2007

Triangulation Based Static Wide Angle Laser Scanning For Obstacle Detection

Kaveh Sahba  
*Edith Cowan University*

Kamal Alameh  
*Edith Cowan University*

Clifton Smith  
*Edith Cowan University*

This Conference Proceeding is posted at Research Online.  
https://ro.ecu.edu.au/ecuworks/1427
Proceedings of the Sixth International Workshop for Applied PKC (IWAP2007)

Edited by Dongguang Li

ISBN: 0-7298-0644-6

Published by School of Computer and Information Science, Edith Cowan University
Perth, Western Australia

The conference was organized by School of Computer and Information Science at the Mount Lawley Campus of Edith Cowan University.
3rd - 4th December, 2007
Preface

IWAP2007 will be the sixth of a series of successful international workshops with focus on research and engineering issues of the applied aspects of public key cryptosystems. The inaugural IWAP event was held in Korea in 2001, and was subsequently held in 2002, 2004, 2005 and 2006 respectively in Taipei, Japan, Singapore and China. The IWAP2003 was cancelled due to the SARS breakout. Theoreticians and practitioners interested in the applied issues of PKC were encouraged to participate and contribute to the continuous success of the IWAP workshop series. The host of the IWAP2007 is Edith Cowan University. It is my pleasure to have the opportunity to chair the IWAP conference in Perth, Australia in 2007.

Security is well recognized as a most important issue in e-commerce applications and national security systems while Public Key Cryptosystem (PKC) is widely accepted to be a key mechanism in secure application systems. As such, infrastructures that facilitate the management and deployment of public key cryptosystems have received much attention from the security community. Authorities and regulators have spent a lot of effort standardizing PKC-related standards and enacting legislations for recognizing PKC in business transactions. However, in reality, due to systems issues and engineering considerations, the adoption of PKC has not been as pervasive as the security community anticipated while high sensitivity application systems remain as vulnerable as they used to be.

The theme of this workshop is to provide a forum for discussing the systems and engineering aspects of security systems that make use of PKC as a basic security mechanism. It's observed that, over the past few years, there have been a growing number of critical application areas (such as the new generation travel documents by ICAO and payment cards by EMV) rely on the presence of some well-designed, well-engineered PKC. While there are existing venues for promoting theoretical aspects of PKC, IWAP 2007 aims to provide a platform for researchers to exchange ideas on applied aspects of PKC, and to stimulate further researchers to innovating and/or important applications of PKC as well as systems and engineering aspects for PKC deployment in a large complex environment.

There are 21 selected papers included in the proceedings. 13 of them are from Australian universities such as ECU, ANU, Deakin and James Cook University. Others are from 8 different countries including USA, Germany, China, Korea, Japan, Ukraine, Iran, and India. Although the conference is small in size it is really an international one. The conference will be opened by Prof Tony Watson, General Co-Chair and Pro Vice Chancellor, and Executive Dean of the Faculty of Computing, Health and Sciences, Edith Cowan University. Participants from ten countries will deliver many outstanding presentations over two intense days. The papers in the Proceedings are ordered according to the original program sessions and their corresponding themes.

All the papers included in the proceedings have been peer reviewed in full by at least two independent reviewers selected from the international program committee. Mention must be made to Associate Professor Jim Cross, Associate Dean of the Faculty of Computing, Health and Sciences, Edith Cowan University, whom have worked tirelessly with me in the preparation of this conference, starting almost one year ago.

IWAP2007 would not have been possible without the dedicated support of the International Steering Committee:
Kwang-Jo Kim (School of Engineering, Information and Communications Univ, Korea)
Kwok-Yan LAM (Tsinghua University, Singapore)
Kouichi Sakurai (Kyushu University, Japan)
Craig Valli (Edith Cowan University, Australia)
Jialin Cao (Shanghai University of Electric Power, China)

I would like to thank all of the members of the International Programme Committee for carrying out the paper reviews with care and competence:

Dongguang Li Chair (Edith Cowan University, Australia)
Xinmin Geng Co-Chair (Shanghai University of Electric Power, China)
Weiguo Pan Co-Chair (Shanghai University of Electric Power, China)
Lisa McCormack Secretary (Edith Cowan University, Australia)
David Veal (Edith Cowan University, Australia)
Heping Tu (Shanghai University of Electric Power, China)
Shaoguang Li (The Jackson Laboratory, USA)
Clifton Smith (Edith Cowan University, Australia)
Paul Maj (Edith Cowan University, Australia)
Lipo Wang (Nanyang Technological University, Singapore)
Jitian Xiao (Edith Cowan University, Australia)
Alfred Tan (Edith Cowan University, Australia)
Huazhong Li (Wenzhou University, China)
Cui Yongrui (Dalian University of Science and Technology, China)
Yingxiu Wang (University of Calgary, Canada)
Yi Zhuang, (Nanjing University of Aeronautics & Astronautics, China)
Mingchu Li, (Dalian University of Technology, China)
Haibin Zhu, (Nipissing University, Canada)
Huaidong Wang (Shanghai University of Electric Power, China)
Yoshifumi Ueshige (Institute of Systems & IT /KYUSHU, Japan)

My thanks also go to the members of the Organizing Committee:

Jim Cross Chair (Edith Cowan University, Australia)
Craig Valli Co-Chair (Edith Cowan University, Australia)
Hao Zhang Co-Chair (Shanghai University of Electric Power, China)
Liz John (Edith Cowan University, Australia)
Rebecca Treloar-Cook (Edith Cowan University, Australia)
Lisa McCormack (Edith Cowan University, Australia)
Heping Tu (Shanghai University of Electric Power, China)
Fei Han (Shanghai University of Electric Power, China)
Bryan Garnett-Law (Edith Cowan University, Australia)

In particularly, I want to thank our invited keynote speakers:

Dr Michiharu Kudo
Manager, Security & Privacy, I&I, IBM Research, Tokyo Research Laboratory, Japan
Prof Chan Yeob Yeun
Information Communication University, Korea
Prof Clifton Smith
Foundation Director of the Australian Institute of Security and Applied Technology, Edith Cowan University, Australia
Prof Saeid Nahavandi
Alfred Deakin Professor at Deakin University, Australia

I wish all the participants of IWAP2007 a fruitful conference and a wonderful stay in Perth.

A/Prof Dongguang Li
General Chair of IWAP2007
School of Computer and Information Science
Faculty of Computing, Health and Science
Edith Cowan University
Australia

30 November 2007
## Table of Contents

<table>
<thead>
<tr>
<th>Title</th>
<th>Author(s)</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Table of Contents</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Trusted Computing Infrastructure and PKI</td>
<td>Michiharu Kudo</td>
<td>6</td>
</tr>
<tr>
<td>New Novel Approaches for Securing VoIP Applications</td>
<td>Chan Yeob Yeun, Kyusuk Han, and Kwangjo Kim</td>
<td>11</td>
</tr>
<tr>
<td>Survey of RSA Implementations and Attacks</td>
<td>Srinivasa Rao, Subramanya Rao, Vinodh George</td>
<td>21</td>
</tr>
<tr>
<td>An Efficient Homomorphic Coercion Resistant Voting Scheme Using Binary Search Tree</td>
<td>A Janic and L.M. Batten</td>
<td>40</td>
</tr>
<tr>
<td>CompressedNestedCertificates Provide More Efficient PKI</td>
<td>V. Kovtun and J. Pelzl</td>
<td>51</td>
</tr>
<tr>
<td>Fast Arithmetic In Jacobian Of Hyperelliptic Curves Of Genus 2 Over GF(p)</td>
<td>Dongguang Li</td>
<td>60</td>
</tr>
<tr>
<td>Australian firearm identification system based on theballistics images of projectile specimens</td>
<td>Dongguang Li</td>
<td>71</td>
</tr>
<tr>
<td>Firearm Identification with Hierarchical Neural Networks by analyzing the firing pin images retrieved from cartridge cases</td>
<td>Hossein Ghodosi</td>
<td>80</td>
</tr>
<tr>
<td>A General Model for Oblivious Transfer</td>
<td>Hossein Ghodosi and Rahim Zaare-Nahandi</td>
<td>89</td>
</tr>
<tr>
<td>A Non-Interactive Multiparty Computation Protocol</td>
<td>Fenyu Zeng and Pan Hua</td>
<td>97</td>
</tr>
<tr>
<td>China’s Information Security Policy Inadequate To Protect Its Netizen’s Personal Rights</td>
<td>Jitian Xiao</td>
<td>107</td>
</tr>
<tr>
<td>Sequencing Clusters of Spatial Join Operations Using Weighted Match</td>
<td>Michael W. David</td>
<td>117</td>
</tr>
<tr>
<td>Mobile Agent for Electrical Power Infrastructure Protection</td>
<td>Clifton L Smith</td>
<td>126</td>
</tr>
<tr>
<td>Triangulation Based Static Wide Angle Laser Scanning For Obstacle Detection</td>
<td>D. Veal</td>
<td>149</td>
</tr>
<tr>
<td>State Model Diagrams and Home Security System Control</td>
<td>Mei Xue, Xinmin Geng</td>
<td>166</td>
</tr>
<tr>
<td>Study on Whole Lifecycle Protection of Digital Contents</td>
<td>C. Y. Jiao and D. G. Li</td>
<td>177</td>
</tr>
<tr>
<td>Data Mining and Genetic Algorithm Application In Bioinformatics With Microarray</td>
<td>Yong Wang, Xinmin Geng, Yu Wang</td>
<td>188</td>
</tr>
<tr>
<td>Three-Dimensional Cellular Automation LFSR Algorithm</td>
<td>Yong Wang, Xinmin Geng, Yu Wang</td>
<td>195</td>
</tr>
</tbody>
</table>
Triangulation Based Static Wide Angle Laser Scanning For Obstacle Detection

K. Sahba1, K. E. Alameh2 and C. L. Smith3

1Western Australia Centre of Excellence for MicroPhotonic Systems
School of Engineering and Mathematics
Edith Cowan University, Australia
E-mail: k.sahba@ecu.edu.au

2Western Australia Centre of Excellence for MicroPhotonic Systems
Edith Cowan University, Australia
E-mail: k.alameh@ecu.edu.au

3School of Engineering and Mathematics
Edith Cowan University, Australia
E-mail: clifton.smith@ecu.edu.au

ABSTRACT

This paper demonstrates discrete laser spot projection over a wide angle using a novel cylindrical quasi-cavity waveguide, with no moving parts. Furthermore, the distance to each spot is calculated using active laser triangulation. The triangulation arrangement and the trajectory of principal rays are modelled using a system of linear equations based on optical geometry. Linear algebra is used to derive the unique baseline and outgoing angle of every projected beam. The system is calibrated by finding optimal values for uncertain instrumental parameters using constrained non-linear optimization. Distances calculated indoors result in accuracies of over 93%.

INTRODUCTION

High power, high pulse rate, fibre and diode eye-safe lasers has allowed terrestrial laser scanning (TLS) to become a highly advanced optical detection device within the defence-in-depth (DiD) model, while also being utilised in civil and military remote sensing. Incorporating beam deflection units, TLS makes multiple range measurements, producing a three-dimensional (3D) reconstruction of the scanned area. In terms of perimeter security, this implies monitoring the perimeter contour and checking for differences in 3D shape between the latest scan and that of a reference, or unperturbed perimeter.

Currently, TLS laser beam deflection is achieved by electro-mechanically driving single or multi-faceted rotating polygon mirrors, sometimes in combination with galvanometric/resonant mirrors. Examples are given in Figure 1. The system depicted in Figure 1(a) contains a motor driven rotating polygon mirror and a sweeping mirror driven by an actor. The outgoing beam is first deflected vertically by the sweeping mirror and then impinges on a polygonal mirror fact which then deflects the beam horizontally, thus producing a raster scan of the surroundings as described in U.S. Patent No. 6480270 (2002). Figure 1(b) shows a single sided, or ‘monogon’ mirror deflecting a laser beam as it is rotated by a motor, in conjunction with an angle encoder (SICK, 2003). In Figure 1(c), a fibre optic cable is aligned with the input aperture of a beam expander which guides the beam to the oscillating mirror. The resonant motor oscillates the mirror in the order of 100Hz. A sinusoidal scan pattern occurs because the resonant scanner assembly and window are moving simultaneously as one entity, in azimuth and elevation. The stepper motor within the upper
portion of the scan head rotates the head at a rate of 1-2Hz. Figure 1(c) is drawn from U.S. Patent No. 6985212 B2 (2006) and Ray, Evans & Jamieson (2005).

Figure 1. Examples of current beam deflection methods.

The intrinsic motion of the mirror and servo motor causes scanning problems which are the hardest to quantify and correct. Acceleration time taken to reach the constant scanning speed from a stationary position can result in range measurements being stored at the wrong corresponding points in the scanned image. Additionally, all mirrors and measurement components must be synchronized exactly. The performance of polygonal scanners, especially with respect to maintaining an accurate deflection beam path, is prone to manufacturing tolerances. Dynamic track and jitter errors are caused by tolerances for polygon machining errors, mounting errors, mounting-hub errors, random wobble caused by ball bearings, motor cogging and torque variations (Stutz, 2005).

Cogging, torque and facet flatness variations cause errors in the actual scan line. Other problems listed with rotational scanners are (Stutz, 2005):

1. Synchronization with other time-dependent elements in the system is rather difficult.
2. Motor stability and durability at higher rotation speeds also present problems.
3. There is an upper limit to the rotation speed due to the tensile strength of the mirror material. The mirror must not disintegrate at the maximum rotation speed.

Vibrations and shock of the whole scanner housing also cause errors in range measurements as the rotating mirror/s become out of phase. In general, a multi-beam stationary optic approach is much less sensitive to vibration (Taylor, et. al. 1998). Also, mirror device scanners are slow, bulky and expensive (Elkhalili, 2004) and being inherently mechanical they wear out as a result of acceleration, cause deflection errors and require regular calibration (Schnadt & Katzenbeißer, 2004). A comprehensive description of rotary mirror scanning errors can be found in Marshall (2004).

In this paper, an approach to generating multiple beams over a wide angle with no moving parts and deriving the range to the corresponding laser spots falling on the surrounding perimeter is demonstrated, within a proof-of-concept phase. A novel optical piece in the form a quasi-cylindrical cavity with a 45° curvature has been fabricated and used to perform structured laser light projection in the form of a spot array. This component acts as a waveguide as an incident beam undergoes multiple reflections within its two dielectric cylindrical surfaces which share the same centre. By depositing a partially transmissive nanolayered thin film, a percentage of light is transmitted at every intersection with the outer interface.

Ray propagation modeling using linear algebra is demonstrated and applied to predict the unique baseline location and outgoing angle of every outgoing beam in the arrangement. The arrangement is modelled using a system of linear equations and the experiment’s principal rays and components are plotted using equations for straight lines and circles. The concept is demonstrated experimentally by adding the quasi-cylindrical optical cavity to a conventional active laser triangulation layout, imaging each spot with a CCD imager and a TV lens. Each spot’s sub-pixel peak intensity position is estimated using an appropriate Gaussian peak estimator algorithm. Coupled with the modelled beam angle and baseline parameters, the forward distance to each spot is estimated.

**MULTI-LASER BEAM GENERATION USING A QUASI-CYLINDRICAL OPTICAL CAVITY**

The custom fabricated concentric concave-convex cavity of 45° curvature is shown in Figure 2(a). It comprises an inner and outer dielectric interfaces of radii \( R_1 \) and \( R_3 \), respectively, separated by a BK-7 glass medium of thickness \( d = R_2 - R_1 \), and non-coated entrance and exit windows. Light transmission is achieved by depositing nano-layered thin film coatings on both interfaces. The rear side is deposited with a highly reflective coating (\( R \geq 99\% \)) and the front side with a partial transmission coating (\( T \leq 13\% \)), effective over the 600 – 900nm waveband.

At every reflection with the outer interface, a fraction of the light is transmitted through the cavity thus generating a laser spot. The reflected power undergoes further reflections within the cavity to generate subsequent laser spots as illustrated in Figure 2(b). A plot illustrating the ray trace for a 90°-cavity is shown in Figure 2(c) for \( R_1 = 0.25m \) and \( R_2 = 0.263m \). The inter-beam spacing and angular resolution are adjustable, according the incident angle of the injected laser beam through the entrance window.
Figure 2. (a) quasi-cylindrical cavity, (b) entrance close-up plot and (b) ray trajectory over 90°.

To trace the path of the reflected and transmitted rays, optical geometry is used with no approximation. Given the radii of curvature of the two interfaces, the slope and ray intercept with the inner interface, the two surfaces and rays are modeled using a system of basic linear equations. Rays are plotted as straight lines, given by

\[ y = mz + b, \]  

Eq. 1

where \( m \) is the gradient and \( b \) is the \( y \)-intercept. The two interfaces are plotted as arcs where

\[ y = \sqrt{R_n^2 - z^2}, \]  

Eq. 2

where \( R_n \) is the interface radius.

Intersections between rays and the surfaces are represented by algebraic solutions to equations (1) and (2). Internal interfaces are modeled as cylindrical mirrors; hence the incidence and reflection angles of a ray are equal.

Gaussian beam behaviour in terms of the spot size evolution has been reported in (Sahba, 2007).

ACTIVE TRIANGULATION GEOMETRY FUNDAMENTALS

Figure 3 illustrates the geometry principle of active laser triangulation. An imaging device of focal length \( f \) is positioned in line with the Z-axis and has the X-axis running through its lens centre. To the left of the lens, at a baseline distance \( \beta \), a laser source launches a light beam at a variable angle \( w \). The image point lying on the \( x \) plane, together with \( \beta, w \) and \( f \) determine the \( X \) and \( Z \) coordinates of the illuminated target point \( P \). The horizontal and vertical distances, \( X \) and \( Z \), to the projected laser spot from the lens centre are given by Hartrumpf & Munser, (1997):

\[ X = x \cdot \frac{f \tan(w) - \beta}{x - f \tan(w)}, \]  

Eq. 3(a)

\[ Z = f \cdot \frac{x - \beta}{x - f \tan(w)}. \]  

Eq. 3(b)
LASER TRIANGULATION SETUP INCLUDING THE OPTICAL CAVITY

Figure 4 illustrates principal rays of the novel triangulation system incorporating the quasi-cylindrical optical cavity. Adopting the linear algebraic ray tracing method from (Sahba, 2007), cavity interfaces and rays are plotted using equations for circles and straight lines, respectively. Figure 4 indicates that each outgoing laser beam has unique $\beta$ and $w$ values in relation to the rotated lens line, $L$.

In calculating the angle between the $n^{th}$ emerging ray and the X-axis, $\alpha_n$, it was found that relying on the law of reflection and Snell’s law produced theoretically correct values but did not predict the real angles. This could be attributed to several factors, namely, a non-homogeneous cavity substrate, an imperfect cylindrical shape or non-uniform dielectric thin film coatings. To derive accurate $\alpha_n$ values, the laser incident angle and cavity index defined in the model were altered so the exit beam position, shown in Figure 4, coincided with the real point of exit at the end of the cavity, within 1mm accuracy. For any outgoing ray, the predicted coordinates of beam intersection with the outer cavity surface, $C(x,z)$ were recorded.
The coordinates \( S(x,z) \) of the corresponding laser spot on the laboratory wall were recorded manually by hand. In this case, the angle of a ray with respect to the X-axis is given by:

\[
\alpha = \tan^{-1}\left( \frac{C(z) - S(z)}{C(x) - S(x)} \right) \tag{Eq. 4}
\]

Each ray’s outgoing angle with respect to the lens line of slope \( L_m \) is:

\[
w = \tan^{-1}\left( \frac{\alpha - L_m}{1 + (L_m \cdot \alpha)} \right) \tag{Eq. 5}
\]

The baseline distance, \( \beta \) is calculated as:

\[
\beta = \sqrt{\left(\beta(x) - L(x)\right) + (\beta(z) - L(z))}, \tag{Eq. 6}
\]

where

\[
\beta(x) = \frac{L_b - P_b}{P_m + L_m}, \tag{Eq. 7}
\]

and

\[
\beta(z) = \frac{(P_m \cdot L_b) - (L_m \cdot P_b)}{P_m \cdot L_m} \tag{Eq. 8}
\]

\( P_m, L_m \) and \( P_b, L_b \) are the slope and y-intercept of a projected ray and the lens line, respectively.

Figure 5 shows the experimental setup that was used to demonstrate active triangulation using the quasi-cylindrical optical cavity of 45° curvature. Twenty laser spots were generated when an incident laser beam was injected through the entrance window. The cavity’s orientation and position were adjusted using a tilt and precision translation stage, respectively.

The incident beam was produced by a 632.3nm, 1mW, HeNe laser, which was mounted onto a rotating stage with a 0.5° step. To image the projected laser spots, a \( \frac{1}{2} '' \) interline transfer CCD imager was employed, comprising of 768(H) \times 494(V) pixels of size 8.4 \times 9.8\, \mu m. A C-mount TV lens of focal length \( f = 12.5\, \text{mm} \), focused at infinity collected the reflected laser light. The lens iris was adjusted appropriately to avoid saturation of the imaged spot. Images from the camera were digitized in 12-bit form using a Spiricon Plug and Play PCI frame grabber.

Both the quasi-cavity and camera were staged on a common rail, the distance between them defining the primary baseline, \( B = 0.3\, \text{m} \), as shown in Figure 5.
Two sets of range measurements were taken to validate the system. Firstly, all the laser spots were projected onto the laboratory walls and imaged. Since the field of view (FOV) of the camera lens is not wide enough to capture all spots instantaneously, the camera was rotated about the lens center in order to acquire two images containing 9 and 11 laser spots, which are shown in Figure 6(a). The camera angle, $L_{ib}$ was set at $46^\circ$ and $69^\circ$ for images 1a and 1b respectively, with respect to the X-axis.

For the second set, a screen was placed 2.5m away from the camera lens centre. Thus spots 17 to 20 were projected onto the screen and the remainders were projected onto the wall. One image was taken of spots 12 to 20 to demonstrate that a closer object’s range, with respect to the wall, could be accurately determined. $L_{ib}$ was set at $64.5^\circ$. The image is shown in Figure 6(b).

For each image, an intensity profile was taken across every spot and the digital pixel array processed to find the peak intensity pixel position using the Gaussian sub-pixel peak position estimator algorithm defined by Fisher & Naidu (1996) as:
\[
\delta = \frac{1}{2} \frac{\ln(f(x-1)) - \ln(f(x+1))}{\ln(f(x-1)) - 2 \cdot \ln(f(x)) + \ln(f(x+1))},
\]

Eq. 8

where \( x \) is the pixel position of the observed peak sensor reading with an intensity of \( f(x) \). The peak position of a laser beam spot imaged at pixel position \( x \) is offset by the estimated pixel fraction \( \delta \).

To calibrate the system, constrained nonlinear optimization was used to find the optimal values of parameters subject to uncertainties. The optimization was based on the minimization of the least square error, namely:

\[
\sum_{i=1}^{20} \left( Z_i - \hat{Z}_i \right)^2,
\]

Eq. 9

where \( Z_i \) is the actual range and \( \hat{Z}_i \) is the calculated range for the \( i \)th laser spot. Note that for the second set of ranges, \( i = 12 \), since only one image was acquired of spots 12 to 20. The two most significant uncertainties in the experimental setup were:

1. Imager pixel size. Although already manufacturer-specified, the pixel pitch was not known, thus producing error in calculating the captured ray’s physical position on the image sensor. Hence, a pixel size scaling factor, \( \eta \), was used.

2. \( L_0 \) is not totally accurate since the camera’s rotating stage was fixed onto the rail using a single bolt, hence making it subject to rotational movement due to slight knocks or vibrations.

Other uncertainties included the exact position of the lens centre along the optical axis within the complex TV lens system and the centre-to-centre alignment of the image sensor and lens. An alignment error attributed to the primary baseline, \( B \), running directly through the lens centre can also exist. Note that if the camera is displaced vertically, the lens will not be in the same plane as \( B \), and this leads to inaccuracy in range measurements.

RESULTS AND DISCUSSION

Four frames were taken at each \( L_0 \) angle and the mean forward range, \( Z \), to every spot obtained as shown in Figure 7. The first set of estimated range measurements, for spots 1 to 20 projected on the laboratory walls, is shown in Figure 7(a). The second set, from spots 12 to 20, is shown in Figure 7(b).
Figure 7. Range measurement results. (a) shows the estimated ranges for 20 laser spots falling on the laboratory walls. (b) shows the estimated ranges for spots 12 to 16 projected onto the walls and spots 17-20 onto a perturbing screen.

Note that Figure 7 shows very good agreement between the measured and calculated ranges, validating the method of deriving $\beta$ and $w$ using linear algebra as described in previously. Note also that Standard deviation of the mean $Z$ remained below 7.68 cm and 0.525 cm for measurement sets 1 and 2 respectively, demonstrating system stability. The minimum ranging accuracies achieved were 93.63% and 98.81% for spot 1 of measurement set 1 and spot 12 of measurement set 2, respectively.

Table 1 shows estimated and optimized $\eta$ and $L_\theta$. Constrained nonlinear optimization of these parameters was carried out using Matlab®’s fmincon search function in the Optimization Toolbox.
Table 1. Optimized triangulation parameters.

<table>
<thead>
<tr>
<th></th>
<th>Image 1a</th>
<th></th>
<th>Image 1b</th>
<th></th>
<th>Image 2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\eta$</td>
<td>$L_\theta$</td>
<td>$\eta$</td>
<td>$L_\theta$</td>
<td>$\eta$</td>
</tr>
<tr>
<td>Min.</td>
<td>0.5</td>
<td>42</td>
<td>0.5</td>
<td>42</td>
<td>0.5</td>
</tr>
<tr>
<td>Max.</td>
<td>1.5</td>
<td>52</td>
<td>1.5</td>
<td>52</td>
<td>1.5</td>
</tr>
<tr>
<td>Estimate</td>
<td>1</td>
<td>46</td>
<td>1</td>
<td>72.5</td>
<td>1</td>
</tr>
<tr>
<td>Optimal</td>
<td>0.7744</td>
<td>50.107</td>
<td>0.9944</td>
<td>72.974</td>
<td>0.9825</td>
</tr>
</tbody>
</table>

CONCLUSION

This paper has demonstrated a novel method for wide angle laser pattern projection in the form of a spot array through multiple internal reflections and refractions. The effect of an off-axis optical system with respect to ray trajectory has been demonstrated. By conjoining as many quasi-cavities as needed, the scanned angle can be extended to 360°. Furthermore, scanning in elevation can be achieved by stacking the quasi-cavities vertically.

Accurate triangulation-based ranging to multiple laser spots generated over a wide angle by the custom quasi-cylindrical optical cavity has been demonstrated. A system of linear equations has been used to simulate the principal rays and components of the triangulation system and obtain the unique baseline distance and outgoing angle of every beam. It has also been shown that the imaging device can be rotated about its lens centre in order to triangulate to a spot array wider than its instantaneous FOV.

Ranging accuracy is heavily dependent on precise system instrumentation of the system arrangement. Calibration has been achieved by non-linearly optimizing values for uncertain instrumental parameters within realistic constraints.

Potential implications of this novel scanning architecture include a longer mean time between failure, and virtually no wear and tear as there are no moving parts. This is particularly beneficial in applications where robustness and mean time between failures is critical, such as perimeter security, collision avoidance and robot navigation.

REFERENCES


