# 3-D MEASURING SYSTEMS BASED ON THEODOLITE-CCD CAMERAS

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ABSTRACT

A 3-D measuring system is proposed which is formed by attaching a CCD camera to the telescope of each of two motorized theodolites. This system can work in the same way as other motorized theodolite systems but using the mounted CCD cameras as vision devices to search targets automatically. It can also work on the photogrammetric principle with the CCD cameras as imaging devices and the theodolites as precise direct orientation tools. High resolution image coverage can be obtained by capturing serial images while swinging the telescope with the camera attached. A function of automated 3-D tracking while measuring can also be incorporated in the system. In this paper, the techniques for system calibration and orientation are described and the accuracy capacity of the system investigated experimentally.

**KEY WORDS:** 3-D; CCD; Theodolite; Calibration.

## 1. THE SYSTEM -- THEODOLITE-CCD COMBINATION

The proposed 3-D measuring system consists of two theodolite-CCD cameras. Each of the theodolite-CCD cameras is made by attaching a CCD camera rigidly on the telescope of a motorized theodolite. The camera and the theodolite are optically independent of each other so that the camera can take images and the theodolite can still measure angles as usual, but both are controlled by the host computer with image processor mounted.

Theodolites have served in geodesy and surveying as angle measuring devices for many years. Their ability to determine three dimensional coordinates is based on the principle of pointwise triangulation. They feature very high pointing accuracy with a panoramic coverage. Modern theodolites have reached the stage of motorization, self correction of instrument error, high precision and high stability. 3-D measuring systems using motorized theodolites have been shown, for example, by the Kern SPACE system, to be very efficient and useful in some industrial sectors (Gottwald,1989).

CCD cameras used in place of conventional film cameras give the technology of photogrammetry the possibility of real-time, on-line and intelligent automation. The suitability of CCD cameras for photogrammetry has been proved by many recent researchers. Photogrammetry features instantaneous multi-point record and lifelike image display. The relative accuracy of digital photogrammetry with available CCD cameras is, however, lower than that of theodolite methods.

Combining theodolites and CCD cameras in a measuring system will enable the system to choose either theodolite methods or photogrammetry, whichever is suitable in a particular case. The two types of methods will complement each other in the system and give the system many exclusive features. Such a combination has very good prospects as part of a universal measuring system or a surveying robot. The detailed advantages of the system can be appreciated from the envisaged working modes as follows.

### Theodolite Scanning Photogrammetry

The CCD camera, rotatable together with the telescope of the theodolite, is mounted with a long-focus lens to take large scale images required by the specified accuracy. The auto-theodolite on which the CCD camera is mounted rotates as a scanning device so that the CCD camera can take a number of images to cover the whole object to be measured. The geometric relationship among all the images taken on the theodolite station can be determined through the theodolite readings.

Having a relatively low accuracy has been the main reason why on-line digital photogrammetry with CCD cameras cannot replace the film based photogrammetry. High resolution CCD cameras with standard photogrammetric accuracy capacity still cost a great deal. Yet, on the principle of theodolite scanning photogrammetry, the proposed system can virtually improve the accuracy capacity of the CCD cameras to that of the theodolites, which could, taking the Kern E2 theodolites for example, amount to 1/200,000 of the object size (Gottwald, 1989). Besides, the system retains all the advantages of CCD camera photogrammetry. The measured object can be recorded patch by patch, which is faster than the point-wise measurement adopted in the pure theodolite system.

### Discrete Point Coordination with Automated Searching

The system can also be used to coordinate discrete targets point by point with theodolite intersection the same way as the Kern SPACE is used. The superiority of the proposed system is that the CCD cameras can act as a pair of 'searching eyes' with wide-angle lenses. In principle, the scene is first imaged by the pair of wide-angle cameras and the targets in the scene are then detected and located roughly by photogrammetry. Finally, the rough three dimensional coordinates are used to guide the telescopes to point at the targets individually for precise determination. In practice, there may be various strategies and tactics of doing this.

Real-Time Photogrammetry with Automated Direct Orientation

The system can be used as a pair of CCD cameras to do real-time photogrammetric work. In this case, both the relative and the absolute orientation parameters of the cameras can easily be determined directly through the theodolites no matter how the scene and the configuration are unfavourable. This orientation procedure can also be automated. The accuracy of this mode is limited by the resolution of the CCD cameras.

Measuring while Tracking

The system is capable of measuring the geometric status of a dynamic object as it is tracking it for kinematic parameters. This function results from the combination of motorized theodolites and CCD cameras and can scarcely be found in other systems. The accuracy of this mode is again restricted to the resolution of the CCD cameras.

Another justification for combining theodolites with CCD cameras is that much photogrammetric practice involves some sort of theodolite operation, either in calibration, control establishment, or in accuracy tests. Integrating theodolites and CCD cameras in a system will change the situation that a high accuracy system cannot work without an even higher accuracy system providing control for it.

The concept of combining theodolites with CCD cameras has, in fact, been mentioned before (West-Ebbinghaus, 1988). The fundamental principle of such systems is no more than some variation of the existing photogrammetric theory. More important, however, is the effort we need to bring this innovative idea into instrumentational research in one form or another.

The current investigation covered in this paper is about the fundamental problems of such systems -- calibration and orientation.

## 2. SYSTEM CALIBRATION

System calibration includes the determination of the camera interior parameters and the geometric relationship between the camera and the theodolite. The latter is stated by three positional parameters and three rotational parameters with respect to the telescope coordinate system. These six parameters can be determined together with the camera interior parameters by using the camera-on-theodolite calibration method where only two targets have to be used (Huang & Harley, 1989,1990). The camera-on-theodolite method relies on the rotation of the telescope and multi-exposure to form an array of target images on the CCD camera from only one or two physical targets. The corresponding 3-D coordinates of those target images with respect to the telescope coordinate system can be determined from the theodolite readings and the target to theodolite distances so as to allow the solution of space resection for the camera parameters and the camera to telescope parameters. This process can be fully automated if auto-theodolites such as the Wild TM 3000 are available.

System calibration should also include the determination and check of the axial correctness of the theodolite; many theodolites we use today are good enough to save this step and if not the established methods in surveying can be used to solve it.

## 3. SYSTEM ORIENTATION

System orientation involves the determination of the relative geometric relationship between the two theodolites. It is apparent that once the system calibration as well as the theodolite orientation have been completed, the orientation of the cameras at any theodolite readings can be derived straightaway. There are a number of methods for theodolite relative orientation:

five-point method for non-levelled theodolites;

three-point method for levelled theodolites;

reciprocal pointing plus one point for non-levelled theodolites;

reciprocal pointing only for levelled theodolites;

horizontal reciprocal pointing plus one point for levelled theodolites;

theodolite orientation via the attached CCD cameras.

The principles of those methods can easily be understood by photogrammetrists and surveyors. The detailed mathematical description of some of them can be found in Kyle's thesis (Kyle,1988) The theodolite orientation process can be fully automated if auto theodolites such as the Kern E2-SE or Wild TM3000 are used. For scaling a known distance is required in using the methods listed.

The absolute orientation which relates the system to any specified real-world reference system can be realized much more easily and flexibly with the help of the theodolites which is itself part of the system.

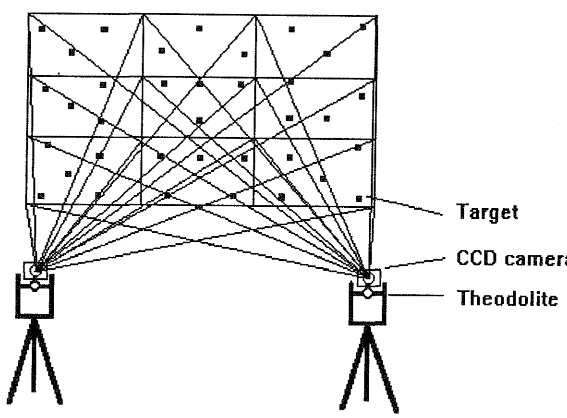
## 4. DIGITAL IMAGE PROCESSING

The targets which have been used in experiments are black discs laser-printed on white paper. The diameters are about seven pixels on images, while larger targets are used for calibration. A local thresholding method is applied to detect target images, which is similar to the one used by Zhou (1990). The method of least squares parabolic edge interpolation followed by elliptic fitting is used to locate target centres on images to subpixel accuracy (Huang & Harley, 1990). The correspondence of conjugate target images is achieved by comparing the closenesses of image points to epipolar lines from left to right and from right to left.

## 5. EXPERIMENTS IN THEODOLITE SCANNING PHOTOGRAMMETRY

Experiments have been carried out to investigate the accuracy of theodolite scanning photogrammetry and the effectiveness of the calibration and orientation methods used. For this purpose, a three dimensional target array of dimensions of 2.3*1.7*0.9 m was coordinated with the Kern E2-ECDS system to an accuracy of 0.01 mm. These coordinates were regarded as true values in accuracy assessment. The accuracy of the photogrammetrically determined coordinates was then assessed by the RMS of the residuals resulting from the coordinate transformation from the determined coordinates to the true coordinates with scale factor as unknown.

Two theodolite stations were set up at a stand-off distance of about 3 metres with base line of 2.2 metres. A Philips frame transfer CCD camera of a 4.5*6 mm sensor chip was used together with a PCVISION Plus image grabber to capture digital images of 480*512*8 bits. The focal length of the camera lens was 25 mm. On each station, 3*3 frames of image were captured so as to cover the whole target array (see the figure). Because only one CCD camera mount was available, it had to be mounted on the two theodolites in turn and the environment kept stable in the meantime. The accuracy in image capture and processing had been checked before other operations and found stable with little (short) warm-up effect.




Theodolite scanning photogrammetry

The theodolite scanning photogrammetry started with the theodolite orientation using the horizontal reciprocal pointing method. The five-point method was also used for comparison. The camera was then mounted on the left theodolite which was followed by the camera calibration using the two-target camera-on-theodolite method where the target to theodolite distances were obtained through theodolite triangulation integrated in the five-point orientation process. 5*5*2 equivalent targets were generated in this method. Two affine and one radial distortion parameters were used. Immediately after the calibration, the 3*3 frames of image were captured as the theodolite was swung to the 3*3 pre-specified directions where the theodolite readings were also recorded (as shown in the figure). The same process was then repeated with the right theodolite station.

Afterwards, the target images were located and matched automatically by the image processing software. The three dimensional coordinates of the targets were then determined simply by photogrammetric space intersection as all the camera parameters needed had been derived from the result of calibration and theodolite orientation and the theodolite readings.

The accuracy of calibration alone was assessed by using check point back ray tracing method and found to be about 0.06 pixel in sample and 0.03 in line. The following tables present the residuals in the transformation from the determined coordinates to the true coordinates. The RMS of the residuals at the bottom of the tables are the measures of 3-D determination accuracy of the system.

## 6. EXPERIENCE AND FUTURE WORK

As is seen in the tables, the relative accuracy of the theodolite scanning photogrammetry with 3*3 frames of image is more than twice as high as a single pair of image would achieve. As to the theodolite orientation, the horizontal reciprocal pointing method gave almost the same accuracy as the five-point method in this experiment. They are both easy to use and could be automated. Testing with the possible longest focus lenses would reveal the practical accuracy potential of the system. We have not, however, been able to do this successfully because at the time of experiment we did not have longer focus lenses satisfactorily fixable to the theodolite mount. This will become part of our future work.

**The accuracy of theodolite scanning photogrammetry assessed with check points**

Final Transformation Values:

Scale = 0.99961914

X Shift = -0.7866 mm
Y Shift = 0.8056 mm
Z Shift = -1.2856 mm

X Rotation = -0.00089 Gon
Y Rotation = 0.00229 Gon
Z Rotation = -0.84044 Gon

esiduals in mm

| £ | Point | X | Y | Z |
|---|---|---|---|---|
| 1 | K2H | -0.0331 | 0.0701 | -0.1043 |
| 2 | C3H | 0.0225 | 0.6917 | 0.1966 |
| 3 | C3AH | 0.0917 | -0.0334 | 0.0012 |
| 4 | CD3 | 0.0085 | 0.1834 | -0.0499 |
| 5 | C4H | 0.2139 | 0.4431 | 0.0159 |
| 6 | X11H | -0.1956 | -0.1203 | 0.0424 |
| 7 | X14H | -0.2707 | -0.6789 | 0.0105 |
| 8 | X21H | -0.1575 | -0.6713 | -0.0405 |
| 9 | X23H | -0.2099 | -0.4830 | -0.0791 |
| 10 | X24H | -0.3000 | -0.8733 | 0.0487 |
| 11 | X12H | -0.0833 | 0.0543 | -0.0443 |
| 12 | C5H | 0.0965 | 0.9235 | 0.1370 |
| 13 | L2H | -0.3339 | -0.0760 | -0.0299 |
| 14 | CD6 | 0.2240 | 0.6469 | 0.0445 |
| 15 | K3H | -0.2414 | 0.1681 | -0.1923 |
| 16 | D3H | -0.1741 | -0.1351 | 0.1482 |
| 17 | D4H | -0.3618 | -0.5893 | 0.0837 |
| 18 | DE3 | 0.0249 | 0.0972 | 0.0584 |
| 19 | D5H | 0.1103 | -0.0200 | 0.0536 |
| 20 | X41H | 0.2417 | 0.2130 | 0.0163 |
| 21 | X42H | -0.0036 | 0.3428 | 0.0442 |
| 22 | X44H | 0.2711 | -0.1222 | -0.0941 |
| 23 | D7H | 0.1875 | -0.1979 | 0.1207 |
| 24 | L3H | 0.0363 | 0.4035 | -0.0919 |
| 25 | E3H | 0.3612 | 0.3687 | 0.0231 |
| 26 | K4H | -0.2794 | -0.0702 | -0.0482 |
| 27 | EF3 | 0.3847 | 0.3115 | -0.0655 |
| 28 | E3AH | 0.0301 | -0.7128 | -0.0224 |
| 29 | F1H | 0.0536 | -0.8699 | 0.3925 |
| 30 | J3H | -0.2177 | -0.2311 | -0.2338 |
| 31 | F2H | -0.0073 | -0.6748 | 0.1625 |
| 32 | E4H | 0.0773 | 0.0866 | 0.0348 |
| 33 | EF4 | -0.1400 | 0.0662 | 0.1251 |
| 34 | EF5 | 0.0086 | 0.7368 | 0.0103 |
| 35 | F3H | 0.1351 | 0.6980 | -0.1767 |
| 36 | J5H | -0.2393 | 0.3747 | -0.2765 |
| 37 | E5H | 0.0982 | -0.1994 | 0.0408 |
| 38 | EF6 | -0.1276 | -1.0336 | 0.1189 |
| 39 | L4H | -0.1633 | 0.2552 | -0.1671 |
| 40 | F5H | 0.1533 | -0.1632 | 0.1039 |
| 41 | J6H | -0.0338 | 0.6355 | -0.5732 |
| 42 | C4BH | 0.2575 | 0.1718 | -0.0087 |
| 43 | D6H | 0.1121 | 0.1600 | 0.0571 |
| 44 | DE6 | 0.1454 | -0.7418 | 0.1903 |
| 45 | E4BH | 0.2272 | 0.5950 | 0.0174 |
| | | 0.1911 | 0.4820 | 0.1479 |

Total RMS = 0.5392 mm

END OF LOCAL TO OBJECT TRANSFORMATION

Final Transformation Values:

Scale = 0.99995179

X Shift = -1.1885 mm
Y Shift = 0.6615 mm
Z Shift = -2.0723 mm

X Rotation = -0.01098 Gon
Y Rotation = 0.00890 Gon
Z Rotation = 0.05627 Gon

esiduals in mm

| £ | Point | X | Y | Z |
|---|---|---|---|---|
| 1 | K2H | -0.0129 | -0.2835 | -0.2575 |
| 2 | K3H | -0.1621 | 0.1479 | -0.3060 |
| 3 | K4H | -0.2571 | -0.2240 | -0.1733 |
| 4 | C3H | 0.1841 | -0.7782 | 0.1004 |
| 5 | CD3 | 0.1386 | -0.6063 | -0.0706 |
| 6 | C4H | 0.3143 | 0.4694 | 0.2141 |
| 7 | C5H | -0.1012 | -0.1485 | 0.2353 |
| 8 | CD6 | 0.0977 | 0.4266 | 0.2185 |
| 9 | C3AH | 0.3588 | 1.4840 | 0.3133 |
| 10 | C4BH | -0.0042 | -0.3519 | 0.0995 |
| 11 | D3H | 0.0622 | 0.3977 | 0.0407 |
| 12 | DE3 | -0.1975 | -0.6149 | 0.0664 |
| 13 | D5H | 0.1327 | 0.7174 | -0.0483 |
| 14 | D6H | -0.1574 | -0.2580 | 0.0031 |
| 15 | D4H | 0.1107 | 0.0844 | 0.1558 |
| 16 | E3H | 0.2232 | 0.0069 | -0.0317 |
| 17 | EF3 | -0.0160 | -0.4773 | 0.1012 |
| 18 | E4H | 0.0977 | 0.0273 | 0.0719 |
| 19 | EF4 | -0.1156 | -0.0863 | 0.1673 |
| 20 | E5H | 0.1662 | 0.1916 | 0.0699 |
| 21 | E3AH | 0.2171 | 0.1678 | -0.0775 |
| 22 | E4BH | 0.0565 | 0.5388 | 0.0492 |
| 23 | EF6 | -0.1734 | -0.4841 | 0.1487 |
| 24 | EF5 | -0.2475 | -0.1259 | 0.1619 |
| 25 | F3H | -0.0462 | 0.1396 | -0.1264 |
| 26 | F5H | -0.0704 | -1.0015 | 0.3871 |
| 27 | F2H | -0.0847 | -0.2639 | -0.1167 |
| 28 | F4H | -0.0762 | -0.4510 | 0.1204 |
| 29 | J3H | -0.1276 | -0.4928 | -0.2958 |
| 30 | J4H | -0.2580 | 0.3279 | -0.4141 |
| 31 | J5H | -0.0709 | 0.2502 | -0.4413 |
| 32 | J6H | -0.2361 | -0.0019 | -0.3843 |
| 33 | X12H | 0.1722 | 0.7160 | 0.0972 |
| 34 | X14H | -0.2135 | -0.2796 | 0.0581 |
| 35 | X21H | -0.0305 | 0.3641 | 0.0168 |
| 36 | X23H | 0.0605 | 0.2489 | -0.0212 |
| 37 | X41H | 0.1920 | 0.0032 | -0.0948 |
| 38 | X42H | -0.2553 | 0.5358 | -0.0556 |
| 39 | X44H | 0.0048 | -0.1790 | -0.0962 |
| 40 | X11H | 0.0326 | -0.7902 | 0.0269 |
| 41 | X24H | 0.0661 | 0.0184 | 0.1770 |
| 42 | L4H | 0.2267 | 0.6347 | -0.0890 |
| | | 0.1644 | 0.4801 | 0.1871 |

Total RMS = 0.5409 mm

END OF LOCAL TO OBJECT TRANSFORMATION

Our future work will also include the investigation of the performance of compact zoom lenses, since zoom lenses are needed in the proposed system and the experience in this respect is still insufficient (Wiley & Wong 1990). When motorized theodolites are available, a program will be produced to automate the calibration and theodolite orientation. Furthermore, the function of fast automated 3-D determination of targets or distinct features based on the theodolite scanning principle will be developed.

## 7. ACKNOWLEDGEMENT

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## 8. REFERENCES

Gottwald, R., 1989, Kern E2-SE, a new instrument for industrial surveying. Kern Swiss Industrial Metrology.

Huang, Y.D. and Harley, I.A., 1989. A new camera calibration method needing no control field. In: Optical 3-D measurement techniques. Wichmann, Karlsruhe. pp. 49-56. [The title was mistakenly published as "Calibration of close-range photogrammetric stations using a free network bundle adjustment".].

Huang, Y.D. and Harley, I.A., 1990. CCD camera calibration without a control field. ISPRS Symposium, Comm.V, Zurich, SPIE Vol.1395, pp. 1028-1034.

Kyle, S.A., 1988. Triangulation methods in engineering measurement. Ph.D. thesis, University of London.

Wester-Ebbinghaus, W., 1988. High resolution digital object recording by video-theodolites. ISPRS Congress, Kyoto, Comm.V, pp.V219-V223.

Wiley, A.G. and Wong, K.W., 1990. Metric aspects of zoom vision. ISPRS Symposium, Comm.V, Zurich, SPIE Vol.1395, pp.112-118.

Zhou, H.B., 1990. Object point detection in a photogrammetric test field. ISPRS Symposium, Comm.V, Zurich, SPIE Vol. 1395, pp.1227-1233.