KINEMATIC MULTI-SENSOR SYSTEMS FOR CLOSE RANGE DIGITAL IMAGING

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ABSTRACT :

Major progress has been made in close-range digital imaging over the last few years in terms of sensor resolution, data rate, and operational flexibility. Thus, the use of such sensors in kinematic applications has become very attractive. To move from the static use of such sensors to kinematic applications, exterior orientation parameters for the sensor are needed in high dynamics situations. In exchange, fully automated data acquisition at high speed can be obtained and the range of applications can be considerably extended. Two basic solutions to the exterior orientation problem are currently available. In the first one, the parameters are determined directly by using suitable position and orientation sensors. In the second one, they are determined indirectly by extracting them from a block of images with a sufficient number of known control points. In the first case the system is more complex, in the second, the operational restrictions are more severe. In this paper the emphasis will be on the first approach, the direct determination of sensor position and orientation, which requires an integrated multi-sensor system.
The presentation will cover both, the concept of multi-sensor integration and implementation aspects. Based on experience with a number of different systems, features common to most systems will be identified and a unified model for multi-sensor integration for close range digital imaging will be formulated. Suitable observables for this model will be assessed, and factors affecting system performance will be discussed. All major features will be illustrated by examples. Finally, data flow optimization and the potential for automation of the data acquisition and feature extraction process will be reviewed with a view to future systems.

1. MULTI-SENSORS SYSTEMS AS A TOOL IN GEOMATICS

Multi-sensor systems have become an emerging trend in geomatics because they allow a task-oriented implementation of geodetic concepts at the measurement level. Examples of such systems can be found in airborne remote sensing, airborne gravimetry, airborne laser scanning, and mobile mapping from vans and trains. All of them have in common 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 disjointed measurement processes and the unavoidable errors inherent in this process are avoided. This results in greater conceptual clarity, task-oriented system design and data flow optimisation, and also offers in most cases the potential for real-time solutions which are becoming more important in many applications.

The trend towards multi-sensor systems in geomatics is fuelled by the demand for fast and cost-effective data acquisition and by technological developments which allow to satisfy 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 digitizing step. They also open 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 ground control points (GPC) or block adjustment procedures. Since results are available in 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 for other reasons. 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 is certainly there.

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, three positions and three orientations, and can be combined with any other georeferenced image of the same scene by using geometry constraints, such as epipolar geometry or object space matching. This is a qualitatively new step because the georeferencing 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. This indirect solution of the problem is currently the standard procedure and is even used in cases where georeferencing information from GPS is employed. It is viewed as one of several possible auxiliary data which are used to support block adjustment and thus the indirect method of georeferencing. 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 close-range imaging applications which use either digital frame cameras, pushbroom scanners, or lasers as imaging components.

In the following, common features in the design and analysis of mobile close-range imaging systems will be discussed and illustrated by examples. Many of these features are also important for general multi-sensor systems; however, the discussion of a more narrow field simplifies the presentation. System design and analysis comprises the following steps as a minimum:

- Data acquisition
- Synchronization and georeferencing
- Integration and data fusion
- Quality control
- Data flow optimization and automation.

These processes will be briefly discussed in the following chapters. 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 (Schwarz et. al. (1993b)):

> ***"A multi-sensor 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."***

2. CONCEPT OF A MOBILE MULTI-SENSOR SYSTEM USING CLOSE-RANGE IMAGING SENSORS

The conceptual layout and data flow of a multi-sensor system for close-range 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 inertial navigation system (INS) with receivers of the Global Positioning System (GPS) 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 this reliability purposes usually unnecessary. However, the addition of an odometer, such as the ABS, may be useful for operational reasons, as for instance keeping a fixed distance between camera exposures.

Imaging sensors can be subdivided by 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 ranges from the camera to the object. Table 2 summarizes the contribution of sensors typically used in close-range mapping applications.

In close-range mapping, photogrammetric methods have been increasing in importance, due to the use of CCD cameras. These 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, color 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 conversions (ADC). Frame grabbers integrated with high-speed computer buses and processing hardware have become a standard commodity. Compared to analog/analytical plotters used in conventional photogrammetry, the use of state-of-the-art computer image boards greatly simplifies measurements.

The selected sensor configuration requires a certain data processing sequence. Part of the processing will have to be done 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 away for post-mission use. In post-mission, the data processing hierarchy is determined by the fact that all images have to be georeferenced first before they can be used in the integration process. The first step is therefore the georeferencing of all recorded images and their storage in a multimedia data base. 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 center at exposure time (3 parameters per image).
- Camera orientation at exposure time (3 parameters per image).
- Interior geometry of the camera sensor.
- The lens distortion parameters

The first two set 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, can be seen as 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 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 of no concern in the data acquisition process.

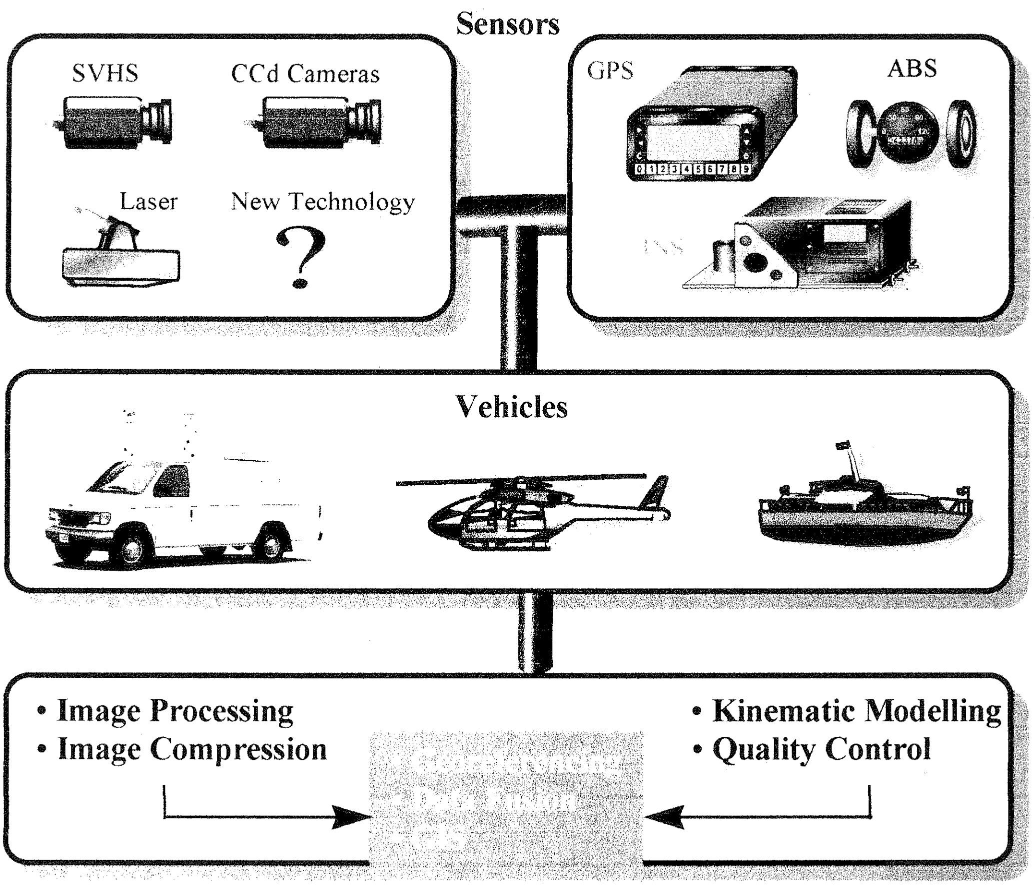

Figure 1: Multi-Sensor Integration in Close Range Application

Type of sensor	Type of information	Characteristics
CCD Cameras	Descriptive/Geometric	Image, geometric accuracy depends on sensor resolution
Imaging Laser	Descriptive/Geometric	Image + Distance between the object and the sensor
Laser Profiles, Laser Scanners	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 measurements, and cross section profiles 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.

Table 2 : Summary of close-range photogrammetry related sensors

Real-time georeferencing is, in principle, possible 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 lock of loss to GPS satellites occurs. In those 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 done. 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. Some details are given in a later chapter.

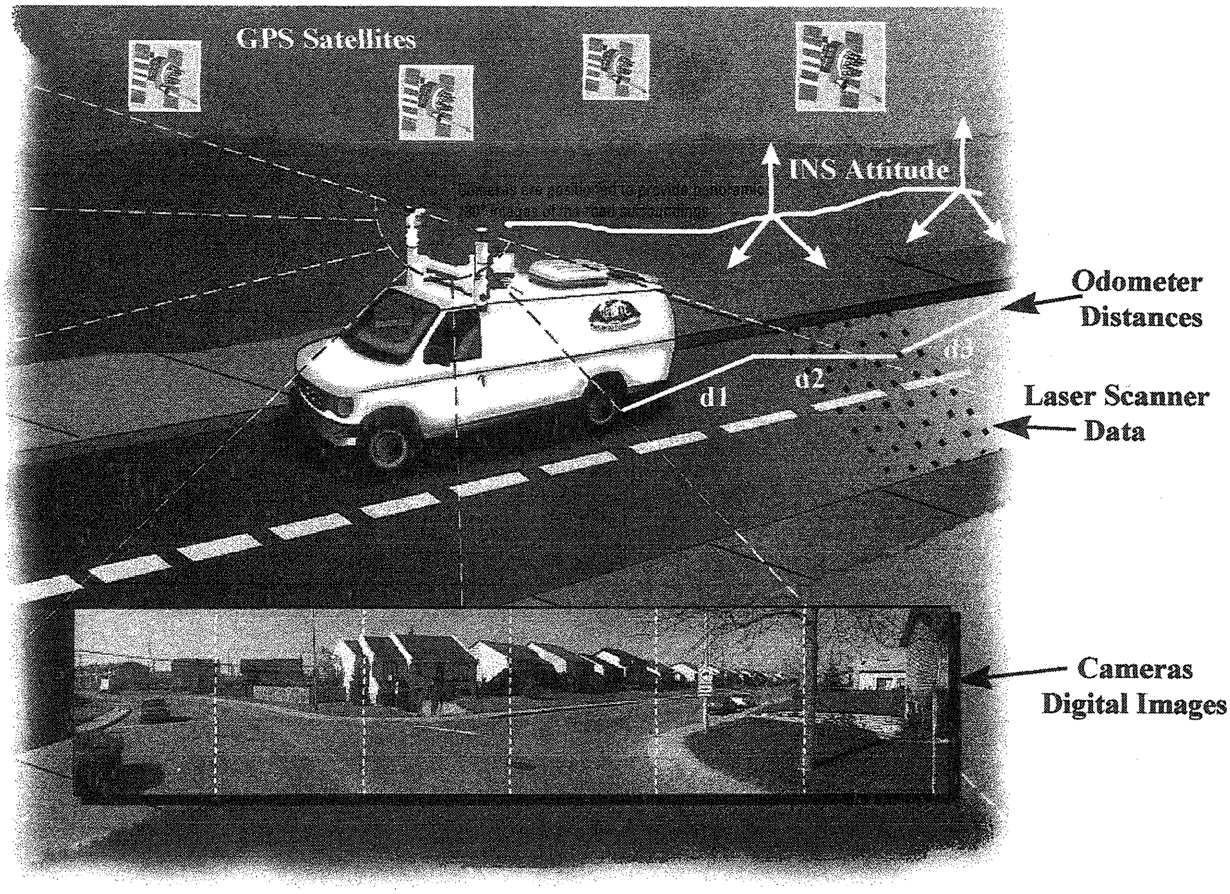

Figure 3 : An example of Data Fusion in Close-Range Applications

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 geometry constraints, the handling of redundant images of the same object, the fusion of data of different type and quality are important considerations. Figure (3) 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. 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. In close-range mapping applications, it 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 view to these sometimes conflicting requirements.

Quality control usually has a real-time 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 mission, one wants to know the percentage of measurements for which the required accuracy has actually been achieved. If the results of the 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 prediction 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 the 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 amount of re-survey.

Data flow optimisation and automation are on the one hand based on the mathematical description and the integration model of the system; on the other hand, they are completely separate from it. Before addressing optimisation and automation, the quiet assumption is usually made that the underlying mathematics of the process is well understood, but that the process of arriving at the results is too slow and requires too much human interaction. The emphasis in this step is therefore on speeding up the process of arriving at the required result, including all essential parameters that describe its quality, and on the automation of all processes that require human expert knowledge and interaction. Very often, the automation process is the more difficult one to accomplish because the further it goes, the more complex it becomes, and the likelihood that it will show a curve of diminishing return is very high. It is therefore not surprising that complete automation is rarely achieved, but that a reasonable level of automation is defined which will cover most of the cases that occur with a certain frequency.

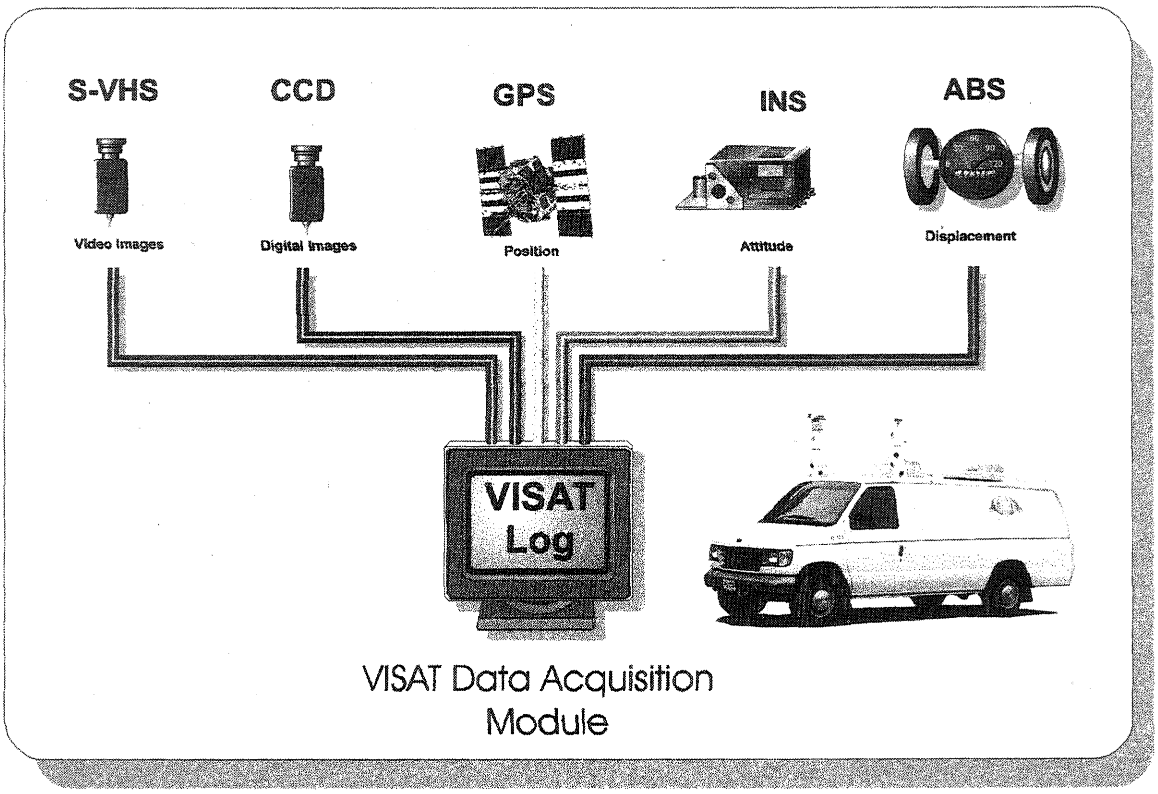

Figure (4) : The VISAT System Concept.

To illustrate the concept of a multi-sensor system, the design of the VISAT system is shown in Figure 4. This system has been jointly developed by the University of Calgary and Geofit Inc. and is now available as a production system. It is installed in a road vehicle, typically moving with a velocity of 50-60 Km/h. The three main sensor subsystems are GPS, INS, and a cluster of eight video cameras. While the first two provide position and attitude for the system, the third one images the surrounding environment at each exposure. The system is synchronized by the Pulse Per Second (PPS) of the GPS receiver clock and the logging PC real-time-clock chip.

The hardware components are a strap-down INS system, two L1/L2 GPS receivers, a cluster of eight video cameras, an Anti-Braking-System (ABS) pick-up, an image control unit, and SVHS camera. In the vehicle, all sensors are interfaced to a Pentium PC which controls the different data streams through programmed interrupt processes. The hardware is housed in three 30 inch rack mounts inside the van.

The function of each component can be explained in terms of primary and secondary functions. 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 center of one of the cameras. The position of this reference with respect to the existing control is determined by differential GPS, while the camera orientation in three-dimensional space is given by the INS. The ABS system triggers the cameras at constant distance intervals using the VISAT controller trigger channel. In terms of secondary functions, the camera cluster provides redundancy, i.e. 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. The ABS data can be used to update the INS data if the GPS signal is blocked for periods longer than the INS bridging level required to fix GPS ambiguities (half a cycle).

3. GEOREFERENCING, SYNCHRONIZATION, AND SYSTEM ANALYSIS

3.1. A Unified Model for the Georeferencing of Multi-Sensor Data

Georeferencing multi-sensor data can be defined as the problem of transforming the 3-D coordinate vector r^S of the sensor frame (S-frame) to the 3-D coordinate vector r^m of the mapping frame (m-frame) in which the results are required. The m-frame can be any earth-fixed coordinate system, such as a system of curvilinear geodetic coordinates (latitude, longitude, height), UTM or 3TM coordinates. For more details on georeferencing of remotely sensed images using INS/GPS data, see Schwarz et al (1993b) and El-Sheimy and Schwarz (1994).

The georeferencing process can be described by the following formula :

$$r_i^m = r_{INS}^m(t) + R_b^m(t)[S^i \bullet R_S^b \bullet r^S + a^b] \qquad (1)$$

where,

r_i^m	is the coordinate vector of point (i) in the mapping frame (m-frame),
$r_{INS}^m(t)$	is the interpolated coordinate vector of the INS (or the GPS) in the m-frame,
S^i	is a scale factor specific to one-camera-one-point combination
$R_b^m(t)$	is the interpolated rotation matrix between the INS b-frame and the m-frame,
(t)	is the time of exposure, i.e. the time of capturing the images,
R_S^b	is the differential rotation between the camera frame (s-frame) and the b-frame,
r^S	is the coordinate vector of the point in the camera frame (s-frame),
a^b	is the offset between the INS and the cameras.

The georefencing formula implies that it is necessary to calibrate the entire system before estimating position and attitude as functions of time for the georeferencing process. As part of the calibration, the camera geometry, the relative orientation between the sensor and the INS b-frame, the offset between the sensor and the INS center, must be determined. The calibration is accomplished by using a bundle adjustment and a test field of control points; for more details on system calibration and the relative orientation constraints, see El-Sheimy et. al. (1995).

Determining the spatial position and orientation of the VISAT reference as a function of time is, in principle, a problem of rigid body motion. The general motion of a vehicle in space can be described by six parameters, e.g. 3 positions and 3 rotations. They can be obtained from the output of GPS receivers and INS. The output of the GPS and INS are the time functions of position and attitude for the vehicle reference point. They provide two components in the georeferencing formula. Together with the calibration parameters and the scale factor S^i obtained by stereo imaging, and the r^S vector obtained by measurement from the sensor output, they complete the set of components needed for the georeferencing process.

3.2 Time Synchronization

Time synchronization is implied in the georeferencing process. If it is not done with sufficient accuracy, errors in the object coordinates will result. The synchronization effect appears in both the interpolated vector r(t) and the rotation matrix R(t). In order to reach the accuracy required for close-range applications, the synchronization should be accurate to few milliseconds (one millisecond is equivalent to 1.8 cm positional error at a velocity of 60 km/h). Synchronization errors can result from the following:

1. Internal hardware delay: This error accounts for the fact that measurements have to be converted, through the A/D conversion process, to digital format and then transmitted to the communication ports.
2. Data Transmission delay: This is the unknown time delay between the sensors and the computer, i.e. the time taken by data to reach the communication boards .
3. Time Tagging Delay: In data logging software of the PCs that handle multi-data streams, the use of interrupt service routines (ISR) is essential for avoiding data losses. Since the computer CPU responds to interrupts in a priority order, called the Interrupt Request Service (IRQ), it is very likely that one interrupt is blocked by another of higher priority for some unknown time before it is serviced.
4. Computer Clock Reading Error: This type of error is due to the fact that the PC timer chips (8253 for XT and 8254 for AT) keeps the time of the day with a counter that has 18.2 Hz ticks, equivalent to 55 ms. With such a coarse resolution, synchronization errors in position could reach 1.55 m. In order to reach higher clock resolution, the channel 0 of the timer has a two byte register for counting the fractional part of 55 ms. For example by using the first 10 bits in this counter the resolution will be increased by 1024 times, that is to 53.78 microsecond. The final computer time will be the coarse time ticks plus the high resolution fraction of the ticks. An error from clock reading could happen when the minor time counter is full and the time-of-the-day counter is read before its counter has been incremented. Such type of errors can be minimized through the use of the computer real-time-clock or special timing boards.

The main effect of delays (1) and (2) is that the solution cannot follow the trajectory of the system. Time tagging errors of type (3) and (4) can be corrected by matching the period between the measurements with a redefined acquisition interval. Obviously, effects of the time tagging error are proportional to the speed of the vehicle, and thus requirements for time tagging accuracy will change for different applications. In land vehicle applications, synchronization errors will introduce an along-track error. Synchronization errors could be dramatically reduced by using either low-level coding software techniques or centralized hardware integration technique. In the former, the real time clock of the host PC is a typical example. The later, is to integrate the hardware in a single board, centralized interfacing board.

system synchronization is performed using the PPS from the GPS receiver. The PPS interrupts the computer every second through either LPT ports or the COM ports of the host PC . The interrupt handler gets a computer time tick, T_{pps}^c, which correspond to the PPS signal. From the GPS position record, the time tag in the GPS time, T_{pps}^{GPS} , is already available. The offset between the GPS time frame and the computer time frame is, therefore, (T_{pps}^{GPS} - T_{pps}^c). Applying this time offset to the cameras, for e.g., time tag in the computer frame will result in the camera time tag in the GPS time frame as given by the following equation :

$$T_{camera}^{GPS} = T_{camera}^c + (T_{pps}^{GPS} - T_{pps}^c) \qquad (2)$$

If there are no delays from the PPS interrupt service routine or any hardware related delays, then this time tagging accuracy should be within the PPS timing accuracy.

3.3 System Analysis and Error Budget

The georeferencing model contains the measured image data as well as all steps in the processing chain, such as GPS positioning, INS position/attitude determination, system calibration, accuracy of cameras, and the effect of image geometry. Also, as mentioned in the previous section, synchronization are also implied by this model. It can therefore be used to assess the contribution of measurement and system errors to the 3-D positioning accuracy. The following system analysis is somewhat simplified because it does not use the explicit model for INS/GPS integration. However, the error model of this integration has been analyzed elsewhere and its characteristic contribution to the error budget is well-known. With this caveat in mind, the model given in formula (3) can be considered as a general model for analyzing the errors in the georeferencing procedure. Its parameters will change from one application to the next. The structure of the error model will, however, be the same.

Using a first-order error analysis of equation (1) and adding the term $(V+\omega)\cdot\delta T$ to reflect the synchronization error, the following formula is obtained:

$$\begin{aligned}\delta r_i^m = {} & \delta r_{INS}^m(t) + \\ & \delta R_b^m(t)\bullet(S^i\bullet R_s^m\bullet r^s + a^b) + \\ & R_b^m(t)\bullet(S^i\bullet\delta R_s^m\bullet r^s + \delta a^b) + \\ & R_b^m(t)\bullet(\delta S^i\bullet R_s^m\bullet r^s + S^i\bullet R_s^m\bullet\delta r^s) + \\ & (V+\omega)\bullet\delta T\end{aligned} \qquad (3)$$

where, V and ω are the velocity and angular rate, respectively.

Equation (3) contains five major groups of errors that contribute to the final accuracy of the 3-D coordinates. They are the INS/GPS position errors, the INS/GPS orientation errors, the calibration errors, the target pointing and geometry errors, and the synchronization errors.

Table (5) summarizes for the VISAT system, how each term in equation (3) contributes to the final accuracy of the 3-D coordinates. The table indicates that all but one error source contribute less than 10 cm and most of them only a few centimeters. The one major exception is the scale factor error δS^i in along-track direction. It is due to the very poor geometry in that direction and is obviously dependent on the distance between camera and target. It should be noted that there is no general distance-dependent error of this magnitude, but that it only occurs when the target is in this direction. Fortunately, under normal operation, a target in this direction can be seen on a large number of images and the unfavorable geometry can thus be excluded by operational procedures.

The only potential error which was not included in equation (3) is the instability of the cameras with respect to the navigation sensors. This instability will increase the error level of δa^b and δR_s^b. Experience available at this point does not indicate that these effects are large enough to be above the general noise level. In general, the variation in δa^b is not as critical as that in δR_s^b.

4. DATA INTEGRATION CONSIDERATIONS

4.1 Constraints in Close-Range Applications

The discussion so far has centered on the use of georeferenced images for 3-D object coordinate determination. Geometric information in the images can be used to enhance coordinate determination and to achieve a more reliable solution of higher quality. Such information may be the fixed relative position and orientation of cameras on a stable base or known geometric features of objects in the images,

4.1.1 Camera Relative Orientation Constraints : Making use of the fact that the cameras are mounted on a stable base, the length of the base and the fixed relative orientation of the cameras can be used as constraints. Written for the two van positions (i) and (j) and the two cameras (cl) and (c2), the constraints are of the form:

- $b^i = b^j$
- $R_b^{c1}(i) = R_b^{c1}(j)$, $R_b^{c2}(i) = R_b^{c2}(j)$
- $R_{c1}^{c2}(i) = R_{c1}^{c2}(j)$ (4)

For the stereo-pair (i),

- $B^i = \sqrt{(X^{c1}-X^{c2})^2 + (Y^{c1}-Y^{c2})^2 + (Z^{c1}-Z^{c2})^2}$
- $R_{c1}^{c2}(i) = R_{c1}^{m}(i)\bullet R_{m}^{c2}(i)$ (5)

Where,

b	is the base vector between each stereo-pair
R_c^m	is the rotation matrix between the camera coordinate frame (c-frame) and the mapping frame (m-frame)
R_{c1}^{c2}	is the rotation matrix between camera (1) and camera (2)

These constraints are very useful in calibrating close-range systems; for details on the use of the relative orientation constraint in this procedure, see El-Shiemy (1996).

Epipolar geometry constraints are another example of using this general technique for 3-D computations. Epipolar geometry is also the foundation for any matching techniques performed with cameras in a known geometric configuration. It essentially reduces the search window to an epipolar line

4.1.2 Object-Space Geometric Constraints : Any known geometric configuration of points in the object space can be used to put additional constraints on the solution. A common example are straight lines which may occur as vertical lines, as for instance a telephone pole, or as horizontal lines, as for instance lane markings or edges of buildings. For a vertical line, the constraint for two points on the line can be written as,

$$X_i - X_j = Y_i - Y_j = 0 \quad (6)$$

Parallel lines provide a powerful orientation constraint for images. By writing a constraint for each line and then adding a constraint forcing the two direction cosines to be the same, redundancy for the short-term attitude can be obtained and the INS attitude be checked.

The use of horizontal line constraint in the image measurements of road centerlines could serve as a first step in the automatic extraction of road features from a sequence of close-range images. Although automatic feature extraction is still a complicated task in general cases, the advantage of georeferencing, spatial orientation and the installation of the cameras greatly simplify the problem. For more details about automatic extraction of line features from sequence of close-range images, see Xin (1995).

Triangulation between images is a very useful feature for complementing GPS/INS data. In theory, it can bridge between images where georeferencing data have bad quality due to long GPS signal blockage. In this aspect all the above constraints could help in extending the bridging length.

4.2 Integrating INS Attitude into a Bundle Adjustment

The integration of INS attitude data into a bundle adjustment program requires some consideration due the fact that the INS attitude data normally refer to a local-level-frame (LL-frame). The attitude of the INS system, i.e. the orientation between the INS measurement frame (b-frame) with respect to the LL-frame, can be described by the attitude matrix R_b^{LL}. This matrix is usually obtained from the matrix product of three elementary rotation matrices which are defined about the axes of the INS b-frame. The angles of this rotation are Euler angles, called roll (r) around the x-gyro axis, pitch (p) around the y-gyro axis, and yaw (y around the z-gyro axis.

Error in	Expected Magnitude	Contribution to δr_i^m	Characteristics
• 1st term (INS/GPS position) δr_{INS}^m	5-10 cm	5-10 cm	Constant for all points in the same image.
• 2nd term (INS attitude) $\delta R_b^m(t)$	1-5 arcminutes	1 - 4 cm at 30 m	Function of the distance between the camera and the objects.
• 3rd term (Calibration)			
1. δR_s^b	1 - 3 arcmin	1 - 2.5 cm at 30 m	1- Constant for the whole mission. The effect on 3-D coordinates depend on the distance between the camera and the objects.
2. δa^b	0.1 - 0.3 cm	2-6 cm at 30 m (fixed base)	2- Depend on the camera configuration used in 3-D computation. Critical for fixed base cameras.
• 4th Term (Target pointing and Geometry)			
1. δr^s	0.5 pixel	0.5 cm at 7 m 2.5 cm at 30 m	1- Depend on the camera configuration used in 3-D computation. Introduce across-track error.
2. δS^i	0.5 pixel	2.5 cm at 7 m 16 cm at 30 m	2- Depend on the camera configuration used in 3-D computation. Introduce along-track error. Critical for fixed base cameras.
• 5th Term (Synchronization)			
1. $V\,\delta T$	1 - 2 msec	1.8 - 3.6 cm for V= 60 km/h	1- Introduce along-track error. Can be reduced by using the PC real-time-clock or special timing boards
2. $\omega\,\delta T$	1 - 2 msec	1.8 - 3.6 arcmin for ω = 30 deg/sec (1.5 - 3 cm at 30 m)	2- Introduce across-track error. Error magnitude function of the distance between the camera and the objects. Maximum along curves.

Table 5 : Error Sources of Close-Range Photogrammetric System and Their Magnitude

The sequence of Euler rotations is not arbitrary, but has to be executed according to the definition of the rotation matrix R_b^{LL}. In the INS processing software, this matrix is normally defined according to navigation conventions as (Wei and Schwarz (1990)):

$$R_b^{LL} = R_b^m = R_3(y) \bullet R_1(p) \bullet R_2(r) \quad (7)$$

The attitude matrix of the camera is defined according to photogrammetric conventions as the rotation from the mapping frame (m-frame) to the camera frame (c-frame) as:

$$R_m^c = R_3(\kappa) \bullet R_2(\phi) \bullet R_1(\omega) \quad (8)$$

where ω, ϕ, κ are the rotation angles around the camera's x-axis, y-axis, and z-axis, respectively.

The integration of the INS attitude data into the bundle adjustment therefore requires the following steps:

1. The coordinate system of the calibration test field should be based on a mapping coordinate system, e.g. UTM or 3TM, based on a local-level coordinate frame (LL). This is necessary because the INS derived azimuth is related to the LL-frame. The use of a different coordinate system for the test field will result in different values for (ω, ϕ, κ) and therefore a different relative orientation between the cameras and the INS system. This would result in a constant azimuth error in all maps produced by a GPS/INS system. The azimuth of the network could be easily determined using a GPS static survey with baselines of about 1 to 2 km length.

2. The estimation of the relative orientation parameters ($\Delta\omega$, $\Delta\phi$, $\Delta\kappa$) between the INS (b-frame) and the cameras (c-frame) requires the product of the rotation matrices R_b^m and R_m^c. In order to obtain meaningful values, both rotation matrices must have the same sequence of rotations about the axes x, y and z which are defined in the same way. It is clear from equations (4) and (5) that the two matrices have different sequences of rotations with respect to the m-frame. Therefore in the implementation of the relative orientation constraints, discussed in section 3.1, both rotation matrices should follow the same rotation sequence. Since the constraints will be implemented in the bundle adjustment program, it will be more feasible to follow the camera rotation sequence. That is the implementation of the relative orientation constraint should take the form :

$$R_b^c = R_m^c \bullet R_b^m = \left[R_3(\kappa) \bullet R_2(\phi) \bullet R_1(\omega)\right] \bullet \left[R_3(y) \bullet R_2(r) \bullet R_1(p)\right] \quad (9)$$

4.3 Error Dependance on Distance and Effect of Geometry Optimization

The georeferencing equation (1) contains four unknowns (3 coordinates and one scale factor) in three equations. With an operating speed of 60 km/h, the van moves 18 m/sec. Using an exposure interval of 5 m, the same object will, therefore, appear in 4-6 consecutive images. Having N images of the same scene will add Nx3 extra equations and N unknowns (scale factors) for the same point (i). This adds extra redundancy and geometry to the spatial intersection problem A least squares solution of the space intersection between the N rays is computed with (3xN - 3 - N) degrees of freedom.

Figure (6) shows the position error for various distances for one specific ground target. This target appears in 7 consecutive images (camera 1/camera 2). The position error is defined as the difference between the system coordinates and the known coordinates. The VISAT system was used in this case to get the measurement data, but the principle applies to any close-range measurement system of this type. As is obvious from Figure (6), the errors in the Y direction are larger than those in the X and h directions. This is mainly due to the scale factor error discussed previously. By using exposures with good geometry, i.e. pairs 1 and 2, errors in y-direction will stay small. This can be used in such cases to automatically select those images which optimize the geometry for all three coordinate directions.

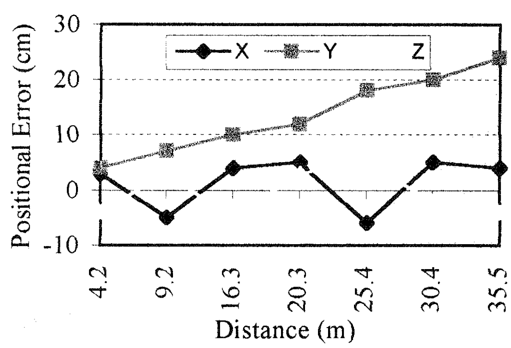

Figure 6: Error Propagation With Distance

This opens interesting possibilities for a mobile system with centimeter accuracy. Such accuracy is usually needed for specific targets of economic importance, such as property corners, and sewerage networks. Figure (7) shows, based on the VISAT system camera configuration, the principle of reducing the effect of geometry on the derived 3-D coordinates by combining data from different runs, surveys, and days. Thus, it is possible to design an operational procedure which optimizes the imaging geometry and the distance to the target based on collinearity error analysis. This will usually be sufficient to reduce the total positioning error to 5-10 cm (RMS). If objects are targeted and cameras with higher resolution are used, it might be possible to reduce the total error to RMS-values below 5 cm.

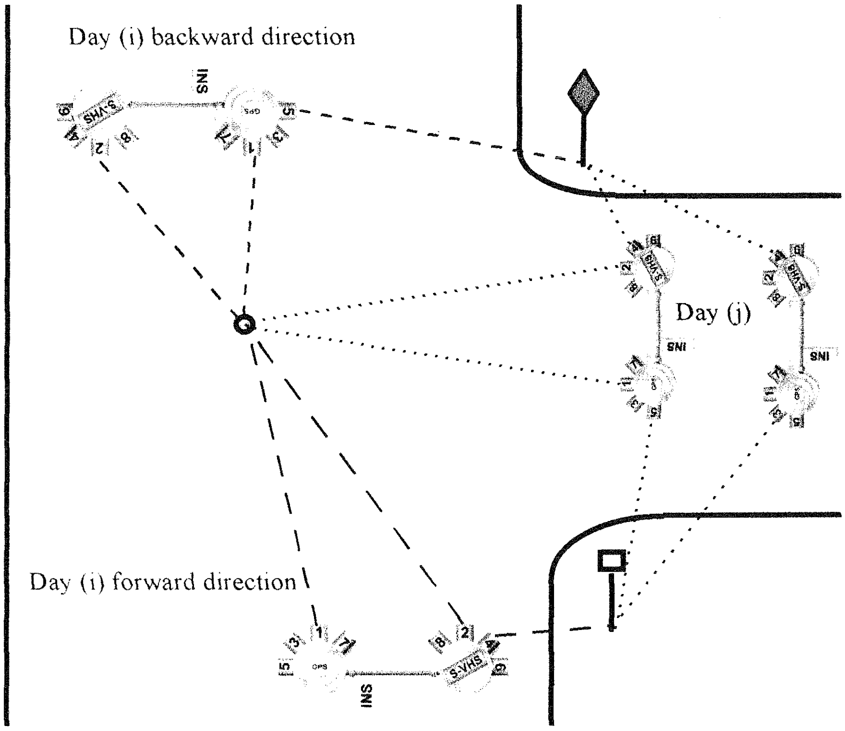

Figure (7): Principle of Using Images From Different Surveys and Days.

5. QUALITY CONTROL AND SYSTEM RELIABILITY PHILOSPHY

The principle of real-time quality control has been outlined in section 2. Instead of discussing general principles in more detail, some aspects of the software implemented in the VISAT system will be discussed. Similar features will have to be considered for all systems of this type, although the actual implementation may differ from one application to the next.

The real-time quality control component consists of an alert system for those situations where the overall performance specifications of the system are not likely to be met by the data set being taken. The post-mission component consists of a suite of programs for cycle slip correction, INS bridging and backward smoothing in case of GPS outages, and geometry optimisation from a cluster of digital images . The major task of this segment is real-time quality assurance, i.e. the certainty that a specified percentage of the stored INS and GPS data are of sufficient quality to allow a continuous computation of the vehicle trajectory within the specified accuracy limits. For example, the requirement to achieve a standard deviation of 30cm in position for 98% of the post-mission trajectory computation would be such a specification.

Since this accuracy can always be achieved for good satellite coverage and signal reception, quality control is in this case mainly concerned with countermeasures to cases of poor GPS satellite geometry, signal blockage, or cycle slips. INS aiding of GPS plays a major role in all of these countermeasures. Since they have to take effect before GPS positioning accuracy deteriorates beyond half a cycle, a real-time system for the detection of such situations is needed to alert the operator. In addition, expert knowledge on INS bridging and backward smoothing are important parameters for the real-time decision. The application of these techniques is, however, done in post mission. The real-time alert will therefore be discussed first, before bridging and backward smoothing procedures are presented, for more details see Schwarz et. al. (1994).

Poor satellite geometry is not a problem if it only increases GPS white noise. Integration with INS and proper weighting will usually alleviate the problem. If, as is often the case, poor satellite geometry generates correlated position errors, regular INS ZUPTs are needed in addition to GPS to maintain the required accuracy level. Since real-time monitoring of deteriorating satellite geometry can be done via the DOP numbers, an alert for such situations can be given.

Signal blockage through houses and trees or a complete lock of loss are indicated by the receiver hardware. Thus, real-time detection of these events is not a problem and an alert can always be given. Fixing ambiguities afterwards is an involved process which depends very much on the specific situation. Countermeasures are INS bridging and smoothing, as well as ambiguity resolution on the fly or a combination of all of these.

The quality control component gives real-time alerts to the operator in situations where the specified trajectory quality can most likely not be achieved. These alerts are determined by the computer which monitors data accuracy of GPS and INS, tracks signal blockage for each satellite, and introduces expert knowledge on INS bridging (smoothing) and the convergence time of OTF ambiguity resolution techniques into the process. In those cases, where an alert is given, the vehicle is stopped to either allow an additional ZUPT or, in more critical cases, an independent ambiguity resolution. Using these additional measurements periods, the required post-mission trajectory accuracy can be obtained in the specified number of cases and resurveys can be avoided.

In post-mission quality control, all available resources are used to obtain the best possible trajectory. This includes the use of INS data for bridging GPS outages, the use of backward smoothing procedures and OTF ambiguity resolution. The integration of INS data and relative positions obtained from triangulation with image data is currently considered as an additional means for bridging GPS outages. The current goal is to reduce the percentage of unsatisfactory data to less than 2%

6. DATA FLOW OPTIMISATION AND AUTOMATION

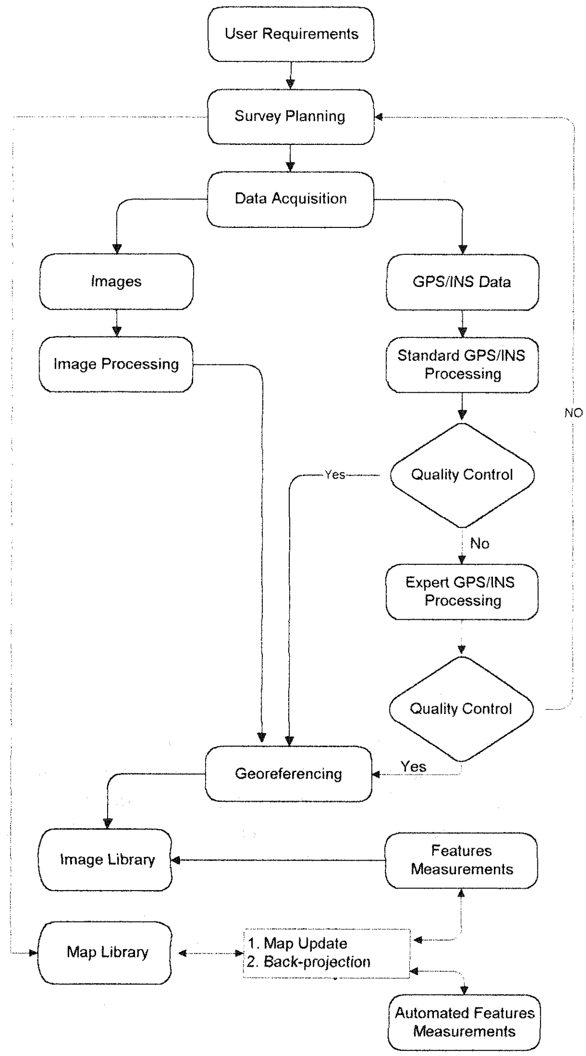

Figure 8: Data Flow of Kinematic Close-Range System.

The data flow of a general multi-sensor system for close-range mapping in kinematic mode is shown in Figure 8. At the top level are the user requirements which include type of survey, accuracy, reliability, image coverage, result presentation (maps, reports, digital output), etc. These user requirements are critical for the survey planning. They determine the selection of the survey route according to parameters such as satellite availability, sun direction, road type, tree coverage, buildings, speed limits, traffic density, spacing between exposures, length of survey, time schedule, etc. To facilitate the set-up of an easy-access survey data base, the survey route is divided into small units which essentially follow the road pattern or other easily identifiable features. The result of optimizing all these factors is expressed in a waypoint file which defines the survey trajectory and the operational constraints.

This file is used to automate the data acquisition stage as much as possible. The driver is guided to the defined waypoints, based on azimuth and distance information contained in the file. The cameras are automatically switched on or off depending on the file information. Alert messages ensure that the data collected is sufficient to provide the user-required accuracy. Vital information is displayed to the survey crew on-line via the navigation control unit. It consists of the camera configuration in use, the number of satellites tracked, the azimuth and distance to the next waypoint, quality control alerts, etc. The information displayed on the navigation control unit is supplemented by spoken messages in critical situations, such as alerts or a change of the survey route.

The images are compressed and downloaded with an identifier which allows easy identification of all images in the same area taken at different times. The navigation data are downloaded after passing through the real-time quality control module. In post mission, the GPS/INS data are processed first. Typically, the majority of them will pass the quality test after standard processing and will be merged with the imaging data for georeferencing. They will then be stored in the image library. Those parts of the total traverse which do not pass the quality test are immediately submitted to a more elaborate second stage of processing. In this fully automated procedure, standard problems, such as those caused by lock of loss, are addressed and automatically resolved. After this stage, most of the data, say 98%, should be available for georeferencing. Those data which still do not satisfy the quality control requirements will either not enter the georeferencing stream or will be subjected to the scrutiny of a human expert who decides on the basis of the processing already done, whether or not further processing is likely to result in a higher percentage of usable data. As the expert knowledge built into the GPS/INS processing software is improved by the analysis of large data sets, the percentage of unusable data will get smaller and smaller. This means that tasks currently done by a human expert will be taken over by the computer.

After georeferencing and storage in the image library, the images can be used to generate the output requested by the user. This output will obviously be different from one user to the next. In many cases, the user will want to do the feature extraction himself. In that case, the georeferenced images are simply transferred together with a standard report on their quality. In other cases, the user may request specific products which can be handled by dedicated application software. In some cases new software development will be needed. To handle the enormous amount of data and to cover a wide range of diverse applications a structured Data Base Management System (DBMS) is absolutely essential. It must be capable of image selection based on location, time of survey, survey unit, best geometry, etc. On the other hand, utility programs for large groups of applications will also be needed. For many applications a partial automation of the measuring process will be highly desirable, such as the automatic measurement of conjugate points using epipolar lines or the automatic identification and measurement of geometrically well-defined objects, For map revision, features such as superimposition and back projection are extremely important. Many of these developments are only in their early stages and will considerably add to the quality of the products to be expected from such systems.

CONCLUSIONS

In this paper, the concept of mobile sensor systems for close-range 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. Accuracy achievable today is about 20 cm (RMS) for general applications and 5 cm (RMS) for targeted points and special operational procedures. 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 data bases. The result of solving these problems will be an enormous extension of close-range digital mapping and its fusion with other multi-sensor data.

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