SINGLE CAMERA SYSTEM FOR CLOSE RANGE INDUSTRIAL PHOTOGRAMMETRY

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Commission V

Abstract

This paper gives a description of an on-line photogrammetry system designed for close range applications (SCS Single Camera System). The system has the ability to perform 3-D point measurements, employing one single CCD camera in combination with a measurement tool. The measurement tool is equipped with LEDs serving as photogrammetric targets, which are precalibrated in the local tool coordinate system. Accuracy results obtained from simulation studies and measurement tests are reported. The possibilities of accuracy improvements by post processing the SCS measurements in a free network bundle adjustment is also discussed.

Key Words: Accuracy, Close Range, Industrial, Photogrammetry

1. Introduction

The Metrology Norway System (MNS) developed by Metronor AS, is an on-line photogrammetry system designed for close range applications (see [1] and [2]). By employing high resolution CCD cameras in combination with the Light Pen, the MNS becomes a portable Coordinate Measuring Machine (CMM). The system allows for rapid and accurate data collection for a variety of metrology tasks.

The metrology concept is based on measuring the spatial (XYZ) coordinates of reflected laser beams or Light Emitting Diodes (LEDs). The laser spots and LEDs constitute the photogrammetric targets. To achieve a favorable signal-to-noise ratio of the sensor observations, the amount of light emitted from each LED is regulated individually for each exposure.

To obtain a favorable accuracy and a user friendly system, the CCD cameras in the system are laboratory calibrated by Metronor AS. This one time calibration process, which involves measuring more than 10 million calibration points for each camera, turns the high resolution CCD camera into an "ideal" photogrammetric camera. Due to the laboratory calibration the system does **not** need to rely on a full self calibration in the setup. The calibration method is a unique and proprietary technique developed and patented by Metronor AS, and will not be further described in this paper.

2. Background

The usual way of operating an on-line digital photogrammetric station is by employing dual- or multi-camera setups. Operation of the system is usually divided into an initialization phase (setup), followed by a measurement phase. System initialization usually involves a relative orientation of the cameras and a scale transformation, eventually also a camera calibration and calculation of exterior orientation. In the measurement phase, 3D coordinates of target points are calculated by intersecting rays of the projected target in each of the cameras, employing the exterior and interior orientation parameters estimated in the setup. To obtain on-line 3D measurements, this technique requires two or more cameras operating simultaneously.

By employing the Light Pen as a measurement tool, it is possible to think of new strategies for on-line photogrammetry. The Light Pen is equipped with a number of LEDs (5 or 6), all precalibrated in the **local coordinate system** of the Pen (X_i^p, Y_i^p, Z_i^p). The interchangeable Pen tip is also calibrated in the same coordinate system. Figure 1 shows the Light Pen.

When the LEDs are imaged on the sensor of a camera, the sensor observations (x_i^s, y_i^s) together with the given 3D local coordinates of the LEDs (X_i^p, Y_i^p, Z_i^p) gives enough information to estimate the position of the Pen **as referenced to the camera** (X_0^c, Y_0^c, Z_0^c). The coordinates of the Pen Tip, which is the touch point when doing a measurement, can then easily be estimated in the camera coordinate system. By employing this technique, on-line 3D measurements can be done with only **one camera**.

The idea of a 3D measurement system employing only one camera (SCS Single Camera System) was initiated at SAAB Scania Aircraft Division in Linköping, Sweden, and developed by Metronor AS. Some of the reasons for developing such a system are:

- To have a system that is designed for measurements on large constructions in the aircraft industry. Typical applications are straightness measurements of airplane fuselages and measurement of wing contour. The SCS is ideal for these applications due to its high angular accuracy (see Section 4).

- To have a system designed for fast operation. The SCS does not need any system calibration (relative orientation) and is therefore favorable for time critical measurements.

- To reach difficult places where a dual- or multi-camera setup is not possible to employ due to physical restrictions on the survey site.

- To benefit from the redundancy when having several sensor observations for each measured object point (several LEDs on the Light Pen), leading to a lower stochastic variance of object point coordinates.

- To have the possibility of measuring hidden points (points that can not be seen directly from the cameras), both reference points and ordinary measuring points.

- To have the possibility of establishing a photogrammetric network with a strong geometry.

3. Single Camera System

The Light Pen forms an integral part of the SCS, and the measurement accuracy and functionality depend much on the geometry of the Light Pen. As a tool in the design process of the Light Pen, simulation studies were utilized to arrive at a favorable solution. Various shapes with various numbesr of LEDs were simulated before ending up with the Light Pen showed in Figure 1.

Each Light Pen contains five or six (depends on Pen size) embedded LEDs. There are several interchangeable tips for the Light Pen, each specially designed for different measurement applications. The Light Pen is compatible with commercially available CMM probes. Tips can also be manufactured on site by the user, and calibrated by employing a special calibration routine that follows the system.

The most important features to consider when designing the Light Pen were:

- **User friendliness.** The Light Pen has a slim construction and is fabricated of light weight composite material. This makes the Light Pen easy to use, also in narrow places.

- **Stability.** Durable composite construction minimizes the effect of temperature variations and other physical constraints.

- **Fast and reliable point identification.** When operating the system, the target points on the Pen are automatically identified by the system based on the given Pen geometry. Due to the simple geometry, the points are easily identified by the point identification software for all Pen orientations.

- **Unique mathematical solution.** A minimum of 3 observed target points are required to obtain a non-singular mathematical solution for estimating the relation (transformation matrix) between the local Light Pen coordinate system and the camera coordinate system. However, only 3 points may lead to ambiguous mathematical solutions. Employing 5 or 6 points with the geometry showed in Figure 1 gives a unique mathematical solution, and enough redundancy to eventually detect gross observation errors.

- **Fast convergence.** The SCS software is based on linearized equations (Equation 1 is linearized) which is solved in iterations. The depth information (Light Pen pointing towards the camera) together with good approximate values for the unknown parameters, gives a fast convergence towards the correct solution.

The SCS is based on bundle adjustment software. Equation 1 express the relation between the sensor observations and the 3D coordinates of the corresponding target points (perspective transformation):

$$
\begin{aligned}
x_i^s &= f * \frac{a_{11}(X_i^p - X_0^p) + a_{12}(Y_i^p - Y_0^p) + a_{13}(Z_i^p - Z_0^p)}{a_{31}(X_i^p - X_0^p) + a_{32}(Y_i^p - Y_0^p) + a_{33}(Z_i^p - Z_0^p)} + dx \qquad (1)\\
y_i^s &= f * \frac{a_{21}(X_i^p - X_0^p) + a_{22}(Y_i^p - Y_0^p) + a_{23}(Z_i^p - Z_0^p)}{a_{31}(X_i^p - X_0^p) + a_{32}(Y_i^p - Y_0^p) + a_{33}(Z_i^p - Z_0^p)} + dy
\end{aligned}
$$

Equation 1: Perspective Transformation where the following is given information;

x_i^s, y_i^s : observed sensor coordinate of a LED (target point) on the Light Pen,

f : calibrated focal length of CCD camera,

X_i^p, Y_i^p, Z_i^p : 3D coordinates of a LED (target point) on the Light Pen in the local coordinate system of the Light Pen,

dx, dy : camera calibration corrections to the primary sensor observations,

and these six parameters are estimated in the adjustment;

X_0^c, Y_0^c, Z_0^c : origin of the camera coordinate system (perspective center of camera) as referenced to the Pen coordinate system (three unknown coordinates),

$a_{11} \ldots a_{33}$: three unknown rotation angles defined by the nine elements in the rotation matrix,

With six LEDs on the Pen, there is a redundancy of six observations (twelve observations, six unknowns) for each measured object point. Equation 1 is linearized and solved in iterations, using the redundant observations to perform a **least squares adjustment** (bundle adjustment) on the sensor observations. The camera position as referenced to the local coordinates system of the Pen is estimated in the adjustment. The reverse transformation, that is the Pen position as referenced to the camera coordinate system, is then easily found.

Approximate values for the unknown parameters, which are necessary for the iterative solution approach, are found using simplified computations together with "rules of thumb".

The points on the Light Pen do **not** contain enough information to perform a successful camera calibration through the bundle adjustment. Therefore, to obtain a favorable accuracy, the SCS has to rely on precalibrated (laboratory calibrated) cameras.

4. Accuracy Characteristics

An important feature of any metrology system is the measurement accuracy. To indicate the accuracy potential of the SCS and also to find a favorable Light Pen geometry, simulation studies have been done. The studies have primarily been focused on measurement **precision** (repeatability).

The 3D point determination is based upon the observations of a given pen geometry in only one camera, and not on the intersection of rays between cameras with known relative orientation. Therefore, the accuracy characteristics is quite different for the SCS compared to a dual- or multi-camera system. Higher accuracy is achieved in the XY plane (lateral and vertical axes which are parallel to the CCD sensor inside the camera) than in Z direction (along the depth axis which is perpendicular to the CCD sensor). Accuracy is a function of camera characteristics, camera to object distance and geometry of the Light Pen. In the simulation studies, the sensor observations have a noise level (σ value) of 0.015 pixels. The simulated Light Pen is equipped with six LEDs and has a total length (y) of 800 mm, and a depth (z) of 200 mm.
Table 1 shows simulated repeatability results for different camera to object distances.

Distance [mm]	σ X [mm]	σ Y [mm]	σ Z [mm]
2000	0.013	0.013	0.05
4000	0.026	0.026	0.18
6000	0.037	0.033	0.41
8000	0.052	0.052	0.79
10000	0.066	0.066	1.25
15000	0.091	0.091	2.65

Table 1: Simulated repeatability results for SCS

To verify the simulation results several experimental measurement test have been done. Table 2 shows the results from a repeatability test for various camera to object distances.

Distance [mm]	σ X [mm]	σ Y [mm]	σ Z [mm]
2000	0.006	0.005	0.05
4000	0.020	0.016	0.13
6000	0.025	0.025	0.26
8000	0.037	0.038	0.54
10000	0.111	0.058	0.87

Table 2: Experimental repeatability results for SCS

There is a good correlation between the simulated and the experimental results. With the exception of one of the results for the longest distance, the experimental results are slightly better than the simulated. This indicates that the simulated σ level of 0.015 pixel on the sensor observation is too high for optimal conditions.

An other experimental measurement test was done to find the accuracy of **surface measurements**. 50 points were measured on a certified plane (plane better than 0.001 mm) of size 200 mm X 500 mm. The optical axis of the camera was aligned to be approximately parallel with the plane. The SCS measurements were fitted to a mathematical plane and the measurement standard deviation was estimated based on the residuals. For a camera-to-object distance of 2500 mm, the accuracy was found to be ($1*\sigma$ level);

Distance [mm]	σ_p [mm]
2500	0.010

Table 3: Plane measurement results for SCS

It is clearly shown that the accuracy in the directions normal to the line of sight (X and Y direction in the simulations and experiments) is superior to the accuracy parallel with the line of sight (Z direction). With other words, the SCS is a metrology system where the angular measurement accuracy is superior to the distance measurement accuracy.

More extensive tests, like standardized CMM accuracy tests, have not yet been done. Nevertheless, both the simulations and the experimental results so far indicate that the SCS meets the accuracy requirements for a variety of industrial metrology applications.

5. Post Processing of SCS Measurements

If on-line measurements are not of paramount importance, accuracy can be significantly improved by repeating measurements of the same object points using different camera positions, and subsequently entering the observations into a post processing module. The accuracy improvement achieved by the post processing approach is based on utilizing the high angular accuracy of the SCS system. The post processing approach is ideal for the establishment of high precision reference networks.

As explained in Section 3, the SCS software is based on estimating the position of the Light Pen tip as referenced to the camera coordinate system. When the Pen tip is pointing to a measurement point, the point of contact is mathematically back-projected on to the sensor, based on the estimated relationship between the coordinate system of the Light Pen and the camera coordinate system (see Figure 1). Equation 1 is used for this perspective transformation. The back-projected point constitutes the "fictitious" observation that is recorded and subsequently input to the post processing bundle adjustment. For every camera position, the same object points (triangulation points) are touched with the Light Pen tip, and the "fictitious" sensor observation is calculated for each of the object points. The accuracy of the back projected point is determined by the angular measurement accuracy of the SCS.

In the post processing bundle adjustment, the 3D coordinates of the triangulation points are estimated. The accuracy of the triangulation points is dependent on the geometry of the photogrammetric network. Network geometry is characterized by the number and orientation of camera stations, and number and position of triangulation points. Due to the approach of "indirect" measurement of triangulation points using the Light Pen, the points are observable from "all" directions. Therefore it is easy to achieve a favorable network geometry when operating the SCS.

The full 3D measurement capability of SCS provides approximate coordinate values for all the unknown triangulation points, which is needed for the post processing. To achieve a high accuracy, the post processing is a free network bundle adjustment only constraining given distances between some of the triangulation points.

6. Applications

To obtain a favorable result for SCS applications, the accuracy characteristics of the SCS must be taken into account. Two main application groups can be defined:

1. Applications where full 3D measurement capabilities are not required, like straightness measurements.

2. Applications with low accuracy requirements, where the moderate length measurement accuracy of SCS is satisfactory.

Some examples include:

- Measurement of the straightness of airplane fuselages. If the line of sight is approximately parallel with the airplane fuselage when doing the measurements, the high angular accuracy will provide a high accuracy of the straightness measurements.

- Measurement of wing contour. If the line of sight is parallel to the wing surface, high accuracy is achieved.

- Measurement of flush and gap on nacelle (aircraft engine cover). Flush is measured with the camera aimed in the length direction of the nacelle, while gap is measured with the camera pointing perpendicular to the length direction.

- Measurements on collision tested cars. This is an application where the accuracy requirements usually are moderate. Measurements inside the crash tested car are particularly easy to perform.

- Establishment of high precision reference networks by SCS in combination with post processing.

References

[1] Alf Pettersen. "Metrology Norway System - Optimum Accuracy based on CCD Cameras". International Archives of Photogrammetry and Remote Sensing, Vol.XXIX, ISPRS 1992, Commission V.

[2] Alf Pettersen. "Metrology Norway System – An On-line Industrial Photogrammetry System". International Archives of Photogrammetry and Remote Sensing, Vol.XXIX, ISPRS 1992, Commission V.

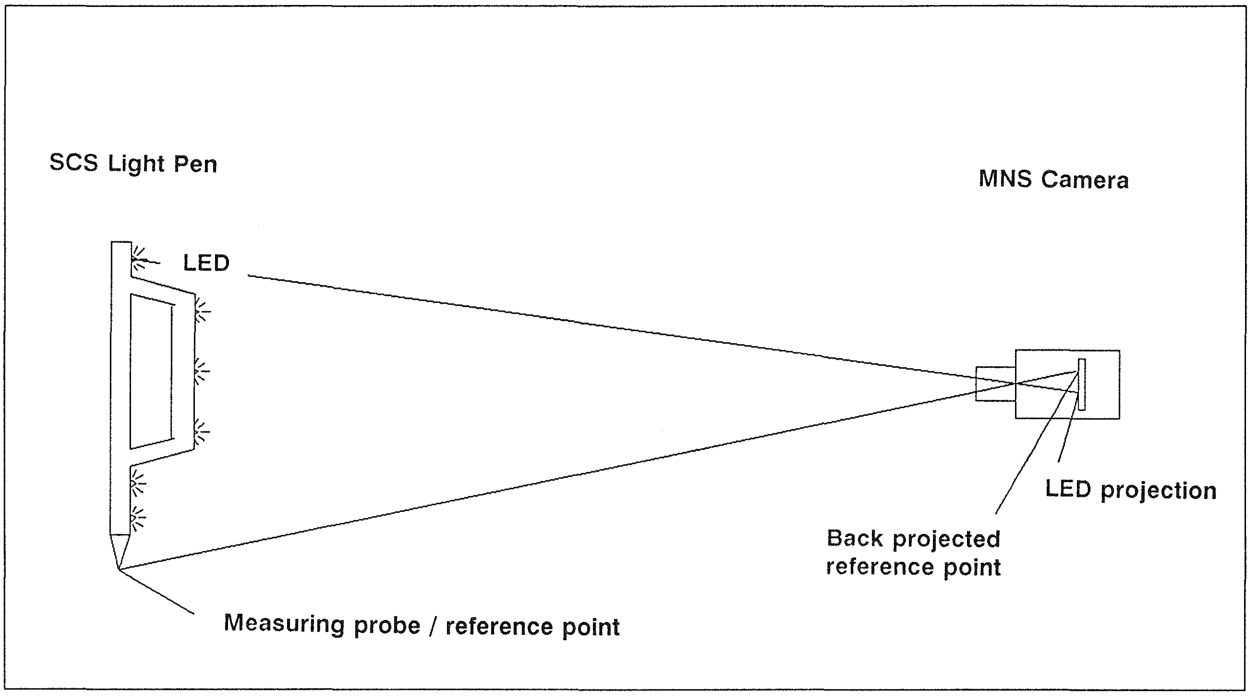

Figure 1: SCS Light Pen