AN INTELLIGENT MOBILE MAPPING SYSTEM

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ABSTRACT

Mobile Mapping Systems (MMS) are an emerging trend in Geomatics because they allow a task-oriented implementation of geodetic concepts at the measurement level. This trend towards MSS in mapping and GIS application is fueled by the demand for fast and cost-effective data acquisition system. The selection of sensors for such data acquisition system obviously depends on system requirements, such as accuracy, reliability, operational flexibility, range of applications and on technological developments which allow to satisfy this demand. In general, the data acquisition module contains imaging sensors and navigation 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 MMS. To achieve consistent accuracy with an integrated GPS/INS under different operational environment, quality control is a must. Since the required accuracy can usually be achieved for good satellite coverage and signal reception, the expert knowledge system is mainly concerned with cases of poor GPS satellite geometry, signal blockage, or cycle slips, and the role of INS aiding in fixing these problems. In a commercial environment, the production cost is a significant factor to take into account. The expert knowledge system optimizes the survey methodology to increase the productivity of a MMS.

The expert knowledge system, therefore, should have 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 analyze the result and performance achieved in different environment to increase the knowledge base of the system. This paper will introduce the expert knowledge developed for the VISAT (Video-INS-SATellite) MMS. This will include the calibration module, the planning of the survey, the definition of essential parameters for accepting an INS ZUPT, the use of INS data for bridging GPS outages, the use of backward smoothing procedures and OTF ambiguity resolution. All major features will be illustrated by examples from field tests. Finally, data flow optimization and the potential for automation of the data acquisition using the expert knowledge will be reviewed with a view to the idea of developing intelligent mobile mapping systems.

1. THE TREND TOWARD MOBILE MAPPING SYSTEMS IN MAPPING APPLICATIONS

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) and Seige (1994)), airborne gravimetry (Wei and Schwarz (1995), airborne laser scanning (Wagner (1995)), and mobile mapping from vans and trains (Lapucha (1990), El-Sheimy and Schwarz (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 measurements processes and the unavoidable errors inherent in such a process are avoided. This results in greater conceptual clarity, task-oriented system design and data flow optimization, 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 digitizing step. They also opens the way towards new and flexible designs of the processing chain, making ample use of mathematical software tools readily available. 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. Since results are available in a digital form, data fusion with the imaging data is easy and real-time applications are possible in principle. 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 georeferencing parameters for each image are obtained in a direct way by independent measurement.

In the following, common features in the design and analysis of an expert knowledge system for mobile mapping application will be discussed and illustrated by examples. The main objectives of the development of the expert knowledge system is to design an intelligent MMS that speeds up the process of arriving at the required results and to automate all processes that requires human expert knowledge and interaction.

To illustrate the major steps, the development of the VISAT system will be taken as an example. 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 PC real-time-clock which is corrected every second by the Pulse Per Second (PPS) of the GPS receiver clock.

2. DATA FLOW OPTIMISATION AND AUTOMATION

Data flow optimization 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 optimization 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 (Schwarz and El-Sheimy, 1996).

The data flow of the VISAT MMS expert knowledge system is shown in Figure 1. At the top level of the data flow are the Project Editor, Map Generator, and the Calibration Modules. The Project Editor includes the project parameters and the user requirements. The project parameters include project area and time allowed for the project while the user requirements include type of survey, accuracy, reliability, image coverage, result presentation (maps, reports, digital output), etc. These parameters are used to allocate the suitable resources for the project and then passed to the Planning module along with the history of previous surveys which is stored in the expert system. They are then used to optimize the survey.

The Map Generator Module is used in georeferencing raster/vector maps and digital images that cover the project area. The output of the map generator is a tiled database of maps and/or images which can be accessed simultaneously according to the resolution required by the user. The calibration Module includes the determination of the cameras inner and relative orientation parameters The inner orientation parameters define the internal geometry of the camera. The relative orientation parameters define the relative location and orientation between the camera cluster and the navigation sensors (GPS and INS). The relative orientation parameters will be used in the transformation of the 2-D image coordinates into the 3-D world coordinates in the georeferencing process.

The input to the planning module are the project properties and the user requirements defined at the top level of the data flow. These information are critical for the survey planning. They determine the selection of the survey route according to parameters such as satellite availability, sun direction and elevation, road type, tree coverage, buildings, speed limits, traffic density, spacing between exposures, length of survey, time schedule, equipment used, etc. To facilitate the set-up of an easy-access survey database, 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 mission file that defines the survey trajectory and the operational constraints. The survey route can be planned using any sort of georeferenced media, produced from the Map Generator Module, such as digital vector maps, digitized aerial photo, and satellite imagery, see Figure 2.
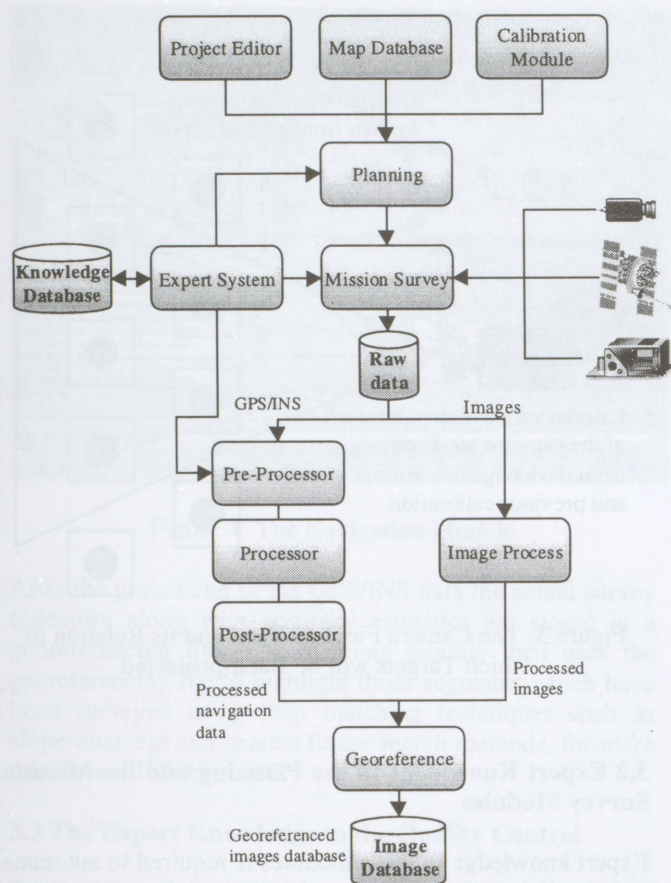
Figure 1: The VISAT Expert Knowledge System

The output of the Mission Survey module are synchronized GPS, INS, and digital images. The images are enhanced using the image-processing module then they are compressed and downloaded with an identifier to a server waiting to be georeferenced. At the same time, the raw GPS/INS navigation data are downloaded after passing through a pre-processor module. The pre-processor analyze the data and establish a processing strategy based on experience gained on previous surveys which are stored in the expert system. Typical examples are, omitting satellites, which frequently disappear, splitting long ZUPTS and defining those parts of the survey that may need backward smoothing processing. The GPS/INS data are then ready to be processed using the processing strategies defined by the pre-processor. 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 Database. Those parts of the total traverse that 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 project accuracy 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, then report that to the expert system. Since the expert knowledge base grow after each mission 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 up to the point that it will be more practical and productive to re-survey a diminutive portion of a the survey than to spent time to achieve the perfection.
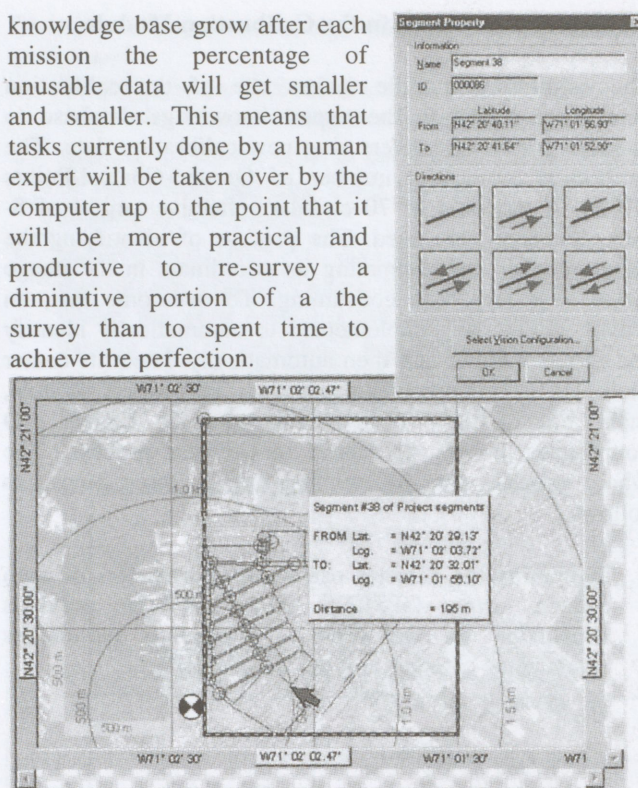

Figure 2: VISAT Planning Module

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 that 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 Database 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.

3. THE EXPERT KNOWLEDGE SYSTEM

The expert knowledge system continuously interacts with the calibration, planning, survey-mission, real-time quality control, and post-mission quality control modules. In the following the expert knowledge in these modules will be discussed in more details.

3.1 Expert Knowledge in the Calibration Module

The calibration module makes use of the calibration parameters stored in the expert knowledge database to estimate better parameters sing new calibration data. The calibration requires a number of Ground-Control-Points (GCP). A test-field of 70 circular reflective targets of 5-inch diameter were used. The process of identifying the target number and estimating its coordinate in the image space is a very time consuming. To overcome that, an expert module was implemented to automatically identify the targets number and then automatically detect its center based on its circular characteristics. The expert module, make use of the GPS/INS data and the targets 3-D coordinates in the automatic recognition process. The whole process can be summarized in three steps, as follows:

1. Estimating the exterior orientation parameters of each camera using GPS/INS data and the previous knowledge on the relative orientation parameters between the cameras and the INS, as follows:

$$R_m^c(i) = R_b^c(i) \bullet R_m^b$$
$$r_{ci}^m = r_{INS}^m + R_b^m \bullet r_{ci}^b \qquad (1)$$

Where,

$R_m^c(i)$ is the rotation matrix between the mapping frame (m-frame) and the camera coordinate frame (c-frame)

$R_b^c(i)$ is the rotation matrix between the INS body frame (b-frame) and the camera coordinate frame (c-frame)

r_{ci}^m is the coordinates of camera (ci) in the mapping frame

r_{INS}^m is the coordinates of the INS in the mapping frame

r_{ci}^b is the coordinates of camera (ci) in the b-frame

2. Estimating the approximate image coordinates of each target making use of the camera exterior orientation parameters and the targets 3-D coordinates. This is a back-projection problem of the photogrammetric collinearity condition. It should be mentioned that only, those targets that fall within the field of view of the camera would be back-projected into the image space (Figure 3). This is simply implemented by using the camera azimuth and field view as a condition for back-projection.

3. Using the estimated 2-D image coordinates of the targets, the system detect, calculate and validate the precise coordinates of the targets making use of their circular characteristics, for more details see El-Sheimy (1996).

While it usually take 3-5 hours to calibrate the system, with the help of the expert module this time is reduced to 15-20 minutes only.
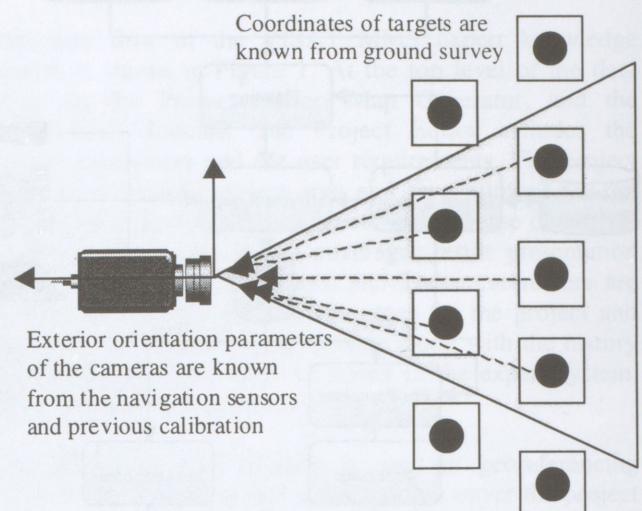

Coordinates of targets are known from ground survey

Exterior orientation parameters of the cameras are known from the navigation sensors and previous calibration

Figure 3: The Camera Field of View and its Relation to which Targets will be Back-projected

3.2 Expert Knowledge in the Planning and the Mission Survey Modules

Expert knowledge in these modules is required to automate and optimize the data acquisition stage as much as possible. The planning component is used to define an optimal survey mission using the knowledge acquired from previous missions for similar environments and equipment. The survey route, whether a straight or curved line, is divided into small line segments, which essentially follow the road pattern of the georeferenced media. The coordinates of the endpoints of these line segments are obtained from the georeferenced media over which the segments are superimposed. With the coordinates of the end points, the azimuth of each segment can be calculated, which is then stored along with the coordinates of the end points in a project database. This information will be used during the survey to guide the driver and then after the survey to evaluate the progress of the project. In the Mission Survey Module, the driver is guided to the defined waypoints, based on azimuth and distance information contained in this file. The cameras configuration and the distance between exposures are automatically selected in real-time during the survey. If the user choose an alternative route because of dense traffic or road closed, the system recalculated a new optimized route to respect the change. Alert messages ensure that the data collected is sufficient to provide the mission-required accuracy. Vital information is displayed to the survey crew on-line via the navigation control unit (Figure 4). 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.
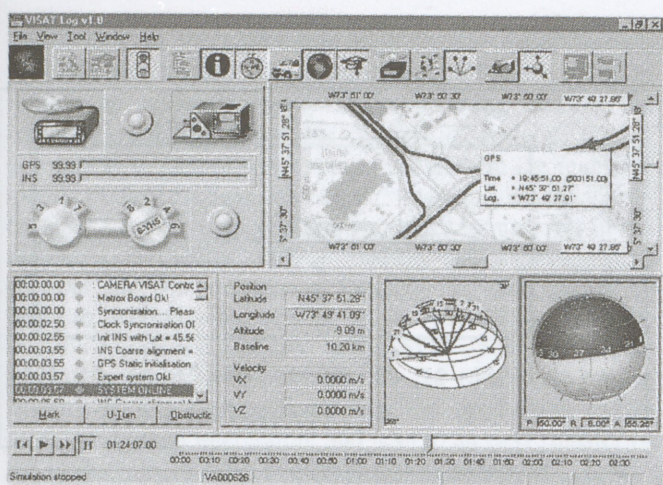
Figure 4: The Navigation Module

After the processing of the GPS/INS data the actual survey trajectory along with accuracy estimates are stored in a georeferencing file. The planning module then uses the georeferencing file to highlight those segments which have been surveyed using map matching techniques such as slope-intercept and nearest future search methods, for more details see Bullock, 1995.

3.3 The Expert Knowledge in the Quality Control

Quality control usually has a real-time and a post-mission component. In the real time component, expert knowledge decide whether a specific set of data is sufficient to provide the required accuracy with a certain level of probability. In the post mission component, knowledge decide analyze the result and performance achieved in different environment to increase the knowledge base of the system. 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 provide a systematic operation procedure that guaranty the quality of the results required for the mission.

Real-time Quality Control: The real-time quality control component gives 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 re-surveys can be avoided.

Examples of expert knowledge rules used in the real-time quality are:
1. Switching to the INS stand-alone mode of operation is the number of tracked satellites is less than 4.
2. Alerting the survey crew to the start/end of the ZUPTs by monitoring the time since the start of INS stand-alone mode of operations.
3. Monitoring the INS gyro rates during ZUPTs such that they do not exceeds certain threshold, In those cases where the gyro rates exceeds the threshold, due to passing cars or movement inside the van, an alert is issued to extend the ZUPT time. See Figure 5, for an example of ZUPT splitting due to movement during ZUPT.
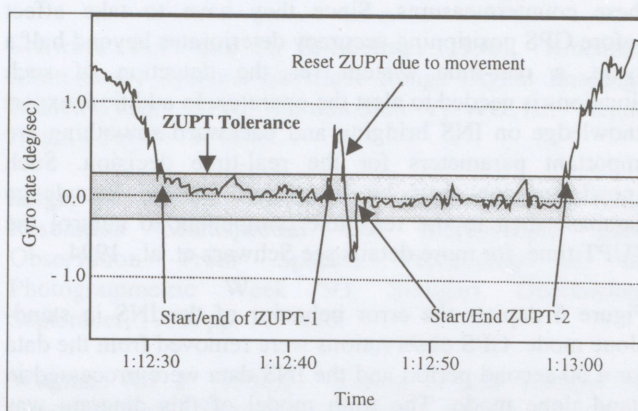

Figure 5: Automatic Detection of ZUPTs

4. Monitoring the GPS data such that if at least 4 satellites have been continuously tracked for certain time period, defined in the expert system database as the OTF convergence time, the expert system switch to GSP/INS navigation mode.
5. Switch off the cameras if the van is outside the planned survey area.

Post Mission Quality Control: In post-mission quality control, all available resources are used to obtain the best possible trajectory. This includes a suite of programs for cycle slip detection and correction, INS bridging and backward smoothing in case of GPS outages. The major task of this segment is 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. The post mission component should therefore provide all the tools to provide necessary information to the expert knowledge database. This information includes:
1. Satellite availability, start/end of GPS static mode and of INS ZUPTs
2. OTF convergence time
3. INS bridging accuracy for both L1 and wide-lane
4. Difference between INS and GPS solution

This information along with the performance achieved in different environments is analyzed and then stored in the expert system database. The information in the database is then used to processing strategy for the real-time and post-processing modules.

4. BUILDING THE EXPERT KNOWLEDGE DATABASE

Since this accuracy can always be achieved for good satellite coverage and signal reception, expert knowledge 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. Such knowledge can then be transferred to the knowledge database then to the real-time component to control the ZUPT time, for more details see Schwarz et. al., 1994.

Figure 6 depicts the error behavior of the INS in stand-alone mode. GPS observations were removed from the data for a 60 second period and the INS data were processed in stand-alone mode. The truth model of this diagram was obtained by using the trajectory computed from the original GPS/INS measurements. Its accuracy is good to a few centimeters. The INS stand-alone positioning results stay below the half cycle level (10 cm for L1 and 43 cm for wide lane) for about 30 seconds for L1 and 65 seconds for the wide lane.
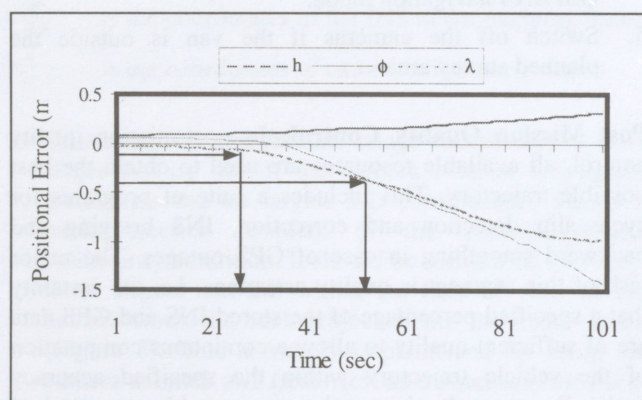

Figure 6: INS Error Behavior in Stand-alone Mode

The output from the Kalman filter was processed again by the Rauch-Tung-Striebel (RTS) optimal smoother, for more details about the RTS optimal smoother, see Gelb (1979). The results of the smoothing are plotted in Figure 7, it has been assumed that there is a GPS position update at the end of the 100 sec. The truth model of this diagram was obtained by using the trajectory computed from the original GPS/INS measurements. They show that the smoother has improved the accuracy and that the INS bridging interval is extended to 100 seconds for both L1 and wide-lane case.
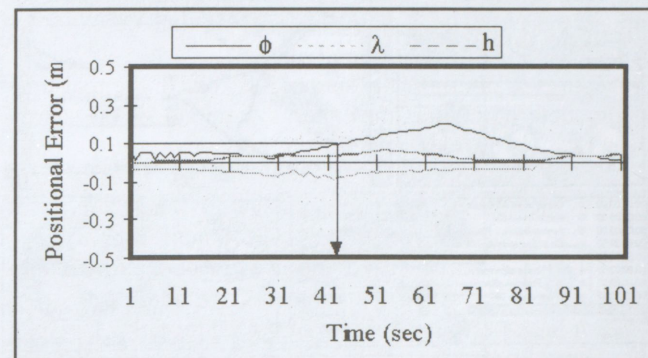

Figure 7: INS Error Behavior in Stand-alone Mode after Backward Smoothing

Signal blockages through houses and trees or complete loss of lock 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 that 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. Such information can easily be monitored in each survey and stored in the expert system database. Figure 8 shows the expert system database for the OTF time to fix the ambiguity for a number of surveys. The table shows that at present only sparse information is available. It will get more fully populated as information from different surveys will increases the knowledge database.
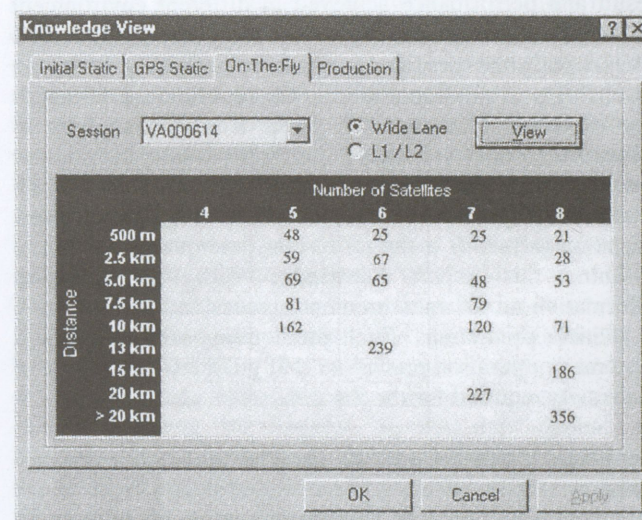

Figure 8: The VISAT Expert System Database

CONCLUSIONS

In this paper, the development of an expert knowledge base system for MMS systems has been presented with emphasis on systems using GPS, INS, and imaging sensors. The expert knowledge is contained in the calibration, planning, survey mission, and real-time and post-mission quality control. The expert system encompasses the total of this

knowledge. In the calibration module, the expert system provides the history of previous calibration in order to reduce the calibration time. In the planning module, the expert system provides the historical with a set of procedures to optimize the survey mission. In the real-time quality control module, the expert system guides the survey crew by a set of rules gained from previous surveys. In the post-mission quality control module, the expert system chooses the best processing strategy for each survey in order to maximize the results. At the same time, the post-mission results are analyzed and used to update the expert system for comparable situation in the future. An expert system of this type will shorten the production cycle, minimize human interaction, and lead to an easy transfer of the technology to other platforms and applications.

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.

Bullock, J. (1995), "A Portable Vehicle Navigation System Utilizing Map Aided GPS), M.Sc. Thesis, Department of Geomatics Engineering, The University of Calgary, UCGE Report 20081.

Cosandier, D., Ivanco, T. A., Chapman, M.A. and Dylke, M. (1994), " The Integration of a Digital Elevation Model in Casi Image Geocorrection", The First International Airborne Remote Sensing Conference, Strasbourg, France, 11-15 September.

El-Sheimy, N. and Schwarz K.P. (1995), "Integrating Differential GPS Receivers with an Inertial Navigation System (INS) and CCD Cameras for a Mobile GIS Data Collection", System, ISPRS94, Ottawa, Canada, October, 1994, pp. 241-248.

El-Sheimy, N., (1996), 'A Mobile Multi-Sensor System For GIS Applications in Urban Centers", ISPRS'96, Commission II, WG 1, Vienna, Austria, July 9-19, 1996.

Gelb, A. (1974), "Applied Optimal Estimation", The M.I.T. Press, Cambridge, Mass., USA, Fourth Print.

Lapucha, D., "Precise GPS/INS Positioning for Highway Inventory System", Report No. 20038, Department of Geomatics Engineering, The U of C, 1990

Schwarz, K. P., El-Sheimy, N., Liu, Z. (1994), "Fixing GPS cycle Slips By INS/GPS: Methods and Experience", KIS94, Banff, Canada, September 1-2, 1994, pp. 265-275.

Schwarz, K.P. and N. El-Sheimy, (1996), "Kinematic Multi-sensor Systems for Close Range Digital Imaging", Invited Paper, ISPRS Commission V, WG III, Vienna, Austria, July 9-19, 1996.

Seige, P. (1993), "MOMS: A Contribution to High Resolution Multispectral and Stereoscopic Earth Observation From Space", Proceeding of the Photogrammetric Week '93, Stuttgart, Oberkochen, September, 1993, pp. 109-120.

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.