Aerobot Autonomous Navigation and Mapping for Planetary Exploration

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Abstract

Mobility is a key requirement for planetary exploration missions. Autonomous airships (aerobots) can be used to explore unknown environments without obstacle avoidance problems, mapping large areas and complex land systems (such as canyons or pluvial areas) to different resolutions and perform a wide variety of measurements and experiments on planetary surface and on the atmosphere too.

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. Vision subsystem 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 monocular and 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 time period, no vision measurements are available. Moreover the SLAM algorithm produce a scattered points map of the whole traveled area.

In this work vehicle position, attitude and mapping estimation accuracy have been assessed through tests on a set of simulated vehicle trajectories on Titan to show the reliability of this navigation solution.

Introduction

Future exploration mission of the planets and the moons of the Solar System will require a global coverage and an extensive analysis of the planetary environment; for this reason mobility is going to be a key requirement for robots devoted to space exploration because enables both geographical coverage and in-situ science. In this context *aerobot* vehicles represent a new way for exploring planets and can be easily considered as a strategic platform for exploration of places with thick atmospheres, such as Venus, Titan and the gas giants.

Aerobots are a good platform to perform a wide variety of measurements due to their favorable dynamic properties. Among aerobots airships have a really stable attitude without vibration effects that can degrade remote sensing measurements. Aerobots have modest power requirements due to the fact that no power is used for the lift of the system; in particular airships provide precise navigation and path following with respect to simple balloons and montgolfiers in which only altitude can be controlled.

Thanks to their navigation capabilities aerobots can perform in-situ measurements across vast distance, executing regional long-range surveys as well as station-keeping for long-term monitoring of local phenomena. For example, changing the navigation altitude of airships, can affect directly the resolution of the images taken by a vision system. After an high altitude, low resolution coverage of a wide area the airship can change its path to perform a low altitude, high resolution mapping only on some selected sites. Moreover the low velocity has a significant impact on the distribution of the retrieved data and, when necessary, the airship can also perform station keeping in order to collect data at a specific site, looking for the evolution of phenomena depending on time or waiting for a good time for specific measurements performing.

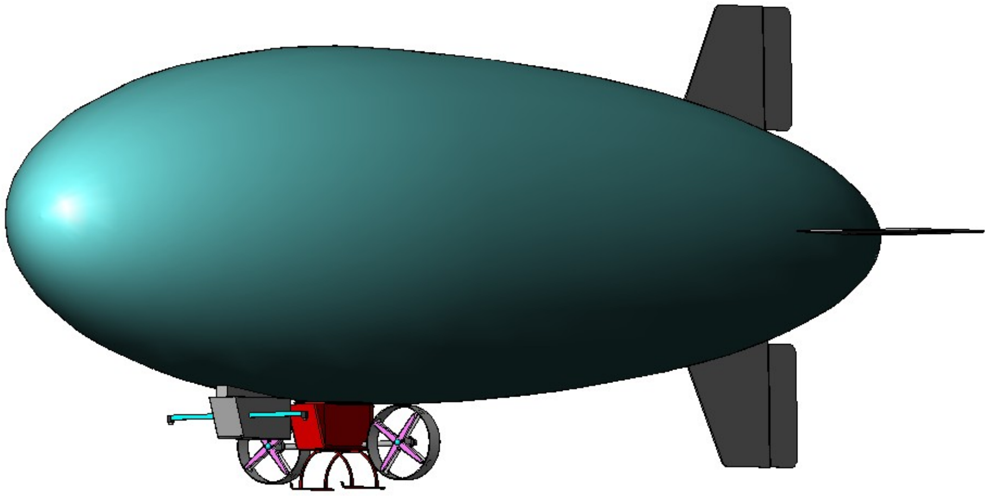

Figure 1: Airship model. See text for specifications.

Finally long distances can be traveled due to the fact that really no obstacle avoidance problem can be raised respect to the attention that must be pointed out for rover mobility.

Airship and mission profile

The considered airship (see Fig. 1) has been modeled as from the Titan Explorer mission [1][2] and the significant parameters are highlighted below:

- 17.5 m length, max diameter 3.5 m
- 25 kg payload, total weight 313 kg

Control actuators on which the control subsystem acts are:

- Main thrusters with deflections capabilities (up to 30°)
- Pitch and yaw rudders on tail

For navigation requirements both a mono and a stereo vision systems have been modeled and used in simulations.

Titan environment has also been modeled but only the parameters necessary for the airship aerodynamic simulation are used and expressed with an altitude dependent formulation [3]:

- Gravity
- Dynamic viscosity
- Density

A simple altitude or time wind dependence has been considered, with maximum wind velocity of 1.0 m/s.

The selected site for simulation is a 45 x 35 km^2 area in the Sikun Labyrinthus region (78S, 29W) where a DTM was available.

Considering a direct communication link between the airship and an orbiter, with orbital period of 5.2 hours, time windows for bidirectional data relay are established in the range (0.35÷75 minutes), depending on the satellite orbit. For this reason at least a 5.2 hours full autonomous navigation capability has to be tested. During the autonomous navigation the airship has an assigned a path (uploaded during the last direct link with the orbiter) and can perform different types of operations: long transfer from one site to another; mapping of the observed area; dedicated survey to specific areas: hovering, circling or ground interactions.

For performing the autonomous phase a set of measurements and informations are required:

- Airship attitude
- Airship velocity and position wrt last known reference position (from orbiter)

The above informations are needed by the airship operation, navigation and control systems in order to:

- Georeference the acquired measurements
- Perform the path planning
- Control the trajectory and the attitude
- Execute the desired operation phase

Simulation approach

Principal modules of the simulator are presented in Figure 2; the simulator is composed by three modules: Environment (ENV), Airship Control (AC) and Navigation (NAV). Simulator AC module manages the vehicle path planning and generates the desired trajectory as a set of way-points that the Airship must reach in sequence. The control module compares the actual vehicle position (from NAV) with the current tracked way-point and computes the commands needed to maintain the airship on the desired trajectory. The NAV module uses IMU measurements and processes stereo and monocular measurements of landmarks produced by the vision sub-system to estimate the vehicle attitude, velocity and position as well as to build and keep track of the map of the explored environment. AC and NAV modules are connected with the ENV module in which airship aerodynamic as well as Titan environment are modeled; ENV contains informations about Titan's atmosphere (density, temperature, pressure), winds and the surface (represented as a DTM). As the airship moves ENV module generates all the necessary data to simulate on board sensors measurements, it adds consistent noise on it and forwards them to the NAV module. Measurements are combined together in a Kalman filter (KF) and actual state vector is estimated. The state vector is then passed to the AC module which computes errors respect desired track and gives inputs to the actuator in order to access the desired dynamics.

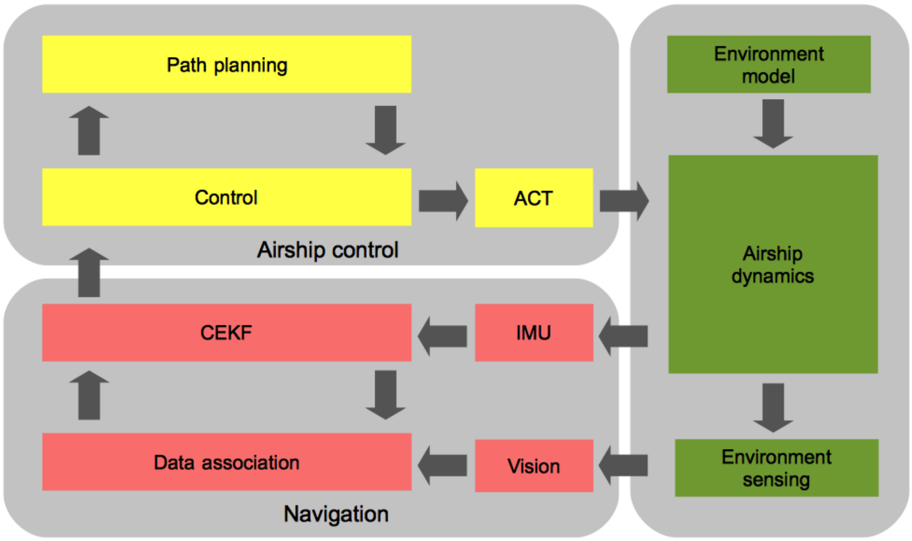

Figure 2: Navigation simulation scheme. The simulator is composed by three modules: environment, airship navigation and airship control.

SLAM technique

Thanks to their versatilely, 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 in the observed environment. These measurements can be used to incrementally build a map of the traversed area and simultaneously estimate airship position and attitude within this 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 [4], SLAM has been formulated and solved as a theoretical problem in a number of different forms and implemented in a number of different domains from indoor robots to outdoor, underwater, and airborne systems [5][6]. Among the different approaches to tackle the SLAM problem, the Extended Kalman Filter (EKF) is the most popular and effective. Moreover Extended Kalman Filter can take advantage of Inertial Measurements Unit (IMU) data to track rapid movements of the vehicle [7][8]. EKF is used under the assumption that sensor errors have a Gaussian distribution [9]. Due to the ability of long transfers the airship can build very huge maps, that require high computational capabilities that might not be available on-board. Therefore for mapping large areas EKF could not be applied to SLAM problem directly. For this reason improvements on data analysis have been studied. In fact the implemented SLAM algorithm relies on a Compress Extended Kalman Filter (CEKF). To reduce calculation in CEKF, only the part of state vector and covariance matrix relative to the features closer to the vehicle are updated at each time step. The the full state update (high computational load) is postponed in time and performed at lower rate. 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.

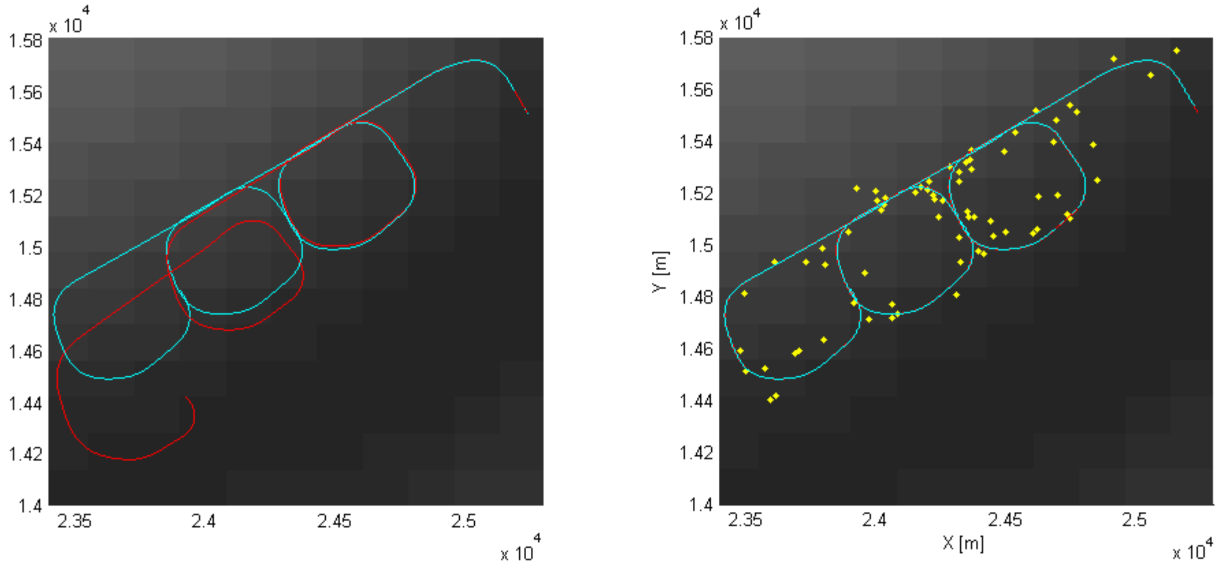

Figure 3: Trajectory reconstruction. Left: integration of IMU data lead to reconstructed trajectory (red) with errors incompatible with planned trajectory (blue); Right: information on landmarks (yellow dots) identified by vision system allow for overlapping of the planned and reconstructed trajectories.

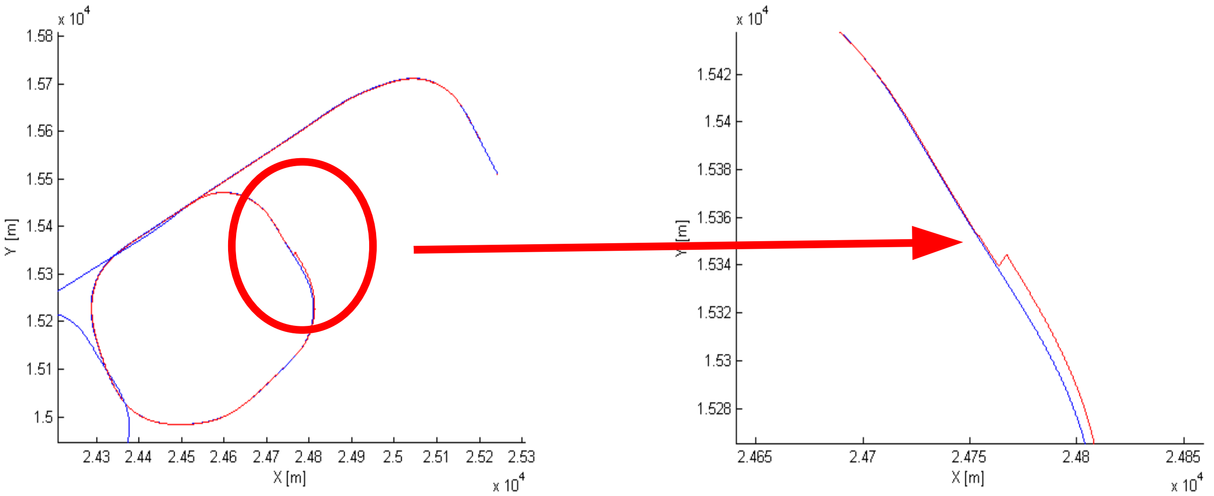

Figure 4: Loop closure. Observation of landmarks already present in the local map allow to reduce errors on reconstructed trajectory.

When landmarks measurements are available the filter *updated* 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 (see Fig. 3).

SLAM is a very powerful technique if the vision system is able to observe a landmark that is already present in it's build map; a particular type of advance motion technique was studied and a specific planned trajectory was designed. In fact the filter is able to correct the estimated trajectory when a known landmark is observed again (see Fig. 4). This allows to highly reduce the errors on the state vector, as an example see Fig. 5.

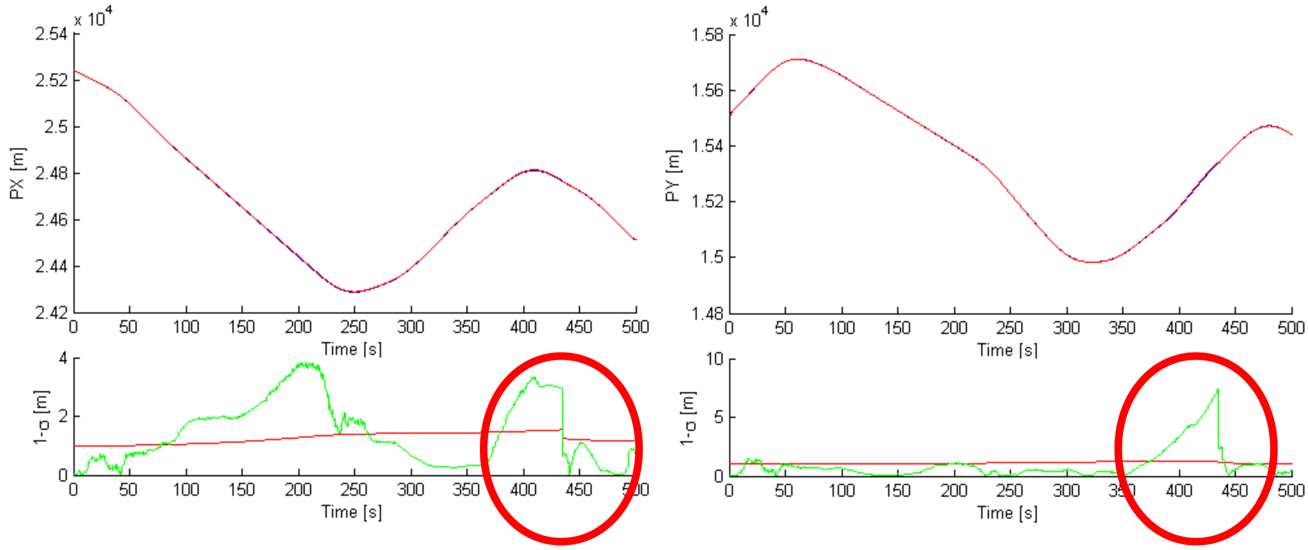

Figure 5: Position update. After observing same feature the filter is able to correct the calculated trajectory. Errors (green) respect to planned trajectory decrease from values >5 m to values below 0.5 m.

Simulation process

The simulation that was developed was constituted by the following steps:

1. Identification of cases for testing of both the aerodynamics and the selected reconstruction algorithms.
2. Identification of the favorable site for testing (Sikun Labyrinthus selected).
3. Generation of the desired trajectory (via way points). Each way point is specified with its absolute position (wrt DTM) and desired airship velocity at that way point.
4. Simulation of the complete aerodynamics of the airship for each test case.
5. Generation of the landmarks on the DTM; each landmark is identified by an ID number and by it's absolute position.
6. Trajectory and dynamic reconstruction via SLAM technique.
7. Reconstruction of the DTM from landmarks identified on the overflown terrain.
8. Error identification of state vector (attitude, velocity and position) wrt planned trajectory and airship attitude.
9. Error identification of the reconstructed DTM

Test cases

Several cases have been selected in order to test the algorithms, both for control and reconstruction; among these we present here (see Figure 6):

1. Long transfer
2. Straight trajectory - canyon entering
3. High resolution mapping of scientific interesting area
4. Hill analysis

In Table 1 the trajectories parameters used con be observed; velocity is controlled and fixed at 5 m/s.

Parameter	**Value**
Airship velocity	5 m/s
Traveled distance	6300 ÷ 80000 m
Trajectory time	0.3 ÷ 5.2 hrs
Wind values	0 ÷ 1.0 m/s
Observed area	0.68 ÷ 15.6 km^2

Table 1. Trajectories parameters

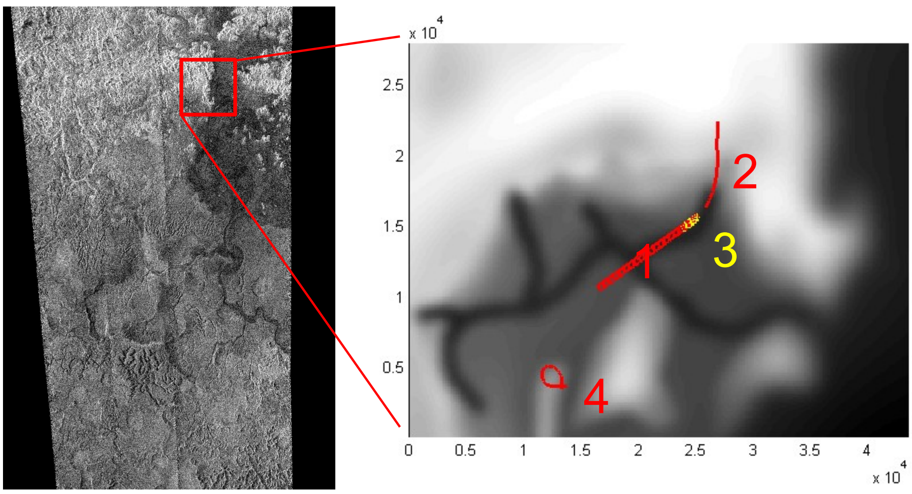

Figure 6: Sikun Labyrinthus selected area. Highlighted the 4 test cases used for algorithm testing. 1) Long transfer trajectory; 2) Straight long canyon entering; 3) High resolution scientific mapping area; 4) Hill loop analysis.

	Long trajectory	Canyon entering	Scientific area (one loop)	Hill analysis
Test #	**1**	**2**	**3**	**4**
Traveled distance (m)	26000	6300	2000	
Length (m)	88400		9810	5900
Total time (hr)	5.2	0.35	0.55	0.35
Altitude variations (m)		74		27
Errors				
X position (m)	18.2	10		
Y position (m)	3.9	6		
Z position (m)		0.4		0.5
Pitch error (deg)			0.02	
Roll (deg)			0.03	

Table 2. Reconstructed trajectories significant parameters; empty cell have to be considered not significant for that specific test case.

Results

Significant parameters estimation for each tested trajectory is presented in Table 2.

First observation that must be outlined is the very small errors on the reconstructed attitude; this is due to the informations arriving from direct measurements of landmarks angles during navigation. This errors are highlighted only for test #**3** showing that acquisition of scientific measurements are possible without major concerns about stability.

Test #**1** shows that after a 5.2 hours autonomous navigation a very small positioning error at the end of the transfer is estimated; this allows the airship to travel for long distances (26 km in our case) without major concerns and can be able to contact again the , once available, without significant difficulties.

Analysis of test #**2** shows, on the other side, that variations in altitude are possible even if the landmarks are not observed during a second passage: in fact, for this test, the landmarks are observed only for a limited amount of navigation time. The 0.4 m reconstructed error, at the end of the canyon entering, gives sufficient margin to the airship in order not to risk a collision with the surface.

Test #**5** shows that even if the tracked landmarks are again observed after a great amount of traveled distance (around 5000 m) the correction on trajectory is possible and final error is bounded (0.5 m in Z position).

SLAM technique also allows to build a map from the retrieved informations on the observed landmarks: see Fig. 7 for the reconstructed DTM of the observed area during test #**3**. The error on the reconstructed DTM are consistent and below 2.5 m for the most part of the DTM. Higher errors are visible in the lower left of the reconstructed DTM but these can be correlated to the relative errors on the reconstructed trajectory.

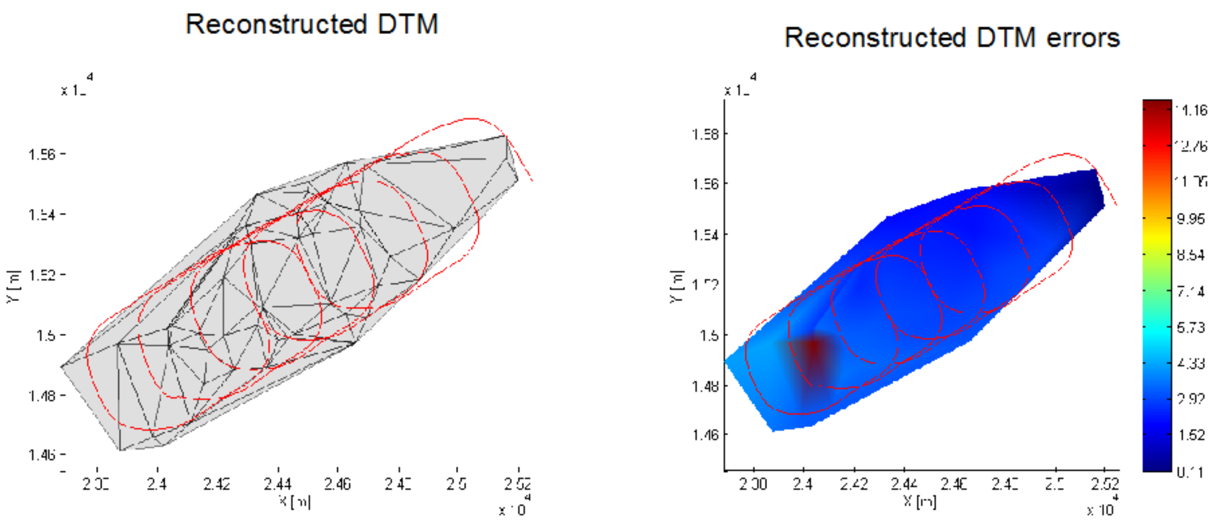

Figure 7: Left: reconstructed map through landmarks identification; superimposed in red the reconstructed trajectory. Right: errors between reconstructed and real DTM.

Conclusions

A consistent simulator of an airship has been developed and tested considering: airship aerodynamics, environmental conditions, control actuators dynamics and autonomous navigation system.

The navigation system, the possible sensors and the data processing algorithms have been identified and tested. Overall system performances have been evaluated through simulation to assess the effectiveness of this vehicle for mapping applications thanks to its controllability and attitude stability.

Different type of trajectories have been tested in order to prove the selected algorithms both for aerodynamics and navigation. The long transfer, 5 hours autonomy case, showed that it is possible to autonomously navigate and have limited errors at the end of the phase (< 20 m on a 26 km journey); the canyon entering pictured that, even if no landmarks is observed twice the developed filter is able to bound the errors and especially the one in height (< 0.4 m for a 6300 m straight trajectory and a 74 m height variation); the high resolution scientific area shows stability of attitude were to perform scientific measurements; while the hill analysis shows that re-observing already acquired landmarks corrects the errors in the estimated trajectory.

Furthermore a map of the observed area has been reconstructed allowing to generate a DTM of the unknown environment; errors, respect to “real” DTM are limited to 2.5 m in most part of the reconstructed map.

Acknowledgements

This activity has been conducted thanks to grant of the Italian Space Agency. The authors want to thank Mike Malaska for the Hypothetical relative elevation model of the Sikun Labyrinthus area .

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