 points to the exemplary "MY" color edge on the surface of foam mold of the human foot. (Foam molds are used in podiatry clinics to create a "mechanical copy" of the human foot. The mold is used to produce individual insole for specific patient). Callouts 2 and 3 point to 4 (of 8) corner color markers. Callouts 4, 5, 6, 7 point to white calibration bars. Color corner markers and calibration bars are integral parts of the scanner design; they are always seen by the camera and used in the post-calibration and 3D reconstruction process.

A. Unique Color Edge Pattern

The described 3D Scanner uses a specially designed color pattern [3] consisting of color strips pairs, white strips and black strips. In the simplest implementation (presented on Figure 1), three basic colors {R, G, B} are used. In this pattern, six unique color edges are created: "RG", "BG", "RB", "GB", "BR" and "GR". It must be mentioned that the exemplary "RG" and "GR" color edges can be easily distinguished by directional color edge detector (as a "color jump" of opposite sign) and, thus, are considered as different.

Usage of color strips enables us to obtain more "structure light lines" from a single 2D image without an "ambiguity problem" [1] and thus lessen a number of images needed to be grabbed for 3D reconstruction. In order

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to additionally increase speed of 3D scan, non-unique white and black "delimiter" strips ("wbw") were added to the pattern (See Figure 1 and Figure 2).

Theoretically, any number of colors can be used to build color strips. However, camera noise restricts the number of colors that can be reliably recognized by software, especially when colored 3D objects are to be scanned. Practically, the pattern presented on Figure 2 (having 153 color edges) appears to be reliable enough, even when inexpensive low quality WEB cameras are used.

In the following examples, the simplest pattern (32 edges) was used, but, instead of the basic set {R, G, B}, a complimentary set {M, Y, C} was used in order to enable pattern printing by using inexpensive ink-jet printer.

B. *Acquisition and Pattern Translation*

Theoretically, the selected approach enables the reconstruction of the 3D shape of the real 3D object by using a single 2D image. Practically, this can be reliably executed only for 3D objects having a white surface. Real-life 3D objects are colored, which distorts pattern colors (surface color is combined with pattern colors). Theoretically, by searching for the "color-edge" jump (instead of the specific colors of the adjacent strips), the 3D reconstruction from one 2D frame can be carried out (in case the surface color changes in a smooth fashion). However, practically, an abrupt color change of the 3D object surface makes this reconstruction non-reliable.

In order to increase the reliability of the 3D scanner, electromechanical means enabling the translation of the slide in the direction normal to the direction of the pattern color edges were added to scanner design.

Callouts 1 and 8 on the Figure 3 point to exemplary "MY" color edge on the surface of foam. It can be seen that the position of "MY" (and other pattern elements) is shifted in the horizontal direction. Additionally, it can be seen that the colors of the pattern are severely distorted by color of the foam (by comparing the strip color on the white calibration bars with colors on the foam surface).

Typically, the slide was translated three times during acquisition (acquisition results in four raw frames). The use of auto-calibration enables the use of an extremely simple low-quality electro-mechanical translator using a stepper motor controlled by PC.

In some tests, each of four raw frames was a robust mean of a number of frames.

C. *True color Image Assembly, Alignment and Decolorizing*

It is clear that on every raw frame only a part of 3D object's surface is illuminated by a white light. Considering that the camera is not moved during acquisition, it is clear that by selecting the "brightest" pixels from all four raw frames, the "true color" 2D image of the object in test can be created (See Callout 9 on Figure 3).

By using the original colors of the surface of the 3D object, it is possible to "de-colorize" all raw frames: referring to callout 10 of Figure 3, it can be seen that the color edges are easily distinguished now and that colors of the strips on the surface of white calibration bars are practically the same as the colors of the strips on the surface of the foam. The decolorizing algorithm may lead to unreliable results at the dark regions (especially on the periphery). To prevent the appearance of "non-existed colors", pixels in doubt are marked as "bad pixels" and seen as "black pixels" (Callout 11).

During the "decolorizing" step, four raw frames are "aligned" by using eight corner calibration markers (as if the camera axis is normal to the calibration bars).

III. Reconstruction Software

A. *Color edge detector and synthetic calibration lines*

The reconstruction software detects all possible color edges on every aligned and decolorized raw frame. Callout 12 of Figure 3 points to the exemplary "MY" color edge detected by the color edge detector (the edge points are drawn as "black"). Callouts 13 and 14 points to the "MY" color edge points detected on the surface of the left and right base calibration bars. The Z coordinate of these bars is set as the zero of Z-axis. Callouts 15 and 16 points to the "MY" color edge points detected on the surface of the left and right upper calibration bars. The Z coordinate of these bars is known as 40 mm.

By drawing a line between sub-lines of callouts 13 and 14, one can obtain the base synthetic calibration line (See Callout 17) and upper calibration line (Callouts 15-16 and 18). Lines 17 and 18 are equivalent to the "standard pre-acquisition" calibration lines. However, they are extracted after the acquisition is finished. If needed, an improved or more sophisticated algorithm can be re-used to create more exact calibration lines.

B. *True color 3D image reconstruction*

After synthetic calibration lines creation, {X,Y,Z} triangulation is trivial. By processing all "black" pixels of all color edges of all raw frames, a cloud of 3D points is created. Referring to reconstructed 2D true-color image, {R, G, B} the color of every 3D point of the cloud can be set. The special sequence of robust algorithms eliminates obvious outliners [4]. Resulted cloud of 3D Points can be presented by any appropriate way.

IV. Results

Typical results of 3D scanner operation are presented on Fig. 4. Callout 1 points to the "Heights map" of the resulted 3D model of the foam mold: the Z-coordinate is encoded as "pixel brightness". Callouts 2 and 3 points to X and Y Height profiles (zoomed for clarity). By using cursors, the Z coordinate and {R,G,B} color can be evaluated for any {X,Y}.

Callout 4 of Figure 4 points to the 3D Model presented by using an “Oblique Projection”. By using this presentation, the 3D model can be seen from any angle.

Callout 5 presents the 3D model as a standard STL file (which can be sent directly to the 3D Printer on CNC).

Typical {X, Y, Z} accuracy of the 3D Scanner was about 0.5 mm.

Typical scan time is about 2 sec (comparing with more than 1 min for the design described in [3]). The processing time depends on the PC speed and is about 30 sec.

V. Conclusions

For the selected application inexpensive (less than $100) non-laser 3D Scanner described above has a typical accuracy of 0.5 mm, which is less than the accuracy of laser-scanning devices. However, structured light scanners can be used when laser usage is not recommended (for example in medical devices) or when the high price of laser scanners makes them impractical. Additional advantages of the developed design are its relatively short scan time and the elimination of calibration step.

It can be assumed that the usage of a new generation of high resolution, inexpensive, and low-noise digital cameras will enable a significant increase in the accuracy and reliability of structured light 3D scanners.

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Figure 1. Structure Light Pattern containing 6 unique color edges.
Total number of edges to be extracted from one 2D image is 32

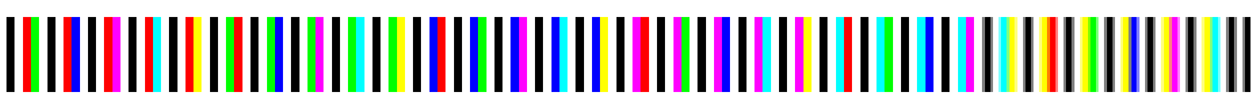

Figure 2. Structure Light Pattern containing 30 unique color edges.
Total number of edges to be extracted from one 2D image is 153.

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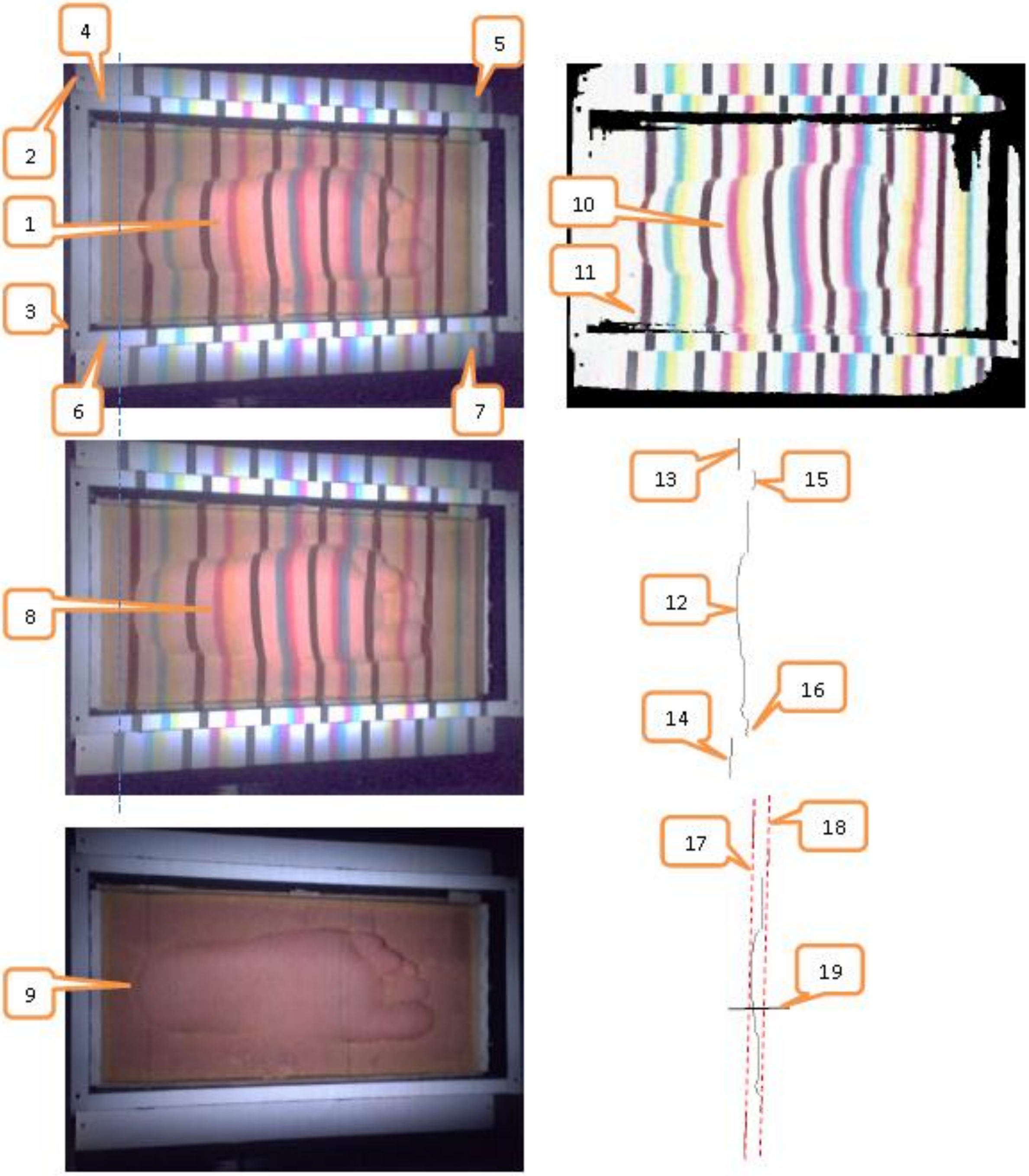

Figure 3. Usage of the pattern shift for reconstruction of true-color 2D image of 3D test object (foam mold) and extraction of {X,Y,Z} coordinates from synthetic calibration lines. (See text for detailed explanations)

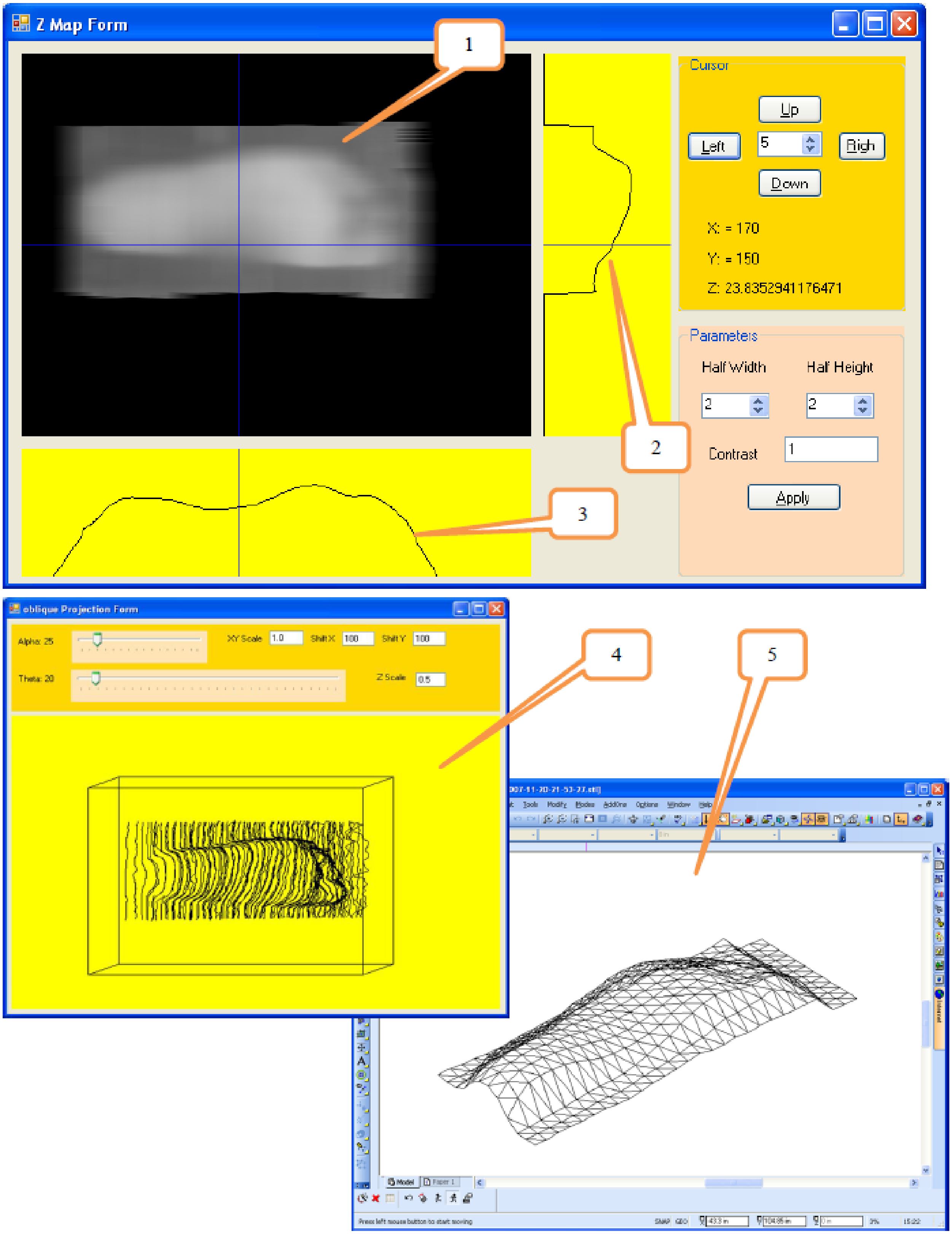

Figure 4. 3D Models of 3D Test Object (foam mold).
(See text for detailed explanations)

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