PROJECT FOR AN AUTONOMOUS MODEL HELICOPTER NAVIGATION SYSTEM

A. Guarnieri[a], A. Vettore[a], F. Pirotti[a]

[a] CIRGEO– Interdept. Research Center of Geomatics, University of Padova, Italy - cirgeo@unipd.it

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ABSTRACT

In this paper we present the first part of a potential project aimed at the development of an autonomous model helicopter. Such vehicle will be used for land photogrammetric surveying, for documentation of archeological sites, for detection of polluted areas at sea and for many other situations where remote surveying is a definite advantage due to accessibility.

Upon checking other projects in bibliography which deal with similar autonomous navigation systems developed with different approaches, we propose here a different solution based on the use of a pair of color digital CCD cameras, which acquire images in continuous mode. Positioning and imaging systems are composed by compact and as lightweight as possible sensors in order to reduce the total payload of the helicopter.

The undergoing project is structured according to a two-stage approach: firstly the model helicopter will be piloted by a human operator from a ground control station. Then, after successful testing in real applications, it is planned to develop an autonomous guidance system resorting to robust control tools and more advanced results in the field of robotics.

Though the project has not yet been financed, the presented system can be regarded as a potential alternative to develop surveying applications in areas which represent a difficult task for existing ground-based mobile mapping systems.

An overview on the selected hardware components and on data integration and processing will be provided.

1. INTRODUCTION

In the last years UAV (Unmanned Aerial Vehicle)-systems became very actractive for various commercial, industrial, public, scientific and military operations. The tasks include pipeline inspection, dam surveillance, photogrammetric survey, infrastructure maintenance, inspection of flooded areas, fire fighting, terrain monitoring, volcano observations and so on. The name UAV denotes all vehicles, which are flying in the air with no pilot onboard and with capability for remote controlling the aircraft. Within this category, helicopters play an interesting role as they are suited for many applications for which fixed-wing aircraft show operational difficulties. Indeed such crafts offer more flexible manouvers, as they allow for vertical take-off and landing, hovering and side flight. These impressive flying capabilities require a well trained pilot to be fully and effectively exploited; moreover the flight range of the piloted helicopter is limited to the line-of-sight or the skill of the pilot to detect and follow the orientation of the helicopter. Such issues have motivated the research and the design for autonomous system guidance which could both stabilize and also guide the helicopter precisely along a reference path. A number of works have been therefore published about the development of fully autonomous or partially-autonomous helicopters (Amidi *et al.*, 1998) (Shim *et al.*, 1998) (Miller and Amidi, 1998) (Vaughan *et al.*, 2000). Small autonomous helicopters have demonstrated to be a useful platform for a number of aerial applications such as aerial mapping and photography, surveillance (both military and civilian) and powerline inspection.

The goal of this work is to present a project for the development and implementation of a model helicopter providing a relatively low-cost and useful surveying platform for applications such as agricolture and land management and monitoring. In a first stage of the project we planned to implement a remotely guided system through radio link with a ground-based control station and in a second stage, after successful testing in real environments, the system will be upgraded by adopting an autonomous guidance system.

In the following sections we will present, at design level, the system architecture, describing the different positioning and measurement sensors adopted and how they will be integrated each other in order to realize a low cost mini-MMS.

2. SYSTEM OVERVIEW

The primary goal of our model helicopter is to provide the user with a top view of the territory without resorting to more expensive classical aerial photogrammetry. The system is designed to collect data for mapping and land monitoring purposes working on areas which represent a difficult task for already existing ground-based mobile mapping systems. From this viewpoint our system can be regarded as a lightweight and low cost complementary mapping tool to existing MMS. According to project specifications, the model helicopter will be used to survey areas of limited extent such as open mines, little rivers, cultivated fields, not only to monitor the land evolution and local changes in the terrain morphology but also to discover illegal uses of land resources. A further example of its application deals with the mapping of small water channels located along the Venice lagoon, which cannot be accurately mapped through classical aerial photogrammetry. These channels are of great interest for undergoing biological studies on the lagoon ecosystem.

Several kinds of UAV-helicopters have been so far developed for photogrammetric data acquisition and terrain or object modeling. For example in (Nagai, 2004) the developed system integrates laser scanner and CCD-cameras with GPS/INS data for constructing digital surface model. This system use a Subaru helicopter with a payload of 100 kg and diameter of the main rotor of 4.8 m. According to the range (3 Km) and altitude (2000), the helicopter can be defined as a mini or close range UAV. In (Sik, 2004) an alternative mini UAV-helicopter is presented, which was used as a photographic system for the acquisition of ancient towers and temple sites. The helicopter should replace high camera tripods and ladder trucks, which are uneconomical in cost and time. The helicopter Hirobo & Eagle 90 has a main rotor diameter of

1.8 m of the main rotor and a payload capability of 8.5 kg. The helicopter could carry different camera systems like miniature (35 mm), medium (6 cm x 4.5 cm) and panorama (6 cm x 12 cm) format cameras and video cameras. A gimbal was designed as a buffer that can absorb noises as well as vibrations. Onboard the system, a small video camera is installed too, which is connected to the ground station to transmit the images to a monitor in real time.

Our proposed mapping system differentiates from existing UAV-helicopters mainly because of the adopted imaging system and the maximum flying height. Indeed we planned to employ a model helicopter equipped with GPS, orientation sensors, two color digital CCD cameras, working in continous mode, synchronisation devices, data transfert unit and batteries as power source. In order to keep the system as compact and lightweight as possible, digital images and positioning data will be sent to the ground control station through wireless communication (radio link). Of course, if such solution should fail, a more complex data storage system, such as on-board CPU and Hard Disk, will be evaluated.

Figure 1 shows a close-up view of the model helicopter we selected for our project, related technical specifications are reported in table 1.

Figure 1: Model helicopter Raptor 90 v2

Table 1: Main technical specifications of the Raptor 90 v2

Fuselage length	1410 mm
Fuselage width	190 mm
Height	465 mm
Main rotor diameter	1580 mm
Tail rotor diameter	260 mm
Total weigth	4.8 kg

All the sensors will be mounted on a suited platform fixed below the helicopter cell between the landing vats. The imaging system will be based on a pair of color lightweight digital cameras (Sony kpc-s700cb) featuring a CCD 1/3" SONY, Super Had (Figure 2), with a size of 30 mm (height) x 30 mm (width) x 28,5 mm (depth). Cameras can acquire images at 25 fps, i.e. in continuous mode, and send the data to remote control station via built-in wireless communication interface. The two CCD cameras will be properly placed on the platform and tilted in order to provide an image overlap between right and left camera of 70%. The baselength will be established according to such requirement and the FOV of the cameras.

Position and attitude of the model helicopter will be provided by on-board GPS receiver and IMU sensor, which will be also used for the direct geo-referencing of the collected images, thus without any ground control points.

As we are at the project stage, such sensors have been not yet acquired and we are evaluating different solutions. For instance the GPS receiver should be very compact, leightweight, with capabilities for the storage of the attitude data as output from the IMU and for sending the whole dataflow to the ground control station through a radio link. An example of this kind of receiver is represented by the Novatel FLEXPAK-G2L (only 350 gr), shown in figure 3.

Concerning the orientation measuring system, we are evaluating between the use of a well proven IMU or MEMS devices, as the latter can be implemented in cheaper and more compact enclosures.

Figure 2: The Sony CCD digital camera

Figure 3: The Novatel FLEXPAK GL2

As mentioned in the previous section, in the first stage of the undergoing project, the helicopter will be piloted in manual mode through a pulse-width modulated (PWM) control unit. Therefore, considering the need for a continuous view of the helicopter and the FOV of the cameras, we forsee to limit the flying height to 100 – 150 m, which is hovever enough for our surveying purposes.

3. MULTI-SENSOR INTEGRATION

Typical system workflow will consist of the following steps: flight planning, image and position data acquisition, measurement of tie points, bundle adjustment and DSM (Digital Surface Model) generation, orthophoto production and derivation of other products.

Concerning the flight planning, the trajectory tracked by the model helicopter will be based on available orthophotos and/or cadastral maps of the area of interest. Unlike UAV systems, as we will manually pilot the helicopter, we do not need to establish any stop points along the trajectory, however the distance between adjacent flying paths will be defined according to the required cross-track overlap of acquired stripes (30 % at least). Similarly, the actual value for the along-track overlap will be set taking into account following factors: the minimum flying speed allowed before the stall of the aircraft, the Field-Of-View of the cameras and the frame rate selected for the image acquisition.

While surveying the targeted area, following data will be acquired: base station GPS data, on-board GPS data, attitude data and CCD images. Though collected with different rates, the data will be properly synchronized each other.

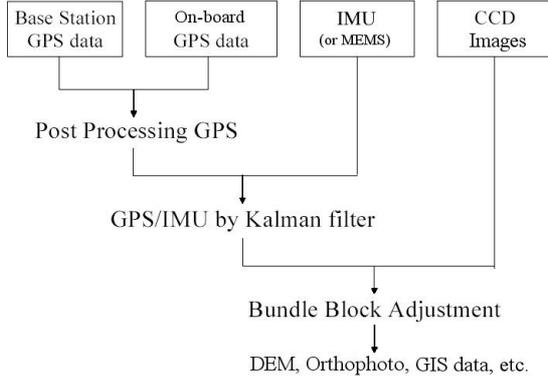The data processing pipeline is summarized in figure 4.

Figure 4: Data processing workflow

Firstly, kinematic GPS post-processing is conducted by using already available commercial software, then processed GPS data and IMU (or MEMS) data are integrated with Kalman filter operation. Thirdly, bundle block adjustment of CCD image is made with the support of position and attitude measurements provided by GPS/IMU sensors. At the end of this pipeline different products can be derived such as DEMs, orthophotos and a wide variety of useful data for GIS applications.

3.1 GPS/IMU integration

In our surveying system, we designed to apply so-called direct geo-referencing of acquired digital images. According to this approach, information about position and orientation of both CCD cameras will be provided by on-board GPS/IMU sensors within the data post-processing stage. It is well known that IMU sensors provide measurements (linear accelerations and angular velocities) at higher rate wrt. GPS, allowing trhough proper data integration to determine the camera pose even between two GPS epochs. Though IMU have a rising quality, they are still affected by systematic errors (i.e. drifts) which can be adequately corrected by mean of a Kalman filter.

In our case, the navigation solution will be provided by combining GPS and IMU data with an Extended Kalman filtef (EKF), in a loosely-coupled approach. Two systems will therefore run indipendently and no IMU data are used by differentially corrected GPS measurements. The generalized structure of such filtering strategy is shown in figure 5.
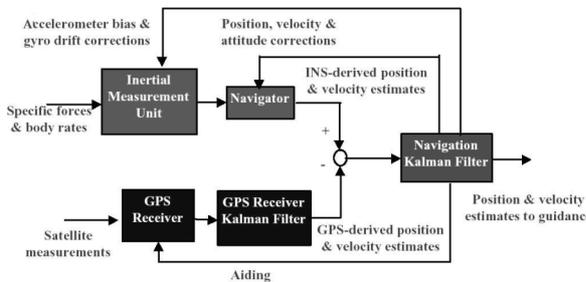

Figure 5: Loosely-coupled KF for GPS/IMU integration

Motion equations for the model helicopter are derived using Newton-Euler equations. Since IMU provide angular rates and linear accelerations, the matrix equations used for data integration is the following:

$$
\begin{aligned}
\dot{p} &= v \\
\dot{v} &= Ra^b + b_I g \\
\dot{R} &= R\omega^b
\end{aligned}
\tag{1}
$$

where p, v are the position and velocity vectors of the origin of the body frame w.r.t. the navigation frame respectively, R is the rotation matrix between these two frames, $b_I = [0\ 0\ 1]^T$, g is the gravitational constant and a^b and w^b are the body linear acceleration and angular rate respectively.

For computation efficiency quaternion $q = [q_s,\ q_x,\ q_y,\ q_z]^T$ is used instead of matrix R to estimate rotation parameters. Furthermore quaternion representation avoids the occurance of singularities as if Euler angles are used. Thus the motion equations can be rewritten as:

$$
\begin{bmatrix} \dot{p} \\ \dot{v} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} v \\ Ra^b + b_I g \\ Wq \end{bmatrix}
\tag{2}
$$

where the rotation matrix R assumes the form reported in (4) and W denotes following 4 by 4 matrix

$$
W = -\frac{1}{2}\begin{bmatrix}
0 & \omega_z^b & \omega_y^b & \omega_z^b \\
-\omega_z^b & 0 & -\omega_z^b & \omega_y^b \\
-\omega_y^b & \omega_z^b & 0 & -\omega_z^b \\
-\omega_z^b & -\omega_y^b & \omega_z^b & 0
\end{bmatrix}
\tag{3}
$$

$$
R = \begin{bmatrix}
q_s^2 + q_z^2 - q_y^2 - q_z^2 & 2q_zq_y - 2q_sq_z & 2q_zq_z + 2q_sq_y \\
2q_zq_y + 2q_sq_z & q_s^2 - q_z^2 + q_y^2 - q_z^2 & 2q_yq_z - 2q_sq_z \\
2q_zq_z - 2q_sq_y & 2q_yq_z + 2q_sq_z & q_s^2 - q_z^2 - q_y^2 + q_z^2
\end{bmatrix}
\tag{4}
$$

Defining the state vector as $x = [p^T\ v^T\ q^T]^T$ and after linearization and time discretization of the system dynamics, we obtain the following state equation:

$$
x(k+1) = F(k+1,k)x(k)
\tag{5}
$$

where $F(k+1,k)$ is the state transition matrix and $k = 1,2,…$ is the state index. Using the position information provided by DGPS data, the measurement vector $z = h(x)$ is then employed for the construction of the EKF model, which can be expressed as:

$$
\begin{aligned}
x(k+1) &= F(k+1,k)x(k) + G(k+1,k)w(k) \\
z(j+1) &= H(j+1)x(j+1) + v(j+1)
\end{aligned}
\tag{6}
$$

with $G(k+1,k)$ as the disturbance distribution matrix, $H(j+1)$ as the observation matrix obtained by the linearization of $h(x)$, $w(k)$ as the disturbance noise and $v(j+1)$ as the measurement noise with associated covariance matrices and with $j = 1,2,…$ as the measurement time index.

Instead of computing the Kalman gain matrix K iteratively, the steady state gain matrix can be used for the correction, reducing significantly the computation time. The EKF is then constructed according to the principle of prediction-correction and can be written as follows:

$$\hat{x}(j+1) = \hat{x}^p(j+1) + K\left(z(j+1) - h(\hat{x}^p(j+1)) \right) \quad (7)$$

where $\hat{x}(j+1)$ is the filtered state and $\hat{x}^p(j+1)$ is the prediction state as computed from the state equation.

Finally for each exposure time, position and attitude of both cameras can be estimated from EKF output and taking into account the various offsets between GPS antenna, the origin of the body frame (fixed with the IMU) and the origin of the imaging system.

3.2 Bundle block adjustment of digital images

Bundle block adjustment is a non linear least squares optimization method based on the use of tie-points inside an image block. By determining an object point through intersection from more than two images, bundle block configuration provides local redundancy for gross error detection and increases both the reliability and the accuracy of object reconstruction. In our case, we will use a BBA procedure to improve the camera position and attitude estimates as output by the EKF and to perform the spatial resection of collected images.

By application of semiautomatic or fully automatic point matching algorithms, DEMs of the surveyed areas will be derived along with orthophotos and other GIS data, according to the final user requirements.

4. FUTURE DEVELOPMENTS

In the second part of this project, effort will be spent for the realization of an autonomous navigation system, based on a continous time control for the stabilization of helicopter flight dynamics. In the mathematical model we are developing the vehicle will have four inputs: the main rotor collective pitch, which will stabilize the vertical shift, thus permitting take-off and vertical movement; the main rotor longitudinal and lateral cyclic pitch, which will control the pitch and roll angle (respectively the across-path and along-path movement); the tail rotor lateral cyclic pitch which will control the yaw angle. At the present time, the starting point of our dynamic model is based on the assumption of the helicopter as a rigid body moving in 3D space in response to gravity, aerodynamics and propulsion. More in detail, the state vector is defined as

$$x = \begin{bmatrix} P \\ v^p \\ R \\ \omega^b \end{bmatrix} \quad (8)$$

where P and v^p denote the position and velocity vectors of helicopter center of mass in the world reference frame, R is the rotation matrix of the body axes relative to the world axes and the w^b represents the angular velocity vector.

The controls to be used are summarized in following vector u

$$u = \begin{bmatrix} \theta_M \\ \theta_T \\ a \\ b \end{bmatrix} \quad (9)$$

where q_m, q_T, a and b denote respectively the main rotor collective pitch, tail rotor collective pitch, longitudinal cyclic pitch and lateral cyclic pitch.

The state equation will then consist of the translational and rotation kinematic and dynamic equations:

$$\begin{bmatrix} \dot{P} \\ \dot{v}^p \\ \dot{R} \\ \dot{\omega}^b \end{bmatrix} = \begin{bmatrix} v^p \\ \frac{1}{m}Rf^b + b_I g \\ R\hat{\omega}^b \\ \mathcal{I}^{-1}(\tau^b - \omega^b \times \mathcal{I}\omega^b) \end{bmatrix} \quad (10)$$

where $b_I = [0\ 0\ 1]^T$ and g is, again, the gravity acceleration, while f_b and t_b are the resulting force and torque acting on the body, respectively. Both force and torque are considered as functions of the control vector u. In the proposed model, we assume that for control purposes, position coordinates (X, Y, Z) and attitude angles (roll, pitch and yaw) will be obtained by the measurement sensors described in previous sections.

CONCLUSIONS

In this paper we have presented a potential project aimed at the development of a low-cost MMS based on an model helicopter. The system is intended to collect directly geo-referenced color digital images flying at small height on areas of limited extent. After photogrammetric processing, such images will be used to produce DEMS, orthophotos and other kind of GIS data which can be used fo several purposes related to land management. Given the capability of survey-ing areas of limited access, the proposed model helicopter can be regarded as a complementary mapping tool of already existing and well proven ground-based mobile mapping systems.

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