ON THE INTEGRATED CALIBRATION OF A DIGITAL STEREO-VISION SYSTEM

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ABSTRACT

A fixed base digital stereo-vision system is a powerful tool for positioning objects in 3-dimensions without control in object space. It can be integrated in a vehicle together with GPS and inertial systems to collect spatial information while driving at highway speeds.

In this paper we discuss the integrated calibration of the stereo-vision system using a simultaneous, constrained adjustment of multiple image-pairs. It is based on the well-known bundle technique which is extended by the following constraints and unknown parameters: the base between the two cameras is measured externally and fixed in the adjustment; as the relative orientation does not change it must be the same for all image-pairs. Furthermore, the interior orientation is left open and additional parameters compensate for lens distortions. A test-field of control points is photographed with the digital stereo-vision system. It serves both as control for the bundle solution and as a reference for an independent evaluation of the accuracy of spatial positioning.

Keywords: Calibration, Close-range, Integrated System, Machine Vision, Stereoscopic.

1. BACKGROUND

The creation of geographic information systems requires enormous amounts of digital information. To date most land-related databases still rely on existing line maps which are manually digitized. In order to collect digital data faster and more accurately the combination of new mapping sensors is necessary. Such an integrated system can produce digital maps on-line on a moving platform; therefore, we talk about "Real Time Mapping".

At the Center for Mapping of the Ohio State University a number of mobile mapping systems have been designed, assembled, and demonstrated. The most successful system to date is the so-called GPS-Van (Bossler, et. al. 1991). Its development was initiated by the US Federal Highway Administration, 38 state transportation agencies, and private companies. In principal it consists of three components: an absolute positioning system, a relative positioning device, and tools for gathering attribute data (figure 1).

Figure 1: The GPS-Van integrates a digital stereo-vision with absolute positioning sensors.

The *absolute positioning sensor* is a combined GPS/inertial surveying unit. Using differential GPS the road-alignment can be mapped with an accuracy of 1-3 meters in a global coordinate frame. The inertial system, which consists of two gyros and a wheel counter, takes over when satellite-lock is lost. For *relative positioning* a stereo-vision system was mounted on the GPS-Van. It yields 3-dimensional coordinates relative to the van; they can be transformed into a global system by the absolute positioning sensors. Finally, an analog video-camera and a touchscreen are available to *collect attributes*. All data captured by the GPS-Van are immediately stored in a relational data-base that was enhanced by an image management and analysis system.

The most important pre-requisite for accurate point positioning with the vision system is the calibration of the cameras, and the determination of their relationship to all other sensors. In this paper we describe the mathematical models used to calibrate the camera geometry, their relative orientation on top of the GPS-Van, as well as their offsets from the GPS antenna and the gyros. Using practical test-data we show how accurately points can be located by the cameras, and how they are transfered into the global coordinate frame. As a short introduction the hardware components of the GPS-Van are discussed. In the conclusions we point out various modifications of the GPS-Van, and its potential for revolutionizing digital mapping.

2. HARWARE COMPONENTS

Absolute positioning of the GPS-Van is achieved by two surveying type GPS-recievers (Trimble 4000ST). One serves as a base-station at a known location, the other one is a rover station mounted on the van. When satellite signals are blocked a dead-reckoning system takes over. It consists of a directional and a vertical gyro, and a wheel counter. The directional gyro measures horizontal angular changes (directions), the vertical gyro determines two angles (pitch and roll) that measure the van's tilts relative to the vertical. Additionally, a magnetic proximity sensor counts wheel-rotations at the disk brakes of the two front wheels. Together these sensors generate the absolute positions of the GPS-Van and its orientation (attitude) at any time.

For relative positioning the stereo-vision system was installed. It consists of two fully digital CCD cameras (Cohu 4110) with a resolution of 732 x 484 pixels. They are mounted on a rack on top of the vehicle. We assume that they are rigidly attached to the van and do not change their attitudes during operations. The two cameras directly interface to a real-time imaging system (Trapix Plus from Recognition Concepts Inc. (RCI)), where the images are temporarily stored in a frame buffer. They can also be processed on-line using a digital signal processor, or they can be sent to the Data Store real-time disk, which has a data transfer rate of 4 MBytes per second and holds 2 GBytes of digital data. It is interfaced to an Exabyte digital tape drive through a SCSI connector.

Finally, a touchscreen is used to control operations of the data-collection procedure and to key in a number of pre-defined attributes as the GPS-Van passes by an object of interest. A color-video camera is applied for photo-logging of the road environment; the video scenes are also related to the GPS-positions. All sensors of the mobile mapping system are controlled by a PC. The vision-system configuration is shown in figure 2.

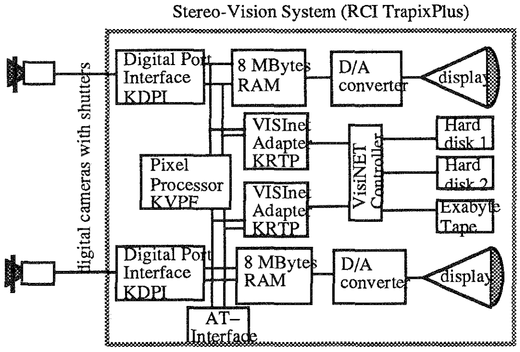

Figure 2: Hardware components of the GPS-Van.

3. INTERIOR AND RELATIVE ORIENTATIONS

By calibrating the vision system we determine parameters that define the camera geometry and the relative locations and attitudes of the camera-pair. The calibration consists of two components: the interior orientation, and the relative orientation. It should be repeated in regular intervals to ensure that the camera-setup did not change. The calibration is performed by analytical methods, which involve capturing images of known control points (test-field), measuring their image-coordinates, and computing a photogrammetric triangulation to obtain the specific parameters. Both orientations were combined for this special application and can be solved simultaneously. Once the calibration is available, any object in the field of view of both cameras can be positioned in three dimensions in a local coordinate system. The transformation of these points to global coordinates is discussed in chapter 4.

The *Interior Orientation* describes the geometry of a camera and consists of the focal length (c), the principal point (x_p, y_p), and lens distortions. For each of the cameras a separate interior orientation must be determined. The *Relative Orientation* defines the tilts of the two cameras in a local coordinate system, which has its origin in the left perspective center, and its Z-axis is perpendicular to the left image plane. The relative orientation is scale-independent; it is defined by five parameters.

The combined solution of interior and relative orientations was developed to ensure that the relative tilt angles of the two cameras as well as the camera geometries are kept constant for all stereo-pairs of the test-field. In general, it is important to acquire a number of stereo-pairs at different, oblique angles and distances from the test-field to ensure an homogeneous positioning accuracy of the stereo-vision system.

External measurements are added to enhance the stability of the least squares solution. We used theodolites to identify the perspective centers of the cameras as the entrance pupils of the lenses. The distance between the perspective centers determines the base of the stereo-vision system. It defines the scale of the local system in which 3-dimensional points are positioned and must be very accurate. It is used as a constraint for bundle adjustment. Figure 3 shows a typical calibration set up of two van positions and the theodolite stations in front of them. In the following the analytical formulation of the combined adjustment is presented, and the physical meaning of each of the parameters is explained.

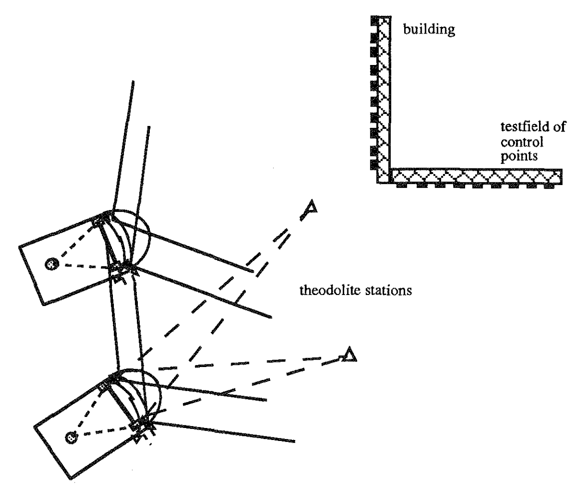

Figure 3: A rigorous calibration of the stereo-vision system is achieved by a combined bundle adjustment with additional camera parameters and geodetic constraints.

The analytical calibration of the vision system is done by the *bundle method* based on collinearity equations (1) (Brown, 1976). To determine the interior orientation parameters simultaneously, they are also treated as unknowns. This means that we compute the coordinates of the principle point (x_p, y_p) and the focal length (c), in addition to the orientation parameters of each camera. We also solve for two parameters to model radial distortions, two parameters to model decentering distortions, and for two affine deformations (2).

Collinearity equations:
$$x = -c\frac{N_x}{D} + \Delta x \qquad (1)$$
$$y = -c\frac{N_y}{D} + \Delta y$$

x,y .... *image coordinate measurements,*

c .... *focal length,*

N_x, N_y, D .... *numerators and denominators of the collinearity equations.*

$$N_x = r_{11}(X - X_o) + r_{21}(Y - Y_o) + r_{31}(Z - Z_o)$$

$$N_y = r_{12}(X - X_o) + r_{22}(Y - Y_o) + r_{32}(Z - Z_o)$$

$$D = r_{13}(X - X_o) + r_{23}(Y - Y_o) + r_{33}(Z - Z_o)$$

with:

X, Y, Z .... coordinates of an object point (target),

X_o, Y_o, Z_o .... perspective center of the camera,

r_{11}, ... r_{33}....... elements of a 3 x 3 rotation matrix modeling the attitude of the cameras.

Correction terms (additional parameters):

$$\Delta x = x_p + x(r^2 - 1)a_1 + x(r^4 - 1)a_2 + (r^2 + 2x^2)a_3 + 2xy\,a_4 + a_5 x + a_6 y$$
$$\Delta y = y_p + y(r^2 - 1)a_1 + y(r^4 - 1)a_2 + 2xy\,a_3 + (r^2 + 2y^2)a_4 - a_5 y \qquad (2)$$

with: *x_p, y_p ..... image coordinates of the principal point,*

a_1, a_2 .... radial distortion parameters,

a_3, a_4 .... decentering distortion parameters,

a_5, a_6 .... affine parameters.

Next, constraints were added to fix the *relative orientation* of the two cameras of any stereo-pair. Basically, we have to introduce six parameters to keep the relative orientations and scales of all stereo-pairs constant. It is of advantage to select the base-vector (b_x, b_y, b_z) from the left perspective center (0_L) to the right one (0_R), and the three rotations of the right image ($\Delta\omega$, $\Delta\varphi$, $\Delta\kappa$) as relative orientation parameters. These values are defined in the left camera coordinate system (figure 4). The relative angles are small as the two cameras are pointing in almost parallel directions, and are mounted orthogonal to the base (= *normal case stereo-pair*).

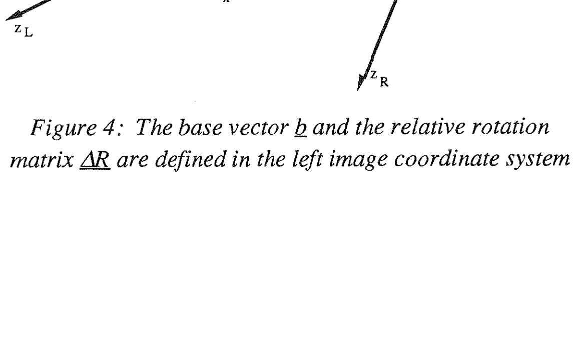

Figure 4: The base vector $\underline{b}$ and the relative rotation matrix $\underline{\Delta R}$ are defined in the left image coordinate system

The analytical formulation of this problem is based on relative rotation matrices ($\underline{\Delta R}$) between the two images of any stereo-pair. In the case of fixed stereo-cameras, $\underline{\Delta R}$ must be the same for all image-pairs, which can be achieved by keeping the relative rotation angles ($\Delta\omega$, $\Delta\varphi$, $\Delta\kappa$), which form $\underline{\Delta R}$, constant. The relative rotation matrix is computed by (3).

$$\underline{\Delta R} = \underline{R}_L^T \underline{R}_R = \begin{bmatrix} \boldsymbol{A_1} & \boldsymbol{A_2} & \boldsymbol{A_3} \\ B_1 & B_2 & \boldsymbol{B_3} \\ C_1 & C_2 & \boldsymbol{C_3} \end{bmatrix} \qquad (3)$$

with: *$\underline{\Delta R}$ .... relative rotation matrix,*

$\underline{R_L}$ .... rotation matrix of left image,

$\underline{R_R}$ .... rotation matrix of right image.

$\underline{R_L}$ and $\underline{R_R}$ are defined in the object coordinate system.

Only the parameters A_1, A_2, A_3, B_3, C_3 are needed for further computations. Their functional relationship with the rotation angles is given in (4).

$$A_3 = \sin \Delta\varphi$$
$$-A_2/A_1 = \tan \Delta\kappa \qquad (4)$$
$$-B_3/C_3 = \tan \Delta\omega$$

The base-vector (b_x, b_y, b_z) can be expressed in the left image coordinate system by (5).

$$\underline{b} = \begin{pmatrix} b_x \\ b_y \\ b_z \end{pmatrix} = \underline{R}_L^T \begin{pmatrix} X_R - X_L \\ Y_R - Y_L \\ Z_R - Z_L \end{pmatrix} \qquad (5)$$

with: *$\underline{R_L}$ .... rotation matrix of the left image,*

(X_L, Y_L, Z_L)......... left perspective center,

(X_R, Y_R, Z_R)......... right perspective center.

Once the base-vectors and the relative rotation matrices of two stereo-pairs are available, they can be set equal to ensure that the orientation parameters of the corresponding images are constrained by the vision system's relative orientation. Assuming that $\underline{b}^{(i)}$ is the base-vector of stereo-pair (i) and $\underline{\Delta R}^{(i)}$ its relative rotation matrix, and $\underline{b}^{(k)}$ and $\underline{\Delta R}^{(k)}$ are the corresponding elements of stereo-pair (k), they must satisfy equations (6).

$$\underline{\Delta R}^{(i)} = \underline{\Delta R}^{(k)}: \qquad (6)$$

$A_3^{(i)} \quad = A_3^{(k)}$ .... for $\Delta\varphi^{(i)} = \Delta\varphi^{(k)}$

$B_3^{(k)} C_3^{(i)} = B_3^{(i)} C_3^{(k)}$ .... for $\Delta\omega^{(i)} = \Delta\omega^{(k)}$

$A_2^{(i)} A_1^{(k)} = A_2^{(k)} A_1^{(i)}$ .... for $\Delta\kappa^{(i)} = \Delta\kappa^{(k)}$

$\underline{b}^{(i)} = \underline{b}^{(k)}$:

$b_x^{(i)} = b_x^{(k)}$

$b_y^{(i)} = b_y^{(k)}$

$b_z^{(i)} = b_z^{(k)}$

Before these six equations can be added as constraints of the bundle adjustment, the formulas must be linarized with respect to the original exterior orientation parameters of the images (the perspective center and the three rotation angles of each image). This is rather complicated as the relative rotation matrices depend on parameters of both photos.

The distance between the two perspective centers of any image-pair is constrained, which is the base-distance d_o that was measured by theodolites (7). Its accuracy is about 0.5 mm. This constraint defines the scale of the local coordinate system in which 3-dimensional positioning is possible.

$$d_o = \sqrt{(X_L - X_R)^2 + (Y_L - Y_R)^2 + (Z_L - Z_R)^2} = \sqrt{b_x^2 + b_y^2 + b_z^2} \qquad (7)$$

with: X_L, Y_L, Z_L...... *coordinates of the left perspective center,*

X_R, Y_R, Z_R...... *coordinates of the right perspective center,*

d_o .... *distance measured between perspective centers,*

b_x, b_y, b_z......... *components of the base vector.*

This constraint is only specified for one stereo-pair; all other base distances are automatically equaled by condition (6). Therefore, there are (m–1) relative orientation constraints for m stereo-pairs, and one base-distance observation.

By collecting all the formulas mentioned before (1), (6), (7), and writing a system of observation equations and constraints, we get (8). The least squares solution is computed by (9).

$$\text{observation equations: } \underline{v} = \underline{A}\,\underline{x} - \underline{l} \qquad (8)$$

$$\text{constraints: } \underline{0} = \underline{B}\,\underline{x} + \underline{t}$$

with: $\underline{A}$ .... *linearized collinearity equations (1) and distance equation (7),*

$\underline{x}$ .... *unknown orientation parameters:*

$x_p, y_p, c, a_1, a_2, a_3, a_4, a_5, a_6$ *for each camera,*

$X_o, Y_o, Z_o, \omega, \varphi, \kappa$ *for each image.*

$\underline{l}$............ *discrepancies (observation minus approximation),*

$\underline{B}$ .... *linearized constraints of the relative orientation (6),*

$\underline{t}$............ *absolute terms of constraints,*

$\underline{v}$........... *residuals of the observations,*

$\underline{0}$........... *zero vector.*

$$\begin{pmatrix} \underline{A}^T\underline{A} & \underline{B}^T \\ \underline{B} & \underline{0} \end{pmatrix} \begin{pmatrix} \underline{x} \\ \underline{k} \end{pmatrix} = \begin{pmatrix} \underline{A}^T\underline{l} \\ -\underline{t} \end{pmatrix} \qquad (9)$$

Once these orientation parameters ($\underline{x}$) are available, 3-dimensional coordinates can be computed for any point identified in both images. This is useful for measuring spatial distances or for creating local 3-dimensional models of small objects in the field of view of the stereo-vision system. However, the positions are only defined in a local coordinate system relative to the two cameras. These coordinates are referred to as local *camera coordinates* (X_c, Y_c, Z_c) and will be transformed into a global system in the next chapter.

4. ABSOLUTE POSITIONING

The local coordinate system derived above corresponds to a stereo-model. To obtain absolute positions of points and features the absolute orientation of this model must be established. It consists of six parameters (3 translations and 3 rotations) to convert points from the camera system (X_c, Y_c, Z_c) into a topocentric system (X_T, Y_T, Z_T) with its origin at the GPS antenna, the X_T axis pointing east, the Y_T axis pointing north, and the Z_T axis identical to the vertical at the ellipsoid. The scales of the two coordinate systems are equivalent. The six transformation parameters are derived from the GPS position of the van (3 coordinates, which correspond to 3 translations) and the inertial measurements (gyros), which define 3 rotations (direction, pitch, roll). To visualize this transformation in a better way, it is separated into two steps:

4.1 Transformation to a Vehicle System

The vehicle coordinate system (X_v, Y_v, Z_v) is directly connected to the van; it is defined by the Y_V-axis pointing in the driving direction and the X_V-axis parallel to the left image plane, as well as to the rear axle of the vehicle. The Z_V-axis is vertical if the van is positioned on an horizontal surface. The vehicle coordinate system is assumed to be parallel to the gyro-axes of the inertial system. This coordinate system can be found by repeated measurements of the GPS antenna and the cameras by theodolite intersections while the van is moving along a straight line. The motion vector of the antenna equals the vehicle axis (Y_V). The origin of the vehicle coordinate system is located at the GPS antenna.

When we transform from camera coordinates (X_c, Y_c, Z_c) to vehicle coordinates (X_v, Y_v, Z_v), the origin is shifted from the left perspective center to the GPS antenna (figure 5). This offset is known from the theodolite measurements. There is a rotation involved, too, which is defined by the downward tilt (τ) of the two cameras. They are dipped by about 8^o on the van in order to provide for better coverage of the road. The mathematical transformation from the camera to the vehicle system is given by (10).

$$\begin{pmatrix} X_V \\ Y_V \\ Z_V \end{pmatrix} = \underbrace{\begin{pmatrix} \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}}_{\text{offset between } O_1 \text{ and GPS}} + \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\tau' & -\sin\tau' \\ 0 & \sin\tau' & \cos\tau' \end{pmatrix} \begin{pmatrix} X_c \\ Y_c \\ Z_c \end{pmatrix} \quad (10)$$

$$\tau' = 90^o - \tau$$

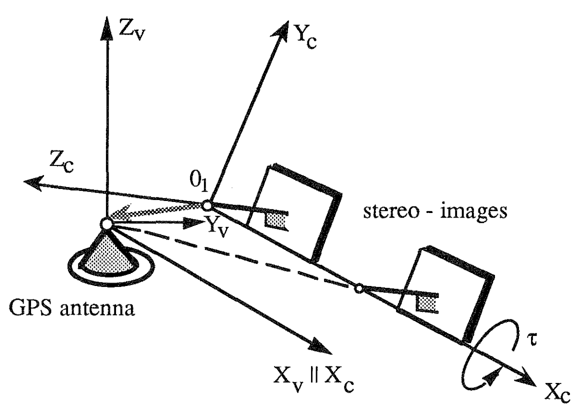

Figure 5: Transformation from the stereo-vision system (X_c, Y_c, Z_c) to a vehicle coordinate system (X_V, Y_V, Z_V).

4.2 Transformation to a Topo-centric Coordinate System

This transformation rotates the local vehicle coordinates (X_V, Y_V, Z_V) into a topo-centric system (X_T, Y_T, Z_T) with the origin at the GPS antenna. The topo-centric system is defined by a tangential plane through the GPS antenna. Therefore, the vehicle system needs to be rotated according to the angles specified by the three gyros (direction [α], pitch [ξ], and roll [κ]): the direction is the primary rotation, pitch is secondary, and roll tertiary. The transformation is given by (11).

$$\begin{pmatrix} X_T \\ Y_T \\ Z_T \end{pmatrix} = \underline{R}_\alpha \underline{R}_\xi \underline{R}_\kappa \begin{pmatrix} X_V \\ Y_V \\ Z_V \end{pmatrix} \quad (11)$$

The local topo-centric coordinates can be easily transformed into geo-centric coordinates by shifting the origin from the GPS antenna to the center of the earth (this vector corresponds to the geo-centric coordinates of the antenna), and by applying the appropriate rotations defined by longitude and latitude (geographic coordinates). Geo-centric as well as geographic coordinates can be used for comparing different positions in a unique worldwide system.

5. NUMERICAL RESULTS OF THE CALIBRATION

The algorithms described above were implemented on our post-processing workstation (Data General Aviion 400 Series). The results of the calibration prove that the accuracies that can be obtained by stereo-positioning from a mobile platform are sufficient for many road mapping applications. The results relate to the two Cohu 4110, digital CCD cameras, which were part of the GPS-Van. They have a resolution of 732 (H) x 484 (V) pixels and use C-mount lenses.

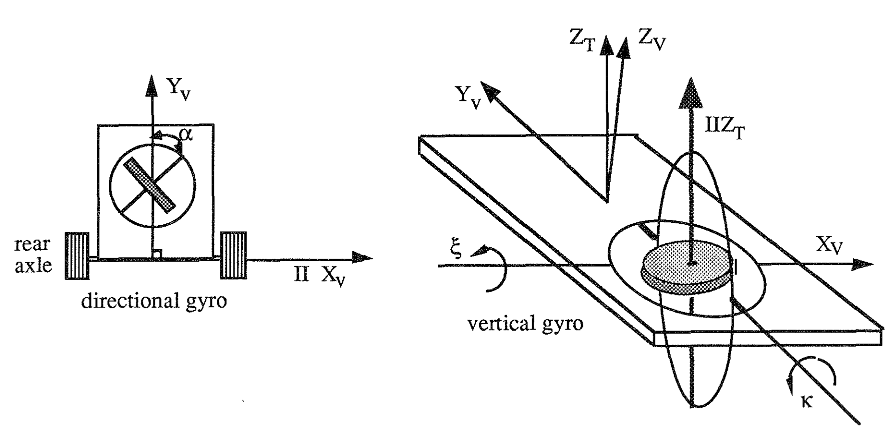

Figure 6: Transformation of vehicle coordinates (X_V, Y_V, Z_V) into a topo-centric system (East, North, Up).

The calibration was done with three digital stereo-pairs of our test-field. They were taken at different distances in front of the wall, ranging from 19 meters to 9 meters, and at different viewing angles relative to the test-field. This variety of angles and distances is important for the reliable recovery of the interior orientations and the additional camera parameters, and also ensures that spatial positioning with the vision system yields homogeneous coordinates at different distances in front of the van (of course, there is a limit due to the narrow intersection angles of light rays for points that are far away from the van).

The image coordinates of eleven control and six tie-points were measured manually on the computer screen with an estimated accuracy of 1/4 pixel in the digital images. The base-length was determined by theodolite intersections. The bundle-triangulation (including the constraints mentioned above) was computed twice, with and without additional camera parameters, to demonstrate their contribution to the positioning accuracy.

The results are combined in table 1. It shows the aposteriori standard deviation σ_o, which corresponds to the mean accuracy of the measured image coordinates both in pixels and millimeters. The additional parameters improved the accuracy by a factor of two, so that it corresponds to about 1/3 of a pixel on the sensor, which is consistent with our assumptions (manual measurement). The principal points and focal lengths of both cameras were always treated as unknowns. The tie-point coordinates computed by the bundle triangulation were compared to their known coordinates at the wall to show the potential point positioning accuracy (s_x, s_y, s_z), if object control is available.

Then we used the computed orientation parameters in an intersection to determine object coordinates from image-coordinate pairs. This corresponds to the positioning of points with the stereo-vision system on the van, independent of any control in object space. This test was done independently for each stereo-pair, and for all points that appear in a stereo-pair. Again, the coordinates of the targets of the test-field were used for comparison. The results are displayed in table 2, showing the RMS errors for each stereo-pair for the two types of calibrations computed before.

One can see that the additional parameters improve the positioning accuracy, and that all derived values are consistent or better than our estimates. It is fair to state that the positioning accuracy of the stereo-vision system is within 10 cm for objects closer than 20 m in front of the van.

To determine the absolute positioning accuracy we measured the image coordinates of the targets on the wall in two stereo-pairs that were not used for the vision system calibration (image pairs 6, 7). The object coordinates were computed by point intersections applying the orientation parameters derived previously. Additional camera parameters were always applied in the intersection. As a result we obtained the object coordinates in two separate local systems. Both were transformed into a common coordinates system to be able to compare the positioning accuracy of the stereo-vision system. Table 3 shows the RMS difference between the point positioning determined from image-pair 6 and those of image-pair 7.

calibration	σ_o [mm]	σ_o [pixels]	s_x [cm]	s_y [cm]	s_z [cm]
without additional parameters	0.0063	0.68	1.95	1.09	7.79
with 6 additional parameters	0.0034	0.37	0.42	0.55	2.09

Table 1: Comparison of a calibration of the stereo-vision system with and without additional parameters. The standard deviation of unit weight (σ_o) corresponds to the mean accuracy of image coordinate measurement. The RMS error in object space at four of the tie-points (which were available in all stereo-pairs and used as check-points) is given by s_x, s_y, s_z.

stereo-pair	calibration with or without additional parameters	object distance [m]	s_x [cm]	s_y [cm]	s_z [cm]	σ_z [cm]
1	without	19.0	3.1	2.0	8.9	9.3
2	without	11.8	1.3	1.9	4.2	3.6
3	without	9.2	1.3	0.7	3.9	2.2
1	with	19.0	2.1	1.2	6.2	9.3
2	with	11.8	0.4	1.1	3.4	3.6
3	with	9.2	0.4	0.5	1.3	2.2

Table 2: Intersection of conjugate image points to evaluate the positioning accuracy without object control. The RMS errors (s_x, s_y, s_z) are computed for each stereo-pair. In the last column the theoretical accuracy limit in the driving direction (σ_z) is displayed. It was computed by: $\sigma_z = \frac{Z}{b}\frac{Z}{c}\,\sigma_{px}$ $(\sigma_{px} = \frac{1}{3}$ *pixel).*

stereo-pair	object distance [m]	s_x [cm]	s_z [cm]	s_y [cm]	σ_z [cm]
6	23.0	4.0	1.6	9.9	14.5
7	17.0				7.9

Table 3: Comparison of point positioning in a local coordinate system. s_x, s_y, s_z are the mean differences between the positions computed from stereo-pairs 6 and 7. σ_z is the theoretical accuracy limit for a given object distance (compare table 2).

As the global van locations and the orientation angles are available after post-processing of GPS and inertial observations, the local object coordinates can be transformed into a global coordinate system. Again, the point coordinates obtained by two different stereo-pairs were compared. The results are shown in table 4. One can see that the global positioning accuracy is somewhat lower than the local accuracy, however, better than the expected GPS position-accuracy. We believe, that the transformation parameters between camera coordinates and global coordinates could still be improved.

units	s_x	s_y	s_z
degrees	0.00000356	0.00000023	28.8 [cm]
centimeters	39.6	2.6	28.8 [cm]

Table 4: Comparison of point positioning in a global coordinate system. The global coordinates were obtained in degrees (longitude, latitude) and meters (height). For easier comparison they were converted to centimeters.

6. CONCLUSIONS

The calibration of all sensors and their application to transform local, spatial coordinates in to a global system are essential tools of the GPS-Van. Without knowing the calibrated parameters with a very high accuracy the stereo-vision system would not be useful. Therefore, these functions are forming the core of our post-processing system. The other important component of positioning with a digital stereo-vision system however, is automatic image analysis. A variety of functions have been implemented on our post-processing workstation to extract features such as road-edges and traffic signs, and to follow lines or to match points. These techniques are subject of another paper of this conference (He, et. al.; 1992).

The initial GPS-Van resulted in a number of follow-on projects and developments. We are currently working on the integration of GPS and a digital mapping camera in an aircraft (MAPCAM). Here we apply conventional photogrammetric triangulation and positioning to digital imagery. As a next step we will integrate a digital camera-pair in an airplane together with three GPS receivers. This will be used to map power-lines and gas pipelines; it is called Utility Mapping System (UMS). Finally, we designed a portable Digital Stereo-Positioning System (DSPS), which consists of two cameras and three GPS receivers. It can be set up by the user on a tripod to capture an image-pair. As both position and attitude of the DSPS are known at any time (both from GPS), every object in the field of view of the cameras is immediately available in a world coordinate system. From the positive reaction and interest by private companies and government agencies, and the successful demonstration of the GPS-Van we conclude that the application of real-time mapping systems is almost unlimited, and that they will revolutionize mobile mapping.

7. REFERENCES

Bossler J., Goad C., Johnson P., Novak K., 1991. "GPS and GIS Map the Nation's Highways." GeoInfo Systems Magazine, March issue, pp. 26-37.

Brown D.C., 1976. "The Bundle Adjustment - Progress and Prospects." Invited paper XIII th Congress of ISP, commission III, Helsinki.

Goad C., 1991. "The Ohio State University Highway Mapping System: The Positioning Component." Proceedings of the Institute of Navigation Conference, Williamsburg, VA, pp. 117-120.

He G., Novak, K., 1992."Automatic Analysis of Highway Features from Digital Stereo-Images." International Archives of Photogrammetry and Remote Sensing, Vol. , Commission III.

Novak K., 1991. "The Ohio State University Highway Mapping System: The Stereo Vision System Component." Proceedings of the Institute of Navigation Conference, Williamsburg, VA, pp. 121-124.

8. ACKNOWLEDGEMENT

The authors wish to thank all transportation agencies that committed money to the development of the GPS-Van. We gratefully acknowledge the exciting research environment and great support of the GPS-Van team at the Center for Mapping of the Ohio State Univesity.