From Mobile Mapping to Telegeoinformatics: Paradigm Shift in Geospatial Data Acquisition, Processing, and Management

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Abstract

Technological advances in positioning and imaging sensors, combined with the explosion in wireless mobile communication systems that occurred during the last decade of the twentieth century, practically redefined and substantially extended the concept of mobile mapping. The advent of the first mobile mapping systems (MMS) in the early 1990s initiated the process of establishing modern, virtually ground-control-free photogrammetry and digital mapping. By the end of the last decade, mobile mapping technology had made remarkable progress, evolving from rather simple land-based systems to more sophisticated, real-time multitasking and multisensor systems, operational in land and airborne environments. New specialized systems, based on modern imaging sensors, such as CCD (charge-coupled device) cameras, lidar (Light Detection and Ranging) and hyperspectral/multispectral scanners, are being developed, aimed at automatic data acquisition for geoinformatics, thematic mapping, land classification, terrain modeling, emergency response, homeland security, etc. This paper provides an overview of the mobile mapping concept, with a special emphasis on the MMS paradigm shift from the post-mission to near-real-time systems that occurred in the past few years. A short review of the direct georeferencing concept is given, and the major techniques (sensors) used for platform georegistration, as well as the primary radiolocation techniques based on wireless networks, are presented. An overview of the major imaging sensors and the importance of multisensor system calibration are also provided. Future perspectives of mobile mapping and its extension towards telegeoinformatics are also discussed. Some examples of mobile geospatial technology used in automatic object recognition, real-time highway centerline mapping, thematic mapping, and city modeling with lidar and multispectral imagery are included.

Introduction

This paper is intended as a review of mobile mapping technology and its transition to support telegeoinformatics, an emerging discipline that integrates geoinformatics, wireless communication, and mobile computing technologies. The focus is on mobile mapping concept definition, its evolution, and the most recent advances in both direct georeferencing, which is the backbone of this technology, as well as on the imaging component and the operational aspects related to a variety of applications. The impact that the availability of the Internet in a mobile distributed environment has brought to mobile mapping technologies is also addressed. The primary objective is to provide the readers with a summary review, supported by extended references, where detailed information can be found. A variety of topics are covered, starting with direct georeferencing techniques and sensors, through the multisensor system concept and its calibration, to future trends in mobile computing, geospatial technology, and location-based services. Example applications in mobile environments are also presented, including real-time highway mapping and coastline mapping and city modeling. The currently achievable accuracy, the newest trends and challenges that the technology still faces, and anticipated future developments, are discussed in the Summary and Conclusions.

Multisensor systems that combine direct positioning and imaging sensors are rapidly becoming a standard source of information for various land-based and aerial mapping applications, including roadway asset mapping, surface reconstruction, orthophoto production, city modeling, etc. Availability of mobile Internet in the distributed environment facilitates the extension of the operational environments to real time, enabling change detection, emergency response, and real-time decision making. An optimal fusion of multisensory data, supported by the geometric fusion facilitated by GPS/INS (Global Positioning System/inertial navigation system), provides complementary information and higher fault resistance. This, in turn, translates to a more consistent scene description, enabling an improved scene interpretation and enhanced knowledge content. However, proper individual sensor calibration and inter-calibration become crucial in providing the required mapping accuracy, because no provision can be made for incorrect or varying sensor models (inner orientation) when direct platform orientation (DPO) is used. For example, a laser ranging device can deliver range information with an accuracy of 2 to 3 cm for airborne applications, and a few mm for ground-based applications. Thus, in order to properly utilize this high quality information, the sensor has to be positioned and oriented with a comparable accuracy. The quality and stability of calibration and time synchronization are especially important for airborne systems, where the object distance is

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significantly larger as compared to the land-based applications. Any error in interior orientation (IO), timing, or boresight components would translate directly into errors in ground coordinates of the extracted objects because, contrary to the aerotriangulation (AT) process, the IO and EO (exterior orientation) are decoupled (no common adjustment procedure that could compensate for imprecise IO or boresight transformation parameters) and the EO estimation process has an extrapolated rather than interpolated nature. To illustrate the importance of calibration of modern multisensor systems, examples of boresight calibration (transformation between the INS body frame and the image sensor frame) for CCD cameras and lidar systems are presented in the section on Imaging Components in Mobile Applications.

Mobile Mapping: Operational Aspects

The concept of the Mobile Mapping System (MMS) dates back to the late 1980s, when The Ohio State University Center for Mapping initiated the GPSVan™ project, leading to the development of the first directly georeferenced and fully digital land-based mapping system in 1991 (Bossler *et al.*, 1991; He and Novak, 1992; He *et al.*, 1994; Bossler and Toth, 1995). At the same time, the University of Calgary started a joint project with GEOFIT Inc., aimed at the development of the VISAT system designed for mobile highway mapping (Schwarz *et al.*, 1993; El-Sheimy *et al.*, 1995). By the mid-1990s more systems based on a similar concept were developed and used worldwide. In the mid-1990s, the quality of DPO reached a level adequate for supporting airborne mapping, following the advances in GPS/INS technology. Consequently, by the mid-1990s, several systems and applications based on fully digital GPS/INS-georeferenced imagery were reported, making a transition from GPS-supported aerotriangulation to virtually ground-control-free photogrammetry (see, for example, Schwarz *et al.* (1993), Lithopoulos *et al.* (1996), Da (1997), Grejner-Brzezinska (1997), and Toth (1998)). Subsequently, more specialized imaging sensors were included, especially in airborne mapping, among them lidar and multispectral/hyperspectral scanners, primarily for gathering terrain and land classification data (Axelsson, 1999; Baltsavias, 1999). A list of major existing land-based mobile mapping systems, and more details on the modern sensors and airborne systems, can be found in Grejner-Brzezinska (2001a; 2001b).

Major operational components of a multisensor mapping system are listed below, while Table 1 presents the primary imaging sensors and their functionality, and Tables 3 and 4 list the primary positioning techniques used in mobile mapping and telegeoinformatics.

- System calibration (usually performed before the mapping mission)
  - Lever arm between INS, which provides the primary reference frame for GPS and other navigation and imaging sensors
  - Camera calibration (IO)
  - INS/camera boresight calibration
- Georegistration and image data collection
  - Sensor synchronization to the primary time reference (usually GPS time)
  - Data logging
  - Image compression and storage, and real-time preprocessing
- GPS/INS postprocessing for six EO parameters (time-tagged image registration to the navigation system positioning results)
- Image processing on a softcopy system (georeferenced images are used for feature location; for less demanding applications, monoscopic image processing suffices; when high accuracy is required, stereo imagery and restitution must be used)
- Recent trends: real-time georegistration and image processing for change detection, emergency response, location-based services, etc.

Table 1. Primary Imaging Sensors and Their Functionality

Primary Imaging Sensor	Sensor Functionality
Digital Camera	Collects imagery used to derive object information. Two (or more) cameras provide 3D location in space.
Laser Range Finder	Supports feature extraction from the imagery by providing precise distance (typical measuring accuracy is about 2 to 5 mm).
Lidar, SAR (airborne systems)	Source of DSM/DTM, also material signature for classification purposes. Supports feature extraction from the imagery.
Multi/Hyperspectral Sensors (airborne systems)	Spectral responses of the surface materials at each pixel location. Wealth of information for classification and image interpretation.
Voice Recording, Touch-Screen, Barometers, Gravity Gauges	Attribute collecting sensors (land-based systems mainly).

Transition from Mobile Mapping to Telegeoinformatics

Recent advances in communication, networking, database management, image processing, and expert systems have contributed to an explosion of new products, applications, and technologies directly focused at the geospatial technologies. As a result, mobile mapping that originally emerged as a purely mapping technology, has started its transition from rather exclusive data acquisition applications supported by high quality GPS/INS, to multitasking information systems capable of acquiring, storing, manipulating, and displaying spatially referenced information to provide a variety of mobile services related to spatial analysis, data management, decision making, etc. At the other end of the spectrum are the location-based services (LBS), which use the spatial (location) information, geographic information systems (GIS) databases, and wireless communication to provide location-specific, real-time service to mobile clients. These applications use georeferencing techniques similar to mobile mapping; however, the accuracy requirement might not be that stringent. Still, the number of applications is growing, and this trend is only expected to continue, provided that the anticipated emergence of mobile sensors and wireless distributed networks will appear in commercial cars in the next few years (Sobottka *et al.*, 1999). The distributed environment that would support fusion of data from mobile sensors such as in-car positioning and imaging, and data from remote servers, especially image and GIS data, will be able not only to support car navigation and LBS, but also to provide real-time data for emergency response, traffic management, change detection, GIS database update, etc.

An emerging discipline of telegeoinformatics (Krishnamurthy *et al.*, 2000), also referred to as geospatial technology, integrates the theory and applications of geoinformatics, telecommunications, and mobile computing technologies. Geoinformatics, combining GIS, remote sensing, and geolocation techniques, has emerged as a discipline that deals with geospatial information, data, and knowledge and their storage, retrieval, and optimal use for problem solving and decision making. Geoinformatics, supported by wireless communication and mobile Internet, translates to mobile computing, which forms a framework for real-time mobile WebGIS (Xue *et al.*, 2002). The key to successful mobile computing is real-time positioning of mobile users, enabling a number of applications listed earlier. Thus, telegeoinformatics, emerging as the spatial information technology of the future, entails mobile digital imaging (mapping), radiolocation, and recently, mobile computing, as well as WebGIS, to support distributed computing, data mining, data and knowledge retrieval and storage, and decision making in a distributed environment. In the following sections a review of the positioning and tracking and imaging techniques used in mobile mapping and telegeoinformatics, and example applications are discussed. More on mobile GIS, distributed computing, and WebGIS can be found in the section on Automated Data Processing in Mobile Geospatial Technology.

Primary Positioning Techniques in Mobile Mapping and Telegeoinformatics

GPS and Inertial Navigation Systems

Several modern airborne digital sensors that work in a continuous scanning mode (multispectral/hyperspectral scanners), or unconventional (non-optical) imaging sensors, such as lidar or multispectral/hyperspectral scanners, require GPS/INS for direct georeferencing. However, area-based sensors used in land-based mobile applications also use direct georeferencing for obvious economic (processing cost) benefits and to enable real-time operations. The fundamental step of any data integration in a mobile environment is time-space registration, most commonly provided by GPS/INS. GPS and INS are navigation techniques based on entirely different positioning principles–as a radio navigation satellite system, GPS provides essentially geometric information, while autonomous INS offers inertial information, i.e., the reaction to the applied force. Consequently, these techniques offer highly complementary operational characteristics. Inertial navigation provides self-contained and independent means of 3D positioning and orientation with potentially high short-term accuracy. In addition, compared to the conventional GPS output rate, INS provides much higher positioning update rates (e.g., 200 Hz or higher). GPS contributes its high accuracy and stability over time, enabling continuous monitoring of inertial sensor errors. Implementation of closed-loop INS error calibration in a Kalman filter environment allows continuous, on-the-fly error update (and thus INS calibration), leading to increased estimation accuracy. Naturally, the accuracy strongly depends on the type of sensors used, and ranges from meters (early systems) to centimeters (new generation MMS). In general, using a GPS-calibrated, high-to-medium accuracy strapdown inertial system, an attitude accuracy of 10 to 30 arcsec can be achieved (Schwarz and Wei, 1994; Abdullah, 1997; Grejner-Brzezinska, 1997; Grejner-Brzezinska and Phuyal, 1998). It should be mentioned that INS provides a 3D reference frame for all mobile sensors, i.e., imaging and the supplementary navigation/tracking sensors.

An additional sensor, which has the potential to substantially improve mobile positioning performance, especially in urban canyons, is the pseudolite (pseudo-satellite). Pseudolites (PL) are ground-based transmitters, which send a GPS-like signal to support positioning and navigation in situations where the satellite constellation may be insufficient. They are usually located on building rooftops, high poles, or any high location in the vicinity of the survey area, which results in a relatively low elevation angle, as compared to GPS satellites. However, the signal from a low PL can strengthen the geometry of position determination, especially in the height direction. An additional PL signal can also support the process of ambiguity resolution. The GPS pseudolites have been primarily used in precision landing systems such as LAAS (Local Area Augmentation System) (see, for example, Barltrop *et al.* (1996) and Hein *et al.* (1997)) and deformation monitoring (Barnes *et al.*, 2002; Meng *et al.*, 2002). Recently, they have been tested in mobile mapping applications, to support a weak GPS constellation in urban canyons (Wang *et al.*, 2001; Grejner-Brzezinska and Yi, 2002; Yi, 2002; Lee *et al.*, 2002).

To illustrate the effects of using PLs on the positioning accuracy in a mobile environment, Table 2 presents a comparison of the positioning quality between the GPS-only weak constellation (four high satellites) and the same GPS constellation supported by three pseudolite signals at elevation angles ranging from 7° to 13°, located at the corners of the mapped area (Grejner-Brzezinska and Yi, 2003).

TABLE 2. RMS DIFFERENCE IN POSITION, VELOCITY, AND ATTITUDE BETWEEN GPS/INS SOLUTIONS USING FOUR HIGHEST SATELLITES AND THE SAME SATELLITES SUPPORTED BY THREE PSEUDOLITES

RMS Diff.	Mean	RMS	Max	Min	Unit
N	2	3	29	0.1	mm
E	2.6	8	50	−3	mm
Ht	12	28	198	0.3	mm
Vn	0.1	0	0.3	0	mm/s
Ve	0.1	0.1	0.5	−0.1	mm/s
Vd	0.3	0.5	3	0	mm/s
Heading	1	2	10	−0.2	arcsec
Pitch	0	0	0.3	0	arcsec
Roll	0	0	0	0	arcsec

Primary Radiolocation Techniques Based on Wireless Networks

A *radiolocation* technique is the most commonly used approach to finding the mobile user's location, using such parameters as signal angle of arrival, time of arrival, signal strength, and signal multipath signature matching. The time of arrival and the signal strength can be directly converted to the range measurements that are subsequently used to triangulate the user's position. The base (reference) stations in the land-based radiolocation techniques are cellular network service towers. Depending on the actual device that performs the positioning solution, i.e., mobile user or the base station, the positioning solution is either *mobile terminal (user)-centric, network-centric*, or *hybrid*. The *user-centric methods* rely on the positioning software installed in the mobile terminal, while in the *network-centric methods* the user's position is determined by the base station and sent back to the user (Hein *et al.*, 2000; Deitel *et al.*, 2002; Andersson, 2002; McGeough, 2002; SnapTrack, 2002). The primary radiolocation techniques and their accuracies are listed in Tables 3 and 4.

Other Location Techniques Used in Telegeoinformatics

Other positioning and tracking techniques commonly used in telegeoinformatics are ultrasonic, magnetic, and optical tracking (Allen *et al.*, 2001; Livingston, 2002). An *ultrasonic technique* utilizes high frequency sound waves (approximately 20,000 Hz) to locate objects either by triangulation of several transmitters, time-of-flight (TOF) method, or measuring the signal phase difference between the transmitter and the receiver (phase-coherence method). This method is sensitive to a change in distance only; thus, the initial distance to the target must be known. Moreover, the inherent problem of an ultrasonic tracker is signal travel delay due to the slow speed of sound (331 m/s at 0° C) that varies with temperature and pressure. *Magnetic trackers* use magnetic fields, such as low frequency AC fields or pulsed DC fields, to determine 3D location coordinates, attitude, and heading relative to the transmitter. The distance estimation is based on the fact that the magnetic field strength decreases with a third power of distance and with the cosine of the angle between the axis of the receiving coil and the direction of the magnetic field. *Optical tracking systems*, also referred to as image-based systems, make use of light to measure angles (ray direction) that are used to find the position location. The essential parts of an optical system are the target(s) and the detector(s). Detectors can be in the form of CCD-based cameras or video cameras often used in mobile mapping, or infrared cameras, or lateral-effect photodiodes. Targets can be active, such as light-emitting diodes or infrared-emitting diodes, or passive, such as mirrors or other reflective materials, or simply natural objects. Detectors are used to observe targets and to derive position and orientation of a

TABLE 3. RADIOLOCATION TECHNIQUES: SUMMARY OF CHARACTERISTICS

Radiolocation Technique	Major Characteristics
	User-Centric
GPS	Measures range to multiple satellites.
Network Assisted GPS (A-GPS)	Uses an assisting network of GPS receivers that can provide information enabling a significant reduction in the time-to-first-fix (TTFF).
Enhanced Observed Time Difference (E-OTD)	The time differences between the signal arrivals from different base stations are used to determine the user's location with respect to the base stations. According to Andersson (2001), this method can also be used in the *network-centric* mode.
	Network-Centric
Cell Global Identity with Timing Advance (CGI-TA)	Uses the *cell ID* to locate the user within the cell; TA enables the proper alignment of a user transmit time and the time the signal arrives at the base.
Time of Arrival (TOA)	Based on the travel time between the base station and the mobile user.
Uplink Time Difference of Arrival (TDOA)	Similar to E-OTD; however, in TDOA the time of user's signal arrival is measured by the network of base stations.
Angle of Arrival (AOA)	Based on the observation of the angle of signal arrival by at least two cell towers.
Location (Multipath) Pattern Matching	Uses multipath signature in the vicinity of the mobile user to find its location.
Received Signal Strength (RSS)	The method can predict the user's location by merging the information about the actual *RSS* with the existing (mapped) signal data.
Hybrid system, such as A-GPS + CGI	Uses GPS ranging and cell ID with timing advance information.

target from multiple angular observations. Another type of optical tracking system is based on laser ranging, which provides range measurements to active or passive targets, or long-range laser scanning systems, such as lidar. A summary of positioning methods commonly used in MMS and telegeoinformatics is presented in Tables 3 and 4.

Imaging Components in Mobile Applications

Sensor Developments

The primary spatial data acquisition tool for any remote sensing system, including land-based, airborne, or spaceborne platforms, is built from active or passive imaging systems. The three basic categories relevant to MMS are (1) small-format digital camera-based systems, used primarily for land-based applications, such as surveying vehicles; (2) high-resolution medium-format digital camera systems, such as the popular 4K by 4K Kodak CCD-based cameras, used either in stand-alone applications or supporting lidar systems; and (3) high-performance digital imaging sensors for airborne applications, such as the ADS40 scanner from LH Systems and the DMC frame camera from Z/I Imaging. In addition to passive imaging systems, active sensors such as terrestrial laser scanners, airborne lidar and InSAR (interferometric synthetic aperture radar) have gained acceptance and are used in a growing number of applications. In fact, the real question is currently not

TABLE 4. POSITIONING TECHNIQUES USED IN TELEGEOINFORMATICS: SUMMARY OF CHARACTERISTICS

Positioning Technique	Positioning Principle	Positioning Accuracy[1]
Radiolocation:		
GPS + PL	Triangulation, 3D	High (cm-level achievable)
Time-based (TOA, TDOA, E-OTD)	Triangulation, 2D	Moderate-to-high
AOA	Triangulation, 2D	Low-to-moderate
RSS	Triangulation, 2D	Moderate
Multipath pattern	Pattern matching	Moderate
CGI-TA	Cell ID + distance to the base	Low
Hybrid systems	Defined by the contributing techniques	Depends on the contributing techniques
INS	Integration of accelerations, 3D	High-to-Low (errors grow with time)
Acoustic (ultrasonic)	Triangulation, 3D Phase coherence, 3D	High (cm for short distances)
Optical	Triangulation, 3D	High (cm for short distances)
Optical ranging	Distance and orientation measurement supported by GPS/INS, 3D	High (cm to dm)
Magnetic	Triangulation, 3D	High (cm for short distances) Affected by magnetic field distortions

[1]The levels of accuracy correspond to 95% CEP (Circular Error Probable) as follows:
– High level equals to 95% CEP within 50 m
– Moderate level equals to 95% CEP within 300 m
– Low level equals to 95% CEP greater than 300 m (Pietila and Williams, 2002).

how to select an imaging sensor for a target application but how to combine several sensors in an imaging suite to provide an information-rich data source.

Sensor Fusion

Sensor fusion is the foundation of any MMS systems because, at a minimum, it entails the integration of the navigation sensors, described earlier, and the imaging device. The simultaneous use of multiple image sensory data, however, represents the next level of integration, which is the process of efficiently combining various sensor data to arrive at optimal spatial information extraction. Furthermore, the fusion process can be extended by using available past data from digital maps or, in general, a GIS database. There are three main categories of sensor fusion: (1) fusion at the sensor level, e.g., color sharpening; (2) feature-level fusion, e.g., road edges extracted from different cameras combined to form a road network, or the combined classification of multispectral images and range data presented in the section on Classification in Urban Areas; and (3) decision-making-level fusion, e.g., buildings extracted from various sensors compared to the existing GIS data. Sensor-level fusion, also called pixel-level fusion, has gained widespread acceptance in the last decade, and most of the research is currently focused on feature-level fusion. The best example is the fusion of airborne imagery with lidar, i.e., the integration of reduced dimensionality intensity data with direct range observations.

An extensive discussion of data fusion in the context of MMS is beyond the scope of this paper; thus, only a few trend-setting examples are discussed below. Because direct orientation is the heart of MMS technology, an aspect critical to achieving high performance is the quality and the in-mission stability of the calibration. The calibration term used here refers to both individual sensor calibration and the inter-calibration of the sensors. It is important to note that the error characteristic of direct orientation systems is different from that of a conventional control point-based orientation, and due to the extrapolation nature of the direct technique, the navigation accuracy requirements are consequently high. Modern research suggests that the system calibration and the feature extraction process, the ultimate goal of using MMS, are closely connected, and therefore these two tasks should be handled together. In the following, two examples will be considered. First, the boresight misalignment process is discussed for land-based and airborne systems for optical imagery, followed by lidar boresight calibration. Second, an early implementation of real-time processing of a land-based MMS will be discussed, where the fusion of navigation data provides on-the-fly support to speed up image processing and thus makes the extraction of features possible simultaneously with image capture.

Boresight Calibration of Imaging Sensors

Boresight calibration, defining the transformation between the georeferencing sensors (GPS/INS) and the imaging sensors, is a crucial component of a multisensor system calibration, especially for high-accuracy airborne mapping applications. The critical components are the rotational offsets, because any angular inaccuracy, unlike a linear offset, is amplified by the object distance and has a significant impact on the photogrammetric data quality. For regular imagery, the boresight transformation is most commonly resolved by comparing the GPS/INS positioning/orientation results with an independent AT solution (see the example below), or as a part of a bundle adjustment with constraints (see, for example, El-Sheimy *et al.* (1995)). Consequently, the quality of the boresight estimation is limited by the quality of the AT adjustment and by the quality of the direct orientation components that are used in the boresight estimation process. Therefore, the availability of a high quality test range with very well signalized points

TABLE 5. BORESIGHT TRANSFORMATION ESTIMATION

Offset in IMU Body Frame [m]		RMS [m]	Misalignment Angles [deg]		RMS [deg]
X	−1.007	0.0044	ω	2.2817	0.4054
Y	0.046	0.0280	φ	11.2003	0.1274
Z	0.450	0.0090	κ	87.7725	0.0388

for AT, which should be used for the calibration process, becomes an important issue.

An example of boresight transformation estimation, including the quality assessment for a land-based system, is presented in Tables 5 and 6. The boresight estimates in Table 5 were obtained as angular and linear differences between the AT and GPS/INS solutions. A ground-based test range, with coordinates surveyed by differential GPS (accuracy of 1 to 2 cm one sigma), was used for the AT. The camera used was a Pulnix TMC-6700, based on a 644 by 482 CCD, with the effective pixel size on the ground of 4.1 mm at nadir, at an object distance of about 3 m. These transformation parameters were used in combination with DPO parameters, to check an independent set of control points, as shown in Table 6. Even though the boresight angle accuracy does not seem to be very high (due primarily to the low optical resolving power of the camera), the stereo measurements provide very good results; it is because the imaging sensor in this MMS is a down-looking camera, resulting in a rather short object distance. Another approach to boresight estimation is to perform a high-accuracy measurement of the boresight linear offsets, because the INS and the imaging sensor are usually rigidly connected, and to estimate the boresight angles as a difference between GPS/INS and AT solutions. Accuracy tests indicate that linear offsets can be measured with mm-level accuracy, and the final estimation of angular components is only limited by the accuracy of GPS/INS and AT. With a high-resolution aerial camera (such as RC30, RMK-TOP, or LMK 2000) and a quality AT (based on sufficiently strong geometry), good quality imagery with precise measurements, and high-accuracy GPS/INS results (1 to 2 cm in horizontal, 2 to 3 cm in vertical), an accuracy of boresight angles of 20 to 30 arcsec is feasible. For example, the errors in boresight angles of 20 to 60 arcsec and 2 cm in offsets translate to about a 2 to 5-cm error (per coordinate) on the ground for a 300-m object distance, which results in accuracies of 2 to 5 cm in horizontal directions, and 3 to 8 cm in vertical directions. The analysis of the impact of boresight angle errors on ground coordinates is presented in more detail in Grejner-Brzezinska (2001b).

TABLE 6. DIFFERENCE BETWEEN THE SURVEYED CHECKPOINTS AND THEIR COORDINATES DERIVED FROM DIRECTLY ORIENTED IMAGERY

	Coordinate Difference [m]		
Model Check Points	N	E	h
461			
12_1	−0.007	−0.001	−0.007
12_2	0.024	−0.017	−0.061
3	0.012	−0.001	−0.067
4	0.006	0.001	−0.049
462			
0	0.014	0.029	−0.121
12	0.024	0.009	−0.040
4	0.003	−0.020	−0.085
45			
12	−0.014	0.028	−0.044
4	−0.008	−0.010	−0.028
3	0.015	−0.015	−0.094
0	0.010	−0.034	−0.043

Lidar boresight calibration is a crucial component of any laser scanning system, primarily due to the fact that lidar systems are rather complex, and include at least three main sensors, GPS, INS, and a laser-scanning device (Figure 1 illustrates a common sensor configuration of airborne lidar systems). The laser system offers a few-cm accuracy in measuring the distances from the sensor to the ground surface. If the laser beam orientation and the position of the laser scanner are known, the coordinates of the ground reflection point can be calculated based on the travel distance (time) of the laser pulse. Because lidar relies entirely on direct orientation, any GPS/INS positioning errors or misalignment between the laser and the navigation systems will translate to an error in the measured surface point coordinates. In general, the lack of feedback in the data flow in lidar systems (no redundancy) makes the whole system more vulnerable to systematic errors that may seriously affect the quality of the lidar data (Toth *et al.*, 2002).

Boresight misalignment of lidar systems is more difficult to determine than that of an aerial camera because there is no easy connection between the measured surface coordinates and the actual objects, which reflect back the laser pulse. Consequently, the use of any ground control (not only points) is difficult, as compared to the signalized targets that are widely used in aerial imagery. Therefore, differential boresight methods are frequently considered. For example, a technique proposed by Toth *et al.* (2002) and Toth (2002) is independent from ground control and is based on the overlapping lidar strips flown in different directions, collected over an unknown surface (ground truth information can also be incorporated, if available). To achieve the ultimate accuracy, precise navigation data (GPS/INS) are required. The approximate values of the three rotation angles between the INS and the laser frames are known from the mechanical alignment. The remaining difference (misalignment) between the nominal and actual angles must be determined based on the horizontal and vertical discrepancies between the overlapping lidar strips. Generally, more reliable results can be obtained if more strips are used. Also, the surface differences must be observed in specifically selected areas, where the discrepancies are mostly pronounced. For example, surface patches closer to the borders of the overlapping area, similar to the Gruber point distribution in stereo photogrammetry, are very suitable. It should be pointed out that comparing different surfaces, formed by randomly scattered points, is a non-trivial task, and the effectiveness of this process depends on the lidar point density and on the overall terrain characteristics of the overlapping area. In the typical solution, a random point distribution is interpolated into a regular grid, allowing for the surface discrepancies to be found relatively easily by surface matching of the selected regions or profile matching of the man-made objects, etc. Once the surface discrepancies have been determined, a least-squares adjustment, parameterised with the unknown misalignment angles, is performed with the surface differences as observations. Based on the observed differences (in 3D), the misalignment angles are iteratively adjusted to reduce the surface discrepancies in object space. Details of the procedure can be found in Toth *et al.* (2002).

Automated Data Processing in Mobile Geospatial Technology

Automatic Feature Extraction from Mobile Mapping Data: Transition to Real-Time Image Processing

The implementation of real-time processing requires a lot of computing power, including fast data transfer, sizeable memory, and rapid CPU time. Therefore, land-based MMS is more appropriate for initial implementation of real-time processing, because the volume of data is substantially less than that of the airborne case. Although images are taken more frequently, the

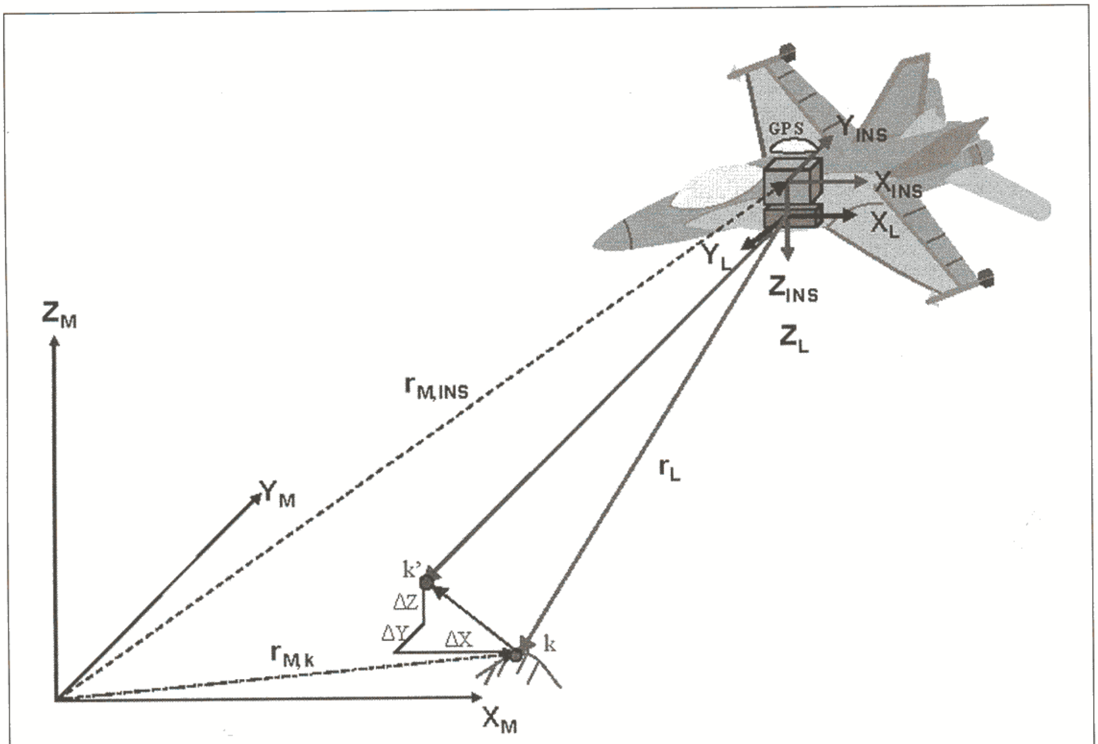


Figure 1. Lidar system sensor configuration: XYZ_L is the lidar reference frame, XYZ_{INS} is the INS body frame, and XYZ_M is the local mapping frame; ΔX, ΔY, ΔZ denote errors on the ground due to the boresight misalignment.

image resolution is small and the object complexity is less severe compared to the aerial case. There are several advantages of using mobile mapping technology in highway applications. Because it employs dynamic data acquisition, mobile mapping technology can be directly used in highway-related applications such as traffic sign inventory, monitoring of speed limits and parking violations, and generation of road network databases. When laser technology is jointly applied, road surface condition inspection can also be performed. As long as traffic velocity is no less than approximately 70 km per hour (45 mph), data can be acquired without disturbing the traffic flow. In addition, a single data collection mission provides diverse information for multiple purposes. Moreover, because data can be both collected and processed in a short time period, frequent repetition of road surveys and updating of databases are feasible.

Automatic and semiautomatic methods have been researched for the extraction of road and highway features such as road centerlines and road signs, traffic lights, and road curb lines. Once extracted, these objects can be automatically loaded into spatial databases. In order to extract a road centerline, an image sequence of the road is needed where each image pair supplies one segment of the centerline. Using land-based MMS imagery, successive road segments are measured and then combined to produce the entire road centerline. The centerline features are automatically enhanced and extracted from each image sequence. Corresponding 3D centerline segments are then generated in object space (He and Novak, 1992). A different approach defines a 3D centerline in object space as a physical Snake Model (Tao *et al.*, 1996; Tao *et al.*, 1998). The Snake Model is optimized to adjust the centerline shape using image features of the centerline as internal constraints, and using geometric conditions derived from other sensors of the system (GPS and INS) as the external constraints. Habib *et al.* (1999) presented an algorithm for automatic extraction of road signs from color imagery using feature detection, hypothesis generation, and verification techniques. Tu and Li (2002) proposed a framework for automatic recognition of spatial features from mobile mapping imagery based on the view-dependent method along with hypothesis test techniques, and they have demonstrated its application in the recognition of traffic lights. Road curb lines (as opposed to painted centerlines) are projected onto the images based on their geometric shapes and material types. Consequently, curb lines can be more difficult to automatically extract and identify. Currently, curb line databases are built using semiautomatic or manual approaches.

A state-of-the-art MMS, recently developed at The Ohio State University, is dedicated to real-time centerline mapping using a single down-looking digital camera (Pulnix TMC-6700, based on 644 by 482 CCD, with an image acquisition rate of up to 30 Hz), oriented by a high-accuracy tightly coupled GPS/INS system. The main goal of the image processing is to determine the centerline image coordinates in real time, so that only the automatically extracted polyline, representing the center/edge lines, would be stored, without a need to store the entire image sequence. In particular, linear features can be extracted from the imagery on-the-fly, using real-time navigation information used to form stereo-pairs. Thus, for the real-time part of the image processing, only relative orientation (RO) is important, while the final processing can be done in a post-mission mode, when the precise navigation data are available. Because this system uses a down-looking camera with an image sensor plane almost parallel to the road surface, the image scale changes are negligible; thus, an almost constant scale along the vehicle trajectory can be maintained. Moreover, the object contents of the images are rather simple and predictable, such as the line marks, surface texture variations, cracks, potholes, skid marks, etc. Consequently, extracting features from a predefined set of objects, assuming almost constant image scale, represents a less challenging scenario, as compared to the generic MMS paradigm, where scale variations (and the richness of features) pose serious difficulty for any automated feature extraction task.

Stereovision in the centerline mapping system is realized by the platform motion, which, in turn, emphasizes the need for high-precision sensor orientation provided by direct georeferencing. In essence, real-time image processing is technically feasible due to a simple sensor geometry and limited complexity of the imagery collected (images of the pavement with about 50 percent overlap, where only linear features are of interest). Feature points are extracted around the centerline area, and are subsequently used for image matching. Note that the availability of the relative orientation between the consecutive images considerably decreases the search time for conjugate entities in the image pair, because the usually 2D search space can be theoretically reduced to one dimension, the epipolar lines. However, errors in orientation data introduce some uncertainty in the location of the epipolar line, stretching it to an epipolar band, whose width depends on the accuracy of EO parameters. An example of the image processing sequence is presented in Figure 2. In the standard image processing, the following steps are included: RGB to S transformation, median filter and binary conversion (thresholding), centerline boundary point extraction, all based on a single image, and, subsequently, feature matching, affine transformation, and centerline strip formation, performed in stereo (Toth and Grejner-Brzezinska, 2001).

Another major use of mobile mapping technology lies in the field of facility mapping. For example, high-voltage power transmission lines can be surveyed by airborne lidar and photographed by a mobile mapping system, and their position can then be measured using the resulting image sequences. A number of important parameters can be calculated from the resulting data, including positions of poles and towers. In addition, positions of insulators at ends of suspending transmission line segments can be located, as well as the lowest point of each suspending line segment. To this purpose, Li *et al.* (1999) presented a method based on Hopfield neural networks for utility object detection and location. In particular, it demonstrated its applicability in mapping of streetlight poles from mobile mapping image sequences.

Current Trends in Mobile Technology Development

Recent advances in direct georeferencing, imaging sensor technology, increasingly enhanced computing power, and easy access to relatively inexpensive telecommunication services have dramatically affected the trends in modern mobile mapping system developments. Building a cost-effective MMS by integrating off-the-shelf hardware and software components is becoming a reality. Cost-effective, high-quality CCD cameras, commercially available GPS/INS systems, and new map matching algorithms contributed substantially to the increasingly low development costs for systems that do not target at the top level of accuracy. More new sensor types have been added to the mobile mapping sensor family, including lidar, short-range laser for road surface inspection, and multi- and hyper-spectral sensors. One example of a high-end mobile mapping system is the mapping and vision systems on board rovers in the 1997 Mars Pathfinder Mission and the 2003 Mars Exploration Rover mission (Li *et al.*, 2002). The new development of real-time mapping and easy access to wireless communication provide mobile mapping technology with an opportunity to expand its uses to many areas which were not traditionally "mapping" business, for example, inventory and maintenance of highway, buildings, and communication facilities; mobile environmental monitoring; emergency management; and location-based services.

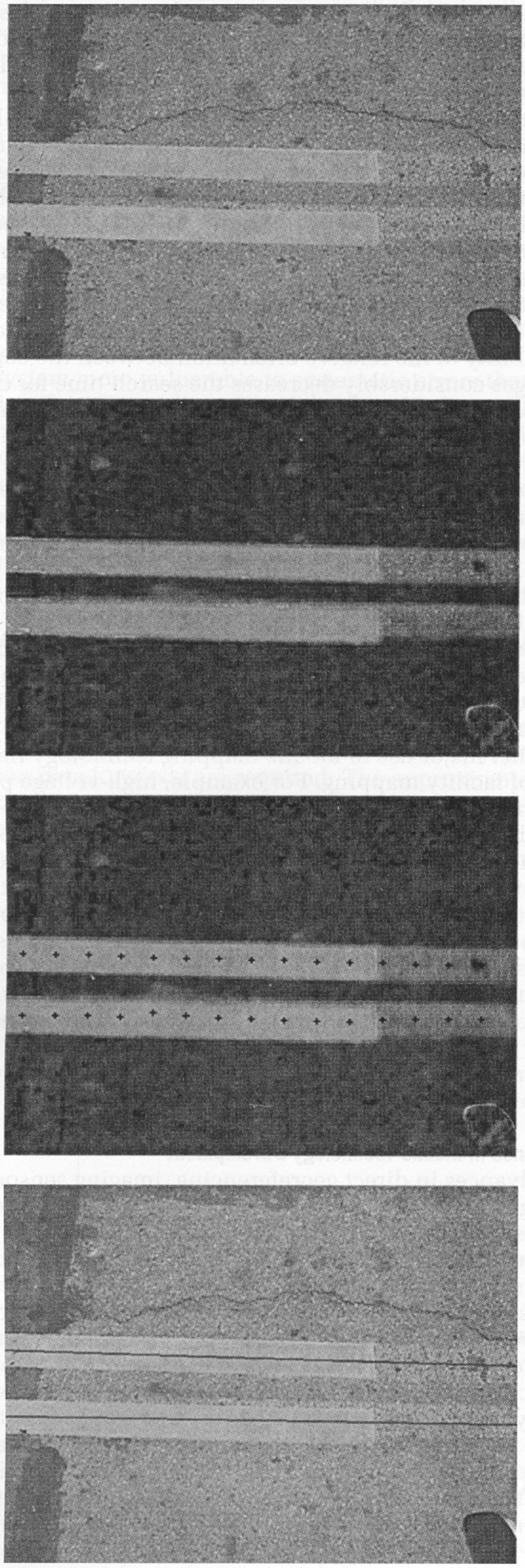


Figure 2. Image sequence processing in real-time.

Mobile Geospatial Technology

Compared with traditional GIS, mobile geospatial technology, also referred to as telegeoinformatics (defined earlier), has two unique components: (1) mobile computing and communication devices, such as PDA (Personal Digital Assistants) and wireless communication, which make the mobile unit capable of being a client or possibly a sever in a large system based on an Internet or wireless network; and (2) location sensors or spatial databases that support services where geospatial information is required.

The wireless communication-accessed information is available in one of the following forms: Wireless Application Protocols (WAP), General Packet Radio Service (GPRS), and I-Mode. Using specialized wireless services (such as GoAmerica) or a wireless modem, PDA users can access the content through the Internet with a Windows CE-based Internet Explorer or other WAP-capable browsers. Mobile geospatial applications can deliver mapping output in a number of different formats, including text, imagery, voice, and video. Geospatial information from Internet servers can be requested using the wireless application protocol-based WML (Wireless Mark-up Language). Because of the current limitation of the technologies involved, the resulting map may not cover the complete project area, but is sufficient for supporting the field operation at a specific location. The interactions between the mobile unit and the server(s) keep this information transition alive and the needed geospatial information updated dynamically.

Componentization is a new trend in Internet GIS that may have an influence on mobile geospatial technology (Yuan, 2000). With the adoption of distributed component technology, it is possible to interact with heterogeneous systems without constraints of traditional client/server relationships (Montgomery, 1997). Under such a distributed architecture, there is no difference between a client and a server. Every GIS component can act as a client or a server based on an individual task. A client is then defined as a unit requesting the service, and the server as a machine that provides the service. This architecture allows for dynamic linkages between the data and the software. Three advanced network technologies support distributed computing environments. They are exemplified by the Common Object Request Broker Architecture (CORBA), the Distributed Component Object Model (DCOM), and the Remote Method Invocation (RMI) (Tsou and Buttenfield, 2002).

Location-based services (LBS) are emerging as one of the major applications of mobile geospatial technology. The very basic services provided by LBS include (Leonhardt *et al.*, 1996)

- Finding the location of a target of interest, and
- Finding the locations of all the targets of interest from a certain location.

Dao *et al.* (2002) reviewed the development of LBS based on its background, mobile wireless communication standards, positioning techniques, spatial data management, and mobile system components. Technical and operational issues were also discussed, including interoperability and privacy protection. LBS will support a wide range of applications where the geospatial information is needed in a dynamic way, for example, for emergency management, fleet monitoring and vehicle dispatching, disaster management, crime fighting, and construction site management.

Mobile geospatial technology and LBS are in their early stages of development. Some restrictions include a limited number of service providers offering wireless data transfer services, a limited area of visual display (e.g., PDA), and limited wireless bandwidth that affects the speed of data transfer. The current transfer speed through the CDMA (Code Division Multiple Access) WAP wireless technique is about 9.6 kbps. The speed of the GPRS WAP technique is about 53.6 kbps. These transfer speeds would be unacceptable for use in transferring large geospatial data sets. An improved transfer speed is expected when the third-generation (3G) communication systems are introduced in the next few years.

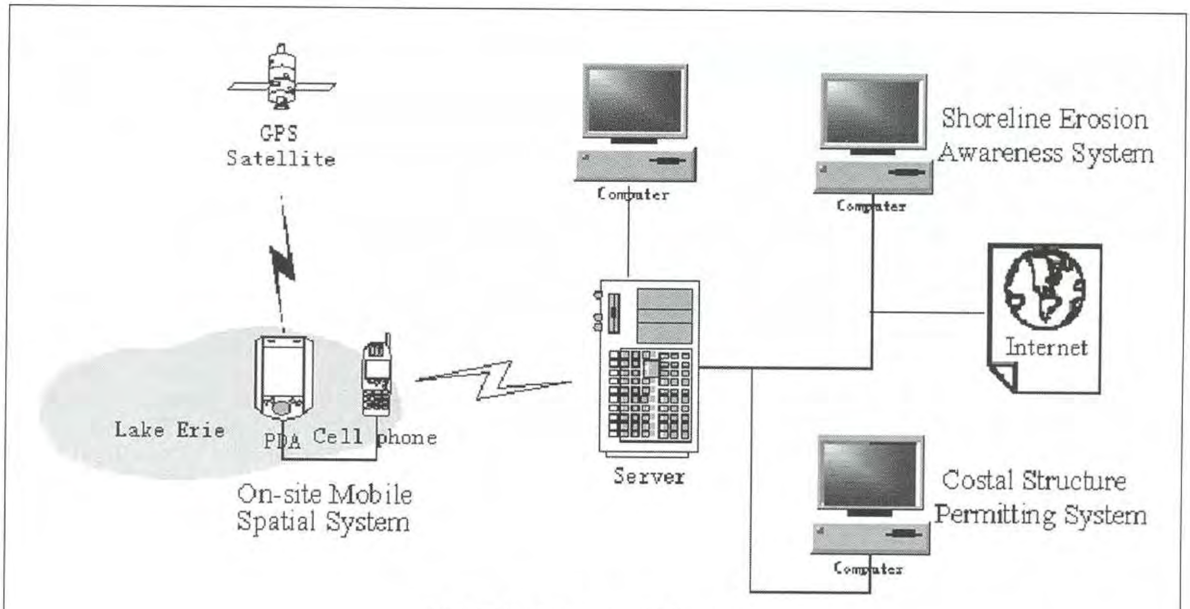


Figure 3. System architecture.

It should be mentioned that, despite the obvious advantages of geospatial technology, the current architecture of storing and analyzing geospatial data has some drawbacks related to the network computing resources. Many mobile geospatial applications are implemented based on the network-centric client/server GIS architecture, in which many clients are linked to an application server that contains application logic and connections to a centralized database. Because the server does most of the computing processes, the application is based on a thin-client architecture. Client-side components, including databases and functions, are separated from the server-side, and they are not interchangeable. GIS software market leaders are expected to develop GIS-specific software and system architecture that will address the above issues (Tsou and Buttenfield, 2002).

Applications of Mobile Geospatial Technology

Applications of mobile geospatial technology can be found in the many areas listed earlier. We introduce an example of an application prototype system developed at The Ohio State University for coastal field inspection and decision making.

The system architecture consists of three components: an on-site mobile geospatial subsystem, a coastal structure permitting subsystem, and a shoreline erosion awareness subsystem (Figure 3). ESRI® ArcSDE is used to manage the spatial database on the server (Figure 4). On the client side, three subsystems are connected to the spatial database. We focus on the on-site mobile spatial subsystem, while the other two subsystems are described in Li *et al.* (2003). A customized ArcIMS-based web page is designed with Active Server Page (ASP) and VB Scripts. Through the ActiveX connector, it communicates with an ArcIMS image service that is established on the server. A PDA (Compaq® iPaq 3850 Pocket PC) is used as a mobile client. It connects to the server through the wireless Internet with a cell phone (Motorola® Star TAC 7860). The user can submit a request to the server through a designed web page. When the server receives a request, it processes the data and transfers the result back to the client. A portable GPS

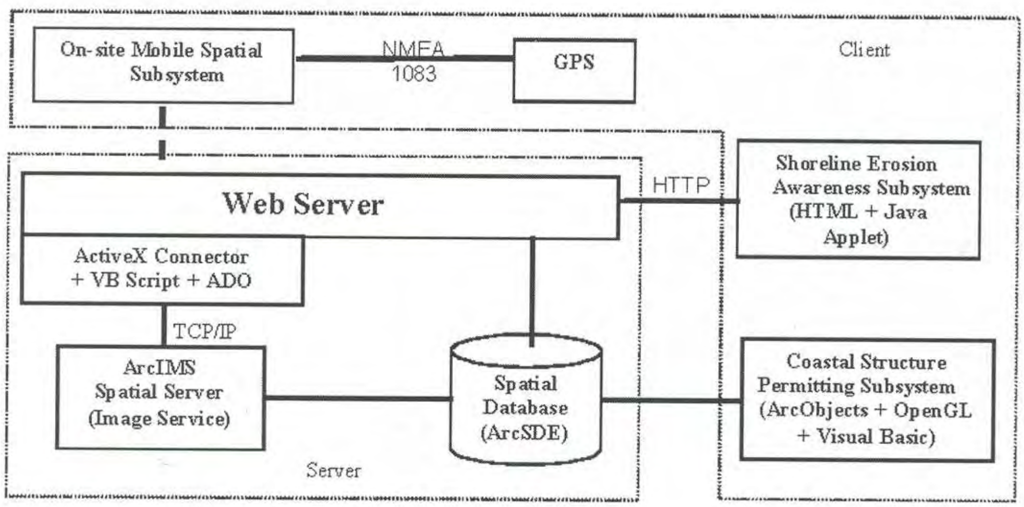


Figure 4. System design diagram.

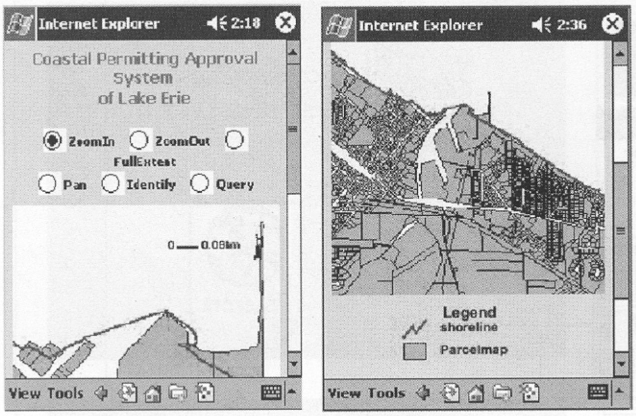


Figure 5. Interface of the Mobile Geospatial Subsystem.

device (Pharos® Portable GPS) is connected with the PDA to provide the location information, which can be used to locate the user's position and update the database through the PDA.

Figure 5 shows the web interface of the mobile geospatial subsystem on the PDA, implemented using ArcIMS, ActiveX objects, and VB scripts. It provides simple map browsing functions, such as zoom in, zoom out, and pan, and various query functions. The data used in the subsystem include parcel maps in Erie County, Ohio, a digital T-Sheet shoreline, and a coastal structure information table. The coastal structure information table stores information related to coastal structures, including parcel numbers, application numbers, center location of the parcels, sizes and materials of the structures, and others. These data are saved in a Window 2000 server in the GIS and Mapping Laboratory at The Ohio State University. The experiment was carried out along the Lake Erie shore in Erie County, Ohio, in early July 2002. The GPS signal was first received for the spatial coordinates of the parcel in the field, which were found to be (370654, 4583966) in the UTM coordinate system. The PDA was connected to the server through a wireless network. The coordinates were then transferred to the query interface (Figure 6a) and submitted to the server with a request for parcel and structure information. The server located the parcel containing the given coordinates and transferred a parcel map surrounding the location (Figure 6b), along with information about the coastal structure (Figure 6c), to the PDA. Such interactions between the client in the field and the server at a processing center supported by the overall system provide a powerful tool for coastal engineers to inspect the field environment of a proposed or existing coastal structure, and to make appropriate decisions in the coastal structure permitting and maintenance processes.

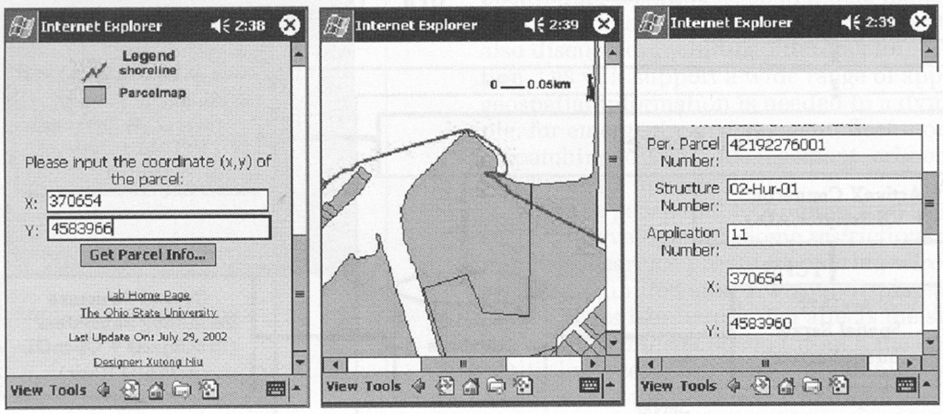
Thematic Mapping and 3D City Models

Location-based services, defined earlier, serve mobile users by integrating features such as accurate positioning, location-dependent processing, and transmission of spatial data via wireless networks. The growing number of LBS results in the increasing requirements for the applied GIS databases. In a typical application, such as car navigation, the standard 2D map-like representations can, for example, be upgraded to a 3D visualizations of the environment. This allows for a more realistic and intuitive presentation of routing information, especially in complex urban areas (Rakkolainen and Vainio, 2001). Another example is the overlay of computer graphics and objects from the user's environment. In the context of location-based services, this application of augmented reality (AR) allows for more intuitive perception and access to the object-related information.

All of these applications require the availability of a detailed and up-to-date 3D database, especially in urban environments. In order to fulfill these needs, tools allowing for an efficient data collection and thematic mapping of urban areas have to be provided. The following examples of the classification of urban areas and the collection of 3D city models demonstrate the advantages of multi-sensor airborne mapping systems for these purposes. With this approach, the degree of automation is increased by the combination of complementary data like multispectral images, DSM (digital surface model) from lidar data, and the existing GIS databases. In addition to spatial data acquisition, mobile mapping techniques (positioning, sensor orientation) can also be applied in LBS. This concept is demonstrated in the subsection on Model to Image Mapping by an integrated approach to the automatic co-registration of terrestrial images to a 3D GIS database. This co-registration can, for example, be used to overlay object-related information to terrestrial outdoor scenes.

Classification in Urban Areas

While human operators can easily extract topographic objects like buildings, streets, and trees from airborne or high-resolution spaceborne imagery, the fully automatic interpretation of complex urban areas has so far remained an unsolved



(a) (b) (c)

Figure 6. Query Example of the Mobile Geospatial Subsystem.

task. Traditionally, thematic mapping is realized by the application of classification techniques. By these means, surface material information is extracted based on the analysis of multispectral imagery. In the past, multispectral classification was restricted to space-borne data with a ground sampling distance of several meters. This situation has changed dramatically due to the availability of digital airborne cameras, as indicated in the section on Imaging Components in Mobile Applications. Currently, multispectral imagery is available at high geometric resolutions. However, the potential of standard classification to enable large-scale mapping of complex urban scenes is limited. One problem, while discriminating different object categories, is the similar reflectance of streets and buildings. Frequently, the same holds true for the distinction of trees and grass-covered areas. Nevertheless, the accuracy and reliability of data collection in urban areas can be improved considerably, if height data are available, because trees and buildings are taller than their surroundings, whereas streets and grass-covered areas are at the terrain level. Thus, local height information allows for improving discrimination and avoiding misclassification, especially in urban areas (Haala and Brenner, 1999; Hoffmann *et al.*, 2000). Based on dense DSMs, which can be provided by lidar, the terrain surface can be derived approximately by applying mathematical grey-scale morphology. This process eliminates all local maxima in height of a predefined size. The resulting DTM is then subtracted from the original DSM in order to calculate the so-called normalized DSM. The normalized DSM then represents all objects above the terrain, approximately located on a plane. In order to integrate this local height with the multispectral information, a standard classification algorithm is applied. In this step, the normalized DSM is used as an additional channel during classification of the spectral data.

The improvement in classification results is illustrated in Figure 7. Figure 7a depicts the classification result based on the spectral channels green, red, and near infrared, as they are provided from a color-infrared aerial image. Figure 7b shows the result when the normalized DSM is included. The benefits of combining optical sensors and lidar measurement for thematic mapping in urban areas are clearly visible.

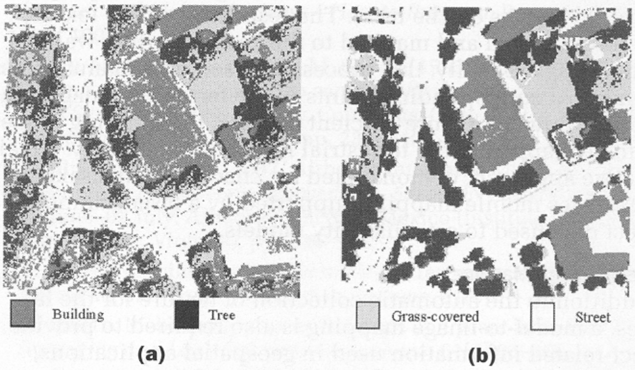


Figure 7. Improvement of classification results by integrating multispectral imagery and lidar data. (a) Channels: green, red, near infrared. (b) Channels: green, red, near infrared, normalized DSM. (Color version at www.asprs.org.)

Collection of 3D City Models

In addition to standard 2D databases, the implementation of location-based services frequently requires 3D geospatial data sets. One example is personal navigation, which is facilitated by 3D visualizations and presentations in complex urban environments based on virtual 3D city models. Additionally, virtual city models are also required for architecture and town planning. Up to now, the growing number of applications resulted in great efforts in the development of tools for automatic and semiautomatic data collection (Baltsavis *et al.*, 2001). Still, the reliable, fully automatic extraction of buildings in densely built-up areas has not yet been demonstrated. Due to the problems in automatic data collection from aerial images, especially in dense urban areas, high-resolution DSM from lidar measurement have instead been applied (Maas and Vosselman, 1999; Rottensteiner and Briese, 2002). This allows for a simplification of the automatic 3D building reconstruction, because the data to be interpreted are already restricted to the required information on surface geometry. If the lidar data are in addition, combined with the given 2D ground plans, an area covering automatic 3D building reconstruction is feasible (Brenner and Haala, 2001). These ground plans, which are frequently available from existing GIS and/or mobile mapping, are very important because they contain structural information. This, however, is implicit information and, in order to use it efficiently, the ground plan must be subdivided into predefined primitives. In this way, the reconstruction of complex buildings can be decomposed into a collection of simple 3D primitives. This approach is based on the assumption that almost all buildings can be modeled using a small number of building primitives. Even if primitives based only on rectangular ground shapes are applied, the majority of buildings can still be modeled. In the first step, the ground plan is subdivided into rectangles, which define footprints of the corresponding 3D primitives to be subsequently reconstructed. In order to determine the unknown parameters, namely, roof type (e.g., flat saddleback or hipped) and slope, as well as the height of the building primitive, a least-squares estimation is applied. Thus, the best fit of the single primitives to the given DSM provided by lidar measurement is computed. After this step, the individually reconstructed primitives are represented by overlapping 3D solids, which are merged to obtain a boundary representation of the building.

Figure 8 shows a 3D city model for a part of Lindau, Germany, generated by this algorithm. In this example, the geometry of the buildings is provided from lidar data and the given ground plans. To enable realistic visualization, image texture is also mapped to the reconstructed object surfaces. Based on ortho images, which are provided from airborne imagery, this texture mapping can be realized easily for the terrain surface and the roofs of the buildings. However, this is

Figure 8. 3D city model reconstructed from lidar data.

not feasible for the facades of the buildings. For this purpose terrestrial images can be used. The respective image texture must be extracted and mapped to the corresponding walls of the buildings. Usually, this process is based on a manual measurement of corresponding points in the terrestrial images. In order to allow for a more efficient process, the building model has to be mapped to the terrestrial image automatically. An alternative approach, demonstrated by Zhao and Shibasaki (2001), uses mobile mapping supported by a laser scanner to collect data used to establish city models.

Model-to-Image Mapping

In addition to the automatic collection of texture for the facades, a model-to-image mapping is also required to provide object-related information used in geospatial applications, such as LBS. For this purpose, an image of the user's environment can be augmented by computer graphics, such as the wire-frame forms of the actual objects, e.g., buildings. The computer graphics, enriched by supplementary information, are generated based on a 3D model of the surrounding area and are then projected to a real image of the user's environment. This approach can be used, for example, to overlay historic views in tourist information systems (Vlahakis *et al.*, 2002), or to present features hidden behind the building facades, such as the location of rooms or power lines during rescue operations. In addition, after the mapping step, spatial queries on thematic information, such as the name and the function of buildings, can be created by pointing to the corresponding image sections, and made accessible via an integrated wireless access to the Internet (Höllerer *et al.*, 2001).

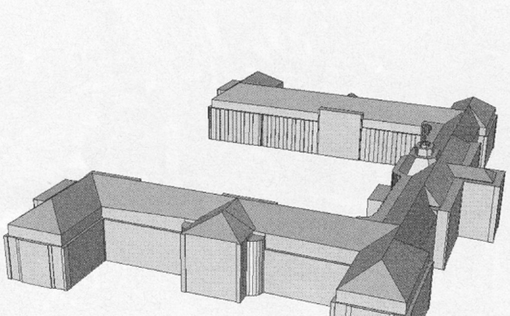
If the captured image is georeferenced precisely, the virtual model of the user's environment can be directly mapped to the image and a correct overlay of the computer graphics to the image is guaranteed. Whereas this accuracy is feasible if GPS/INS integrated technology is applied, the provision of LBS usually requires less expensive hardware solutions. As an option, low-cost, less accurate sensors can be used, if the georeferencing is refined by an integrated approach for the orientation of urban scenes (Haala *et al.*, 2002). An example of this approach is given in Figures 9a and 9b. The image is captured by a standard digital camera, and integrated in a hand-held device based on DGPS (differential GPS), which measures the camera position within an accuracy of several meters. In addition, a digital compass and a tilt sensor provide the camera orientation with an accuracy of 3° to 6°. Based on this EO, the building model (Figure 9a) can be projected to the image. Due to the errors in georeferencing, the projected building model, which is represented by the white outline (Figure 9b), does not fit the image. Thus, the silhouette must be mapped to the image by using, for example, a Generalized Hough-Transform, to allow for a correct overlay of the wire-frame of the building to the image. Next, the image texture can be mapped automatically to the corresponding parts of the facade. More importantly, the refined exterior orientation allows the spatial model of the user's environment to be precisely mapped to the image. After this step, access to the object-related information can be realized by pointing to respective regions of interest directly on the image display (telepointing).

This example demonstrates the integration of the imaging sensors with direct georeferencing, the concept that originates in mobile mapping technology, and the existing GIS data to facilitate real-time geospatial applications—an approach which will become of increasing importance in telegeoinformatics.

Summary and Conclusions

In this paper, an overview of the mobile mapping technology and its evolution over the past decade was presented. We discussed sensor technology and relevant algorithmic solutions that contributed to the success and expansion of this technology. Several examples of mobile applications were also presented. Some examples of state-of-the-art mobile technology and applications presented here illustrate well the power of multisensor systems as important mapping/GIS tools, enabling the much-desired automation of photogrammetric data collection and interpretation. The aspect of real-time mobile mapping/mobile computing, based on GPS/INS, automatic image processing, and telecommunication networks, was indicated as the newest trends in MMS technology, linking towards modern telegeoinformatics. Although some tasks related to calibration and image data processing can be done automatically, in many cases a human operator is still needed. Thus, more research in the area of automatic interpretation and image data fusion are expected in the near future. Still, it is fair to expect that these challenging topics may not be resolved in the next decade or two. On the other hand, the advances in mobile GIS and telegeoinformatics indicate that location-based computing and location-based services may shortly become a widespread reality.

In summary, mobile mapping technology, initiated over a decade ago, has substantially evolved to a level of sophistication and automation not viable at its outset. Proliferation of navigation and image sensor technology, state-of-the-art computing power, and easy access to relatively inexpensive


(a)

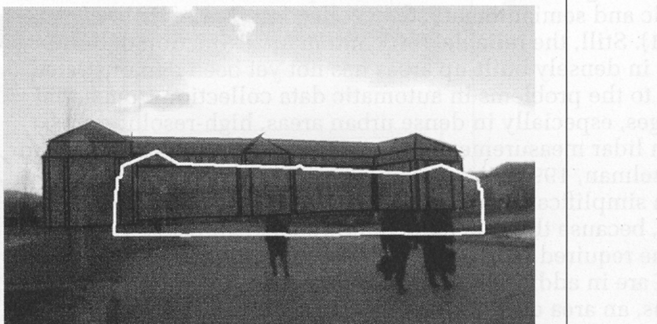

(b)

Figure 9. (a) 3D building model. (b) Automatic model-to-image mapping.

wireless telecommunication services totally redefined the early paradigm of mobile mapping, shifting it towards more automation, real-time operation, and extended sensor suites that meet the requirements of various applications and environments, very different from traditional mapping. Telegeoinformatics evolved from mobile mapping technology, and, by adopting mobile computing and wireless communication, it widened its scope and became de facto a framework for mobile geospatial applications. On the other hand, these applications, such as car navigation or LBS, require 2D and often 3D GIS databases and digital maps provided by mobile mapping. Clearly, these technologies interact closely, and the boundary between them is flexible. Thus, its current level of advances and still expected improvements in sensor and data processing technologies, as well as the extending market, can only indicate that mobile mapping in its continually evolving form is, indeed, a technology of the future.

Acknowledgments

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