

An Overview of Mobile Mapping Systems

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SUMMARY

An emerging solution to the problems faced in modern data collection campaigns is the integration of various navigation and remote sensing technologies together on a common moving platform. These Mobile Mapping Systems (MMS) are capable of providing fast, efficient, cost-effective, and complete data collection. Their development has been motivated by a desire to overcome the problems with alternative methods of spatial data collection. These alternative methods include point-wise GPS and traditional terrestrial surveying – which are ill suited for rapid or dense data collection. MMS share none of these disadvantages, while still being capable of providing similar object space accuracies.

This paper provides a brief history of MMS, including a summary of some of these systems developed up to now. It then details the development of the geo-referencing formulas used by MMS and shows how such formulas can be used to determine the accuracies of points measured by the system. The paper concludes with a closer examination of number of van-base, person-base and airborne-base mobile mapping.

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1. MOBILE MAPPING SYSTEMS AS A TOOL IN GEOMATICS

Mobile Mapping Systems (MMS) have become an emerging trend in mapping applications because they allow a task-oriented implementation of geodetic concepts at the measurement level (Schwarz and El-Sheimy, 1996). Examples of such systems can be found in airborne remote sensing (Cosandier et. al. (1994), airborne gravimetry (Wei and Schwarz (1995)), airborne laser scanning (Wagner (1995)), and mobile mapping vans and trains (El-Sheimy et. al. (1995), and Blaho and Toth (1995)). All of these systems have a common feature in that the sensors necessary to solve a specific problem are mounted on a common platform. By synchronizing the data streams accurately, the solution of a specific problem is possible by using data from one integrated measurement process only. The post-mission integration of results from a number of disjoint measurement processes and the unavoidable errors inherent in such a process are avoided. This result in greater conceptual clarity, task-oriented system design and data flow optimisation, and also offers in most cases the potential for real-time solution, which is becoming more important in many applications.

The trend towards MMS in Geomatics is fuelled by the demand for fast and cost-effective data acquisition and by technological developments which satisfies this demand. Two developments are especially important in this context: Digital imaging and precise navigation. Digital imaging sensors considerably reduce the data processing effort by eliminating the digitising step. They also opens the way towards new and flexible designs of the processing chain, making ample use of mathematical software tools readily available. In the form of digital frame cameras, they are inexpensive enough to make redundancy a major design tool. In the form of pushbroom scanners, they provide additional layers of information, not available from optical cameras.

Precise navigation has developed to a point where it can provide the solution of the exterior orientation problem without the use of GCPs or block adjustment procedures; for details of the principle, see Schwarz (1995); for results and practical considerations see Cannon (1991) and Skaloud et. al. (1994). Since results are available in a digital form, data fusion with the imaging data is easy and real-time applications are possible in principle. Operational flexibility is greatly enhanced in all cases where a block structure is not needed. Costs are considerably reduced, especially in areas where little or no ground control is available. Current accuracy is sufficient for many mapping applications; see for instance Schwarz (1995). The potential to solve even high-accuracy cadastral applications certainly exists.

Combining these two developments, the concept of the georeferenced image as the basic photogrammetric unit emerges. This means that each image is stamped with its georeferencing parameters, namely three positions and three orientations, and can be combined with any other georeferenced image of the same scene by using geometric constraints, such as epipolar geometry or object-space matching. This is a qualitatively new step because the georeferenc-

ing parameters for each image are obtained in a direct way by independent measurement. This is conceptually different from the notion that a block of connected images and sufficient ground control is needed to solve the georeferencing problem. The direct method, in contrast, does not require connectivity information within a block of images to solve the georeferencing problem, and thus offers much greater flexibility. It is especially intriguing to consider its use for mapping applications which use digital frame cameras, pushbroom scanners, or laser scanners as imaging components.

2. COMPONENTS OF MOBILE MAPPING SYSTEMS

In the following, common features in the design and analysis of MMS will be discussed. System design and analysis comprises the following steps as a minimum; for more details see El-Sheimy (1996):

1. Data acquisition
2. Kinematic Modelling
3. Synchronization
4. Calibration
5. Georeferencing
6. Integration and data fusion
7. Quality control
8. Data flow optimisation and automation.

The conceptual layout and data flow of a multi-sensor system for mapping applications is shown in Figure 1. The selection of sensors for such a system obviously depends on system requirements, such as accuracy, reliability, operational flexibility, and range of applications. The data acquisition module has, therefore, to be designed keeping both the carrier vehicle and the intended applications in mind. The data acquisition module contains navigation sensors and imaging sensors. Navigation sensors are used to solve the georeferencing problem. Although a number of different systems are used in general navigation, the rather stringent requirements in terms of accuracy and environment make the integration of an INS with GPS receivers the core of any sensor combination for an accurate mobile mapping system for short range applications. This combination also offers considerable redundancy and makes the use of additional sensors for reliability purposes usually unnecessary. However, the addition of an odometer type device, such as the ABS, for close-range applications may be useful for operational reasons, as for instance keeping a fixed distance between camera exposures.

Imaging sensors may be subdivided based on the way they contribute to the information about the object space. They may provide descriptive information, as for instance grey scales, or geometric information, as for instance direction or range from the camera to the object. Table 1 summarizes the contribution of sensors typically used in multi-sensor systems for mapping applications.

Table 1 : Summary of Mapping Related Sensors

Type of sensor	Type of information	Characteristics
Analogue aerial cameras	Descriptive/Geometric	Photos; high geometric accuracy
Multi-spectral linear scanners (Pushbroom)	Descriptive/Geometric	Multi-spectral images, geometric accuracy depends on sensor resolution
CCD cameras	Descriptive/Geometric	Images; geometric accuracy depends on sensor resolution
Imaging laser	Descriptive/Geometric	Image + Distance between the object and the sensor
Laser Profiles, Laser Scanners	Descriptive/Geometric	Distance between the object and the sensor, scanning angle
Impulse radar	Descriptive/Geometric	Thickness of objects (mainly used for pavement structure voids)
Ultra sonic sensors	Geometric	Distance between the object and the sensor. Road rutting measurement, and cross-section profile measurement
GPS positioning and attitude determination	Geometric	High accuracy position and medium accuracy attitude, global reference
Inertial sensors	Geometric	Low-to-high accuracy relative position and attitude.
Odometers	Geometric	Distances.

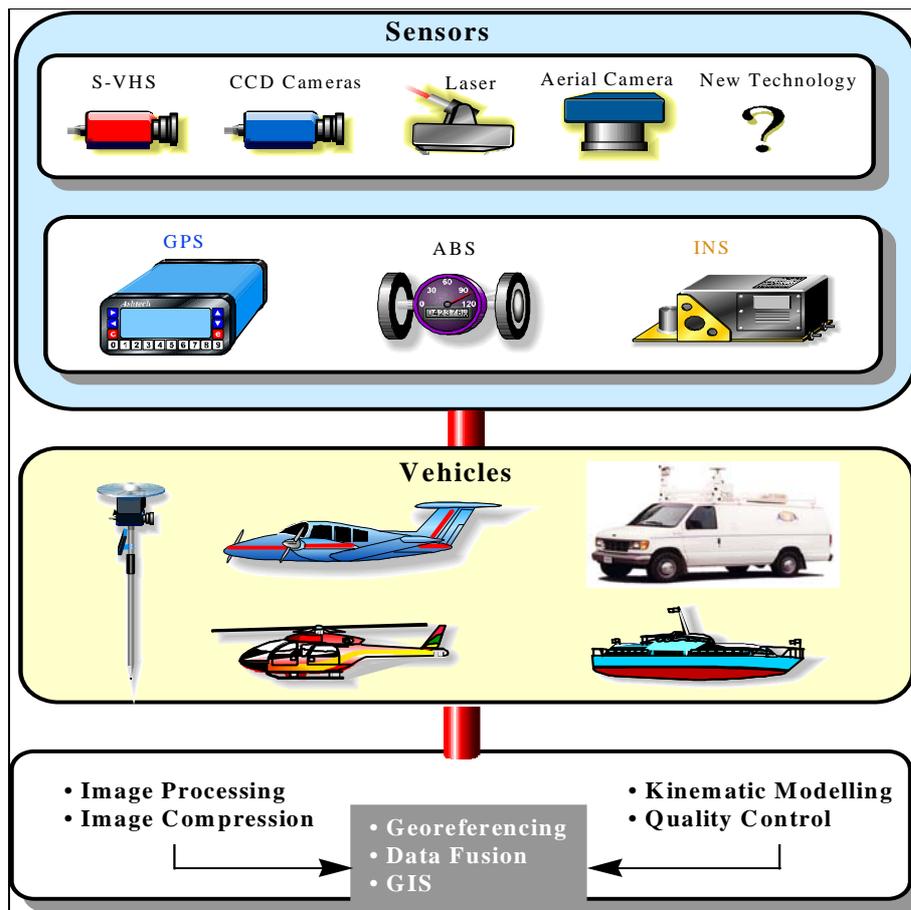


Figure 1: Multi-Sensor Integration for Mapping Application

The selected sensor configuration requires a certain data processing sequence. Part of the processing will have to be performed in real time, such as data compression for the imaging data and initial quality control processing for the navigation data. Most of the data, however, will immediately be stored for post-mission use. In post-mission, the data processing hierarchy is determined by the fact that all mapping data have to be georeferenced first before they can be used in the integration process. The first step is, therefore, the georeferencing of all mapping data and their storage in a multimedia data base.

In mapping applications, photogrammetric methods have been increasing in importance, due to the use of CCD cameras. CCD sensors have overcome two major disadvantages of film-based photographic cameras: single-frame, slow-rate photography and highly specialized processing equipment. Recent trends in CCD technology are characterized by increased resolution, colour image acquisition, and improved radiometric quality (anti-blooming, reduced cross-talk). Another important development which supports the use of CCD cameras in photogrammetric applications is the advancement of fast analogue-to-digital conversion (ADC). Frame grabbers integrated with high-speed computer buses and processing hardware have

become a standard commodity. To determine 3-D coordinates of objects visible in CCD camera images, the following information is needed for a pair of cameras:

- Position of the camera perspective centre at exposure time (3 parameters per image),
- Camera orientation at exposure time (3 parameters per image),
- Interior geometry of the camera sensor, and
- Lens distortion parameters.

The first two sets of parameters are known as exterior orientation parameters, while the other two sets are known as interior orientation parameters. The general problem in photogrammetry, aerial and terrestrial, is the determination of the camera's interior and exterior orientation parameters. The exterior orientation parameters are determined by a combination of GPS and INS, the interior orientation parameters by field or laboratory calibration. This means that exterior orientation is tied to a real-time measurement process and its parameters change quickly. In contrast, interior orientation is obtained by using a static field calibration procedure and can be considered as more or less constant for a period of time. Thus, it can be done before or after the mission and is not generally affected by the data acquisition process.

Real-time georeferencing is possible, in principle, because the interior orientation can be done before the run and the exterior orientation parameters can be computed in real time. However, it is not advisable in applications where frequent loss of lock to GPS satellites occurs. In such cases, real-time georeferencing will be much poorer in accuracy and reliability than post-mission processing.

Implied in the georeferencing process is the synchronization of the different data streams. The accuracy of georeferencing is dependent on the accuracy with which this can be achieved. The synchronization accuracy needed is dependent on the required system performance and on the speed with which the survey vehicle moves. It is, therefore, much more critical for airborne applications than for marine and land vehicle applications. Fortunately, GPS provides a well-defined time signal to which the other sensors can be slaved. Still, the implementation of sensor synchronization is not a trivial process and should be done with care.

Model integration and data fusion comprises all steps necessary to extract the desired result from the georeferenced images. If the objective is to extract 3-D coordinates of objects in the images, then the application of geometric constraints, the handling of redundant images of the same object, and the fusion of data of different type and quality are important considerations. Figures 2 and 3 show typical examples of data fusion in mapping application. Figure 2 shows the example of a mobile mapping system which uses digital images and laser profile data for the imaging component and GPS, INS, and ABS data for georeferencing the two other data types. Figure 3 shows the example of an airborne mapping system which uses digital full-frame images and laser profile data for the imaging component, and GPS and INS data for georeferencing the three other data types. The objective may, however, be much wider than object coordinates. Data fusion generally means that data from various sources and different nature are merged together to provide a versatile resource for mapping applications, a typical example could be a combination of the two systems shown in Figures 2 and 3. Therefore,

data fusion in its general sense means images of different scale, geometry, and radiometric characteristics can be combined together. Model integration and data fusion are closely related to the issue of quality control because in most system designs accuracy of the final results is but one issue. Reliability and economics are usually equally important considerations and a well-designed system will be balanced with a view to these, sometimes conflicting, requirements.

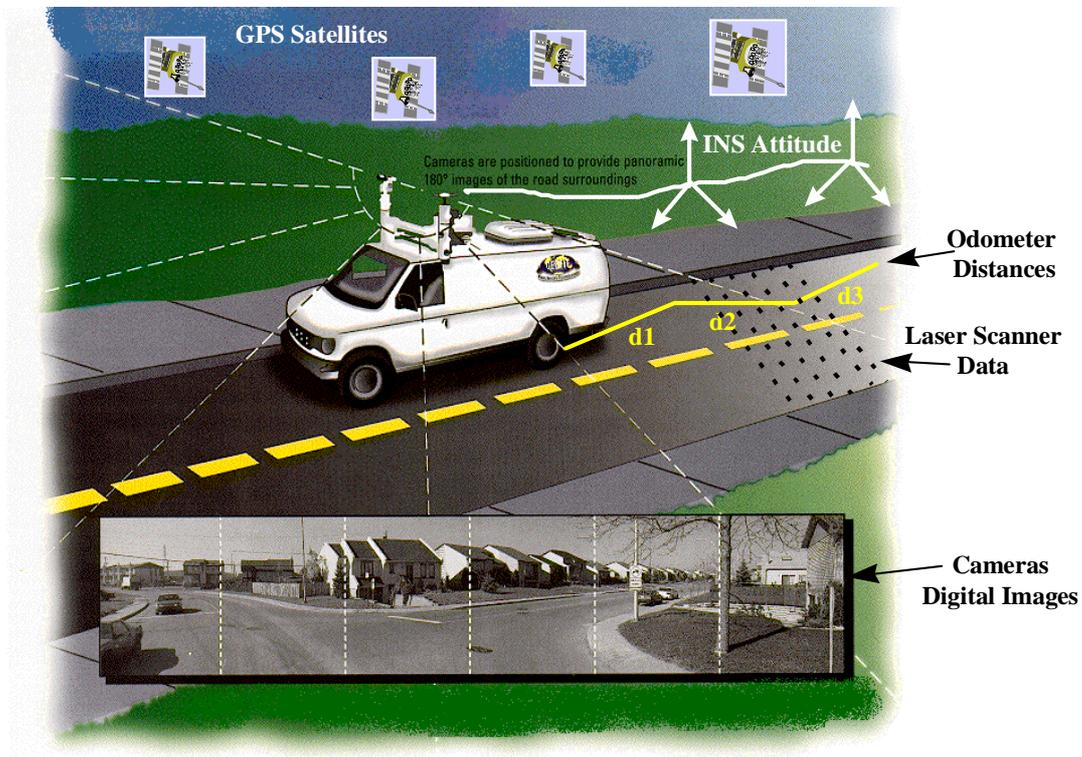


Figure 2 : An Example of Data Fusion in Close-Range Applications

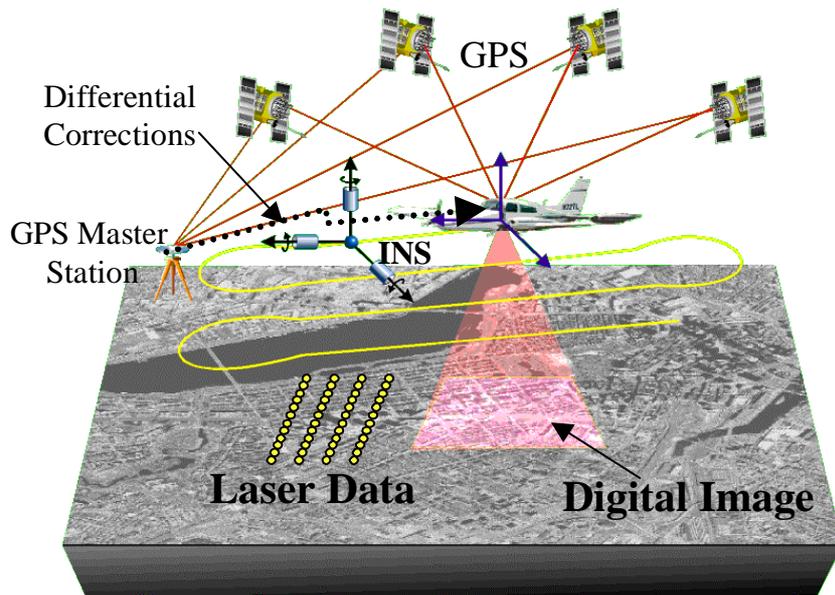


Figure 3: An Example of Data Fusion in Airborne Applications

Quality control usually has a real-time component and a post-mission component. In real-time, one wants to decide whether a specific set of data is sufficient to provide the required accuracy with a certain level of probability. In post-missions, one wants to know the percentage of measurements for which the required accuracy has actually been achieved. If the results of real-time prediction differ considerably from the results of post-mission analysis, the real-time model needs improvement. This can only come from the analysis of large discrepancies between predicted and post-mission results. Thus, each real-time model includes a certain amount of expert knowledge that has been gained in post-mission analysis. It is the art of real-time quality control to combine this expert knowledge with minimum information on the measurement process and still to arrive at reliable predictions. Such predictions would normally contain an acceptable level of poor data without requiring a large number of re-surveys.

2.1. Kinematic Modelling

Kinematic modelling is the determination of a rigid body's trajectory from measurements relative to some reference coordinate frame. A rigid body is a body with finite dimensions, which maintains the property that the relative positions of all its points, defined in a coordinate frame within the body, remain the same under rotation and translation. The general motion of a rigid body in space can be described by six parameters. They are typically chosen as three position and three orientation parameters. The modelling of rigid body motion in 3-D space can be described by an equation of the form:

$$\mathbf{r}_i^m = \mathbf{r}_b^m(t) + \mathbf{R}_b^m(t) \cdot \mathbf{a}^b$$

(1)

where,

- r_i^m are the coordinates of point (i) in the m-frame,
- $r_b^m(t)$ are the coordinates of the centre of mass (b) the rigid body in the m-frame at time (t),
- $R_b^m(t)$ is the rotation matrix between the b-frame and the m-frame at time (t),
- a^b is the fixed distance between point (i) and the centre of mass of the rigid body.

The right-hand side of Equation (1) consists of a translation vector $r_b^m(t)$ and a rotational component ($R_b^m(t) \cdot a^b$). The vector a^b can be any vector fixed in the rigid body with its origin at the centre of mass of the rigid body. Its rotation is equivalent to the rotation about the centre of mass of the rigid body. Figure 4 illustrates the basic concept. The coordinate “b-frame” is fixed to the body and rotates in time with respect to the coordinate m-frame in which the translation vector r_i^m is expressed. The m-frame is, in principle, arbitrary and, thus, can be chosen to simplify the problem formulation. The m-frame can be a system of curvilinear geodetic coordinates (latitude, longitude, and height), a system of UTM or 3TM coordinates, or any other earth-fixed coordinate system.

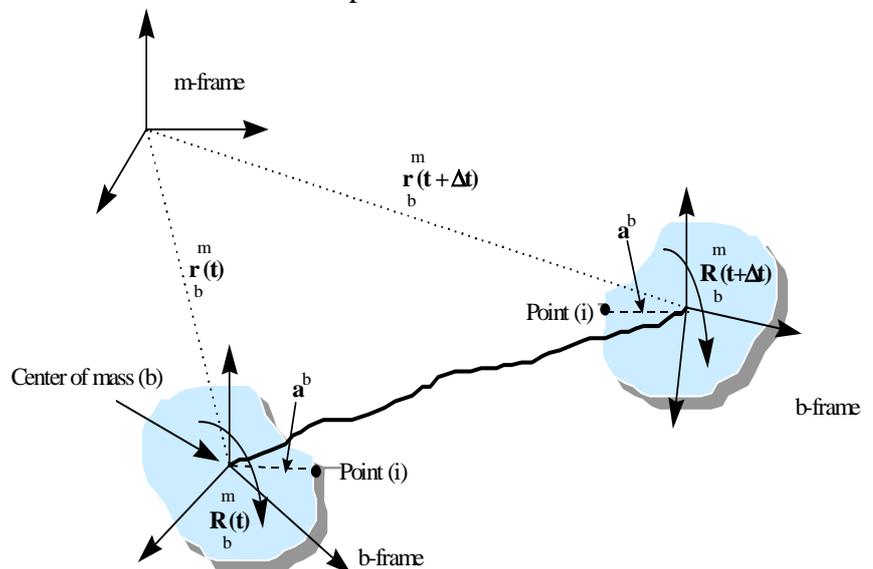


Figure 4 : Modelling Rigid Body Motion in Space

Determining the position and orientation of the rigid body in 3-D space is, in principle, a problem of trajectory determination that requires measuring systems with the capability to sense six independent quantities from which these parameters can be derived. Most notables among them is INS and receivers linking into the GPS.

In general, the INS consists of three gyroscopes and three accelerometers. Gyroscopes are used to sense angular velocity ω_{ib}^b which describes the rotation of the b-frame with respect to the i-frame, coordinated in the b-frame. The i-frame is a properly defined inertial reference frame in the Newtonian sense and, thus, can be considered as being non-accelerating and non-rotating. Accelerometers are used to sense specific force f^b in the b-frame. The first set

of measurements, the angular velocities ω_{ib}^b , are integrated in time to provide orientation changes of the body relative to its initial orientation. The second data set, the specific force measurements f^b , are used to derive body acceleration which, after double integration with respect to time, give position differences relative to an initial position. Specific force and angular velocity can be used to determine all parameters required for trajectory determination by solving the following system of differential equations (see El-Sheimy, 1996) :

$$\begin{pmatrix} \dot{r}^m \\ \dot{v}^m \\ \dot{R}_b^m \end{pmatrix} = \begin{pmatrix} D^{-1}v^m \\ R_b^m \cdot f^b - (2\Omega_{ie}^m + \Omega_{em}^m) \cdot v^m + g^m \\ R_b^m \cdot (\Omega_{ib}^b - \Omega_{im}^b) \end{pmatrix} \quad (2)$$

To solve the system, the observables f^b and ω_{ib}^b are needed as well as the scaling matrix D^{-1} , the gravity vector g^m , the Earth rotation rate ω_{ie}^m and the dimensions of the implied reference ellipsoid. The gravity vector is normally approximated by the normal gravity field, while the Earth's rotation is assumed to be known with sufficient accuracy. The scaling matrix D^{-1} is obtained in the integration process using the implied reference ellipsoid.

GPS is another measuring system that can be used for trajectory determination. The system output in this case are ranges and range rates between the satellites and receiver, derived from carrier phase data. The models that relate the position and velocity with the measurements are well known. In GPS stand-alone mode, a multi-antenna system can be used to provide both position and attitude. The feasibility of attitude determination using multi-antenna systems has been shown for applications not requiring the highest accuracy, see El-Mowafy and Schwarz (1994). Similar to the INS model, the GPS trajectory equation can be written in state vector form:

$$\begin{pmatrix} \dot{r}^m \\ \dot{v}^m \\ \dot{R}_b^m \end{pmatrix} = \begin{pmatrix} v^m \\ 0 \\ R_b^m \cdot \Omega_{mb}^b \end{pmatrix} \quad (3)$$

In this equation, the angular velocities in the body frame are obtained by differencing between antennas, satellites, and epochs. Note that the translation parameters of the trajectory are obtained by differencing between the master station receiver and the rover receiver, while the rotational parameters are obtained by differencing between the rover receivers only. Other models can be found in Schwarz et. al. (1989).

Thus, both INS and GPS are, in principle, capable of determining position and attitude of the rigid body. In practice, due to the double integration of the INS acceleration data, the time-dependent position errors will quickly exceed the accuracy specifications for many trajectory

determination applications. Frequent updating is, therefore, needed to achieve the required accuracies. GPS on the other hand, can deliver excellent position accuracy, but has the problem of cycle slips, which are in essence gross errors leading to a discontinuity in the trajectory. The combination of the two measuring systems, therefore, offers a number of advantages. In the absence of cycle slips, the excellent positioning accuracy of differential GPS can be used to provide frequent updates for the inertial system. The inertial sensors orientation information and the precise short-term position and velocity can be used for cycle slip detection and correction. In general, the fact that nine independent measurements are available for the determination of the six required trajectory parameters greatly enhances the reliability of the system.

2.2. Georeferencing of Mobile Mapping Data Using GPS/INS

The integration of MMS data requires a unified model for georeferencing such data. Unified in this context means that the model can be applied to most, if not all, sensor data without the need to account for a different set of parameters for each sensor. Such a model is very important for the fusion of different sensor data. For the sake of simplicity, the unified georeferencing model will be derived for a camera system which can be used in both airborne and close-range applications. Modifications required for other sensors will be given when necessary.

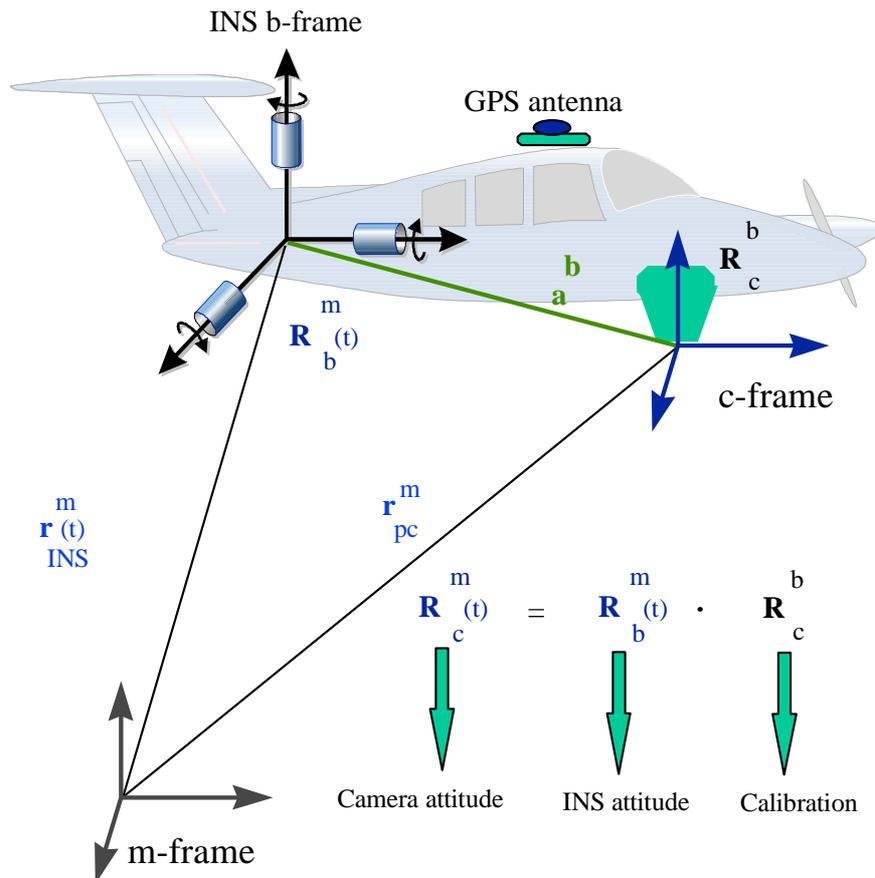


Figure 5 : Detailed Diagram of Elements of Georeferencing for the Airborne Case

Georeferencing of images can be defined as the problem of transforming the 3-D coordinate vector r^c of the camera frame (c-frame) to the 3-D coordinate vector r^m of the mapping frame (m-frame) in which the results are required. The m-frame, as mentioned before, can be any earth-fixed coordinate system such as curvilinear geodetic coordinates (latitude, longitude, height), UTM, or 3TM coordinates. The camera coordinate system, c-frame, changes position and orientation with respect to the m-frame. Georeferencing is possible if at any instant of time (t) the position of the camera projective centres (p.c.) in the m-frame, i.e. $r_{pc}^m(t)$, and the rotation matrix between the c-frame and the m-frame $R_c^m(t)$ have been determined. The georeferencing equation can then be written for any object point (i) as :

$$r_i^m = r_{pc}^m(t) + s^i \cdot R_c^m(t) \cdot r^c \quad (4)$$

where

- r_i^m is the position vector of an object (i) in the chosen mapping frame;
- r_{pc}^m is the coordinate vector from the origin of the mapping frame to the centre of the position sensor on the moving vehicle, given in the m-frame;
- R_c^m is the 3-D transformation matrix which rotates the c-frame into the m-frame;
- (t) is the measurement epoch, i.e. the time of capturing the images in this case;
- r^c is the vector of image coordinates given in the c-frame;
- s^i is a scale factor specific to a one-point/one-camera combination which relates the image coordinates to the object coordinates.

Equation (4) is, however, only a first approximation of the actual situation. It implies that the coordinates of the projective centre of the camera can be directly determined. This is usually not the case because the navigation sensors - GPS antenna/INS centre- cannot share the same location in space with the imaging sensors. Thus, small translations and rotations between the different centres have to be considered. The actual situation is shown in Figure 5. It has been assumed that the camera is mounted in the cargo area of the airplane, that the positioning sensor, a GPS antenna is mounted on top of the airplane, and that the attitude sensor, an inertial measuring unit is mounted in the interior of the aircraft, somewhere close to the camera. In this case, aircraft position and attitude are defined by the INS centre and the internal axes of the inertial measuring unit (b-frame). Similarly, Figure 6 shows the actual situation for the close-range case.

If the vector between the origin of the INS body frame (b-frame) and the camera is given in the b-frame as a^b , $r_{pc}^m(t)$ can be written as:

$$r_{pc}^m(t) = r_{INS}^m(t) + R_b^m(t) \cdot a^b \quad (5)$$

where

- $r_{INS}^m(t)$ is the vector of interpolated coordinates of the INS in the m-frame at time (t), and
- a^b is the constant vector between the camera perspective center and the center of the INS b-frame, usually determined before the mission by calibration.

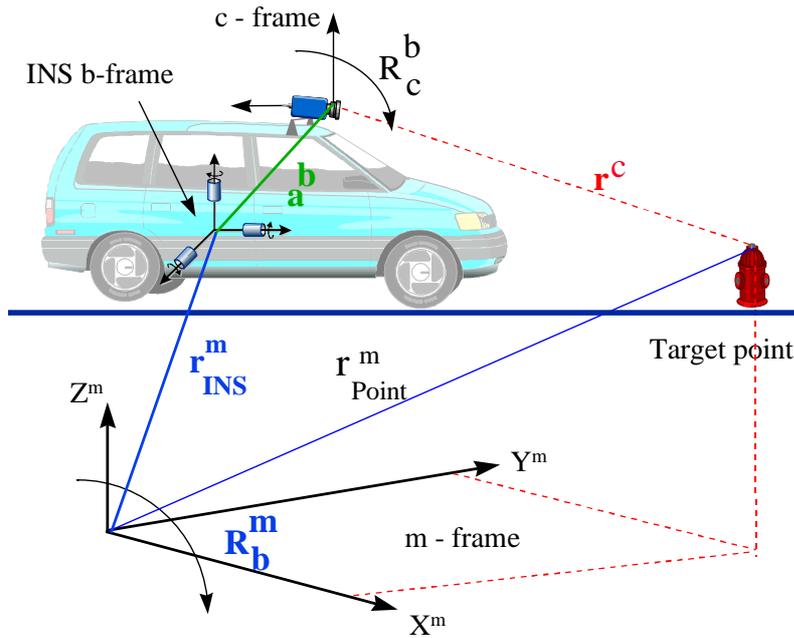


Figure 6: Detailed Diagram of Elements of Geo-referencing for the Close-Range Case

The INS position r_{INS}^m is the position resulting from the INS/GPS integration. In the event of a continuous loss of the GPS signal, the INS will be used in stand-alone mode to extend the mission. The high data rate of the INS, 50 Hz, facilitates the interpolation of camera coordinates.

In addition to transformations between sensors, rotations between different sensor frames have to be taken into account. The INS b-frame (gyro frame) cannot be aligned with the c-frame. The constant rotation R_c^b between the two frames is again obtained by calibration. In this case, $R_c^m(t)$ can be written as:

$$R_c^m(t) = R_b^m(t) \cdot R_c^b \quad (6)$$

where R_c^b is the rotation between the c-frame and the INS b-frame as determined from a calibration process.

Applying Equations (5) and (6) to Equation (4), the final georeferencing formula can be written as :

$$r_i^m = r_{INS/GPS}^m(t) + R_b^m(t) [s^i R_c^b r^c + a^b] \quad (7)$$

where R_c^b transforms the vector r^c from the c-frame to the b-frame and $R_b^m(t)$ transforms the vector $[s^i R_c^b r^c + a^b]$ from the b-frame to the m-frame. R_c^b and a^b are determined through calibration procedures before the survey. Table 2 outlines how different quantities are obtained. For more details on the georeferencing process see El-Sheimy (1995).

Table 2: Elements of the Georeferencing Formula

Variable	Obtained from
r_i^m	Unknown (3)
$r_{INS/GPS}^m(t)$	Interpolated from the GPS/INS positions at the time of exposure(t)
$R_b^m(t)$	Interpolated from INS gyro outputs at the time of exposure(t)
s^i	Determined by stereo techniques, laser scanners or DTM
R_c^b	Calibration
r^c	Measured image coordinates
a^b	Calibration

3. MOBILE MAPPING FROM ROAD VEHICLES

To illustrate the major steps, the development of the VISAT system will be taken as an example. The design objectives for this system were as follows:

"A mobile mapping system is required that positions all visible objects of interest for an urban GIS with an RMS accuracy of 0.3 m while moving through a road corridor with a maximum speed of 60 km/h and a maximum distance to the desired objects of 30 m. Data acquisition must be automatic and should contain real-time quality control features. Data processing, except for quality control, will be done in post mission and should have separate modules for georeferencing, image data base management, imaging, and quality assessment."

It has been developed to satisfy the growing demands for a precise and up-to-date urban GIS. Results achieved indicate that it may also have interesting applications in highway engineering. The survey van is equipped with an integrated system consisting of a GPS receiver, a strapdown inertial system, and a cluster of 8 CCD cameras. All components are precisely time-tagged to minimize errors from insufficient sensor synchronization. The system has been called VISAT to indicate the integration of video, intertial, and satellite technology. In terms of primary functions, the camera cluster provides three-dimensional positioning with respect to the VISAT reference which in most cases is the perspective centre of one of the cameras. The position of this reference with respect to the existing control (master sta-

tion) is determined by DGPS, while the camera orientation in three-dimensional space is given by the INS. In terms of secondary functions, the camera cluster provides redundancy (more than two images of the same object), the GPS controls the INS error propagation, and the INS, when used in positioning mode, bridges GPS outages, corrects GPS cycle slips, and gives precise interpolation between GPS fixes. In urban centres, VISAT can be operated in INS stand-alone mode, i.e. both position and attitude are determined by the INS. This requires

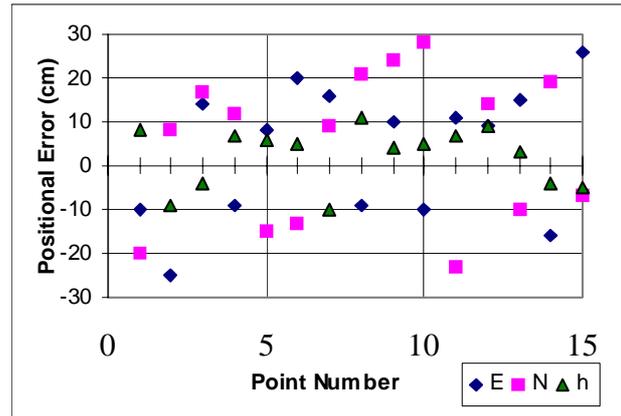


Figure 7: The VISAT Absolute Accuracy

a different mode of operation. To control error growth, the van has to be stopped briefly at regular time intervals. It is this latter feature, i.e. the operation in INS stand-alone mode, that requires a high accuracy INS. Otherwise a low-cost IMU could be used for the orientation as long as the distances between the VISAT reference and the object points are short (< 35 m).

To check the system absolute accuracy, some well-defined Ground Control Points (GCP) along one of the test runs were used for comparison. Figure 7 shows the difference between the GCP coordinates and the coordinates obtained from the VISAT system. They are obtained by deriving GPS-based coordinates from the VISAT system and transforming them to 3TM coordinates. These coordinates were then compared to the completely independent GCP coordinates. The GCP were about 10-30 m away from the van.

The figure indicates that an RMS of 0.3 m in the horizontal and a few centimetres in height are achievable for distances up to 25 m under normal conditions. For more details about the absolute accuracy of the VISAT system, see El-Sheimy, 1996.

4. MOBILE MAPPING FROM PORTABLE SYSTEMS

The VISAT system described above is perhaps the most rigorous and complete implementation of a van-based MMS, and the accuracies it obtains are suitable for all but the most demanding cadastral and engineering applications. However, this accuracy doesn't come cheaply. The VISAT system and others like it cost well over \$200,000 USD. This cost primarily stems from the navigation-grade IMUs used – such sensors cost \$90,000 and higher. Additionally, the platforms and other sensors used in van-based are also expensive. Because of their high cost, the market for such van-based MMS is rather small, and such systems are “one-off” systems that are operated by the companies or institutions that build them. In effect, this means that while several companies are making a profit using MMS, nobody is making a profit manufacturing them. This also means that the benefits of mobile mapping – in particular the lower costs and greater efficiency of data collection – are not being enjoyed by a wide community. Additionally, the van-based systems are extremely complex, and many smaller survey or mapping firms do not have the expertise required to operate them. To overcome the above-mentioned disadvantages of current van-based MMS a backpack MMS is in development at the University of Calgary. The backpack MMS competes in both accuracy and initial

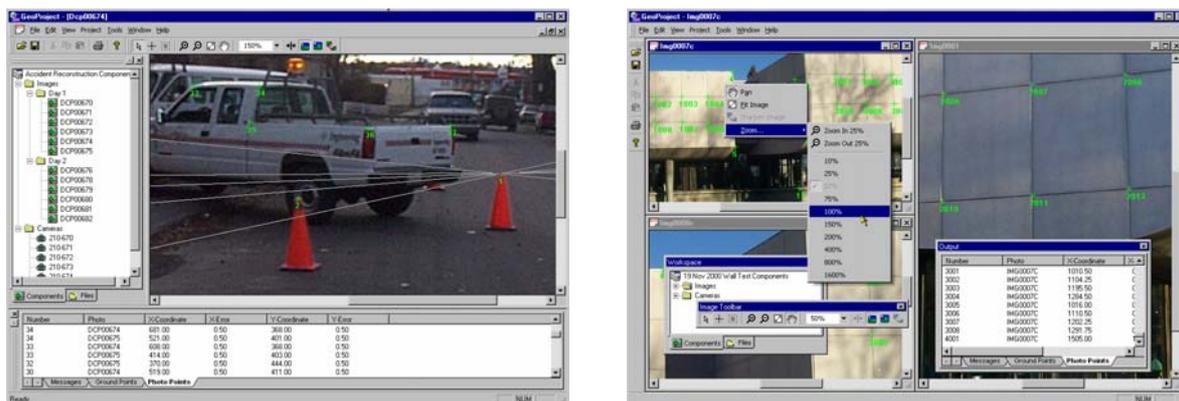
cost with current methods of GIS data collection, while offering the increases in data collection efficiency and flexibility that only an MMS can provide.

The positioning sensor used in the Backpack Mobile Mapping System is a dual-frequency GPS receiver. GPS is used for the same reasons it is used in nearly all MMS – namely, no other positioning technology offers anywhere near the same accuracy and flexibility at the same cost and size. For a portable MMS, the latter feature is particularly important. The selection of a dual-frequency receiver would appear to run contrary to the design goal of a less-expensive system. However, the relatively poor accuracy of the orientation sensors in the Backpack MMS means that the GPS positions are important for controlling the orientation of the photogrammetric networks measured from the images taken by the system. Thus, the increase in cost of a dual frequency receiver is warranted by its significantly better accuracy and reliability.

4.1. Operation

The operation of the backpack MMS is essentially the same as for VISAT or any other MMS. However, because of the low accuracy of the orientation sensor, positioning by direct georeferencing will give poor results. Therefore, the ‘best’ mode of operation is to use the measured position and orientation in a bundle adjustment. The bundle adjustment optimally combines the image point measurements with the observed positions and orientations. The adjustment also enables other information – such as a known distance between object space points, or constraints enforcing verticality or zero-height differences – to be included.

Like VISAT, the backpack MMS also has an associated software package, and, also like VISAT, the software used to manipulate the data collected by the backpack MMS is as important as the MMS itself. Indeed, it is probably more accurate to claim that the software is *part* of the MMS, as nearly every MMS has had dedicated software developed for it. For the backpack MMS, user-friendly software is vital for it to achieve its goal of bringing MMS to less-specialised users. Screen shots of the software for the backpack MMS are shown below in Figure 8.



(a) Multiple Epipolar Lines

(b) Advanced GUI

Figure 8: Close-Range Photogrammetric Software for the Backpack MMS.

4.2. Accuracy

The development of the Backpack MMS is still in progress, however, the results of preliminary tests are very encouraging. For the test whose results are presented below, a target field was established that simulated a “typical” urban environment in which the backpack MMS would be expected to operate. The target field had nearby vertical structures, pavement, and foliage – in short, somewhat of a worse case environment for GPS. It also had nearby metal buildings and light standards that could influence the azimuth reported by the DMC.

The absolute accuracies of the Backpack MMS in a variety of configurations are shown below in Table 3 and Table 4. From the Tables, it can be seen that with as few as five image point measurements at a 20m camera-to-object distance it is possible to achieve mapping accuracies comparable with L1 RTK GPS systems. This accuracy level is something of a benchmark for any MMS as such single frequency GPS systems are currently used in many spatial data collection projects. It is also worth noting that this accuracy exceeds the accuracy of the VISAT system described the previous section. Unfortunately, the good performance at 20m is not reflected at 40m, especially in elevation. The poor performance at 40 m has two causes:

- *Poor imaging geometry* – The exposure stations for this test were nearly collinear. In this arrangement, the GPS positions do not significantly help to define the orientation of the photogrammetric network measured from the MMS’s images. The entire network is essentially free to swing about the axis formed by the exposure stations with only the roll and pitch angles from the DMC constraining the rotation.
- *Poor image point measurements* – The images from the camera are stored in JPEG format. Because of the lossy compression used in JPEG images there is a loss of image fidelity. This problem is obviously compounded as the camera-to-object distance increases, and for some points – particularly those in shadows – it is believed that the measurement error could have been as high as 2 pixels.

The above problems are two important considerations that a user must keep in mind when operating the backpack MMS. However, the first cause – poor imaging geometry – can also be used to illustrate an important advantage of the backpack MMS – namely, the mobility of the backpack MMS means that a user should normally be able to take advantage of the best possible geometry. Additionally, it should be noted that the problems specified above are the same as experienced by any MMS, but that the poorer performance of the orientation sensor in the Backpack MMS means that the errors due to poor imaging geometry or poor image point measurements are amplified.

For more information about the Backpack MMS, see Ellum and El-Sheimy, 2001 and Ellum (2002).

Table 3: Backpack MMS System Absolute Accuracy
(20m camera-to-object distance)

Number of Image Point Measurements	Horizontal		Vertical	
	Max	RMS	Max	RMS
<i>3 Images</i>				
5 Image Points	0.13 m	0.10 m	0.10 m	0.06 m
10 Image Points	0.13 m	0.10 m	0.12 m	0.07 m
<i>6 Images</i>				
5 Image Points	0.06 m	0.05 m	0.14 m	0.11 m
10 Image Points	0.07 m	0.05 m	0.17 m	0.11 m

Table 4: Backpack MMS System Absolute Accuracy
(40m camera-to-object distance)

Number of Image Point Measurements	Horizontal		Vertical	
	Max	RMS	Max	RMS
<i>3 Images</i>				
5 Image Points	0.82 m	0.69 m	0.91 m	0.78 m
10 Image Points	0.47 m	0.35 m	0.91 m	0.78 m
<i>6 Images</i>				
5 Image Points	0.81 m	0.69 m	0.76 m	0.59 m
10 Image Points	0.52 m	0.38 m	0.74 m	0.59 m

5. REAL-TIME AIRBORNE MAPPING SYSTEM FOR FOREST FIRE FIGHTING (F³) SYSTEM

The systems presented so far are working in post-mission mode of operation. In this mode of operation, the data is collected in the vehicle (van, airplane, or ship) and processed off-site in order to extract the information of interest. Due to the post-mission mode of operation, very high accuracy, in position (≤ 0.1 m "RMSE") and attitude (≈ 0.02 degrees "RMSE") can be achieved. This is accomplished by using the precise GPS carrier phase in Differential mode (DGPS: uses two GPS receivers; one in static mode over known control point and the second on the vehicle) and by tightly coupling DGPS and INS data through Kalman filtering.

In many remote sensing applications, however, there is no need for real-time processing of the data and therefore post-mission mode of operation is adequate. Many emerging remote sensing applications, specifically forest fire fighting; the requirement for real-time mapping is more important than the highest possible accuracy. One of the main problems in combating forest fires is monitoring the time history of the fire. Understanding the size, location, and speed of advance of the fire front is critical to optimal allocation of fire fighting resources and maintaining safety of the fire crew. Investigation of major wild-land fire accidents involving loss of life often indicates that the crews became imperiled because of insufficient or untimely information about the location and speed of advance of the fire.

5.1. Components

Accurate and up to date map information on a forest fire is crucial, enabling ground crews, water bombers and helicopters to mount an effective initial attack. To date, this information is collected by airborne surveillance with a spotter aircraft flying a pre-assigned route using navigation charts and a navigator observing the forests and looking for smoke. The data (radio-based) exchanged between the aircraft and the land-based Forest Fire Information System (FFIS) could overload the air radio network, contributing to heavy pilot/navigator workloads.

Recently, GPS has replaced the navigation charts used for airborne patrol. The use of GPS frees the pilot and navigator from looking up the navigation charts. Also, the accuracy in reporting the location of a new fire is greatly improved since the pilot can "freeze" the GPS coordinates of the plane's position at any instant of time. However, there are still the following limitations to such systems:

1. The accuracy of reporting the position of the fire is limited by the accuracy of the on-board GPS system, which is at the ± 30 m level.
2. Haze, smoke or darkness can reduce visibility and, therefore, make it very difficult to report the actual fire situation.
3. Usually, the location of the fire is the only information reported to FFIS by radio communication. This is usually insufficient - a complete assessment of the fire, its area, propagation, etc. is required.

Further, the use of satellites to obtain fire data for model tuning is possible, but there are complications imposed by limited satellite spatial resolution, and short satellite loiter time over the target area.

The F³ system integrate imaging sensors (Thermal InfraRed "TIR" Cameras) with real time navigation technologies (Wide Area Differential GPS "WADGPS" and low cost INS). The system is very useful in reporting the exact situation of fires, assisting the FFIS in accurately assessing the fire and precisely directing water-bombers and fire-fighting crews. The use of infrared/thermal infrared cameras, which sense the heat emitted in the form of infrared radiation, will enable early detection and location of forest fires in reduced visibility due to haze, smoke or darkness. Apart from assisting in fire fighting, the proposed system will have other uses as well. One of the most labor-intensive jobs firefighters have is "mopping up" and patrol. When a fire has been contained and suppressed, there is a possibility of smoldering fires underneath the surface flaring up days after the fire has been put out. Even though it is an arduous task, patrolling and mopping the perimeter fire lines for days after the fire has been put out is essential to ensure the fire is totally out. Through its infrared capabilities that can detect smoldering fires underneath the surface, the proposed system will facilitate the mop-up and patrol process by directing the ground fire fighters to the areas of active heat emission, saving not only time and effort but also protecting the lives of the ground fire fighters. Figure 9 shows the min components of the F³ system. For information about the F³ system, see Wright. and El-Sheimy (2003).

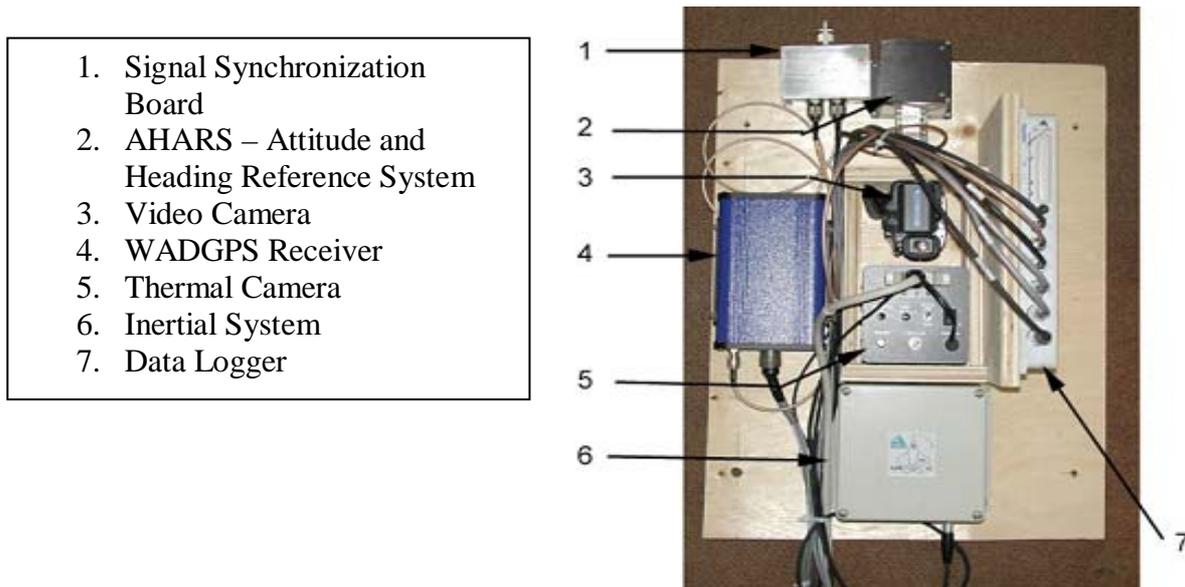


Figure 9: Hardware of the F³ System

5.2. Operation

To determine 3-D coordinates of the fire from the images, the position vector (3 parameters per image) and direction/orientation (3 parameters per image) of the camera at exposure times are needed for a pair of images. These parameters will be obtained from the WAGPS and INS data. After the georeferencing process, the images can be used for feature extraction using photogrammetric intersection techniques. As a first step, image processing techniques will be applied to the TIR images. The purpose of the image processing is to identify, isolate, and track the hotspots and fires in real-time. Different filtering techniques; such as thresholding, morphological, texture and variance filtering are used for identifying and isolating hotspots and fires from the rest of the image. Once the hotspots and fires are identified within the video sequence, they must be tracked from frame to frame to accurately position them. The goal is to track the hotspot across as long as possible to give the space intersection calculation as wide an angle as possible (see Figure 10). Following the 3D coordinate computation of the hotspots and fires, this information will be sent to the web server using one of the satellite communication techniques, e.g. the European Space Agency REMSAT (Real-time Emergency Management via Satellite).

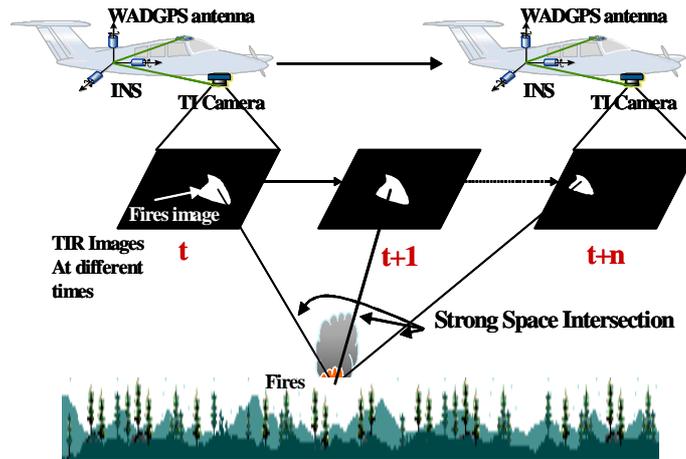


Figure 10: Principle of the Operation of the F³ System

5.3. Accuracy

The objective of the Fire Hawk system is the determination of 3-D coordinates of any fire hot spots within the field of view of the thermal video cameras. The accuracy of these 3-D coordinates is a function of the complete processing chain, which involves WADGPS positioning, SINS position/attitude determination, target localization in the images, system calibration, flying height, and the camera geometry used in the 3-D computation. To facilitate determining initial system accuracy estimates, a basic test area was defined by surveying fire pits at the Bowness Park picnic area, in Calgary, Alberta. Two fires were set and monitored while multiple flight passes, with two separate flight tests made. Two passes are used to estimate camera bore sight alignment, and then the remainder of the the passes are used to evaluate the accuracy obtained. To obtain the actual flight path and image orientation, the raw GPS/INS data for each flight was post processed with KINGSPAD – KINmeatic Geodetic Software for Position and Attitude Determination developed at the University of Calgary, with these post processed results considered as true for comparisons of horizontal position (Figure 11) determined by the F³ System.

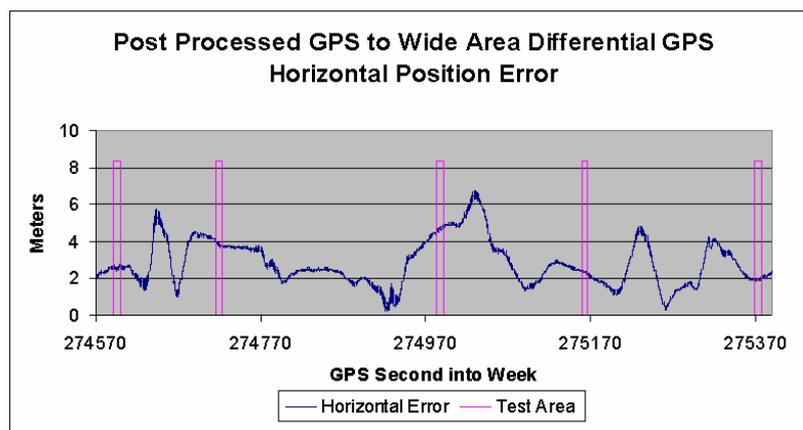


Figure 11: Post Processed vs. WADGPS Horizontal Position Error: 2.974 m RMS

6. CONCLUSIONS

In this paper, the concept of georeferencing of MMS data for mapping applications has been presented with emphasis on the common features of such systems. Imaging and navigation hardware currently available is of such a quality that three-dimensional georeferencing can be achieved with an accuracy sufficient for many GIS tasks in urban and rural areas. In most cases an integration of GPS, INS and an array of digital cameras will provide the optimal solution. It offers sufficient redundancy and the different sensors have enough complementary features to guarantee a safe operation. Although the integration concept is well understood, its implementation is by no means a standard procedure and requires attention to details, such as synchronization, data fusion, loss of sensor output, and weighting of update measurements. Considerable work is needed in the areas of real-time and post-mission quality control, automation of GPS/INS integration in case of frequent lock of loss, automatic feature extraction in post-mission processing, and the efficient and user-oriented manipulation of extremely large databases. The result of solving these problems will be an enormous extension of mobile mapping systems and their fusion with other sensor data.

REFERENCES

- Blaho, G. and Toth, C. (1995)**, "Field Experience With a Fully Digital Mobile Stereo Image Acquisition System", The Mobile Mapping Symposium, Columbus, OH, USA, May 24-26, 1995, pp. 97-104.
- Cannon, M.E. (1991)**, "Airborne GPS/INS With An Application To Aerotriangulation", Ph.D. Thesis, Department of Geomatics Engineering, The University of Calgary, Calgary, Canada, UCSE Report Number 20040.
- Cosandier, D., Ivanco, T. A., Chapman, M.A. and Dylke, M. (1994)**, "The Integration of a Digital Elevation Model in Cirs Image Geocorrection", The First International Airborne Remote Sensing Conference, Strasbourg, France, 11-15 September.
- El-Mowafy, A. and Schwarz, K.P.,(1994)**, "Epoch by Epoch Attitude Determination Using A Multi-Antenna System in Kinematic Mode", Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, KIS-94, Banff, Canada, pp. 331-340, August 30 - September 2.
- Ellum, C.M. (2002)**, "The Development of a Backpack Mobile Mapping System". M.Sc. Thesis. University of Calgary. Calgary, Canada.
- Ellum, C.M. and N. El-Sheimy (2001)**, "A mobile mapping system for the survey community", Proceedings of The 3rd International Symposium on Mobile Mapping Technology (MMS 2001). Cairo, Egypt. January 3-5, 2001. On CD-ROM.
- El-Sheimy, N., Schwarz K.P., and Gravel, M. (1995)**, "Mobile 3-D Positioning Using GPS/INS/Video Cameras, The Mobile Mapping Symposium", Columbus, OH, USA, pp. 236-249, May 24-26.
- El-Sheimy, N. (1996)**, "A Mobile Multi-Sensor System For GIS Applications In Urban Centers", ISPRS 1996, Commission II, Working Group 1, Vienna, Austria, July 9-19, 1996,
- Schwarz, K.P., Cannon, M.E., and Wong, R.V.C. (1989)**, "A Comparison of GPS Kinematic Models for the Determination of Position and Velocity along a Trajectory", *Manuscripta Geodaetica*, 1989, 14(2), pp. 345-353.

- Schwarz, K.P (1995)** , “Integrated Airborne Navigation Systems for Photogrammetry” The Wichmann Verlag, ISBN 3-87907-277-9, Photogrammetric week’95, Stuttgart, Oberkochen, Germany, pp. 139-153.
- Schwarz, K.P. and El-Sheimy, N.**, (1996), “Kinematic Multi-sensor Systems For Close Range Digital Mapping” , ISPRS 1996, Commission V, Working Group III, Vienna, Austria, July 9-19, 1996, **Invited Paper**.
- Wagner, M. J. (1995)**, “Seeing in 3-D Without the Glasses”, Earth Observation Magazine (EOM), July, 1995, pp. 51-53.
- Wei, M. and Schwarz, K.P. (1995)**, “ Analysis of GPS-derived Acceleration From Airborne Tests”, IAG Symposium G4, IUGG XXI General Assembly, Boulder, Colorado, July 2-14, 1995, pp. 175-188. Published by Department of Geomatics Engineering, UofC, Report Number 60010.
- Wright, B. and El-Sheimy, N. (2003)**, "Real-Time Direct Georeferencing of Thermal Images For Identification and Location of Forest Fire Hotspots”, 6th Conference on Optical 3D Measurement Techniques, Zurich, Switzerland, September 22-25, 2003.
- Skaloud, J, Cosandier, D., Schwarz, K.P., Chapman, M.A. (1994)**, “GPS/INS Orientation Accuracy Derived From A Medium Scale Photogrammetry Test”, Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, KIS94, Banff, Canada, pp. 341-348, August 30-September 2.

BIOGRAPHICAL NOTES

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