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Small and Low-Cost Mobile Mapping Systems**

1. Introduction

The increasing demand for large amounts of geo-spatial data causes the scientist and manufacturers to develop more efficient approaches to their collection. In the last 20 years the considerable progress in performance of passive and active sensors capable of capturing data for large areas was observed. The various multi-sensor systems able to acquire data not only from airborne but also from terrestrial mobile platforms are being investigated and implemented by manufacturers. These systems consist of at least one mapping sensor like digital camera, laser scanner or radar (SAR) and also other, mentioned further, supplementary geo-referencing devices. The mobility of such systems allows rapid data capturing but on the other hand is the source of problems with correct data geo-referencing. To solve such problems, the mapping sensors are integrated with geo-referencing devices. Systems providing mobile, direct-geo-referenced data acquisition are called mobile mapping systems (MMS).

The first applications of direct geo-referencing in land applications were reported since early nineties. The subsequent rapid development of geo-referencing methods was possible owning to increasing capabilities of GPS system. In 1993 the initial operational capability (IOC) of GPS was announced, and the civilian use of the system became free of charge. In 1995 the 24th satellite completed the GPS constellation and the full operational capability (FOC) was announced. Till the year 2000 the accuracy of autonomous solution improved form 100 m to 20 m level. The accuracies of differential solutions reached the sub centimeter level for survey, dual frequency sets. The prices, size and weight of receivers has dropped down making the construction of small, low-cost mobile mapping systems easier.

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** This work was realized within the chair's research project no. 11.11.150.949

The progress of another group of geo-referencing devices, namely IMUs (Inertial Measurement Units), which are now widely used in many mobile mapping applications, was of a different kind [16]. The high-accuracy gyros and accelerometers were developed much before 1990. The navigation-grade IMUs used in early nineties, based mainly on laser ring gyros, were however hardly ever used due to their extremely high prices often exceeding 150 000 $. The high weight of such IMUs was an additional disadvantage. In the mid-nineties smaller, tactical-grade IMUs emerged, fulfilling the demands of a bulk of less accuracy-demanding applications. The prices of such devices (20 000 $) are now comparable to the prices of GNSS sets.

Nowadays the progress in miniaturization of inertial units is meaningful because of the MEMS (Micro Electronic Mechanical Systems) technology development. MEMS makes the production of a cheap and ultra light-weight sensors possible. On the other hand the accuracies of MEMS-based IMUs are still insufficient for the autonomous position and angular orientation measurements.

The high costs of top-class geo-referencing devices and a complexity of sensor integration process makes the prices of commercial mobile mapping systems unacceptable for smaller companies or research centers. Additionally such systems are large-sized and heavy so that they are predicted to be mounted on vehicles like vans or planes. This limits their usage flexibility and potential applications. This paper summarizes current researches concerning low-cost photogrammetric MMSs, concentrating mainly on small systems i.e. hand-held systems and low--cost van systems. It also gives the overview of devices that can be used in such constructions. The practical aspects of using digital cameras in MMSs will be discussed and then the closer look at performances of certain sensors and their usefulness for direct image geo-referencing will be given. The attention will be paid to small and low-cost devices, suitable for constructing inexpensive photogrammetric mobile mapping systems

2. Low-Cost Mobile Mapping Systems – Practical Experiences

Until now several small and low-cost mobile mapping systems has been constructed. Table 1 presents the exemplary constructions. All systems in the table are constructed using low-cost elements. The first MMS is relatively expensive, because it consists of two GPS receivers and tactical grade IMU. The last one, NEXUS, is a kind of a tourist information system, not suitable for mapping because of too low geo-referencing accuracies.

Table 1. Exemplary low-cost mobile mapping systems

System & constructors	Platform & roughly estimated cost	Application	Camera	Geo-referencing devices and their accuracies	Declared mapping accuracies
Low cost MMS; Land, Environment and Geo--Engineering Department, Politecnico di Torino [14]	van, system can't be used on other vehicle 32 000 €	Surveys for cadastral map of roads in Italy. Road axis, horizontal and vertical signal measurements.	Logitech webcam, controlled by a PC. Resolution: 1600 × 1200	– 2 Leica 1200 GNSS receivers. Position error: 3 cm; azimuth (determined from 2 GPS measurements) error: 2° – FOG (Fiber optic gyro) IMU-700 Crosbow. Roll, pitch, yaw bias: 20°/h; accelerometer X,Y,Z bias: 12 mg.	For mapping distance 11 m: (RMSE) X: 10 cm Y: 5 m Z: 3 cm
GI-Eye; NAVSYS Corporation [2]	van, car or airborne platforms 17 000 €	Data collection for generating maps or GIS attribute databases	Monochrome CCD camera. Resolution: 1024 × 1024	– Real-time DGPS receiver. Position error: 1–3 m, 0.1 m after post processing & with reference station – FOG tactical grade IMU. Roll, pitch, yaw bias: 1–10°/h ; accelerometer X, Y, Z bias: 0.2–1 mg.	For mapping distance 400 m: (Residuals for exemplary check point) Y: –0.51 m X: 0.98 m Z: –0.77 m
Backpack MMS; CIRGEO – Interdep. Research Center of Geomatics – University of Padua – Italy [4, 7]	backpack 15 000 €	Building facade mapping, small area topographic mapping, surveys in areas inaccessible by land vehicles	Nikon D 2000 SLR camera, Resolution: 2560 × 1920	– GPS L1/L2 Novatel receiver. Position error: about 1 cm – Leica DMC-SX digital compass with tilt sensor. Roll, pitch, yaw accuracy: 0.15°/ 0.15° / 0.50° in homogeneous magnetic environment	For mapping distance 20 m and 4 image measurements: (RMSE) Horizontal: 0.31 m Vertical: 0.43 m
NEXUS; Institute for Photogrammetry, University of Stuttgart [10]	hand--held 4 000 €	Image-based access to object-related information	Sony DWF-500 camera, Resolution: 640 × 480	– GPS Garmin LP-25 consumer-grade reciever: Planar position error 7-10 m – Height determined from DTM – Digital compass & undefined tilt sensorRoll, pitch, yaw accuracy: 2°/2°/0.6–1.5° in homogeneous magnetic environment	No accuracy evaluation was carried out. The estimated accuracy would be about 10 m for mapping distance 40 m

The exterior orientation (EO) parameters determined during the measurement by first two systems are treated as fixed and are not utilized in the bundle adjustment. The coordinates of mapped points are calculated from photogrammetric intersection, utilizing EO provided directly by geo-referencing devices. In contrast, the constructors of a backpack MMS utilize measured position and angles in the bundle adjustment, so that image EO is refined. It is worth mentioning that expect backpack MMS, all other systems are equipped with low-resolution cameras. The angular EO parameters in Backpack and NEXUS systems are provided by digital compasses and tilt sensors. The mapping accuracy of all systems presented in the Table 1 was claimed to be adequate for the mapping application, the system was constructed for, while the total costs of involved devices are at least few times lower then costs of commercial MMSs.

3. Mobile Mapping System Components

3.1. Cameras

There are at least two kinds of cameras which are worth considering when constructing a low-cost photogrammetric MMS: CCD video cameras and digital single lens reflex (SLR) cameras. Video cameras designed for technical application are relatively small sized, light-weight and solid devices, which can meet the demands of systems designed for working in various atmospheric conditions. However CCD video cameras have certain drawbacks and limitations which are: lower resolution when compared to SLR cameras, high distortion values, drift of sensor coordinates during even 2-hour-long warm-up period and power supply requirements [12].

In contrast to video cameras, the SLR digital cameras providing over 10 Mpx resolution are easily available. The concurrent resolutions of such cameras is sufficient for bulk of mapping applications. SLR cameras could be calibrated separately with different lenses however care must be taken to fix the focus during all calibration exposures, and keep it unchanged during mapping campaign. A majority of manufacturers provide the SDK (software development kit) together with the device. The SDKs contain the DLL libraries and other files (like C++ header files) making the software creation and sensor integration easier. Some models of SLR cameras are equipped with the interface suitable for GPS image geo-tagging. When the GPS position is fixed, a scene can be captured and the coordinates as well as the GPS time are written into the image EXIF file header.

Currently an increasing number of digital cameras with integrated GPS receivers are available on the market. The accuracy of GNSS coordinate measurement in such cameras is however to low for most of the mapping applications.

3.2. Geo-Referencing Devices

GNSS Sets

As can be seen from lists of so far constructed mobile mapping systems, for example this one given by da Silva *et al.* [5], or presented in the table 1, almost every construction is equipped with GPS receiver. The determination of camera projection center (PC) by means of GPS is much cheaper then by means of IMU. Less accurate consumer sets are useful for image approximate position determination rather then for an accurate geo-referencing. In contrast, a sub meter accuracies could be achieved by GIS – class or higher class single frequency GPS receivers, provided good satellite visibility. This could be enough for some applications like small area topographic mapping or road mapping [5], but for higher accuracy demanding tasks, a survey sets are necessary. The survey GPS sets working in the real time kinematical mode, downloading the correction from reference station provide sub centimeter accuracy.

We should be aware that the accuracy of object coordinate determination by photogrammetric mobile mapping systems besides position measurement errors will be affected by errors of determined angular EO parameters. Considering that the camera-to-object distance is equal to 40 m, which is typical for many terrestrial mapping applications, the error of 1 cm, results from angular error of about 52". Such accuracy can be achieved only by top-class IMUs. The costs of having the influence of angular measurements error on mapping accuracy lower is under most geometric assumptions much higher then the cost of improving the accuracy of projection centre coordinates determination. For many applications the accuracy to price tradeoff is more favorable for GNSS sets then for IMUs, so buying the survey GPS receiver and antenna seems to be the reasonable choice for constructing MMS. The sizes and weight of such sets is not problematic when constructing small-sized MMS, however the costs contributed by GPS receiver become significant.

In mobile mapping surveys carried out from moving cars (like road cadastral surveys) the determination of an approximate azimuth of a camera axis can be done only from two consecutive GPS measurements. All measured EO values can be improved via bundle adjustment. Experiments show that the mapping accuracies achieved by such systems fulfill the demands of a national norms for certain mapping purposes [5, 13, 14].

Inertial sensors

Inertial devices like inertial measurement units (IMUs) and attitude and heading reference systems (AHRS) perform high-frequency measurements of accelerations and angular velocities, calculating subsequently the position and angular orientation with respect to the reference frame. AHRS are designed to determine only the attitude (roll and pitch) and heading (yaw) but may also consist of accelerometers to achieve a better robustness of calculated values, for example by means of a Kalman filter.

Table 2 presents the overview of IMU classes that can be used for image geo-referencing. The values given in the table are just rough ranges of certain parameters, but should give the imagine about each of three IMU classes. A comparison experiments of the IMU models of different classes could is presented by Samsó *et al.* [15] and by Elikam *et al.* [6] Only the navigation grade IMUs can be regarded as reliable autonomous geo-referencing devices, nevertheless drifts of gyros and accelerometers would impact considerably the determined EO parameters of acquired images, so that the usage of GPS is necessary to compensate for systematically growing errors. The prices and weight of navigation grade IMUs are much too high for mobile mapping systems considered in this paper.

Table 2. IMU Classes

Parameter	Navigation grade IMU	Tactical grade IMU	Low-accuracy IMU
Positon error	about 2 km/h	about 20–40 km/h	> 2 km/min
Gyro drift	0.002–0.1°/h	0.1–20°/h	> 20°/h
Price	about 100 000 €	about 20 000 €	about 2 000 €
Weight	about 9000 g	about 1500 g	about 50 g

Source: [11]

Tactical grade AHRS / IMU technology is based mainly on higher class MEMS sensors (accelerometers and gyroscopes) and fiber optic sensors. Such IMUs were successfully used in already created terrestrial MMSs [1, 14]. Tactical grade IMUs were used also in airborne MMSs like HELIMAP [17]. In order to use tactical IMUs for direct geo-referencing, integration with GNSS measurement is required, because of significant sensors drift. The price of tactical IMUs is nearly the same as the price of survey class GPS sets, so using it in a MMS would double the total system cost. The weight of tactical grade IMU could also be problematic for hand-held MMSs.

The low-cost IMUs, that emerged rapidly in the last decade, are constructed mainly using MEMS sensors. However it should be noted that MEMSs currently provide a tactical-grade accuracy as well. The MEMS technology has a number of advantages that are very attractive to constructors of low-cost MMSs. They are small, light weighted and need a low power consumption. The production of MEMs sensor is cheap as they can be manufactured from small number of prefabricated parts. For example MEMS gyros consist of only 3 parts whereas FOG gyros of about 30 parts [18]. MEMS gyroscopes can operate on a principle of perpendicular vibration detection. Construction of a MEMS gyro often includes the tuning fork element, which is oriented initially in the movement plane so has only in--plane vibrations, but when the body turns, the tuning fork starts to vibrate in the perpendicular plane due to the Corilos force. Now the only thing to do is to sense this vibrations by means of voltage changes generated on electrodes which are mounted inside the fork.

Due to the low accuracies of a discussed MEMS IMUs, the integration with other sensors like GPS receivers and digital compasses is required. The first tests show the high potential for MEMS IMUs for many airborne mapping applications like Oil&Gas pipelines [8]. The potential of using low-cost IMUs for terrestrial photogrammetry is also worth investigating. As the MEMS technology is relatively young, its development potential is high and the further accuracy demands are expected to be fulfilled soon.

Digital Compasses

Basically digital compasses are the sensors that measure X and Y components of the Earth magnetic field in the body reference frame to determine the azimuth. Earth magnetic field has the intensity of about 0.5–0.6 Gauss. The magnetic azimuth differs from the geographic azimuth by the value of magnetic declination so to use the digital compass to determine the geographic north the magnetic azimuth must be corrected. The declination value could be determined from magnetic field models.

There are several kinds of digital compass, but not all are suitable to be used for geo-referencing. For example fluxgate compasses are quite heavy and have to long response time. The most suitable for mobile mapping applications, due to its small size and quick response time, are magnetoresistive sensors. The accuracy of the azimuth determination by means of digital compass is directly related to the accuracy of measurement of X and Y magnetic filed components To achieve the accuracy of 0.1°, which is now guaranteed by many devices, the accuracy each of X and Y component measurements must be below 0.35 milligaus [3].

The measured magnetic azimuth has to be corrected for sensors heading. The attitude direction, defined by two angles (roll and pitch) could be determined for example using Earth acceleration components sensed by IMUs accelerometers, provided that no other acceleration are present. The accuracy of roll and pitch determination is usually higher then heading accuracy, so that attitude compensation would not affect the accuracy of calculated azimuth. The ferrous elements located near the device distort the earth magnetic field sensed by a digital compass. This can often occur on the mobile mapping platforms, so that it is recommended to perform a simple calibration procedure described for example by Caruso [3].

Although digital compasses are dependent on supplementary attitude sensors and are sensitive to ferrous effects, they can be regarded as an attractive geo--referencing sensors for a mobile mapping systems. First of all their readouts are free from drift and have sub degree accuracy which is more then enough for approximate angular EO values. Additionally digital compasses can be easily integrated with IMUs.

4. Sensor Integration

Each geo-referencing device can measure certain values that can be used to determine certain image EO parameters. Only IMUs enable determination of all EO parameters, but especially low-cost models provide unsatisfying accuracy even for approximate values. Each type of device has its advantages and shortcomings. Sometimes the disadvantages of one sensor can be compensated by advantages of another one, giving the effect of synergy. Photogrammetry can also be used to improve GNSS or inertial measurements, so one can think of photogrammetry as an aid for navigation, if only implementation of real time integration algorithms is possible. When constructing a low-cost mobile mapping system top--accuracy sensors are usually unavailable, so maximum effort should be put into proper sensor integration to achieve highest geo-referencing accuracies available. Table 3 gives the various approaches to integration of photogrammetry with geo--referencing sensors. Table 4 provides methods of direct geo-referencing sensor fusion.

Table 3. The approaches to integration of direct geo-referencing sensors with photogrammetry

GNSS	Low cost IMU (3 axis)	Digital compass
1. Coordinates of projection centers (PCs) can be determines by GPS. They are uses as approximations or observations in the bundle adjustment [3, 7, 10] 2. The observation equations of GPS double difference carrier phase measurement can be included into bundle adjustment [7]	1. All image EO parameters can be determined by IMU. Depending on accuracy, they can be used as approximations or observations in the bundle adjustment,. They can be used also as final EO parameters [2, 14] 2. IMU outputs can be treated as Kalman filter predictions and integrated with EO values obtained from image resection [1]	1. Azimuth, determined by a digital compass after correcting for declination can be used as an good approximation of one of EO angles (yaw), or included as an observation in the bundle adjustment [4, 7, 10]

Table 4. The approaches to integration of direct geo-referencing devices

Low cost IMU + GPS	Low cost IMU + digital compass	Digital compass + GPS
1. GPS PC estimation is used to reset the IMU PC estimation [18] 2. The differences between GPS and IMU position and velocity estimates form input to the integrating Kalman filter (loosely coupled systems) [8, 9, 18] 3. The differences between GPS pseudo-range measurement and IMU pseudo range estimation form input to the integrating Kalman filter [9, 18] 4. Navigation through GNSS signal outages (navigation grade IMUs) [9]	1. If the movement of MMS platform is smooth (car, plane), the azimuth determined from two consecutive GPS measurement or by two GPS revivers, mounted on the vehicle, can by verified by azimuth determined by compass.	1. Angles (roll, pitch) measured by IMU can be used for digital compass attitude correction [3] 2. IMU can correct for short term magnetic field distortions 3. Digital compass measurements can stabilize gyro drift

If already integrated devices (like INS + GPS system) are involved into MMS construction, there is usually no need to implement separate sensor fusion algorithms. They are normally provided by device manufacturers. To utilize mathematical algorithms of sensor integration, all sensors should be mechanically integrated in a proper way. This means that the coordinates systems of all devices mounted on MMS platform should remain fixed when the measurement is carried out. If the relative movement of certain coordinate system is allowed (for example camera tilt), we must be able to incorporate proper corrections. The week point and additional source of errors for MMSs is the time synchronization between cameras and geo-referencing sensors. The various approaches to the time synchronization problem can be found in [4, 13, 14]. Besides time synchronization the MMS calibration (concerning system geometry) is necessary. Such calibration usually involves (depending on used sensors): boresight estimation, lever arm estimation and estimation of GNSS antenna offset with respect to IMU.

Exemplary procedure and mathematical models of boresight and lever arm estimation are given by Bayoud [1]. The lever arm vector can also be measured directly but with limited accuracy.

5. Summary

Looking at the development of a low-cost mobile mapping systems and analyzing exemplary constructions the following conclusions can be drawn:

– The examples of low-cost MMSs mentioned in this paper and the overview of the geo-referencing sensors show that the construction of mapping devices suitable for a particular mapping application is possible.

- Construction of photogrammetric MMS is a few-stage task involving camera and geo-referencing sensors fusion in a sense of: appropriate platform construction, time synchronization and measurements integration via mathematical model.
- GPS measurements play the dominant role in the determination of PC coordinates.
- GPS measurements can be aided by inertial measurements. However at least tactical-grade IMUs are necessary in order to obtain considerable accuracy increase.
- Using a digital compass and tilt sensors like accelerometers, the angular camera EO can be measured with higher accuracy then by using only a low-cost IMU. Using MMSs in magnetically instable environment is a considerable problem for compass-based MMSs.
- In the near future we are likely to observe the increase of MEMS IMUs accuracy. The MEMS technology will cause a breakthrough in inertial technology prices.
- In the further future the super-accurate cold atom inertial sensors are predicted to revolutionize the IMU technology providing the superior sensor for direct-geo-referencing.
- The integration of inertial, magnetic and GPS measurements with photogrammetric measurements should be more deeply investigated. For example measurement-level integration of GPS and photogrammetry allows the utilization of even single-satellite measurements.
- The direct geo-referencing shortens the time of photogrammetric workflow so it is of primary importance for real time or near real-time applications.

Finally it should be mentioned that the trend of miniaturization and costs reduction of MMSs will be further observed. The photogrammetric mobile mapping technology will become more available for wider range of users.

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