An optical triangulation method for non-contact profile measurement

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Abstract—In this paper we present a triangulation based range sensor for non-contact profile measurement. The sensor measures distances and orientations of objects and surfaces, based on the triangulation principle. This method is highly independent from optical surface properties and allows significant range measurements. Then a polynomial approximation based direct calibration method of this sensor is described. Next we present a prototype of the measuring system where the object is illuminated with laser sheet of light and viewed with the camera. The illumination angle, viewing angle and baseline between laser source and camera gives the triangulation geometry from which the depth information and 3D shape of the object is to be measured. A simple method for obtaining depth information using least square method is explained next. A comparison with range sensor results with standard calibrated results is performed to judge the suitability and accuracy of the system.

Index Terms—automatic dimensional measurement system, calibration, Laser range finder, optical triangulation.

I. INTRODUCTION

During the past decade the centuries old concept of absolute range measurement by means of optical triangulation has experienced a dramatic increase in use. This has been due to the availability of the laser diode as a light source and the increasing need for accurate non-contact range sensing in a variety of applications. In this paper our main area of application is the dimension measurement of standard hot/cold rolled products in steel manufacturing industries like TMT bars, angles, rails, beams, channels, flats etc. The other applications include auto bodies on the production line [7], profiling of turbine blades [8], and high speed profiling of joints and beads for active control of welding processes [9]. A rapidly growing area is detailed profiling of complex 3-D shapes to produce computerized databases for reverse engineering or other purposes [10].

The development of robots with high flexibility of functions is deeply dependent from the improvement in sensorial systems. The robotic sensors usually used in measuring distance and orientations are based either on ultrasonic, microwaves or optical techniques. These sensors have some advantages over mechanical probes namely in providing higher speed of operation and by doing the measurements out of contact [2].

In the recent years, 2D laser range finders mounted on mobile robots have become very common for various robot navigation tasks. Theory provide in real time accurate range measurements in large angular fields at a fixed height above the ground plane, and enable robots to perform more confidently a wide range of tasks by fusing image data from the camera mounted on robots [1] [5]. In order to effectively use the data from the camera and laser range finder, it is important to know their relative position and orientation from each other, which affects the geometric interpretation of its measurements. Also these sensors have very useful applications in areas such as computer vision based automatic control systems in micro robotics [4].

The calibration of each of these geometric sensors can be decomposed into internal calibrations parameters and external parameters [6]. The external calibration parameters are the position and orientation of the sensor relative to some fiducially coordinate system. The internal parameters, such as the calibration matrix of a camera, affect how the sensor samples the scene. This paper assumes the internal sensor calibration is known, and focuses on the external calibration. There has been a great deal of work on calibration for laser scanners, which are the parts of active vision systems that project a point or a stripe which is then viewed by the camera. Finding the geometric relationship between the laser scanner and the camera is vital for creating metric depth estimations to build textural 3D models. Given the camera intrinsic parameters and its relative location with respect to the laser plane, the position of the corresponding point in the laser stripe can be estimated by triangulation. Finally, these can be transformed into 3D coordinates by incorporating the known motion of the object relative to the laser plane.

In section II we discuss the basic principle of laser triangulation and briefly describe the hardware used for the test setup. Section III describes the calibration method used and in last section we discuss the measurement results obtained from trial experiments.
II. MEASURING PRINCIPLE

1) Laser Triangulation

The geometrical relationship for various parameters of laser, camera and their relative positions is shown in Fig 2. From simple trigonometric formulas, the following expressions with respect to Fig 2 can be derived:

\[ r = \frac{B h}{h_1} \]

Since,
\[ \frac{h_1 + h_2}{\sin(90 + \beta)} = \frac{h_0}{\sin(90 - (\alpha + \beta))} \]

or,
\[ h_1 + h_2 = \frac{h_0 \cos \beta}{\cos(\alpha + \beta)} \]

or,
\[ h_1 = \frac{h_0 \cos \beta}{\cos(\alpha + \beta)} - (L - s)\sin(\alpha + \beta) \]

Finally,
\[ h = (L - s)\cos(\alpha + \beta) = \left( \frac{h_0 \sin \alpha}{\cos(\alpha + \beta)} - s \right) \cos(\alpha + \beta) \]

From laws of trigonometry,
\[ \frac{L}{\sin \alpha} = \frac{h_0}{\sin(90 - (\alpha + \beta))} \]

or,
\[ L = \frac{h_0 \sin \alpha}{\cos(\alpha + \beta)} \]

So,
\[ r = \frac{B \left( \frac{h_0 \sin \alpha}{\cos(\alpha + \beta)} - s \right) \cos(\alpha + \beta)}{\cos(\alpha + \beta) - (\frac{h_0 \sin \alpha}{\cos(\alpha + \beta)} - s)\sin(\alpha + \beta)} \]

Since, object height = \( R \), it can be estimated using the dislocation of the points along the stripe, since it is proportional to the object depth. The relationship between the object depth and stripe dislocation can be established using the information of the camera and the laser location and their configurations [3].

The object is illuminated from one direction with a laser line projector and viewed with the camera from another as shown in Fig. 1. The illumination angle, the viewing angle, and the baseline between the illuminator and the camera define the triangulation geometry, from which the camera calculates the 3D shape. The exact height of each spot on the laser line can be calculated by intersecting the corresponding camera projection ray with sheet of light.

The measuring principle of laser range to acquire 3D shapes is based on the method called laser triangulation, or sheet-of-light range imaging.
Therefore,
\[
\text{Object height} = \frac{\beta - s \sec^2 \alpha}{h_s + s \tan \alpha}
\]

2) IVP ranger M50 camera hardware

The core of the IVP ranger camera is the smart vision sensor M12 and the Intel StrongArm processor [12]. The architecture is built of three main components: the M12 sensor, the processor and the high-speed serial interface (HSSI) module. The sensor has two parallel 32 bit wide buses, one is used for feeding instructions from the Strong Arm processor, and one is used for outputting data over the HSSI-link. The HSSI link can send and receive data at high speed (Max. 330 Mbit/s) to the PC. In addition to the HSSI interface there is a RS232 serial port and 5 digital in and 1 digital output on the camera. The digital I/O can be used to synchronize the measurements with the movement of the object or the sensor system.

The Camera dimensions are 97 x 50 x 50 (1 x h x w) mm and the unit is threaded for standard 1" C lenses. The Camera unit supports power supply between 12 and 24VDC. The distance between the PC and the camera is maximum 50 meters with a twisted pair SAH HSSI cable. Camera model M50 has a 512x1536 pixel sensor area.

The processing to convert the image of the laser line into a vector with 3D shape data is very time consuming. IVP smart vision sensor with built-in RISC processors, the conversion from 2D images to 3D shape data can be done already on the sensor chip. The image of the laser line never leaves the sensor chip, only the calculated 3D data itself; this is the key to the extremely high speed of IVP ranger.

The IVP smart vision sensor M12 has a width and height resolution of up to 1536 x 512 pixels. With the sophisticated ranger 3D profiling software it is possible to obtain 3d data with a resolution of up to 1/5120 of the height measurement range.

The laser used for our experiments is a line projector with visible green light with 35 mW power. The laser has a manually adjustable focus between 10 mm and 4000 mm.

3) Measuring technique

All standard algorithms work with the laser line aligned horizontally with the rows on the sensor. That means, when viewing an image of a flat object illuminated with the laser a flat horizontal laser line appears in the image. The algorithms support region of interest windowing, and thereby height measurement range can be traded for speed. Using a smaller region on the sensor enables measurements at a higher profiling rate. The ROI-height (Region of Interest) is defined by selecting the number of sensor rows to be use.

The basic function of all the measurement algorithms is to compute the impact position of the laser line for all columns on the sensor. The light intensity distribution from the laser line along a sensor column can be described as in Fig. 3.

The location of the laser spot image center can be determined by the following methods:

Position = (a+b)/2 or (m+n)/2
or
COG (center-of-gravity).

\[
\text{Peak \_ Position} = \sum xj(x) / \sum j(x)
\]

The laser line will form a distinct light peak distributed over a number of pixels within the sensor column. The center of this peak will be defined as the impact position of the laser line on that sensor column. The 3D algorithms, HorThr and HorMaxThr, uses thresholds to calculate the impact position while the Hi3D algorithm uses the center-of-gravity (COG) method. The usage of thresholds increases the height resolution of the measurement, with one threshold a ½ - pixel resolution can be obtained and with two thresholds a ¼ - pixel resolution can be obtained.

The usage of COG gives an increase in height direction, typically 1/10 - pixel resolution. The integration time is defined as the time used to collect light on the sensor for one profile sample. With a fixed light intensity from the laser, two different integration times will result in different intensity values on the sensor.

The result from one measurement (scan) is a range profile of 3D-values (ranges) and optionally also an intensity profile of intensity-values. The IVP ranger algorithms use parameters to set all the measurement techniques described above. The behaviour of the selected algorithm is defined by the current parameter setting for that particular algorithm at the time when the algorithm is started.

4) Camera Software

The profiling software in the camera consists of algorithms for 3D profiling, data buffer options and possibilities to synchronize the 3D measurement with external signals.

The standard algorithms are: Horizontal thresholding (HorThr), Horizontal maximum and thresholding (HorMaxThr), High resolution range (Hi3D) and Image. The three first are 3D-range algorithms and the last one is a grey scale algorithm.
The horizontal thresholding algorithm is the fastest of the standard algorithms. The impact position of the laser in each column is computed as described in section above. Two thresholds may be used to achieve higher range resolution. A (3x1) median filter can be applied to the range data to smoothen the data, and to reduce laser speckle influences. The acquisition speed of the HorThr algorithm is dependent on the current setting of the algorithm and the synchronization parameters.

The horizontal maximum (and) thresholding algorithm computes maximum intensity values related to each Range1. These values represent the intensity of the laser line at the impact position in each sensor column. The result from this algorithm is one range profile and one intensity profile. 3x1 Median filtering can be applied on this algorithm too. The acquisition speed of the algorithm is dependent on the current setting of the algorithm and the synchronization parameters. The resolution of the intensity value is directly mapped to the AD resolution in the HorMaxThr algorithm.

The High resolution range algorithm is designed for high resolution range scanning with moderate speed requirements and moderate height field-of-view. The algorithm handles a large dynamic range on the reflected signal, from very dark to very bright. There are two components as a result from this algorithm, one range profile and one intensity profile. The acquisition speed of the algorithm is dependent on the current setting of the algorithm and the synchronization parameters. The AD resolution of the Hi3D algorithm represents both the range and intensity value but it is not linearly mapped.

The image algorithm is a traditional 2D grey-scale imaging algorithm. ROI windowing can be used in the same fashion as in the range algorithms.

III. CALIBRATION METHODS

1) Direct Calibration method

A calibration was done with the laser mounted vertically and camera at certain angle to view the scene. A known diameter of rods are selected as calibration specimens and placed under the scanned area as shown in Fig.4. The resulted profile scanned is shown in Fig.5. The data obtained are plotted against the pixel positions as shown in Fig.6. We approximated the set of points using a 3rd order polynomial as shown in Fig.7

The fitted polynomial function is,

\[ y = p_1 x^3 + p_2 x^2 + p_3 x + p_4 \]

Where the coefficients are:

- \( p_1 = 1.362e-005 \)
- \( p_2 = -0.0037583 \)
- \( p_3 = 0.4828 \)
- \( p_4 = -10.669 \)

Fig.4. Test specimen for calibration

Fig.5 The profile shown on PC

Fig.6 Known diameters vs. pixel position

Fig.7 Polynomial fitting of the calibrated diameters
2) Model based calibration method

A test setup was made as shown in Fig.8 and a calibrated grid of 88 circular holes is scanned as shown in Fig.9. The profiles of 8 rods can be visualized in a PC as in Fig.10.

Given that the 2D to 3D point correspondences,

\[ x_i = P X_i \]

Where \( x_i \) are 2D points, \( X_i \) are the corresponding 3D points and \( P \) is the projection matrix which is to be solved.

The above equation leads to

\[ \min \sum d(x_i - PX_i)^2 \]

Where \( d \) is distance between the measured image points \( x_i \) and the known world points \( X_i \).

IV. MEASUREMENT RESULTS

After the system calibration is performed, several experiments were performed to judge the measurement system capability and accuracy. A stack of 12 floppy disks were scanned one upon another as shown in Fig.11 and the results were tabulated in Table 1. Fig.12 shows the difference between actual and measured dimensions.

![Fig. 8. test setup](image)

![Fig. 9. Calibration Object](image)

![Fig. 10. Profile of calibrated grid object](image)

For each position of the object, we note the position in pixels of the images laser spot in the camera image. So we get a set of measures, which associates a distance and an image position. A least square estimation [11] of this set gives the characteristic graph of the sensor.

![Fig.11. Scanned stack of floppy disks](image)

### TABLE I

<table>
<thead>
<tr>
<th>Actual(mm)</th>
<th>Measured (mm)</th>
<th>Error (A-M) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3x1 = 3.30</td>
<td>3.18</td>
<td>-0.12</td>
</tr>
<tr>
<td>3.3x2 = 6.60</td>
<td>6.50</td>
<td>-0.10</td>
</tr>
<tr>
<td>3.3x3 = 9.90</td>
<td>9.79</td>
<td>-0.11</td>
</tr>
<tr>
<td>3.3x4 = 13.20</td>
<td>13.07</td>
<td>-0.13</td>
</tr>
<tr>
<td>3.3x5 = 16.50</td>
<td>16.33</td>
<td>-0.17</td>
</tr>
<tr>
<td>3.3x6 = 19.80</td>
<td>20.49</td>
<td>+0.69</td>
</tr>
<tr>
<td>3.3x7 = 23.10</td>
<td>23.71</td>
<td>+0.61</td>
</tr>
<tr>
<td>3.3x8 = 26.40</td>
<td>26.98</td>
<td>+0.58</td>
</tr>
<tr>
<td>3.3x9 = 29.70</td>
<td>29.96</td>
<td>+0.26</td>
</tr>
<tr>
<td>3.3x10 = 33.00</td>
<td>33.20</td>
<td>+0.20</td>
</tr>
<tr>
<td>3.3x11 = 36.30</td>
<td>36.49</td>
<td>+0.19</td>
</tr>
<tr>
<td>3.3x12 = 39.60</td>
<td>39.56</td>
<td>-0.04</td>
</tr>
</tbody>
</table>
Similarly different regular polygons were scanned, measured and compared with the actual dimensions and the results are tabulated in Table 2.

**TABLE II**

<table>
<thead>
<tr>
<th>Object</th>
<th>Profile</th>
<th>Error (A-M) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentagon</td>
<td>Side-length A=25.21 M=0.65xHeight of pentagon =0.65x38.78 =25.21 Error = 0.00</td>
<td></td>
</tr>
<tr>
<td>Hexagon</td>
<td>Side-length A=22.52 M=0.58xHeight of Hexagon =0.58x38.96 =22.60 Error = 0.08</td>
<td></td>
</tr>
<tr>
<td>Octagon</td>
<td>Side-length A=16.91 M=0.41xHeight of Octagon =0.41x40.72 =16.70 Error = +0.21</td>
<td></td>
</tr>
</tbody>
</table>

V. CONCLUSIONS

A triangulation based range sensor is described in this paper. The camera hardware and software algorithms are discussed briefly and the measurement system calibrated using a direct polynomial fit based method. A model based calibration method is proposed and its implementation is discussed. A test was performed to check the accuracy of the system and the results were satisfactory. In future 3D model generation through 2D ranger data will be studied and will be implemented in real time industrial applications and robotic vision applications.

VI. REFERENCES