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Lighter-Than-Air UAV with slam capabilities for mapping applications and atmpsphere analysys

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Abstract. Exploration of the planets and the moons of the Solar System has, up to now, been performed by remote sensing from Earth, fly-by probes, orbiters, landers and rovers. It must be outlined that remote sensing probes and orbiters can only provide non-contact, limited resolution imagery over a small number of spectral bands; on the other hand, landers provide high-resolution imagery and in-situ data collection and analysis capabilities, but only for a single site; while rovers allow imagery collection and in-situ science across their path. These characteristics of the described means highlight how mobility is a key requirement for planetary exploration missions. Autonomous Lighter-Than-Air systems can be used to explore unknown environments without obstacle avoidance problems, mapping large areas to different resolutions and perform a wide variety of measurements and experiments while traveling in the atmosphere.
Sensor fusion between Inertial Measurement Unit (IMU) and vision systems can be used to support vehicle navigation and variable resolution surface mapping. In this work a minimal sensor suite composed by a navigation-grade IMU and stereo camera pair has been studied. At altitudes below 100 m stereo vision techniques can provide range, bearing and elevation measurements of a set of scattered points on the planetary surface. Simultaneous Localization and Mapping (SLAM) extended Kalman filter algorithm has been adapted to deal with stereo camera observations. Sensor fusion with IMU measurements is used to track rapid vehicle movements and to maintain the vehicle position and attitude estimation also if, for a limited period of time, no vision measurements are available. Moreover the SLAM algorithm produces a scattered points map of the complete traveled area. In this work we analyse the dynamics of the airship in response of the encountered environment of Titan moon. Possible trajectories for an extended survey are investigated; this allows to have a precise quantitative analysis of the power necessary for a journey on the satellite. Analyses are conducted both in a quiet situation with no wind and in wind conditions. A 1.2 km x 1.4 km region is selected as baseline: time necessary for performing a complete survey is investigated.

Key words. Airship - Autonomy - Navigation & Mapping - SLAM

1. Introduction

Up to now, planetary exploration has used landers and rovers for in situ measurements

Send offprint requests to: G. Colombatti and orbiters for remote sensing. However, landers and rovers can only study specific sites and limited areas of a planet: square meters for landers and square kilometers for rovers. Analysis of landing sites performed from Earth or orbiters require them to be as flat as possible in order to have a safe landing for landers and rovers. But, the flat sites are, usually, not so scientifically interesting as regions where different morphologies are present or where there is the presence of liquid components (like methane for Titan). For the above reasons, mobility will be essential for space exploration robots because enables extensive geographical coverage and in-situ science (Fink, W. et al. 2006; Lorenz R.D. et al. 2008; V. Kerzhanovich et al. 2009). In this framework robotic Lighter-Than-Air (LTA) vehicles must be considered as a strategic platform for the exploration of planets and moons with an atmosphere, with Earth, Venus and Titan being key candidates (Cutts, J. 1999; A. Elfes et al. 2006; Colozza, A. 2004; J. Hall et al. 2006).

LTA vehicles have, on one hand, low power requirements and, on the other, extended mission duration (Colozza, A. 2004b); in particular airships provide precise navigation and path following with respect to simple balloons in which only altitude can be controlled. Thanks to their navigation capabilities aerobots can perform both in-situ measurements across huge distances, and perform wide areas long-range surveys as well as station keeping for long-term monitoring of local phenomena (Geneste, E. et al. 2001). In fact, airships can perform surface imaging or remote sensing measurements at different resolutions simply changing their altitude. A high altitude, low resolution coverage of a wide area can highlight interesting sites that can be mapped at higher resolution with a second inspection at low altitudes. In addition to the unique imaging and remote sensing data collection capabilities of air vehicles, they also provide a measure for direct sampling of a planet's atmosphere. This sampling can be performed over a region of the atmosphere and potentially at different altitudes: for example, an airship could be used to sample the atmosphere over a region looking for signs of life.

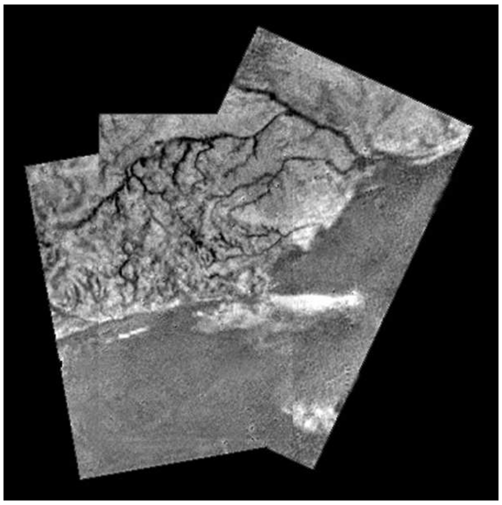

Fig. 1. This mosaic shows a high ridge area including the flow down into a major river channel from different sources; possible scenario for a regional survey through airship. (Credit: ESA/NASA/JPL/University of Arizona).

Moreover aerobots can also transport and deploy scientific instruments and can be used in conjunction with land based (rovers and landers) and space based (orbiters) exploration means to provide a complete set of capabilities for planetary exploration. In the last decades many autonomous and remotely operated vehicles for field robotics applications have been developed. Nowadays there are a lot of proposed robotic architectures for Unmanned Vehicles and the research in this field has gained impressive results (J. Hall et al. 2009). In the space exploration field the Mars Rovers have shown that the technology is mature to provide autonomous exploration capabilities. This justifies the study of navigation capabilities of an autonomous aerobot equipped with a minimal sensor suite composed by a navigation grade Inertial Measurement Unit (IMU) and a stereo vision system. In fact the airship must integrate data from several different instruments on board and identify autonomously the desirable site for sampling when possible.

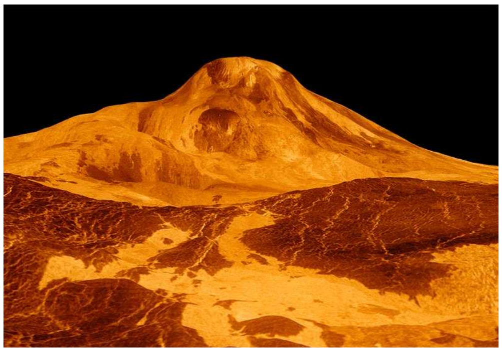

Fig. 2. Maat Mons is displayed in this computer generated three-dimensional perspective of the surface of Venus. Possible harsh environment area explored by Venus with LTA vehicle with SLAM capabilities (Credit: JPL).

2. Applications

Autonomous airships have demonstrated their exceptional ability for near-surface investigations and furthermore the capacity for regional-scale coverage on Earth and their potential use for space exploration (Atkinson, D. 1999; A. Elfes et al. 2008). Airships have a wide spectrum of applications as observation and data acquisition platforms. They can be used in several fields related to geology, physics and climate research and monitoring (Lorenz R.D. et al. 2006). Airships are platforms from which perform measurements not previously available to scientists due to difficulties in reaching the desired sites (liquid areas, volcanic regions, sandy sites, etc.)(J. Hall et al. 2002, 2009) (Fig. 1). Possible terrestrial and planetary applications are:

- Meteorology and Circulation
- Atmospheric Characterisation
- Near Surface Atmospheric Chemistry
- Surface studies
- Geological investigations
- Hydrogeology analysis
- Surface and Interior Interactions

Airships have demonstrated to be the possible mean for reducing the gap between high resolution analysis performed by landers and wide surveys carried out by orbiters. In fact airships can accomplish both in situ and remote measurements of atmospheric parameters, soil formations and geological features unavailable for investigations by landers and rovers, such as canyons, valleys, volcanic and impact craters and liquid areas (Fig. 2).

The airship use will enable the scientific investigations of regions not at all accessible, up to now, by other means (Fink, W. et al. 2006):

1. canyons (e.g. Devana Chasma, a big rift valley on Venus);
2. mountain ranges (e.g. Isthar Terra on Venus);
3. sites of suspected magmatic-driven uplift and associated tectonism and possible hydrothermal activity (e.g. Maxwell Montes on Venus);
4. polar ice features;
5. suspected ice deposits within impact basins (e.g.,)
6. volcanoes of diverse sizes and shapes (e.g., Venus);
7. ancient terrains and associated volcanism (e.g., Venus)
8. regions indicating potential recent hydrologic or hydrocarbon activities such as spring-fed seeps (e.g., Titan);
9. chaotic terrains
10. dunes (up to 1500km by 200 km on Titan) (Lorenz R.D. et al. 2006)
11. liquid areas (lakes and rivers) (e.g., Titan)

All of the above features and many other interesting areas on the planetary bodies of the Solar System are fundamental for acquiring knowledge for space exploration missions and are, in particular, key examples for sample return missions. These target features contribute to the success in identifying potential life-containing habitats.

Furthermore, an autonomous air vehicle is able to change the planned path in order to visit scientifically interesting areas observed during navigation and can change its altitude in order to respond to possible emergencies (sand storms, high winds, etc.).

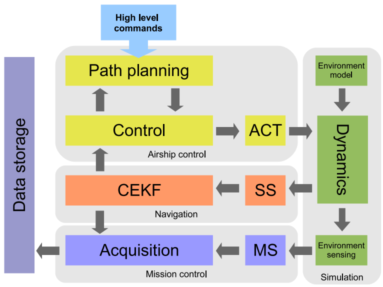

Fig. 3. System architecture and simulation procedure. The simulation software and implemented algorithms are organized to reflect the real system architecture.

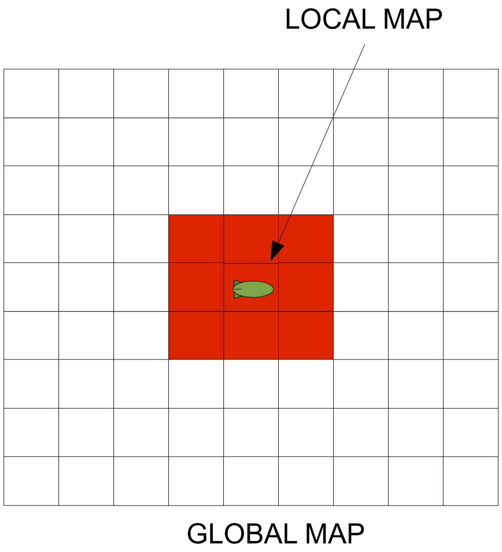

Fig. 4. Filter update: consider only points closer to the vehicle depending on the stereo vision range capabilities (Local Map); the Global Map is updated at lower rate.

3. Operations concept

A standard exploration mission can be divided in different tasks. Starting from the desired spatial and temporal measurement distribution, a nominal path and the flight time can be computed on earth and preloaded on the on board navigation control system. In this phase the airship dynamic model is used to control the trajectory and the velocity of the vehicle. The flight time and the necessary power will depend on the airship velocity with respect to the atmosphere and, consequently, different nominal paths are defined for different possible wind conditions. If necessary the flight can be divided in a set of *measurement sessions* compatibles with the airship autonomy. Finally measurements are scheduled with respect to mission time.

Prior to mission beginning, the airship is *aligned* with respect to a known position (respect a feature on ground or an orbiter position) to set initial navigation conditions. An *initial alignment* procedure can be repeated for each measurement session to provide more accurate mapping and position referencing of the collected data. This alignment procedure can be based on the link between the aerobot and an orbiter, can be done with respect to a beacon released from the airship at the beginning of its mission or can be performed with respect to known features on the planetary surface. At this point the nominal path and measurement scheduling are sent to the airship and uploaded on the navigation system's memory and the measurement session can start. As shown in Fig. 3 the airship is able to follow the nominal path and to perform scheduled measurements. The navigation module provides in real-time the airship position w.r.t the initial position, necessary for referencing the acquired measurements and for the trajectory control.

If unexpected events (such as winds) force the airship away from the nominal path, the navigation system is able to re-plan its trajectory and the measurement sequence in order to recover the trailing of the original mission profile. If the recovery of the nominal mission is not possible the procedure can be aborted and the airship can begin a predetermined command sequence to reach a safe configuration (for example increasing its altitude to overfly possible obstacles). At the end of the mission, acquired data (both from mission and system sensors) can be downloaded on ground and processed.

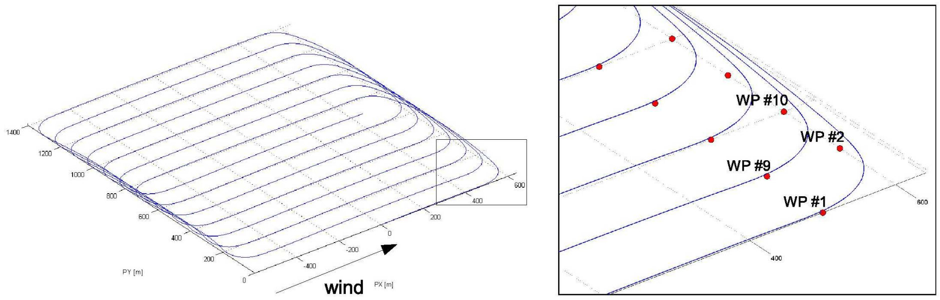

Fig. 5. Airship trajectory for full coverage of 1200x1400m area (left). Altitude of the simulation is 100m; separation between each loop is 100m in order to have a sufficient overlapping in the stereo-camera footprints for SLAM. This flying technique allows to have a complete coverage of the mapped area for navigation and science investigations. Image showing the waypoints during the turn and the displacement due to wind (right).

4. Simultaneous navigation and mapping

Thanks to their multipurpose capabilities, vision systems can be employed to perform vehicle motion estimation as well as mapping tasks. In particular stereo-vision techniques can provide measurements of range, bearing and elevation of a set of scattered points of the unknown surrounding environment. These measurements can be used to incrementally build a map of the covered area and simultaneously estimate airship position and attitude within the constructed map. Simultaneous Localization and Mapping (SLAM) techniques try to solve this problem for a moving robot capable of acquiring *relative observations* of a number of unknown land-marks. From the first approach (Smith, R.C. and Cheeseman, P. 1986), SLAM has been formulated and solved as a theoretical problem in a number of different forms and implemented in a number of different fields from indoor to outdoor robots, underwater and airborne systems (Durrant-Whyte, H. and Bailey, T. 2006; Bailey, T. and Durrant-White, H. 2006). Among the different approaches to face the SLAM problem, the Extended Kalman Filter (EKF) is the most fashionable and efficient. Moreover Extended Kalman Filter can take advantage of Inertial Measurements Unit (IMU) data to track high frequency movements of the air vehicle (Kim, J.H. and Sukkarieh, S. 2003, 2007). The SLAM EKF state vector is composed by the vehicle pose and the position of each mapped feature; therefore the dimensions of the state vector grow as the vehicle moves and maps new features. Therefore for mapping extended regions EKF could not be applied to SLAM problem directly. To compensate for this shortcoming the Compressed Extended Kalman Filter (CEKF) (Guivant, J. and Nebot, E. 2001) can be used; only the part of the state vector and of the covariance matrix relative to the features closer to the vehicle are updated at each time step. The full state update (high computational load) is postponed in time and performed at a lower rate (see Fig. 4).

Implemented SLAM algorithm relies on a CEKF. During the *propagation* steps IMU data are used to predict the vehicle state. IMU data are useful to track rapid vehicle movements and oscillations. A navigation grade IMU can also guarantee that state estimation can be maintained even if vision subsystem do not provide good measurements for short periods of time. When landmarks measurements are

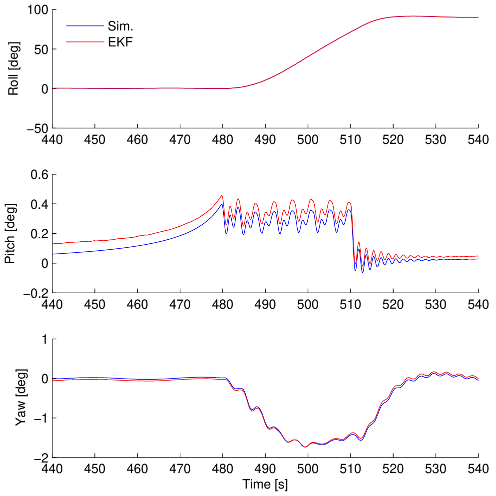

Fig. 6. Estimated attitude: errors results to be less than 0.15 °. The filter is able to track the small airship oscillations due to navigation control with good accuracy; vehicle attitude is very important to perform scientific instruments pointing and measurements compensation.

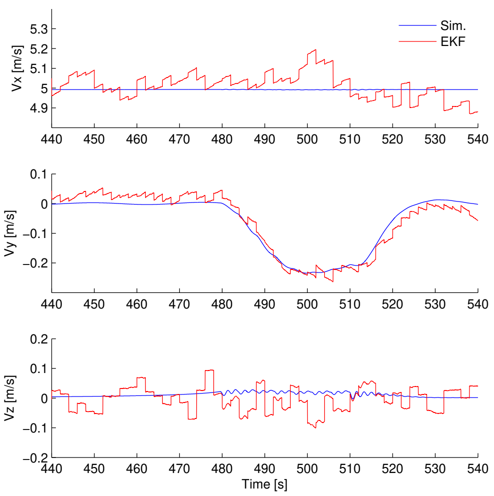

Fig. 7. Estimated velocity: errors results to be less than 0.2 m/s. Velocity estimation accuracy is directly related with vision system performances and acquisition frame rate, note that vision system do not perform direct velocity measurements.

available the filter *update* stage provides a refinement of the whole filter state. If a mean level of features are present on the imaged scene the filter becomes stable and the vehicle position and map error uncertainties become bounded.

5. Trajectory simulation

Navigation capabilities have been evaluated on a set of several simulated trajectories for an airship on Titan. Each test trajectory has been defined in a way to map a given area following the procedure described in §3. Airship dynamics, control system and actuators dynamics as well as the effects of environmental disturbances have been accurately modeled to produce trajectories that represent well a real application scenario. A detailed description of the whole airship modeling can be found in La Gloria, N. et al. (2009). Simulations have been conducted considering an IMU sampled at 100Hz with gyroscope of 0.005 $°/h$ class and accelerometers of 50 μg class. CEKF update frequency is 0.5 Hz for stereo vision mode.
The CEKF capabilities with stereo vision aiding, have been tested for the mapping of a 1200x1400m area at 100m altitude; used trajectory has been plotted in Fig.5. The following ranges have been simulated:

- Airship velocities: 3.0 5.0 -7.0 m/s
- Wind velocities: 0.0 1.0 2.0 m/s
- Altitude: 100 m
- Way point change: 30 m

6. Mapping and trajectory determination

Attitude determination is shown in Fig.6 during a left turn maneuver. The max error in attitude estimation is $< 0.15°$, the CEKF is able to track with good accuracy the airship oscillations due to the trajectory control; attitude knowledge is important to perform instruments pointing and to compensate remote sensing measurements such as radar, lidar and high resolution imaging devices.

CEKF techniques allow to estimate the velocity with a max error of $< 0.2\,m/s$ see Fig.(7). It must be noted that IMU nor stereo

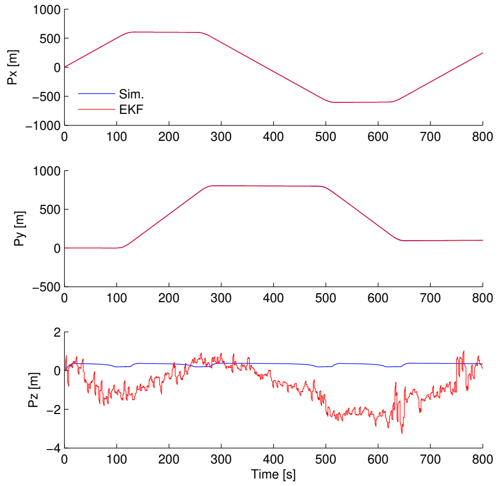

Fig. 8. Estimated position: errors results to be less than 5 *m*.

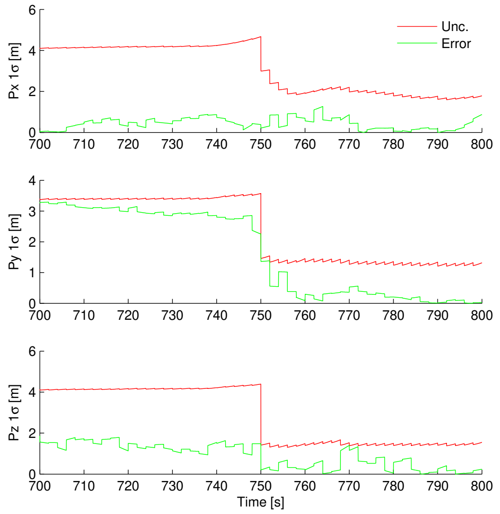

Fig. 9. Position 1σ uncertainty and position errors at loop closure.

vision system provide direct velocity measurements. These results are completely repeatable during the whole trajectory confirming the filter stability and that the navigation errors are bounded.

Error in the estimated position is $< 5\,m$ for the whole trajectory, this confirms the capability of this system to reference mission data. Position errors result to be bounded from the stereo vision measurement performances as expected. Mapped points are well correlated thanks to the vehicle trajectory and the stereo vision measurements, these correlations are maintained by the filter in the state covariance matrix. In particular, when the vehicle closes one loop, the navigation system re-observes previously mapped landmarks, updates their positions (thanks to the new measurements) and also, using the cross covariance informations, it is able to improve the vehicle position (Fig. 8, attitude and the whole map estimation. This loop closure process is shown in Fig.9, note that the trajectory is designed to guarantee the loop closure periodically during the mission. Finally in Fig.10 mapped landmarks position errors with respect to ground truth are shown. After loop closure, the 63% of the land-marks are positioned with an error $< 2m$, 31% results in the range $2-5m$, 5% results in the range $5-10m$ and only the remaining 1% has an error greater than 10m. Also the map error depends strongly from the stereo-vision performances. Flying at lower altitudes, or changing cameras parameters and baseline result in higher measurement accuracy.

7. Conclusions

A complete simulator has been developed for planetary exploration and investigation. A sensor suite for airship navigation has been studied. Navigation performances have been assessed through simulation in a realistic scenario. At altitudes below 100 m the on-board stereo vision system is used. Attitude estimation error results to be $< 0.15\,^{\circ}$, velocity estimation error is $< 0.2\,m/s$, position error is $< 5\,m$ and map points position error is $< 5\,m$.

Navigation system performances are suitable for vehicle navigation, scientific instruments pointing and measurement referencing, moreover a rough map of the explored area has been produced without any a priori information about the traversed zone.

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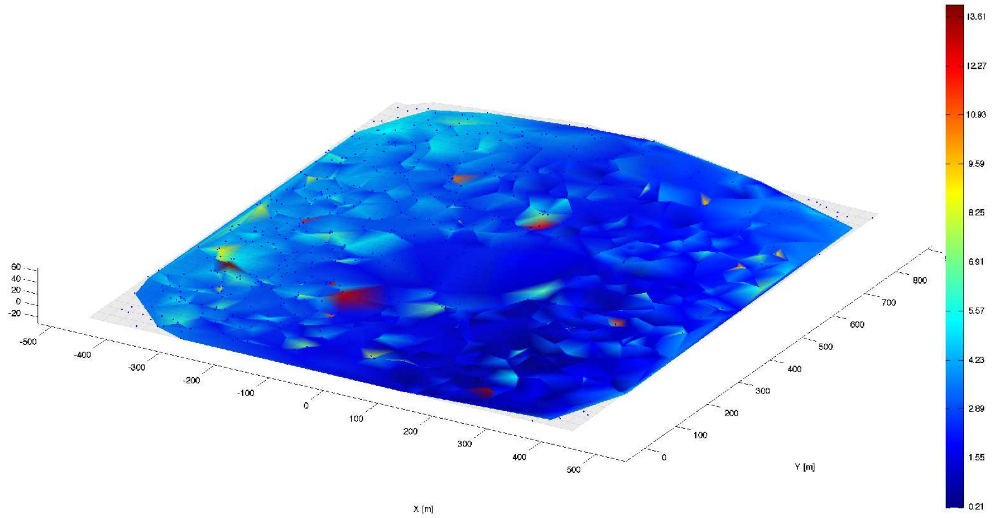

Fig. 10. Estimated map error. Mapped landmarks represent the surface of the traversed area, and are used to build a mesh of the observed surface. SLAM has been tested on a hill Digital Terrain Model (DTM). The mesh, colored proportionally to the estimation error, is superimposed to the real DTM.

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