

Calibration of a Wrist-mounted Range Profile Scanner

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Abstract

The wrist-mounted range profile scanners developed in this laboratory provide depth information which is distorted due to the scanning mechanisms. Methods of removing the nonlinearities to provide an orthographic projection have been developed for other range finders, but for a variety of reasons, these have been found unsatisfactory for the large depth of view sensors. A new method and apparatus for calibration are described in this paper. Linear interpolation over multiple known samples of uncalibrated data are used to build a lookup table. The lookup table, stored in RAM, is accessed in realtime using the scanner hardware to provide calibrated data at a rate of 13 calibrated scans per second.

KEYWORDS: calibrate, 3-D, range finder, robot vision.

1. Introduction

The problem of calibrating 3-D laser range finders is an important issue in the application of sensor technology in the Laboratory for Intelligent Systems. A laser range finder that was specifically designed to be mounted on a robot wrist is described in [1]. This particular range finder was designed to have a large depth of field, and provides a single range profile. This is why it is referred to as a range profile scanner. The mechanical arrangement of the range profile scanner is shown in Fig. 1. Several methods have been used to transform the output from range finders to real world Euclidian space. [2][3] This paper deals specifically with calibrating the wrist-mounted laser range finder using linear interpolation.

The apparatus for collecting the raw data to be used in the calibration, and the procedure to do that collection, is nontrivial. These aspects of the calibration are theoretically not crucial to the calibration itself, but if not implemented in a user friendly manner will render the entire process cumbersome and unusable. The objective herein is to document the calibration method and describe the apparatus that has been developed. The system is documented in further detail in [4]. In section 2 the building of the calibration lookup table (LUT) using linear interpolation is described. The success of the calibration process can be measured by the ability of the range profile scanner to produce data in Cartesian coordinates that accurately depicts the surface being scanned. The accuracy of the scanner after calibration is discussed in section 3. Conclusions on the method described are found in section 4.

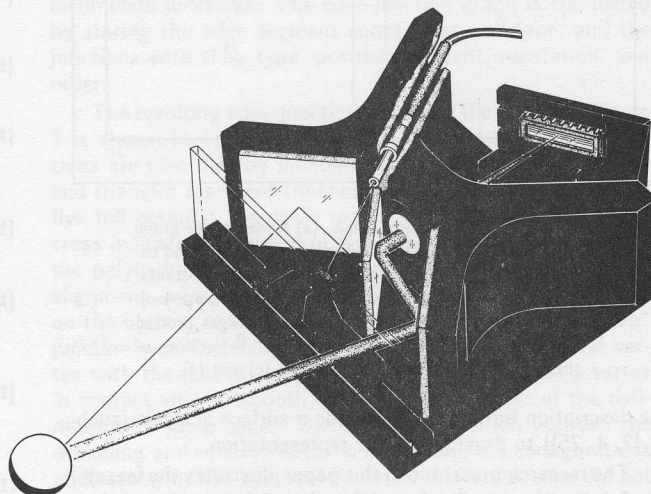


Figure 1. The mechanical arrangement of the wrist-mounted laser range finder to be calibrated.

2. Linear Interpolation for Calibration

The calibration process described here addresses problems of geometric and radiometric distortion related to optical and electrical components used in the range finder. [1]

The task is to couple the distorted polar coordinate system and the more useful Cartesian system by creating a lookup table. The lookup table contains Cartesian coordinate locations and is indexed by the raw range data, and the *azimuth* position. This azimuth position is simply the index, 1-255, of the scan drive system, which represents the angle of projection of the laser beam from the scanner. Interpolation is done between two adjacent scans of range values for each azimuth to obtain the Z values in the Cartesian coordinate system. These Z values are placed in the LUT. The X values for the X-Z coordinate pairs are computed using the Z values obtained from the table, and the linear equation of the azimuth in question. The method used to calculate the azimuth equations is described in section 2.2.

2.1 Advantages of Linear Interpolation

The calibration lookup table is affected by any degradation in the quality of raw data. There is some degradation in the raw data at the extremity of the scan due to

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partial blockage of the return path of the laser in this particular range finder. This problem is not serious, as it is localized to small regions at one end of the scans at short standoffs, and at the opposite end of the scan at large standoffs. Linear interpolation, being a local function, will restrict this phenomena to a small number of points in the extremities of the lookup table.

Due to the geometric design of the camera, the resolution of this sensor is much higher at short standoffs than at larger standoffs where the fine resolution is less important. This function can be represented by showing the change in range values collected from the range finder as it is moved through its field of view. Fig. 2 shows Z vs. Range values. Note that at short standoffs, the range values are changing very fast compared to the change in Z. It is this property that results in good accuracy at the short standoffs, which deteriorates as the standoff distance increases.

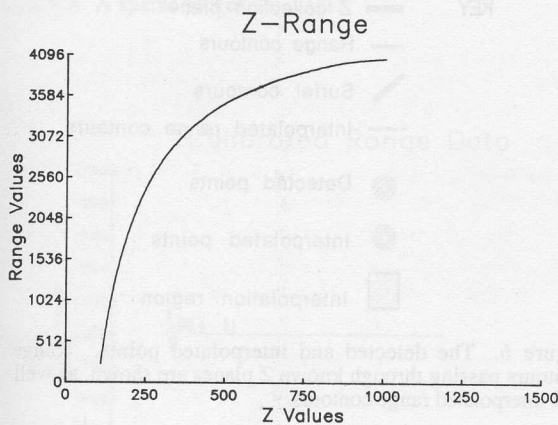


Figure 2. The range values collected at each Z. This shows that the shortest standoff distances have much higher resolution in range than the larger standoffs. The range values at the centre of the scan are used for this plot.

2.2 Determining Position in X

The field of view of the range finder is illustrated in Fig. 3. The concentric curves in this figure represent all points equal to one range value. For reference, a collection of these points for a given range value is termed a *range contour*. The CCD, through the peak detection algorithm [5], can resolve 4096 different range contours representing 12 bits of information. The scanning mechanism scans with 255 azimuth steps in the X direction. A collection of all range readings (4096 values) at the same azimuth position is termed an *azimuth contour*. These azimuth contours are radial lines extending outward from the range finder over the full field of view (Fig. 3).

Calibration for the X direction is done by computing the linear equations of the data passing through the azimuth contours. (See Fig. 3) This is possible because the azimuth contours in the Range-Azimuth coordinate system remain linear in the X-Z coordinate system. This is evident if the reader considers that the shape of the field of view will not change as the data is transformed to Cartesian coordinates. Once the linear equations of the azimuth contours are calculated, these can be stored and used to calculate the X coordinates by simply substituting the Z values into the equations as they are extracted from the LUT.

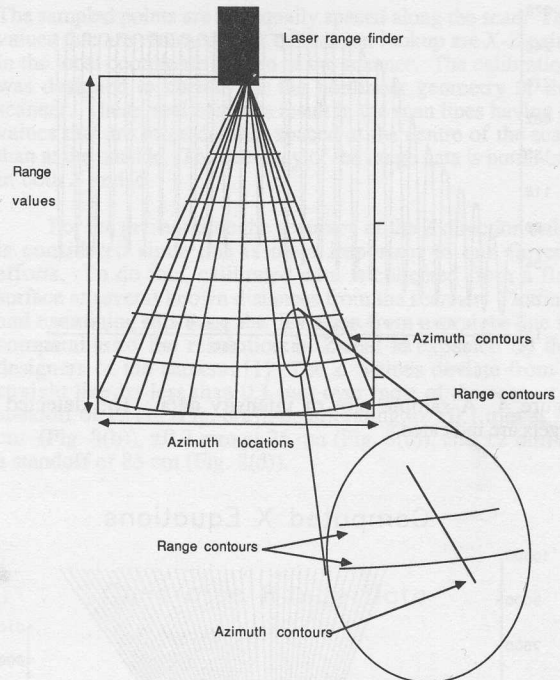


Figure 3. The full field of view of the range finder. The distorted polar coordinate system is illustrated.

The method used to calculate the equations of the azimuth contours is as follows. Several Azimuth-Range coordinate pairs must be obtained for each azimuth. A line is fitted to these coordinates which minimizes the error of the equation in a least squares sense. The resulting equations can be used to determine the X values in Cartesian space. Azimuth-Range coordinate pairs must be determined at each azimuth. This is accomplished experimentally. Intensity data is collected over targets which consist of a number of equally spaced black bars. An example of the raw intensity data collected from a target is shown in Fig. 4. The larger gap observed in the middle corresponds to the size of the bars at the centre which is twice the spacing between the bars to indicate the X origin of the Cartesian coordinate system. The targets used at various standoff distances have differing bar width to allow for the changing resolution of the sensor through its field of view.

Using these black targets, the X values are computed for each azimuth. The X origin of the Cartesian coordinate system which is at the centre of the large spacing between the bars is detected. From this position, values of X equal to the distance between two bars are assigned to each azimuth position previously calculated. These measured target azimuth values and their corresponding X values are used to linearly interpolate X values for each azimuth step in between them.

On each scan the first and the last target detected does not correspond to the end of the scan. Therefore, the first and the last positions detected are used as the starting points for extrapolation to the ends. Thus, the equations of the azimuths at the outer edges of the field of view are not as accurate as the central region.

The X values are calculated for each of the 255 azimuths. The equations of the azimuth contours are calculated as described above. A sparse plot of these azimuth contours is shown in Fig. 5. This figure gives the reader a feeling for the

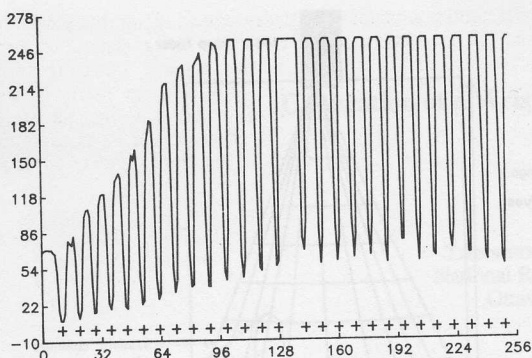


Figure 4. A sample plot of intensity data. The detected targets are indicated.

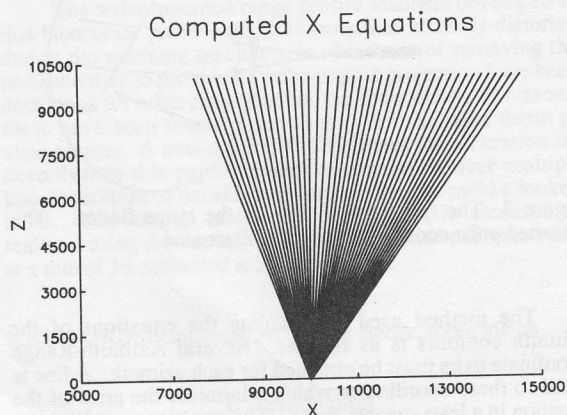


Figure 5. Calculated equations of the azimuth contours.

shape of the range finder's field of view as well as an indication of how the resolution in X is decreasing as the standoff increases.

2.3 Interpolating in Z

The range and azimuth contours discussed above represent the range finder's distorted polar coordinate system. The mapping of this system to the Cartesian coordinate system is achieved through sampling the field of view of the range finder with Z collection planes. The frequency of sampling is directly related to the accuracy needed for the calibration table. (For a discussion on accuracy refer to section 3). The Z collection planes intersect all azimuth contours as well as a number of range contours. Consequently, information can be collected from both coordinate systems about every point on these planes. These points establish a direct relationship between the distorted polar coordinate system and the Cartesian coordinate system from which the Z lookup table is constructed.

The range value and azimuth position, (in the polar coordinate system), are collected from the scanner hardware for each point within the Z collection plane. The Z position, in Cartesian coordinates, is recorded from the calibration bench. The interpolation process involves choosing points for which pertinent information in both coordinate systems is known. These points, illustrated as detected points in Fig. 6, occur at

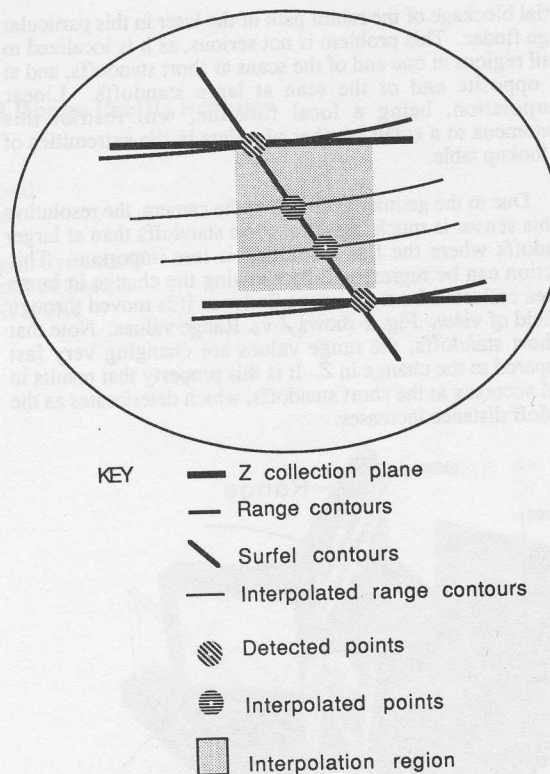


Figure 6. The detected and interpolated points. Range contours passing through known Z planes are shown, as well as 2 interpolated range contours.

the intersection of the azimuth contour, the range contour, and the Z collection plane. Two such points are needed for the outer limits of the interpolation regions. These points must be located on adjacent Z collection planes as well as belonging to the same azimuth contour. These constraints effectively define the range as the independent variable in the polar coordinate system. It can be assumed that the X and Z axes in the Cartesian coordinate system are independent. Thus, linear interpolation can be applied to calculate Z values for any range value within the interpolation region without regard to the X direction. Only values corresponding to the 11 bit range contours (2048 positions) within the interpolation region are calculated to restrict the lookup table to a manageable size. The lookup table is populated horizontally by repeating the process described above for all azimuth contours and populated vertically by iterating between all collection planes within the working range of the scanner.

The Z values have a resolution of 0.1 mm for the table entries. They are indexed by their corresponding range and azimuth values. The table has (2048 x 256) entries and occupies 1 Mbyte of memory. It is inspected for gross errors by plotting a sampling of the table. In Fig. 7 the LUT is plotted sparsely giving the reader an idea of the shape of the data in the table. Note that the LUT resembles an inverted polar coordinate system, which is what one would expect to remove the spherical distortion in the range data.

3. Accuracy Determination

Determining and expressing the accuracy of the profile scanner after calibration is quite difficult for several reasons.

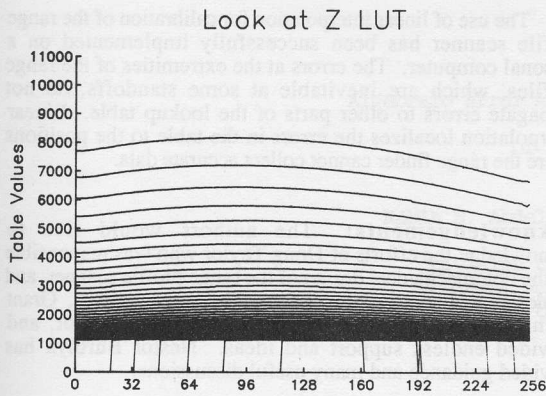
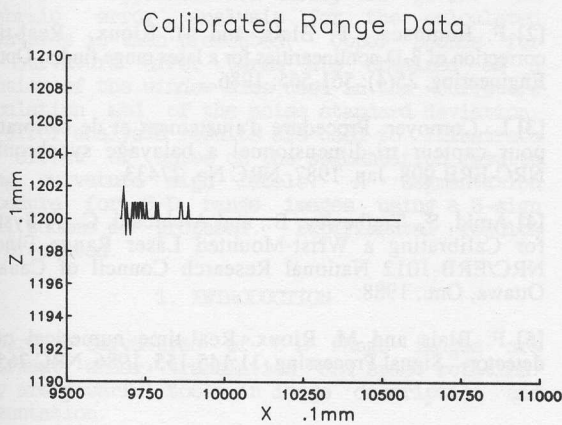


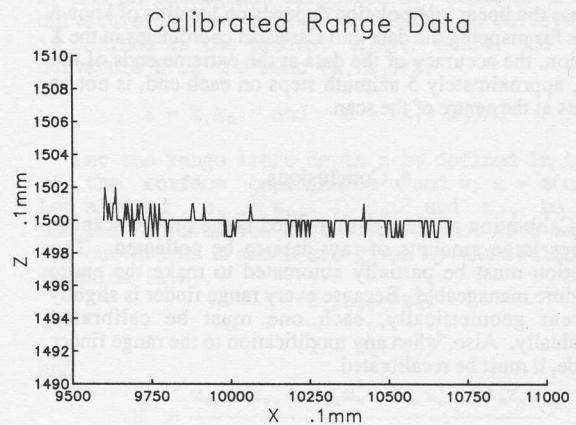
Figure 7. A sparse plot of the LUT.

The sampled points are not equally spaced along the scan. The values that are returned after calibration lookup are X-Z pairs in the local coordinate system of the scanner. The calibration was designed to correct for the nonlinear geometry of the scanner. These nonlinearities result in the scan lines having X values that are more densely spaced at the centre of the scan than at the outside. The accuracy of the range data is nonlinear in both X and Z.

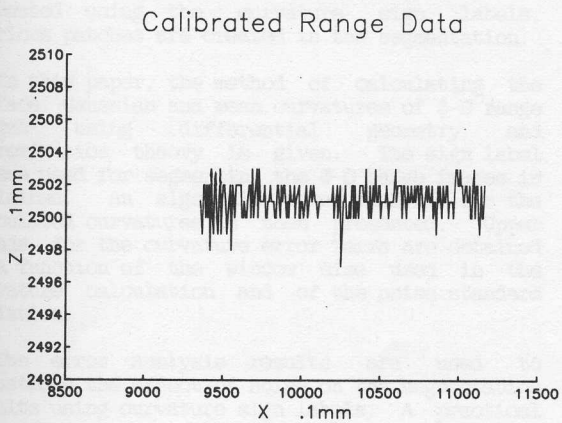
For the present time the accuracy of the Z direction only is considered since this is more important to our current efforts. To do this, calibrated data is collected from a flat surface at several known distances from the scanner. Plotting and examining this data, the deviation from a straight line is comparable to the resolution in Z that is expected by the designers of the camera. [1] The Z values deviate from a straight line by less than 0.1 mm over most of the scan at a standoff of 12 cm (Fig. 8(a)), deteriorating to ± 0.1 mm at 15 cm (Fig. 8(b)), ± 0.2 mm at 25 cm (Fig. 8(c)), and ± 2 mm at a standoff of 85 cm (Fig. 8(d)).



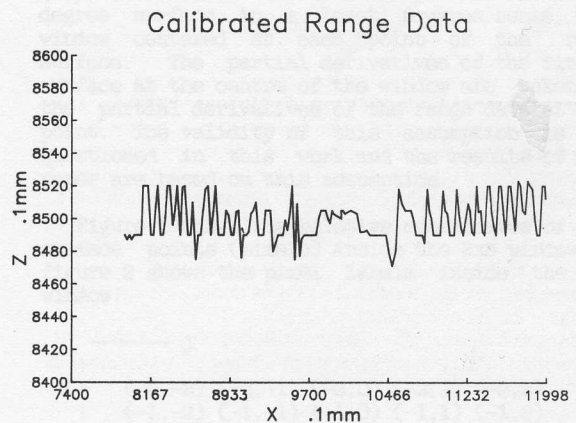
a



b



c



d

Figure 8. Accuracy determination by examining calibrated range data for a flat surface with a very high gain on the Z axis: (a) standoff = 12 cm, (b) standoff = 15 cm, (c) standoff = 25 cm, (d) standoff = 85 cm.

Accuracy of the range finder when measuring the distance to an ideal flat surface is somewhat different than expressing the accuracy or ability of the scanner to perform some real world task. There are other issues to be examined before the applicability of the scanner to perform a specific task can be determined. The shadow effect, for example, is greatly reduced using the synchronized scanning technique, but measuring this is truly dependent on the application. Usually a machine vision system must express its accuracy in terms of the particular application, for example, "these manufactured parts will be inspected to an accuracy of 1 mm in diameter".

Another major factor in expressing accuracy is the reflectivity of the surface being scanned. If the CCD saturates due to a highly reflective surface, the accuracy will drop dramatically, or no data will be available at all. This problem has been examined closely, and it is currently believed that the laser power can be dynamically attenuated to ensure that a reflective surface will not saturate the CCD. The cost of this attenuator is quite high, and it is not known if this will be a cost effective approach.

Accuracy in the X direction is a slightly different issue. Because the linear interpolation depends on location of known targets for mapping the data into Cartesian coordinates in the X direction, the accuracy of the data at the extreme ends of the scans, approximately 5 azimuth steps on each end, is not as good as at the centre of the scan.

4. Conclusions

Calibration of the wrist-mounted range profile scanner requires large amounts of raw data to be collected. The collection must be partially automated to make the entire procedure manageable. Because every range finder is slightly different geometrically, each one must be calibrated individually. Also, when any modification to the range finder is made, it must be recalibrated.

The use of linear interpolation for calibration of the range profile scanner has been successfully implemented on a personal computer. The errors at the extremities of the range profiles, which are inevitable at some standoffs, do not propagate errors to other parts of the lookup table. Linear interpolation localizes the errors in the table to the positions where the range finder cannot collect accurate data.

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