REAL-TIME MAPPING TECHNOLOGY

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ABSTRACT

At the Center for Mapping of The Ohio State University a number of research projects focus on the development of mobile mapping systems. Typically, these devices are used to capture land-related data from airplanes, cars or trains in digital form. Spatial positions and attributes of objects are extracted automatically in the mobile system or during post processing, and are immediately transferred to a GIS. The research in real-time mapping technologies was fostered by the need of current and accurate spatial data for geographic information systems.

This paper investigates different concepts of mobile data acquisition systems using the prototypes developed at The Ohio State University as examples. The integration of different types of sensors, such as the global positioning system, inertial navigation devices, as well as digital and video cameras is the most important characteristic of real-time mapping systems. Storage, integration, and post-processing of the data is a very difficult task. Today's commercial GIS's are not capable of handling the tremendous amount of information acquired with these systems efficiently. Multi-media data-bases which can access data stored in different formats and on different devices are necessary to fully integrate and utilize the information captured with real-time mapping systems.

Key Words: GIS/LIS, GPS, Mapping, Real-time, System design.

1. INTRODUCTION

The quick implementation of Geographic Information Systems (GIS) and their never ending need for accurate, current, spatial data promotes the development of new approaches for automatic and fast data acquisition. Ideally, the human operator ought to be replaced entirely by a data capture system which can identify spatial objects, analyze their relationships, and store them in a data-base. These functions should be performed at the rate of data-capture. The mapping sciences put considerable research effort into solving these goals; however, progress is slow and does not seem to keep pace with the ever increasing demand for digital map-data by government agencies, transportation departments, utility companies, and many sectors of private industry.

Two years ago a new research program was started at the Center for Mapping of The Ohio State University, which focuses on the development of both instrumentation for fast data acquisition and algorithms for automatic data analysis. The key for successfully solving the data capture problem is the full integration of different mapping technologies, such as geodesy, photogrammetry, inertial surveying, and remote sensing, to develop a *mobile mapping system,* which can feed information into a GIS while data acquisition is still in progress. This research program initiated a number of interesting projects, some of which resulted in the implementation of operational prototypes (GPS-Van, MAPCAM) and gained national attention (Bossler, et. al., 1991), while others did not succeed beyond the concept stage (real-time satellite remote sensing).

In this paper we try to explain the concepts behind these novel approaches of data-capture and analysis; we refer to it as *"real-time mapping"*. The hardware components that can be used in a mobile mapping system, such as GPS, inertial navigation systems, digital cameras, are discussed with respect to their potential for solving specific problems, and their accuracy. The basic algorithmic and structural concept of a real-time mapping system is presented. Then the major developments of the Center for Mapping are described, the degree of automation of data-processing is shown, and their potential applications are analyzed. In the conclusions we point out the commercial potential of real-time mapping technology and motivate future developments.

2. CONCEPTUAL DESIGN OF A MOBILE MAPPING SYSTEM

Before we begin with designing a mobile data acquisition and analysis system we have to identify the applications of the digital information and the accuracy requirements. These specifications determine the types of sensor that can be used for the mobile mapping system. Obviously, other sensors are needed to capture road alignments and street addresses, than to detect cracks or rutting (deformation) of road surfaces. Furthermore, it is important to know under which environmental conditions the system will operate, and what source of external information can be used to established a global reference. For example, the application of satellite positioning has limitations in certain parts of the world, because of foliage cover or other obstructions that block signals from reaching the sensor. Backup devices or alternate sensors are needed to overcome these limitations.

Any mobile mapping system creates land related information; therefore, it requires a positioning sensor to determine the *absolute location* of the vehicle that carries the system at any time. The term vehicle refers to the carrier of the mobile mapping system; it could be land-based (car, train), air-borne (plane, satellite) or water-based (ship, submarine). The most popular devices for absolute positioning are the Global Positioning System (GPS), inertial navigation devices, and LORAN-C hyperbolic navigation. A number of other sensors may be used to obtain information relative to the vehicle. They range from video-cameras for capturing a visual record of the environment to pavement sensors to determine the roughness of road surfaces. Some of these devices might generate *attributes*, such as the above mentioned video cameras, while others can measure 3-dimensional coordinates *relative* to the *position* of the vehicle, such as radar from airplanes or a stereo-vision system on a van.

Once the configuration of sensors has been selected we have to decide about the sequence of *processing and storing the data*. All captured data must be integrated (data fusion) in order to create a comprehensive data-base, that combines spatial positions with attributes, images, and various other measurements in a GIS. As some of the sensors depend on the information extracted from others, it is important to define the hierarchy of data processing. Usually, absolute positions must be available before relative observations can be integrated, however, some types of data can be evaluated in a combined analysis.

Ideally, all processing takes place on the mobile mapping platform; however, limitations of processing speed and lack of reference information (such as the base-station observations for differential GPS processing) may handicap this objective. For many computing intensive operations, such as feature extraction from digital imagery, the only realistic solution may be the storage of raw data in the vehicle and the post-processing in a data-center.

Another approach is the discrimination between observations that must be processed before they are permanently stored, and data that can be saved to be analyzed only if there is specific need to do so. An example, for the latter case is digital imagery from satellites, airplanes or a van-based stereo-vision system; features need only be extracted if certain attributes are required, such as the traffic signs from a sequence of highway images or the road network from satellite scenes.

Finally, we must address the *storage and data-base management* problem. As all data captured on a mobile platform is land-related, a geographic information system will be the basic tool for handling the data. Due to the multitude of sensors, however, a variety of data-types, file formats, and even storage media must be supported. Most of today's GIS's provide only limited data fusion capabilities. The simple integration of rasters and vectors is accomplished by many, but once information cannot be stored on the same device or is spread out over different computers with different data-file formats, the availability of appropriate systems is very limited.

For organizing this information we distinguish between a *spatial* and an *attribute data-base*. The spatial data-base consists of 3-dimensional points, lines, and vectors, while the attributes provide additional information related to the spatial positions. Both are tied together by data-base management software. As data capture and storage is integrated in a real-time mapping system, we must handle a sequential stream of diverse information. Object orientated data-bases are the ideal tools to manage this type of input; when capturing road-alignments together with digital imagery, the images and any extracted attributes should be stored relative to the absolute road network. This also has advantages for the retrieval of raster data, which may be stored sequentially on digital tapes.

The basic layout of an integrated mobile mapping system is shown in figure 1. All components are physically connected, so continuous data-flow is guaranteed, and the whole unit is self-contained.

3. HARDWARE REQUIREMENTS

Following the basic concept displayed in figure 1, we want to investigate hardware components that are available for integration in a mobile mapping workstation. We will compare absolute and relative positioning sensors, devices for collecting other measurements, their operational modes, and accuracies. In order to be usable in this environment sensors and computers must respond in real-time; for many applications, though, the concept of real-time can be relaxed to intervals of 1 to 5 seconds, sometimes even longer. Devices that require long, static observations, however, cannot be used.

3.1 Absolute Positioning Sensors

There are two types of absolute positioning sensors: devices that depend on external signals received from a transmitter (GPS, LORAN-C) and instruments that measure the changes of the platform independent of any exterior observations (Inertial Systems). A combination of both creates the ideal positioning system.

The choice for determining absolute locations of a mobile mapping platform is the *Global Positioning System (GPS)*. It will allow for accurate positioning anywhere on the globe once the full satellite configuration is available. Currently, its application is restrained to certain time periods. Dependent on the quality of the receiver and the mode of operation, GPS yields accuracies between 30 meters and 3 centimeters. The application defines the type of receiver and processing mode to be selected; for example, for mapping road alignments differential processing of pseudo-ranges can be performed which yields accuracies of 1-5 meters (C/A code). For aerial triangulation exposure stations must be known to 5 centimeters to eliminate ground control; in this case, phase measurements must be used for processing (kinematic GPS). Unfortunately, this technique requires constant lock to at least four satellites and an initialization point to solve for ambiguities. If the satellite signals are obstructed at any time (cycle slips), kinematic processing fails. With a new generation of dual-frequency, P-code receivers these problems will be solved, so that centimeter level accuracies can be obtained even if satellite lock is lost for a short period of time.

Another external positioning system is *LORAN-C*. It is based on a network of stationary transmitters. A receiver measures the signals emitted by the reference stations and computes the vehicle's location. For most mapping applications LORAN-C and other radio-navigation systems do not yield sufficient accuracies, therefore, they are mostly used for marine navigation. However, they might be applicable for mapping, when they are integrated with GPS.

In many applications satellite signals are obstructed for extensive time periods (e.g. in submarines, cars in urban

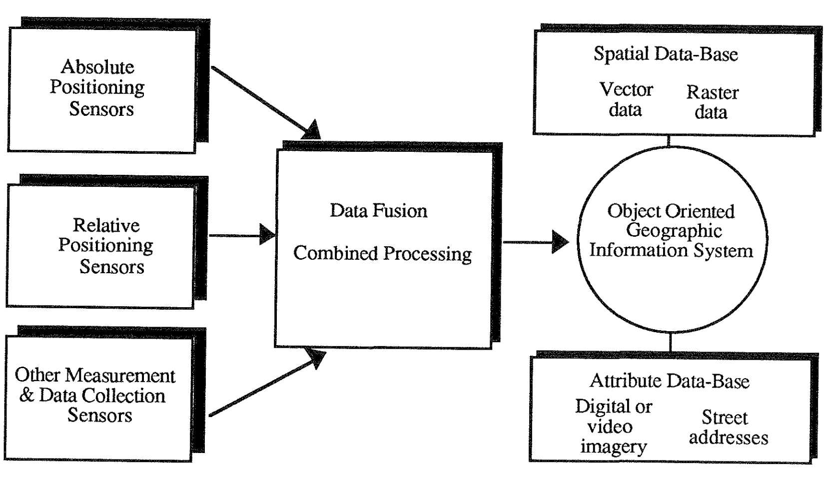

Figure 1: Conceptual design of a mobile mapping platform that integrates various sensors, data-analysis functions, and an object oriented data-base.

areas). Therefore, a *dead reckoning system* is needed to determine the vehicle's positions without exterior observations. Combined with an absolute positioning device for initializing and updating the positions, they allow for continuous tracking of the vehicle.

The most accurate dead-reckoning devices are *strap-down inertial systems*. They measure accelerations along three perpendicular directions, and around the coordinates axes (rotational accelerations). These observations must be integrated twice; thus, there will be a position-drift which is a function of the distance traveled without exterior updates. The dimension of this drift depends on the quality of the instrument, as well as the mathematical model (Kalman Filter) applied for data processing. If fully integrated with GPS, the position updates can be done on the fly, without stopping the vehicle. Unfortunately, the high cost of strap-down inertial systems is prohibitive to their integration in most commercial mobile mapping systems.

For lower accuracy requirements a simple *gyro-based inertial system* might be adequate. Such a device consists of a directional and a vertical gyro; it is combined with a distance measurement unit (e.g. a wheel-counter in a car). The gyros measure tilts of the vehicle and can be combined with observations of the traveled distance in order to reconstruct smooth lines of motion. These lines can be transformed into an absolute coordinate system with the help of the absolute position fixes (GPS). As with all inertial systems we must limit gyro-drift by regular position updates using external measurements.

Table 1 compares external and inertial positioning systems. A combination of these sensors enables us to obtain more accurate and reliable spatial information.

3.2 Relative Positioning Sensors

They are designed to position objects relative to the vehicle in a local coordinate system. A variety of instruments can be used for this purpose, dependent on the specific application. Imaging sensors allow to acquire raster-information by frame or linear array CCD sensors or by radar, and to extract spatial objects by photogrammetric techniques. Regular film cameras are not counted in this category, as they cannot be used for real-time mapping.

Conventional photogrammetric point positioning is based on object space control. This concept was also applied to digital and real-time photogrammetry control targets must be available at the object, which are automatically detected by the computer. For real-time mapping we want to avoid object space control. Any control shall come from the vehicle; only tie-points and other geometric constraints need to be available in object space to strengthen an analytical solution. The feasibility of this principle was demonstrated by GPS controlled aerial triangulation without ground control points, and by a digital stereo-vision system mounted on a van (see chapter 5.1).

Data collected by imaging sensors are either stored in the vehicle (car, airplane) or directly transmitted to a data-center (earth observation satellites). Currently, on-line processing and extraction of features from digital imagery in the vehicle is limited due to the lack of computer power, therefore, post processing is mandatory. This, however, does not contradict the principle of real-time mapping, as images can be considered attributes of a GIS.

Beside imaging sensors a suite of other non-optical measurement devices can be added onto the vehicle. For highway mapping road-roughness sensors are attached to the front of a van to survey elevation profiles and rutting; in the case of satellites or airplanes radar altimeters serve a similar purpose. Most of these sensors have been developed for very specific applications, but the analysis of these observations yields relative positions.

Table 2 shows some relative positioning sensors, the vehicle type in which they can be installed, and their price. The accuracies depend on many different factors, such as imaging geometry, object distance, vehicle speed, so that it can not be included in this table. For accuracies achieved with relative positioning sensors refer to chapter 5.

All measurements made by instruments described in this chapter are relative to the vehicle. The transformation into a global reference frame is possible by a six parameter, spatial similarity transform. The parameters are derived from the full orientation (position and attitude) of the vehicle which is available at any time. They depend on the calibration of the offset between the different sensors.

3.3 Attribute Collection Sensors

This category of sensors captures information which does not consist of spatial positions, but of attributes which relate to the respective vehicle location. Typically, these data are stored in the attribute data-base.

A large variety of sensors is available that suite this purpose. Analog video cameras permit to collect a visual record of the environment from a moving vehicle. They are

	System	Measurement	Accuracy	Price
External Positioning	absolute GPS	C/A code	30-100 m	< $1,000
	differential GPS	pseudo-ranges	1-5 m	$2,500
	kinematic GPS single frequency	carrier-phase	1-10 cm	$2,500
	kinematic GPS dual-frequency P-code	carrier-phase	1-10 cm	$30,000
Inertial Positioning	Strap-down inertial system	accelerations	10 cm	> $150,000
	gyros & wheel-counter	angular changes & distances	1-3 m	$15,000

Table 1: Comparison of different external and inertial positioning sensors. The accuracies of inertial positioning devices depend on distances traveled without updates. The prices are only rough approximations and change continuously.

Relative Positioning Sensor	Platform	Price
frame CCD	car, plane, boat	$1,000 - $20,000
linear array CCD	satellite, plane	
stereo-vision system	car, boat, train, helicopter	$35,000
radar	airplane, satellite	

Table 2: Relative positioning sensors, the platform on which they can be mounted, and their price. The quoted prices for these devices may vary considerably dependent on the application.

commonly used for video-logging to create highway inventories or for remote sensing applications from airplanes. Unfortunately, the attributes contained in the videos must be extracted manually during post-processing unless advanced image understanding functions are available. Other sensors of this category measure temperature, air pressure, gravity; they can be mounted on various vehicles, as mandated by the application.

4. DATA FUSION

Now that the sensors of the mobile mapping platform have been identified, we want to investigate data processing procedures. For that purpose, three points must be considered:

(a) some sensors depend on others (e.g. all relative positioning sensors depend on the absolute positioning sensors), therefore, the sequence of processing must follow a defined hierarchy;
(b) we want to combine data of different sensors to obtain a more reliable and stable result, rather than processing the measurements captured by each device individually;
(c) we are limited by the processing power available in the vehicle; thus, it is necessary to store some information instead of directly processing all.

The absolute positions create the frame-work for all other sensors. In order to obtain smooth, continuous curves that represent the motion of the vehicle during the mapping operation, it makes sense to integrate external and inertial sensors. For example, in one of our projects which will be discussed in chapter 5.1, GPS was connected with a gyro-based inertial system and a wheel-counter (Goad, 1991). While GPS coordinates serve as absolute position fixes, the inertial observations create continuous lines which bridge over areas where satellite signals are blocked. The measurements of both systems (pseudo-ranges, angular differences, and distances) are combined in a least squares adjustment, in which the GPS fixes are assigned weights dependent on their positional accuracy (PDOP). The result of this combination is shown in figure 2.

A combined analysis of the measurements is possible in the vehicle by applying sequential adjustment techniques (Edmundson, 1991). For GPS processing an on-line data-exchange between mobile and base stations must be available in this case. As a result of the adjustment of all absolute positioning sensors we obtain positions and orientations (attitudes) of the vehicle at any time. This information can be immediately stored in a spatial data-base.

The observations of relative positioning sensors are considered attributes of the absolute positions. Therefore, they are first stored in an attribute data-base related to the positions. This is only necessary if on-line processing is not possible, for example, when we store digital road images relative to the road alignment. Once these images were analyzed (by feature extraction and image understanding) we obtain spatial positions of points, lines, and objects, which are defined in a local coordinate frame relative to the vehicle. For most applications it is appropriate to assume that the known positions and orientations of the vehicle can be directly applied to transform this local system into a global system. Thus, any object detected is immediately available in absolute coordinates.

Another approach would be to combine the measurements of the absolute and the relative positioning sensors in a combined adjustment. As an example, let us use an aerial triangulation with GPS controlled exposure stations. The GPS observations determine the absolute locations of the airplane (exposure stations of the cameras), while the air-photos correspond to relative observations (relative to the airplane). Instead of computing the GPS positions of the airplane and using these positions as absolute constraints in the aerial triangulation, one could directly solve a combined adjustment of both phase-measurements of the GPS and image coordinate measurements of the photos. This would enable us to completely eliminate the camera orientation, and directly compute the ground coordinates of tie-points from satellite orbits.

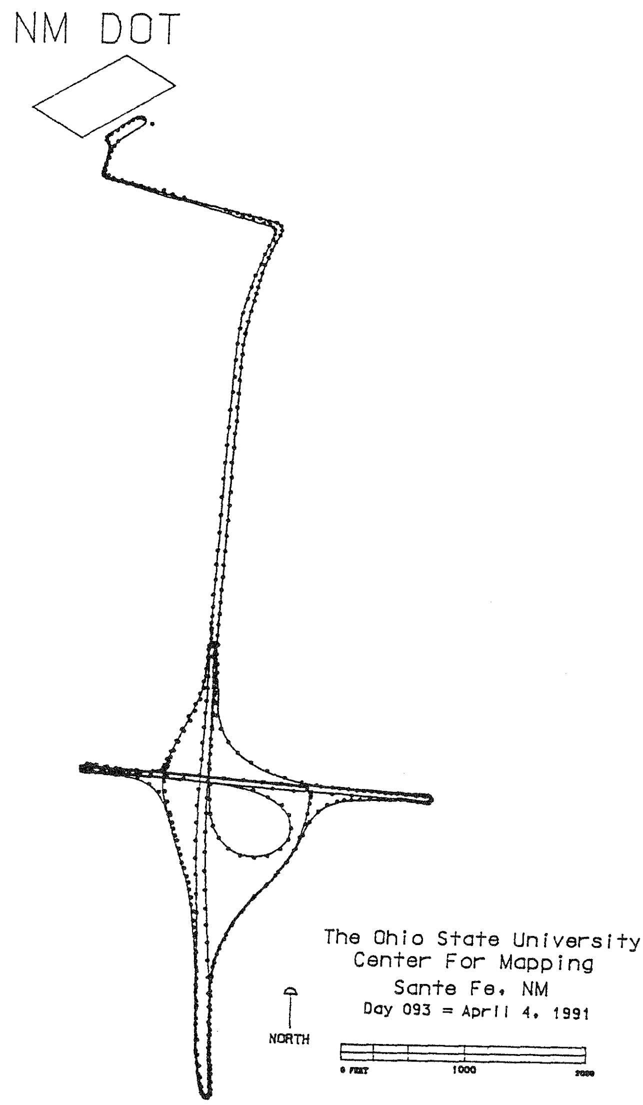

Figure 2: Resulting alignment of a combination of inertial and GPS observations. The circles indicate position fixes by GPS.

5. PROTOTYPES OF MOBILE MAPPING SYSTEMS

In this chapter some developments conducted at the Center for Mapping of The Ohio State University are presented. Two of these systems have been actually implemented and tested in an operational environment. The third is at the concept stage and might be pursued in the future.

5.1 The GPS - Van

This is a mobile mapping system for creating digital highway inventories while driving along the road at regular highway speeds. The GPS-Van was built during a two year research project sponsored by 38 US State Transportation Agencies, the Federal Highway Administration, NASA, and some private companies and government agencies (Johnson, et. al., 1992). The prototype is shown in figure 3.

Figure 3: The GPS-Van which combines GPS, inertial navigation and stereo-vision technologies with GIS.

The GPS-Van integrates a global positioning system receiver, a gyro-based inertial system, a wheel-counter, a digital stereo-vision system, and a color video camera in a mobile platform. Absolute positioning is achieved by GPS and inertial system. Continuous road alignment files are created, even in areas where satellite signals are blocked due to trees, buildings, tunnels, or bridges (Goad, 1991). Relative positioning is performed with a stereo-vision system. Once calibrated, every point in the field of view of the digital camera-pair can be located in 3-dimensions relative to the van (Novak, 1991). For the transformation of these points into a global system we apply the orientations and positions of the van, which were derived by post-processing of the absolute positioning observations (figure 4).

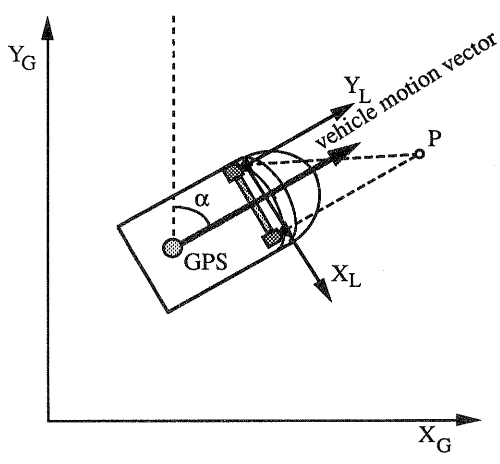

Figure 4: Transformation of relative positions determined with the stereo-vision system into the absolute coordinate frame.

Additionally, attributes, such as traffic signs, intersections and bridges, can be collected by an operator manually; he hits a button on a touchscreen when the van passes the desired feature. They can also be visually identified in the color video. We are currently developing advanced feature extraction techniques to automatically extract road edges and traffic signs, and we also experimented with the reading of text on traffic signs (Novak, 1991). Figure 5 shows a road image in which the edges and dashed center-lines have been automatically detected, and approximated by straight lines. These lines are immediately available in the global system and can be directly stored in a GIS.

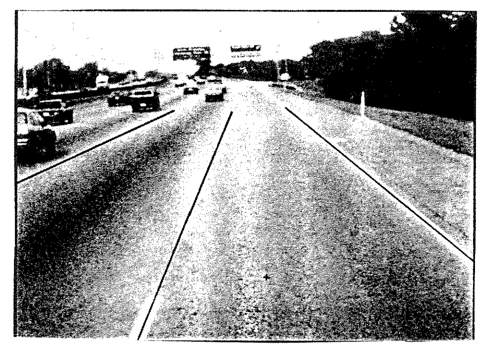

Figure 5: The road edges and center-lines can be automatically extracted and approximated by straight lines.

In order to obtain smooth road-alignments, GPS and inertial measurements were integrated in a least squares adjustment. We used differential GPS and pseudo-range observations. The resulting absolute accuracies are 1-3 m for the road alignment. Stereoscopic positioning with the vision system is better than 10 cm at a distance of 20 m in front of the van (without any object control). These values are only relative to the vehicle, the accuracy of absolute coordinates fully depends on GPS.

5.2 MAPCAM

Another research project currently conducted at the Center for Mapping attempts to integrate a digital, high-resolution camera with GPS in an airplane. The principle is similar to GPS-controlled aerial triangulation, except that we apply a fully digital camera that is completely integrated with GPS in a portable platform (figure 6). Absolute positioning is achieved by kinematic GPS, while relative positions are derived from overlapping digital imagery. At this stage no other sensors have been implemented, yet.

Using single frequency GPS receivers, continuous phase-observations can not be obtained with high reliability. It is possible to avoid cycle-slips if one flies without banking the airplane, and if enough satellites are high above the horizon. If satellite lock can be maintained over the whole flight, the exposure stations are computed to better than 10 cm, thus eliminating the need of ground control completely.

Otherwise, regular pseudo-ranges are processed, such as in the GPS-Van. An accuracy of 1-5 meters is obtained in that case, which provides good approximations for aerial triangulation and a perfect reference for the image data-base in the GIS. With new dual-frequency, P-code receivers loss-of-lock will no longer be a problem of kinematic GPS. Therefore, ground control is (almost) obsolete.

The exterior orientations of all images are computed by bundle adjustment, in which the known exposure stations are used as constraints. Additional ground control is not needed in that case, however, it might be desirable to identify some checkpoints in order to verify the accuracy of the results. The images can be used for manual stereo-mapping on a 3D-computer screen or to automatically extract digital elevation models and digital orthophotos.

The applications of MAPCAM are manyfold: they range from civil engineering surveys and inventorying utility lines, to digital mapping of construction sites. This system will become a powerful data-acquisition tool for soft copy photogrammetric stations.

5.3 Real-Time Earth Observation Satellite

The last system described here is still at the conceptual level and has not been implemented, yet. We plan to develop a pair of high-resolution (5 m or better) earth observation satellites, that cover the ground stereoscopically, and can be used for spatial mapping. Instead of using array scanners, frame CCD cameras are installed in two satellites; they would provide a more stable model for orientation and mapping. The satellites would be constantly positioned by GPS. This is feasible as GPS satellites fly much higher (20,000 km above earth surface) than regular remote sensing satellites (800 km). For stereo-coverage these rather small satellites would track each other while orbiting around the globe, and cover the same area on the ground. The base distance between the satellites would be determined very accurately with GPS (figure 7).

The two satellites would down-load data to movable receiving stations, which could process the information immediately. As the satellite positions would be transmitted, too, accurate spatial mapping can performed in real-time.

6. CONCLUSIONS

Real-time mapping systems are an exciting new research tropic for photogrammetrists, remote sensors, geodesists, and mappers. The development of this technology is important for the fast creation of digital, spatial data-bases. Its successful implementation depends mostly on the cooperation between different fields of the mapping sciences; therefore, these efforts are considered highly inter-disciplinary. At The Ohio State University we successfully implemented two mobile mapping systems in close cooperation of the various disciplines represented by the Center for Mapping.

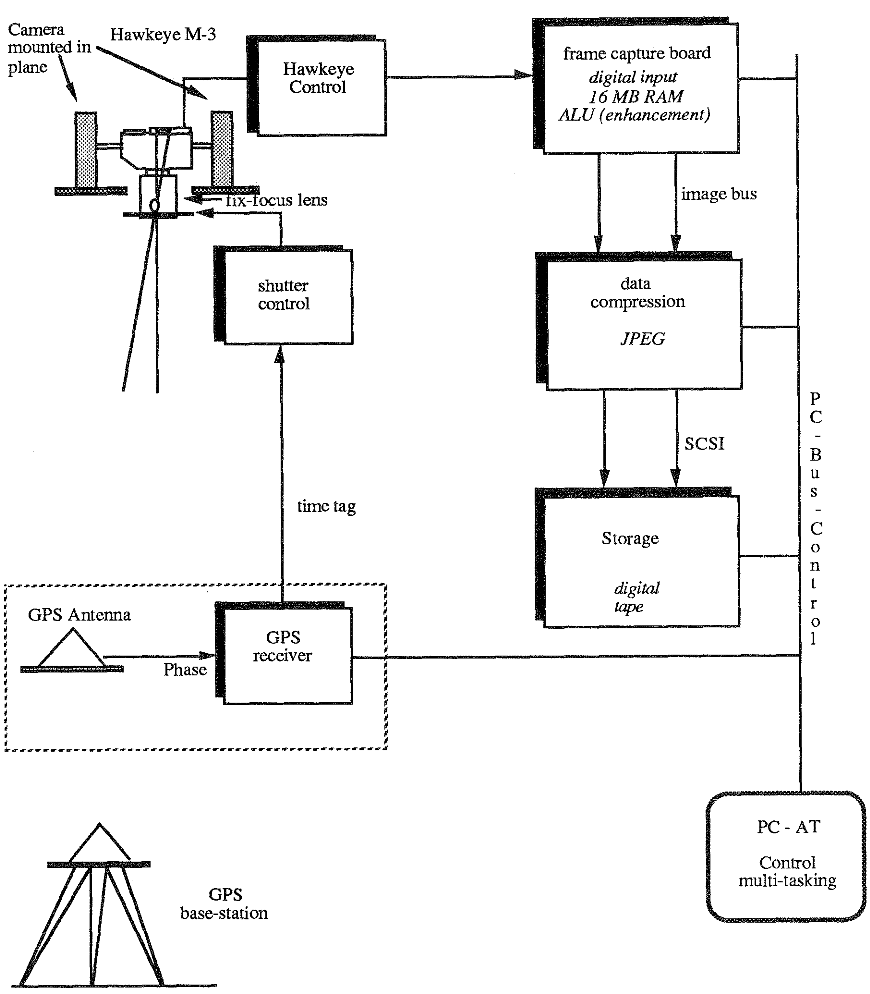

Figure 6: The system chart of the GPS controlled digital high-resolution mapping system (MAPCAM).

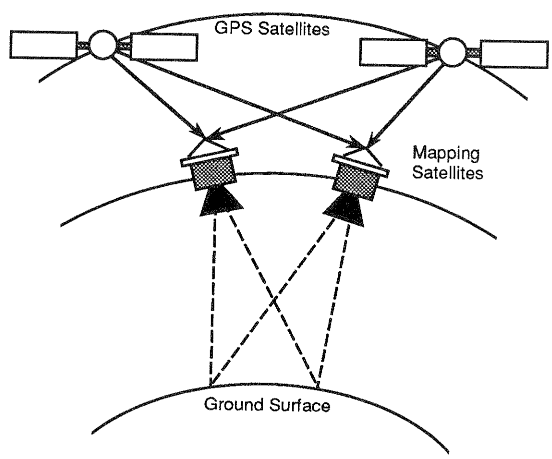

Figure 7: Concept of spatial stereo-mapping from space in real-time.

During the development of our prototypes we did not only attract interest from scientists around the world, but we discovered the huge economic potential of this new technology. As every state, county or city is in urgent need of digital maps, manual digitization of existing line maps proves time consuming and expensive. Any device that can collect and analyze data cheaper and more accurately has a potential for replacing these old procedures. An integrated real-time mapping system can do this job faster, cheaper and more accurately. The combination of various sensors creates a high degree of redundancy and reliability. The most important characteristic of real-time mapping compared to various other data capture techniques is the *currency* of the data. Currency means that the digital map accurately represents reality and that changes are updated dynamically. Currency was rated the most important feature of this technology by companies that were interviewed about their potential need of digital maps.

As more advanced and more accurate sensors become available, it will be possible to process all collected data directly on the mobile platform. Then we will be able to create digital maps on-line. This will have a tremendous impact on the GIS industry, as well as on applications, such as car navigation, fleet tracking and mail deliver, as the need of accurate, reliable, and current spatial data can be satisfied by real-time mapping systems.

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