APPLICATION OF DIGITAL CAMERAS AND GPS FOR AERIAL PHOTOGRAMMETRIC MAPPING

Kurt Novak
Department of Geodetic Science and Surveying, Center for Mapping
The Ohio State University
Commission I

ABSTRACT

This paper describes the development and application of a fully digital, aerial image acquisition system which is integrated with GPS. A high resolution digital camera captures overlapping vertical images from an airplane. The exposure stations are tagged with the GPS time and the accurate position of the airplane. During post-processing images and navigation data are integrated. All information is stored in an image data-base related to a GIS. Kinematics GPS is applied to determine the exposure stations within ten centimeters. An aerial triangulation solves for additional camera parameters and is controlled by the GPS locations of the perspective centers. The major application of this new system will be the mapping of utility lines, roads, pipelines, and the generation of digital elevation models and orthophotos for engineering applications.

Keywords: Aerotriangulation, Camera, Digital Systems, GPS, Integrated System

1. INTRODUCTION

The development of integrated mobile mapping systems is a major research focus at the Center for Mapping of the Ohio State University. The most famous so far is probably the GPS-Van, which is a vehicle-based mapping system that combines GPS, inertial sensors and a digital stereo-vision system for creating highway inventories (Novak, 1991; Bossler et al., 1991). The same sensors used in the GPS-Van can also be implemented in an airplane. Some hardware components are not absolutely necessary in the airplane, such as the inertial system or a second camera, as the parameters measured by these devices can be easily recovered by analytical triangulation techniques.

The digital aerial mapping system described in this paper was named MapCam. It consists of a fully digital, high-resolution, frame CCD camera that can capture imagery at pre-defined times and store the data on a digital tape. A GPS receiver operating in kinematic mode allows to tag the images with the accurate position of the airplane; it is applied during post-processing to control aerial triangulation. All information captured during the flight is stored in a GIS; flight-lines and exposure stations define a geographic reference, and the images are stored relative to these locations as attributes. Any image can be displayed on the computer-screen by selecting its geographic location on a digital map. All photogrammetric operations, such as image coordinate measurement, aerial triangulation, DEM and feature extraction can be done on a post-processing workstation semi-automatically. The extracted information is directly available in the GIS.

GPS controlled aerial triangulation is being applied operationally by various organizations (Lapine, 1990). The purpose of GPS is to eliminate ground control for aerial mapping; to our knowledge, however, all applications relate to metric, aerial, film cameras, so that the analysis of the imagery must be done by an operator on an analog or analytical stereo-plotter.

Electronic cameras have been applied for remote sensing purposes in airplanes. In most cases low resolution, analog video cameras were used. Some special sensors have been developed for digital, aerial mapping, such as the MOMS (Ebner et al., 1991) camera. Both are based on pushbroom type CCD arrays, which provide in-flight stereo by a vertical, as well as a forward and an aft-looking scan. The high price of these systems, which are mostly at the prototype stage, and the complicated geometrical camera model prohibited their wide distribution to date. To our knowledge nobody experimented with high-resolution frame CCD cameras together with GPS in airplanes.

In this paper various aspects of the development of MapCam are discussed. In the next chapter the hardware components are described. Then we explain the mathematical model which we applied to perform aerial triangulation and camera calibration. Some products, such as DEMs and digital orthophotos, are derived and displayed in a 3-dimensional perspective view. In the final chapter potential applications are shown to demonstrate the versatility of MapCam.

2. HARDWARE COMPONENTS

The MapCam system consists of three major components: a digital, high resolution CCD camera, a GPS receiver and a computer-control and storage unit. Our CCD camera is a Kodak Hawkeye M-3 (figure 1), which incorporates a solid state CCD sensor of 1280 (H) x 1024 (V) pixels in the body of a regular Nikon F-3 camera. The exposure is controlled by the electronics of the Nikon camera. It applies a slit-type focal plane shutter. The CCD sensor transfers digital data to a frame buffer, which is installed in a separate box together with a portable harddisk that holds up to 120 images. The Hawkeye M-3 camera can be operated from a battery and can be easily carried around. In order to circumvent the limitations of the harddisk we connected the data-capture box to a digital tape drive (Exabyte) through a SCSI interface. We also included a data-compression board to reduce transfer rates and save storage space. One Exabyte tape holds up to 5 GBytes of uncompressed data which corresponds to 3,850 images. Currently data-transfer is limited to one image per second.

We experimented with two different types of GPS systems: for metric mapping applications we used a pair of Trimble 4000 ST survey-quality receivers. They operate in kinematic mode, which means that one is positioned over a known base-station, the other is mounted on the fuselage of our top-wing airplane. They are both observing phases of the GPS carrier signal, and provide a clock for synchronizing all components of MapCam. With these type of receivers we can completely eliminate ground control for aero-triangulation, as the exposure stations can be determined to better than 10 cm. However, satellite lock must be maintained continuously once the airplane's GPS antenna was initialized over a known target on the runway. This means that the pilot must fly very wide turns without banking the airplane.

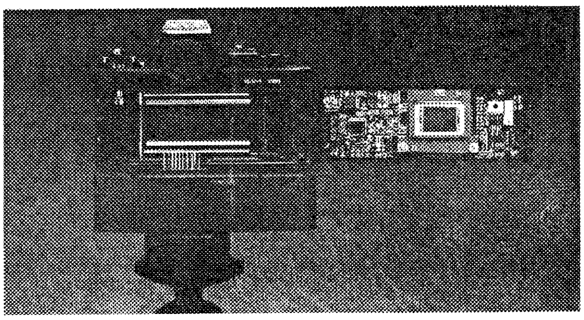


Figure 1: The Hawkeye M-3 high-resolution, digital camera system.

For coarse positioning of the airplane and navigation purposes we installed a Navstar real-time differential GPS system. This unit sends the base-station corrections via a radio link to the airplane's receiver, so that an improved position is immediately available. As pseudo-ranges are measured the accuracy of this method is in the range of 1-5 meters, which is sufficient for many remote sensing purposes and tagging the images in a data-base.

Finally, the system is being controlled by a board level PC, which is installed with most other components in a portable box. We do not use a hard-disk in the airplane, as the storage requirements during operation are minimal; instead a small RAM-disk was included. The PC software receives time signals from the GPS receiver, it computes the corresponding exposure time of the camera and activates the shutter. The user interface consists of a flat-screen with a touch panel overlay. It displays information from all sensors, as well as a small video image of the area covered by the most recent exposure. As there is no keyboard the user simply selects functions by hitting buttons on the touch-screen.

A diagram of the full MapCam system is shown in figure 2. Notice that the GPS units are exchangeable dependent on the application and its accuracy requirements. This equipment was installed a Cessna 207 aircraft owned by the Ohio Department of Natural Resources.

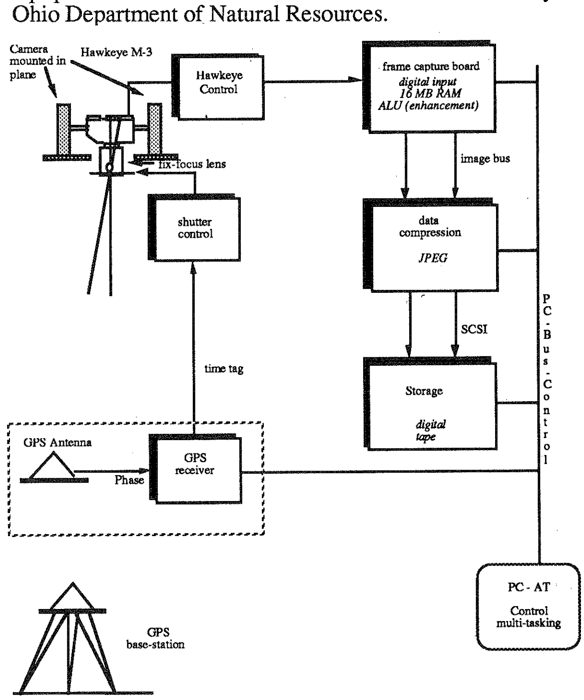


Figure 2: Layout of the complete MapCam system.

3. SYSTEM CALIBRATION

Before MapCam can be used for aerial mapping all sensors (Hawkeye M-3, GPS) must be calibrated. We need to determine the geometry and distortions of the camera, the offset of the GPS antenna's phase center from the perspective center of the digital camera, as well as any time delay between the shuttering of the camera from the PC and the actual exposure of the image.

3.1 Camera Geometry

As the Hawkeye M-3 uses major components of an amateur camera (Nikon F-3), its interior orientation is unknown. We assume that the CCD sensor itself is free of distortions, such as unflatness or irregularity of pixel-spacing. The manufacturer of the sensor (Kodak) specifies the size of its square pixels as 16 microns. This results in a sensor size of 20.48 mm x 16.38 mm, which is smaller than regular 35 mm film. Therefore, we have to use a fairly short focal length to get wide angle coverage. We chose a 20 mm lens which was focused to infinity. The focusing ring was taped at that position to avoid changes of the interior orientation.

Using a 3-dimensional test-field, which was established on a building at The Ohio State University, we performed a pre-calibration of the camera. Its major purpose was to determine a good approximation of focal length and principal point, as well as to estimate lens-distortions. The pre-calibration was computed by standard analytical techniques: the bundle-solution with self-calibration and additional parameters. The results of this adjustment show the great potential of a high-resolution digital camera; the bundle solution also considered radial distortions which can considerably improve the results when corrected (Table 1).

We will apply these parameters for aerial triangulation to find out, if self-calibration is necessary for each block of images.

3.2 Antenna Offset

The vector between the perspective center and the phase-center of the GPS antenna must be derived. This offset can be included in the aerotriangulation as control information. The offset vector must be determined in the image coordinate system (figure 3). It is applied to bundle adjustment by constraint (2) which relates a perspective center O_i with the corresponding GPS position G_i. The offset vector $\underline{\Delta O}$ is transformed into the ground coordinate system by the rotation matrix $\underline{R}_i$.

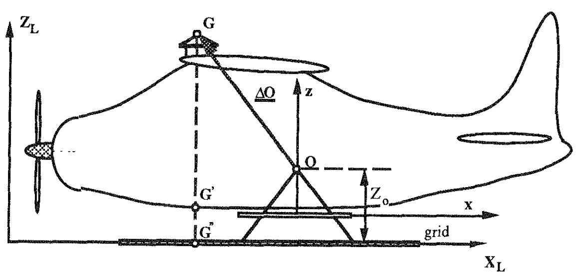
$$G_i = O_i + \underline{R}_i\,(\underline{\Delta R}_i)\,\underline{\Delta O} \qquad (2)$$

with:
G_i........GPS position for exposure station i,
O_i........perspective center of image i,
$\underline{R}_i$........rotation matrix of image i,
$\underline{\Delta R}_i$......correction for camera leveling if recorded during the flight,
$\underline{\Delta O}$.......offset vector in the image coordinate system.

The offset vector is tied to the motion of the aircraft. If the camera is attached to a mount which can be leveled during the flight, which means that the direction of the vector changes relative to the image coordinate system, it must be multiplied by another rotation matrix $\underline{\Delta R}_i$ that considers these attitude changes. $\underline{\Delta R}_i$ can only be computed, if the angular changes caused by leveling the camera mount are automatically recorded during the flight. In our experiments we did not change the camera mount during operations, so that the initial calibration was maintained and $\underline{\Delta R}_i$ could be omitted.

Method	x_p [mm]	y_p [mm]	c [mm]
interior orientation	-0.009 (±0.011)	-0.409 (±0.011)	20.281 (±0.019)
w/radial	-0.141 (±0.004)	-0.434 (±0.004)	20.354 (±0.006)
w/radial and decentering	-0.152 (±0.008)	-0.337 (±0.009)	20.371 (±0.006)

Table 1: Results of the pre-calibration of the Hawkeye camera: interior orientation parameters (principal point x_p, y_p, focal length: c) were derived by different versions of the bundle adjustment. The values in the brackets give the estimated precision.



X_L, Y_L, Z_L ....*local grid coordinate system,*
x, y, z ....*image coordinate system.*

Figure 3: Calibration of the offset vector in the image coordinate system.

All measurements in the airplane were done in the hangar with the airplane strapped to the floor in a position which comes close to the one it would assume during flight. A test grid was laid out beneath the aircraft to define a local coordinate system (X_L, Y_L, Z_L) in which the offset vector $\underline{\Delta O}$ was determined. First, an image of the grid was captured by the Hawkeye M-3 camera in its mount. This is possible as the short focal length of the digital camera has a large field of view and thus creates a sharp image of the grid even at this short distance of about 1.5 m. Then, a number of theodolite intersections were measured to locate the GPS antenna's phase center G, its vertical projection onto the grid (G"), and a number of grid points on the floor. All coordinates were determined in the local grid system. Additionally, we marked a point G' at the bottom of the airplane, which is used to initialize the GPS survey of the mapping flight over a known target with a plumb. The image coordinates were measured in the grid images. Together with the interior orientation from the pre-calibration they were used to compute the perspective center (O) and the camera attitude in the grid system. The offset $\underline{\Delta O_L}$ is defined as the vector from O to G. By applying the rotation matrix it is transformed into the image coordinate system (3).

$$\underline{\Delta O} = \underline{R}_L^T \cdot \underline{\Delta O_L} \qquad (3)$$

with: $\underline{\Delta O}$......... *offset vector in the image system,*
$\underline{\Delta O_L}$....... *offset vector in the local grid system,*
$\underline{R_L}$......... *rotation matrix of the captured image.*

During our first test flights the offset vector was calibrated as $\underline{\Delta O}$ = (1.695, - 0.269, 1.434).

3.3 Time Delay of the Shutter

During our first test flights we found that there is a delay between the exposure time recorded by the computer and the time when the shutters actually opened. This is due to the fact, that the PC sends a signal to the Hawkeye and records the GPS time of this signal. However, the exposure is somewhat delayed due to the electronics transmitting the signal. This delay can be as large as 1 millisecond, which corresponds to an offset of 5 cm if the aircraft is traveling at a velocity of 160 km/h.

There are two ways to calibrate this delay Δt: first, one can try to measure it with an oscilloscope and a light sensitive diode behind the shutter. This would tell us, how long the camera takes to respond, once the signal was transmitted from the PC. The other approach would try to correct for Δt by an additional block-invariant parameter in the bundle-solution. The problem is that this parameter is fully correlated with the principal point coordinate x_p (if the camera's x-axis is parallel to the flight line). This would only be a problem, if a self-calibration is computed during aerotriangulation.

4. OPERATION OF MAPCAM AND POST-PROCESSING

For the test flights conducted with the first version of the MapCam system we used a Cessna 207 aircraft. It had a hole and camera mount in the bottom, so that we only had to install a small adapter for our Hawkeye camera. The installation of all equipment takes about half an hour, not including the calibration which was done separately. Once a basic operation test was performed in the hangar, the airplane was taxied to a known target on the runway of the airport. By using a plumb line the horizontal offset between this position and the GPS antenna is determined, the vertical offset is already known from the original calibration. By this procedure the GPS survey is being initialized. From this time on the pilot must try to maintain continuous satellite lock, which is possible if the airplane is not tilted more than 10^o during the flight. We managed to avoid cycle-slips during both test-flights which lasted more than one hour each. After the flight the known point was revisited to close the survey.

Once airborne, the operation of MapCam is straight forward: the operator simply hits a button to start capturing images. This can be done at time intervals larger than one second, or at a constant, user-defined overlap. In the latter case MapCam uses on-line navigation data from GPS to determine the airplane's speed and relative position changes.

After the flight, post-processing of the GPS measurements is completed by combining observations of base and rover stations. Either pseudo-ranges or phase measurements can be analyzed, dependent on the requirement. As a result we obtain the flight-lines with the images attached as attributes (figure 4).

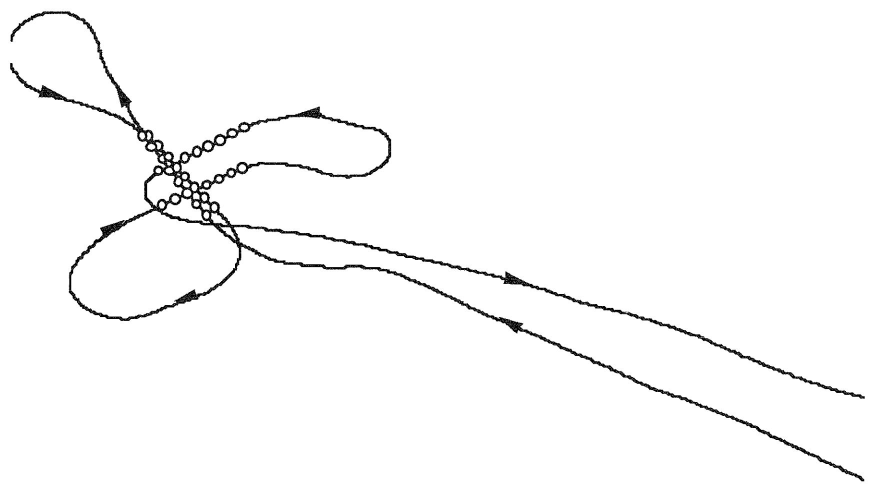


Figure 4: Flight-lines of the first test-flight after differential GPS processing. The images are marked by circles.

Image coordinates can be measured in any digital image processing system on a computer monitor. We used the ERDAS Digital Ortho Module for image analysis. A number of check and tie-points were measured in the digital images. Together with the GPS flight-lines, the interior orientation and the offset vector a bundle triangulation can be computed to determine the exterior orientations of all photos. The orientation data is applied for various post-processing tasks, e.g. the derivation of digital elevation models (DEMs) and orthophotos. Figure 5 shows a MapCam image of the Columbus Zoo.

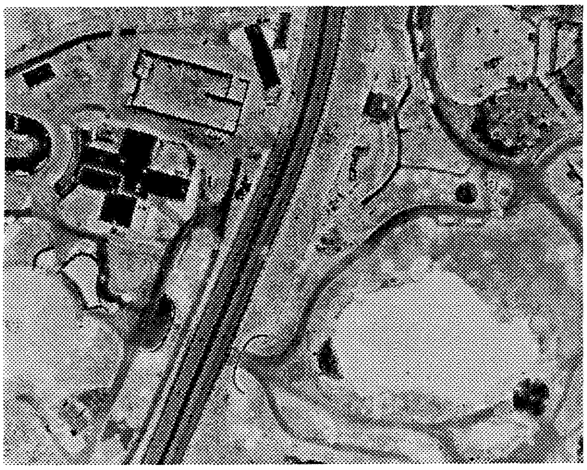


Figure 5: MapCam image covering the Columbus Zoo. The ground resolution is 25 cm per pixel, the image covers an area of 320 m by 256 m, and was taken at a flying height of 300 m above the ground.

5. CONCLUSIONS

Although research on MapCam is not completed yet, we found that a digital, aerial, GPS-controlled mapping system has a great potential for fast, spatial data collection. The major advantage over conventional aerial surveys is its quick turn-around time, as digital imagery is immediately available for image analysis after the flight. The resolution of digital cameras will not match film in the near future, but for many applications, MapCam provides enough detail and accuracy. Digital mapping cameras will become especially important with the availability of digital softcopy workstations. As scanning of aerial photography is a very time consuming and expensive task, users will sacrifice resolution for speed and currency of the data.

The current version of MapCam is still closely related to conventional, aerial mapping systems. However, there are a number of enhancements and modifications we plan in the future. First, a number of video cameras of lower resolution should be added. Each one would be equipped with a filter to capture a narrow spectral band. This would result in multispectral, aerial images, which could be applied for various remote sensing tasks. The other major enhancement would be the installation of a camera-pair in an airplane to map 3-dimensional positions in real-time. A major application would be the mapping of power-lines. The two cameras would be installed at the wing-tips. This would allow for stereo-positioning in a local coordinate system relative to the airplane. If the plane would fly relatively low the accuracy would be acceptable for many applications. In order to get absolute coordinates three GPS antennas would be installed at the wing-tips and the vertical stabilizer. They would provide both global positions and attitudes of the aircraft. This so-called Utility Mapping System is currently being designed at the Ohio State University; we believe that it will allow the user to map global positions form an airplane in real-time.

6. REFERENCES

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7. ACKNOWLEDGMENT

The research discussed in this article was funded by NASA's Center for the Commercial Development of Space through OSURF project #725527. The author wants to thank Kodak, Inc. for their donations and support of this work.