TOWARDS THE DEVELOPMENT OF A LOW-COST REMOTELY-PILOTED LAND MOBILE MAPPING SYSTEM

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ABSTRACT

The acquisition of spatial data is a critical operation in situations where conditions are unfavourable for man-operated mapping systems. Such situations include monitoring constrained environments, emergency response, and firefighting. Low-cost unpiloted vehicle platforms offer a great opportunity for developing mobile mapping systems, enabling the automated collection of spatial data in critical environments. In this paper, an overview of a low-cost unmanned remotely piloted mobile mapping platform and its onboard sensors are given, including system requirements, design consideration and system components. This low-cost remote-piloted vehicle platform is equipped with an onboard navigation system (GPS, inertial measurement unit (IMU), magnetometer), a digital camera, and a remote control communication system for rapid 3D data collection. To support functions such as command, control, monitoring of the mobile mapping platform and sensor location and 3D feature extraction, a proposed approach for direct georeferencing, sensor localization, time synchronization and system calibration is presented.

INTRODUCTION

Unmanned vehicles (UV) were developed primarily for military application, but recently a new generation of civilian micro, mini and close range UV started to be employed for time-critical operations, such as monitoring constrained environments, emergency response, and firefighting. The use of low-cost unmanned mobile mapping systems (UMMS) for mapping, monitoring and tracking is at a very early stage of development, but over recent years the geospatial information industry has significantly expanded in both government and industry sectors. As such, the demand has increased for fast and efficient techniques for acquisition, processing, and presentation of large quantities of geospatial data. The ultimate goal of the UMMS is to provide metric and thematic data about the mapped features and objects in the form of geo-products, DEM/DSM and orthoimages, 3D models and video data. The fundamental step in generating this geospatial data is the transformation of data collected by imaging and ranging sensors, such digital cameras or Light Detection and Ranging (LIDAR) laser scanners, from the local body platform frame to a mapping frame. This is the well-known process of georeferencing.

Initially, georeferencing was performed indirectly using image block adjustment and ground control points (GCPs) through photogrammetric triangulation (PT). Establishing ground control is an expensive, time-consuming and challenging task. Further, the PT process is also time-consuming, requires an experienced operator and is not well-suited for real-time applications. Consequently, mobile mapping systems (MMS) are being developed to overcome these drawbacks by eliminating the use of ground control. These systems are commonly implemented on terrestrial vehicles, or aerial platforms, such as helicopters or planes. For a detailed examination of mobile mapping systems, see Li (1997). Current MMS have not gained much popularity in the geomatics industry because of their complexity and high costs. This research aims to develop a UMMS that is user-friendliness and more importantly, low-cost, while achieving comparable accuracies to the aforementioned traditional survey techniques.

SYSTEM REQUIREMENTS

This paper details the development of a UMMS, using low-cost sensors on-board a low-cost unmanned ground vehicle platform. The MMS integrates navigation sensors, mapping sensors, logging computer, and through processing algorithms, the 3D positions of points are determined remotely. Navigation sensors, such as GPS and inertial measurement units (IMU), determine the exterior orientation (position and attitude) of the mapping sensors;

this is known as direct georeferencing. Imaging and ranging sensors determine the position of points external to the platform. The system being developed is set to achieve RMS positioning accuracy in the range of 1/100 with respect to the given control framework. The specified accuracy is required in all environments, including urban areas, where GPS positioning is unreliable. This paper will detail the tasks required to satisfy this requirement. Firstly the selected system hardware is described, followed by methods of GPS/IMU/Camera integration and synchronization, the georeferencing model is then developed, finally sensor and system calibration techniques are described.

SYSTEM DESIGN

The UMMS uses onboard navigation sensors to directly determine the position of the vehicle platform and the pose parameters of the imaging sensor. A proven solution is an integrated navigation system that integrates a Differential GPS (DGPS) and an Inertial Navigation System (INS). The navigation sensors are divided into two categories: positioning sensors, and attitude sensors.

Positioning Sensors

GPS will provide the position because no other positioning technology offers the same accuracy and flexibility at the same cost. Further, GPS is widely accepted in the surveying and mapping industry. Also, the GPS receiver outputs a precise clock signal (1 PPS) that can be used for synchronization of the system components.

Ellum and El-Sheimy (2001) list several modes of GPS operation that are potentially applicable to a low-cost MMS. The L1 carrier-phase Real-Time Kinematic (RTK) GPS solution is the most applicable to a low-cost terrestrial MMS. Geodetic-grade receivers with firmware supporting RTK-GPS are very expensive compared to general-purpose GPS receivers. This is one reason why RTK-GPS is still not popular and is used only for limited application areas. Takasu (2009) constructed a low-cost single-frequency RTK-GPS receiver and obtained cm-level positioning accuracy. However, expensive dual-frequency receivers have an advantage of much shorter time for ambiguity resolution. With a single-frequency receiver, at least a few minutes are necessary to obtain a first fixed solution.

Attitude Sensors

Ellum and El-Sheimy (2001) list possible sensors for attitude determination and provides the advantages and disadvantages of each. A low-cost inertial measurement unit (IMU) is the chosen attitude sensor because, unlike the alternatives, it operates independently to provide a complete navigation solution - position, velocity and attitude, thus it is able to bridge GPS outages. Further, the IMU's a high data rate allows for precise interpolation between GPS fixes.

The main source of error in position comes from the errors in the determination of the azimuth. The high drift rate of the low-cost IMU will not allow accurate azimuth determination without the use of azimuth updates from heading sensors. Thus, the UMMS will integrate a magnetic sensor into the system to provide the azimuth angle updates in the Kalman filter. A digital compass can provide a relatively stable accuracy of up to ±0.5°. Magnetic north does not coincide with geodetic north, thus magnetic sensors require knowledge of the earth's magnetic field. Highly accurate global and regional models of the earth's magnetic field are freely available. For a general introduction to digital compasses, see Caruso (2000).

Mapping Sensors

It is shown in Li (1999) that with accurate calibration and at the object to camera distances that the UMMS will be used at (less than 30 m), mm level accuracies in the determination of object space coordinates are possible with a consumer grade digital camera.

Single Board Computer

The UMMS requires a powerful, but flexible, central processing unit that is easily integrated and expanded for use with different sensors and vehicle platforms. This embedded computer gathers and processes all the information from the GPS receiver, IMU and other sensors. The Linuxstamp serves as the UMMS processor. It is an open source processor module based on the AT91RM9200 microprocessor.

Ground Control and Command Station

The control and command station (CCS) consists of a laptop, a RF transceiver module and a GPS base station. The UMMS communicates wirelessly to the CCS through a XBee-PRO 900 RF module. It sends raw observations, computed navigation solutions and other information, while receiving L1 GPS observations to compute the RTK solution. The XBee transceiver was chosen because it has wide range (10 km), low latency and high data rate (156 Kbps).

Alternatively, the GPS base station can be replaced with a network RTK (NRTK) server. In which case, UMMS requires a radio modem to connect to an NTRIP caster via Internet. In either case the GPS observations will be in the RTCM (version 2 or 3) data format. This method is more attractive because it significantly reduces the cost and the amount of equipment used, while increasing the flexibility and efficiency of the UMMS.

Data Logging

Part of the processing is performed in real time, such as image compression and initial quality control. However, real-time geoferencing is not reliable in urban areas, due to frequent loss of lock to GPS satellites. Thus most of the data will be stored for post-mission processing.

SYSTEM CONFIGURATION

The four sensors that will be used in the UMMS are a NovAtel OEMStar GPS receiver, an ADIS16364 IMU from Analog Devices Inc., a KVH Azimuth 1000 digital compass, and a Kodak Digital Science DC260 digital camera. The hardware configuration of the low-cost navigation system is shown in Figure 1.

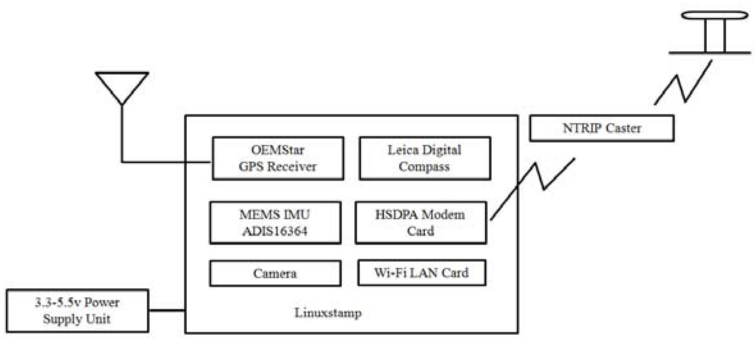

Figure 1. Hardware configuration of low-cost navigation system**.**

The NovAtel OEMStar is a low-cost, single frequency (L1) GPS receiver. It was chosen because it outputs code and carrier phase observations in a simple data stream, its pass-through logging feature facilitates system synchronization, and a data decoder was readily available. A Wi-Fi LAN card and HSDPA (high speed downlink packet access) modem is installed to communicate to connect to a NRTK NTRIP caster. Raw measurement data and antenna position will be transmitted as RTCM (version 2 or 3) data.

The ADIS16364 IMU was selected because it was readily available and El-Diasty and Pagiatakis (2009) showed that with appropriate calibration and stochastic modelling, an accurate INS/GPS navigation solution can be obtained. Specifications of the ADIS16364 IMU are given in Table 1.

Table 1. ADIS16374 IMU specifications (Analog Devices, 2009).

3 Gyros	
Initial bias error	±3 °/s
In-run bias stability	0.007 °/s
Bias temperature coefficient	±0.01 °/s/°C
Angular Random Walk	2 °/√h
3 Accelerometers	
Initial bias error	±8 mg
In-run bias stability	0.1 mg
Bias temperature coefficient	±0.005 mg/°C
Velocity Random Walk	0.12 m/s/√h

The KVH Azimuth 1000 digital compass was chosen because it met the accuracy requirements (±0.5°) and because of its small size, light weight, and low power consumption.

The Kodak Digital Science DC260 camera was chosen because of its low-cost and it has the ability to fix its focus at a specified setting, thus fixing the interior orientation of the camera between exposures. The camera is able to use an external flash to enable the time of exposure to be captured and recorded. It has a reasonable image size (1536 x 1024 pixels), large memory, and a self-contained power supply.

METHODOLOGY

3D Feature Extraction

The objective of the UMMS is to accurately extract 3D point coordinates in the mapping frame. The most common method to obtained 3D point coordinates from image point measurements uses a least squares bundle adjustment. This entails the exterior orientation (position and orientation at exposure time) and interior orientation (interior geometry and lens distortion) to be known for at least a pair of cameras. Thus the final accuracy of the 3D coordinates depends on the accuracy of the GPS position, INS position and attitude, camera position and attitude, system synchronization, system calibration, and sensor quality. These factors will be discussed in the following sections.

Time Synchronization

The georeferencing process requires different data streams to be time-synchronized. 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.

There are three main synchronization methods, depending on synchronization frequency. For low frequency applications, the PPS signal of the GPS receiver triggers the ancillary sensor by direct connection. The Novatel GPS receiver's pass through logging feature performs synchronization in this manner, this will be used to synchronize the digital compass' date stream. Medium frequency applications (tens of Hertz) may use an event marker, also provided on some GPS receivers, to time-tag mark events from the ancillary sensor. This feature can be used to time-tag the exposure times of the images captured by the digital camera (Ellum, 2001). Synchronization for high frequency (hundreds of hertz) systems may be performed using a centralized synchronization board. El-Sheimy (1996) explained how to reduce common synchronization errors in this method, such as hardware, transmission and timing-tagging delays when synchronizing an INS.

System Calibration

As mentioned above, system calibration is a prerequisite to extracting 3D information form imagery. The exterior orientation parameters are determined by a combination of GPS and INS, the interior orientation parameters by field or laboratory calibration.

The physical relationship between a camera, an inertial measurement unit (IMU), and a GPS antenna in a MMS is given by El-Sheimy (1996) and shown in Figure 2. The model transforms the position of the point of interest measured in the camera (image) coordinate system, r_i^c, to the position vector in the mapping frame, r_i^M, by using:

$$r_i^M = r(t)_{GPS}^M - R_b^M(t) R_c^b \left(r_{GPS}^c - s_i r_i^c \right) \tag{1}$$

where, at time t, r_{GPS}^M is the position of the GPS antenna, R_b^M is the rotation matrix between the mapping and IMU coordinate frames, determined using integrated IMU measurements, R_c^b is the rotation matrix between the camera and IMU frames, determined from boresight calibration, r_{GPS}^c is the vector of position differences between the GPS antenna and camera, determined from lever arm calibration, and s_i is the scale between the image and the mapping frames, determined using stereo techniques, laser scanners or DTM. Ellum and El-Sheimy (2002) examine three elements of integrated system calibration are examined: lever-arm calibration, boresight calibration and camera calibration.

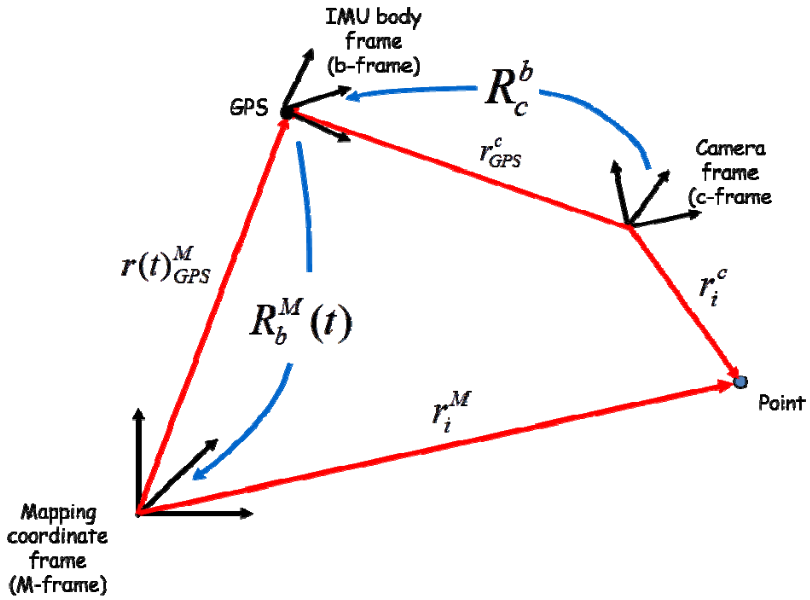

Figure 2. Georeferencing model.

Lever Arm Calibration. The lever arm between the GPS antenna and perspective center of the camera, r_{GPS}^c , is commonly determined by measuring it using conventional survey methods. The accuracy of this method is limited to the centimeter level because the phase and perspective centers of the GPS antenna and camera, respectively, cannot be directly observed. An alternative method is to use the difference in GPS antenna positions determined by the GPS observations, r_{GPS}^M , and the camera positions determined from a bundle adjustment, r_c^M . This technique requires a target field. The offset in the camera coordinate frame can be calculated using:

$$r_{GPS}^c = R_M^c\left(r_{GPS}^M - r_c^M\right) \tag{2}$$

where R_m^c is the rotation matrix between the mapping and camera coordinate frames, which is determined from the bundle adjustment. To improve the calibration accuracy, multiple images are used and the orientation angles is averaged or used in a least-squares adjustment.

Boresight calibration. Boresight calibration refers to the determination of the rotation matrix relating the axes of the IMU to the axes of the camera, R_b^c . Unlike the lever-arm calibration, it is not possible to directly measure the relative orientation parameters. The common method to perform this calibration requires R_M^c and R_M^b to be determined. This is done by collecting images of a known target field with the camera while collecting IMU measurements. Photogrammetric resection is used to estimate the camera orientation (ω, ϕ, κ) and determine the rotation matrix R_M^c . R_M^b is determined using the roll, pitch and yaw measurements from the IMU. R_b^c is then calculated using:

$$R_b^c = R_M^c\left(R_M^b\right)^T \tag{3}$$

To improve calibration accuracy, multiple images are used and the orientation angles is averaged or used in a least-squares adjustment.

IMU Calibration and Initial Alignment. Low-cost INS can experience rapid degradation in the navigation solution due to the low quality of the IMU. The error sources in gyros and accelerometers, mainly biases and scale errors related to non-orthogonalities of the axes, cause unstable errors in positions, velocities, and attitudes though the integration process. Calibration methods have been developed to remove systematic error, bias and scale errors.

The method used to calibrate a low-cost IMU considers that the Earth's spin cannot be observed as it is completely buried in high level white noise. Also, the bias and scale errors are temperature-dependent and they change from switch-on to switch-on and during the mission, thus field calibrations will be applied.

The multi-position calibration method described by Shin and El-Sheimy (2001) does not require precise alignment of the IMU axes and can be applied in the field. The main disadvantage of this method is the scale and non-orthogonality errors for low-cost sensors cannot be estimated because Earth rotational rate needs to be measured. Instead of using Earth rotational rate as an excitation signal, Syed et al. (2007) modified the multi-position calibration method using a rotational rate excitation from a single-axis turntable with 26 independent sensor positions (as opposed to the 18 positions in the Earth rotation method). This is the most suitable method to calibrate the low-cost IMU.

The inertial measurements are also contaminated with random errors, which mainly consist of a high frequency and a low frequency noise component. The high frequency component has white noise characteristics and can be reduced by using a low-pass filter. The low frequency component is characterized by correlated noise and can be modelled using random processes such as, random constant, random walk, Gauss-Markov, periodic random or autoregressive processes (Nassar, 2003). The most commonly used process is the first-order Gauss-Markov process.

The INS integration assumes the initial values of velocity, position and attitude. Therefore, an initial alignment is required before navigation. The inertial system can be initialized by first sensing the gravitational acceleration in a stationary and surveyed position. With this sensed gravity vector, the pitch and roll of the vehicle platform can be coarsely resolved; however, there is an ambiguity in determining the heading of the platform. The consumer grade inertial sensor's quality is not sufficient to gyrocompass by sensing the Earth's rotation to detect the east direction. Therefore, the inertial measurement yaw axis is aligned with the north direction from the magnetometer. This initial condition is sufficient for a fine alignment Kalman filter procedure.

Camera Calibration. Camera calibration must be performed before using any metric or digital camera in photogrammetric applications. The most common technique of camera calibration in close-range photogrammetry is self-calibration because it can be done quickly and it does not require specialised equipment nor specialised operators. This technique solves for the interior orientation parameters in a least-squares bundle adjustment. That is, the collinearity equations are augmented with additional parameters to account for adjustment of the calibrated principal point coordinates (x_p, y_p), lens focal length (f), two or three elements for symmetric lens distortion (k_1, k_2, k_3), two elements for tangential lens distortion (p_1, p_2). In addition, the position (X_o, Y_o, Z_o) and the orientation (ω, ϕ, κ) parameters of the camera are solved for. El-Sheimy (1996) provided details about the approach.

Inertial Navigation System

The inertial navigation system is comprised of an IMU, the platform on which it is mounted and the computer that performs the calculations needed to transform sensed accelerations and angular rates into navigationally useful information: position, velocity, and attitude. The dynamic equations show the behaviour of the states in terms of the linear (linearized) differential navigation equations (perturbed navigation equation). The nonlinear navigation dynamic system diagram is shown in Figure 3.

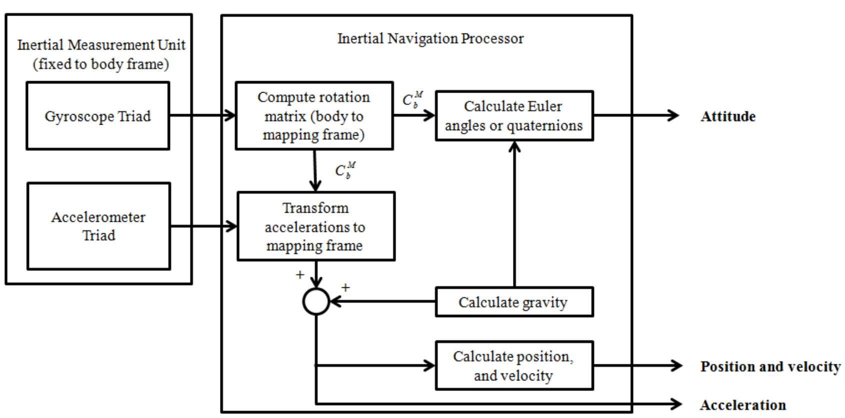

Figure 3. Inertial navigation processing.

In strapdown systems, the quaternion method to represent attitude is preferred over both Euler angle and the direction cosine methods because it offers accurate and efficient computation methods without singularities. Kong (2000) describes a quaternion approach of the INS algorithm for low-cost IMU.

Kalman Filter Design

A filtering technique is applied to optimally estimate the navigation solution (position, velocity and attitude) together with the sensor errors by combining the measurements from the GPS, IMU and digital compass in a Kalman filter. Hasan et. al. (2009) presented a comparative study of various Kalman filter configurations applied to air, land and marine navigation applications. Skaloud (1999) presented and analysed different Kalman Filter implementations used to estimate the state vector. The indirect (error state) implementation is very popular in terrestrial aided INS because the dynamics are low frequency error propagation equations. These equations are adequately represented as linear, as opposed to the highly non-linear model in the total state description. The closed-loop (feedback) implementation is chosen for this application because it generally performs better than the open-loop (feedforward) filter. The loosely-coupled (decentralized) filtering approach was chosen over the tightly-coupled (centralized) filter because of its modularity and smaller filter size.

With a loosely coupled integration, a navigation processor calculates position and velocity using GPS observables only. An external navigation filter computes position, velocity and attitude from the raw inertial sensor measurements and uses the GPS position and velocity to calibrate INS position errors δR velocity errors, while the filtered compass attitude is used to calibrate the INS angular errors ψ . The model is augmented by some dominant sensor errors, such as accelerometer biases $\delta\alpha$ and gyro drifts $\delta\omega$. In the feedback configuration, the estimates of the sensor errors are used to correct the raw inertial sensor measurements before they are integrated in the INS. Figure 4 illustrates the feedback configuration of the GPS/INS filter.

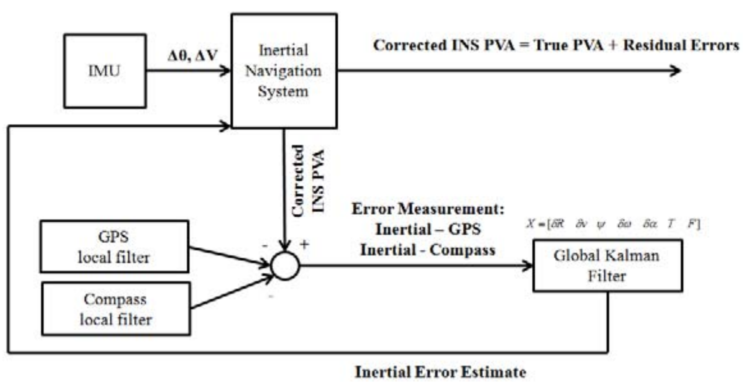

Figure 4. Kalman filter design**.**

CONCLUDING REMARKS

This project aims to develop an unmanned mobile mapping system (UMMS) using low-cost sensors on-board a low-cost unmanned ground vehicle (UGV). The UMMS will provide near-continuous positioning of the platform and simultaneously collect 3D geo-spatial data. Direct georeferencing will be used, with no external information, such as ground control, except for the GPS base station. Navigation will be based on single frequency differential GPS, loosely coupled with a low-cost digital compass and INS (Inertial Navigation System) based on MEMS (Micro Electronic Mechanical Systems) technology. The navigation system will autonomously provide position, velocity, and attitude data in a mapping reference frame together with measurements of linear acceleration and angular rate in the body axes. As storage capacity is limited due to payload restrictions, direct downlink of data through wireless communications is used in conjunction with onboard processing.

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