The Vision-Based Terrain Navigation Facility: A Technological Overview

Antonio Toma[1], Marcello Chiaberge[2], Mario Silvagni[1], and Gianluca Dara[2]

[1] DIMEAS, Politecnico di Torino, Turin, Italy
{antonio.toma,mario.silvagni}@polito.it
[2] DET, Politecnico di Torino, Turin, Italy
{marcello.chiaberge,gianluca.dara}@polito.it

Abstract. The VTNF (*Vision-based Terrain Navigation Facility*) is an innovative platform designed as a test bed for studying open issues related to the navigation of a planetary lander in its *Entry-Descent-Landing* (EDL) phase. The facility makes available a safe indoor flight volume, fully tracked by infrared cameras, an autonomous quadrotor equipped with a camera and a diorama representing a portion of Martian surface. The quadrotor is used to trigger pictures of the diorama from coordinates that are scaled according to a virtual mission in its EDL phase, simulated on a dedicated workstation. The pictures are then processed to provide information about the presence of particular geological features (craters, canyons, hills . . .) and to estimate an hazard-free descent trajectory. This article offers an overview of the design solutions implemented in the facility, both from the hardware and from the software/control point of view.

Keywords: aerial robotics, motion capture system, quadrocopters, autonomous systems, VTNF.

1 Introduction

In the last ten years, research about micro-aerial autonomous systems has gained a great momentum. Part of this success has been triggered by the remarkable results reached by a number of research institutions and laboratories that have focused their work on the study of the dynamics of small aerial vehicles (e.g. multirotors and coaxial small helicopters) and their control. In particular, many of these results have been made possible by the development of special test beds that typically provide a large flight volume in which the exact position and attitude of one or many agents is accurately measured by an optical tracking system. The *MIT Raven* [4] test bed is commonly considered the first described in literature, with *STARMAC* by Stanford University [3], the *Flying Machine Arena* at ETHZ [7] and UPenn's *GRASP Laboratory Test Bed* [9] being other noticeable examples of this technology. The uses of these test beds range from the study of aggressive or coordinated multi-vehicles manoeuvres [8],[10], to architecture [13], construction [6] and entertainment [1]. In this paper, we present the *Vision-based Terrain Navigation Facility.* The VTNF is similar in design to the

J. Hodicky (Ed.): MESAS 2014, LNCS 8906, pp. 56–66, 2014.

already mentioned test beds, and it is explicitly designed in order to provide a simulation and validation environment in the study of vision-based routines and algorithms for space applications. By providing a scenario as similar as possible to the actual operative one, the VTNF allows a deep analysis of the *EDL* (Entry Descent and Landing) phase of a virtual Martian lander approaching Mars. In the experiments, a quadrotor with a camera attached on it facing down is used to trigger some shots on the diorama surface. The motion of the rotorcraft is dependent by the analysis of the pictures, since the quadrotor is controlled in order to reach defined waypoints in the indoor fixed flight volume, computed as a result from the image processing part. The whole system has been designed and integrated by *Thales Alenia Space Italy (TASI)* and *LIM (Mechatronics Lab)* of *Politecnico di Torino*.

2 Functional Layout

From the functional point of view, the facility is composed by three main components:

- the Tracking System;
- the Quadrotor;
- the Ground Segment.

Figure 1 depicts the main data flows exchanged between every single module.

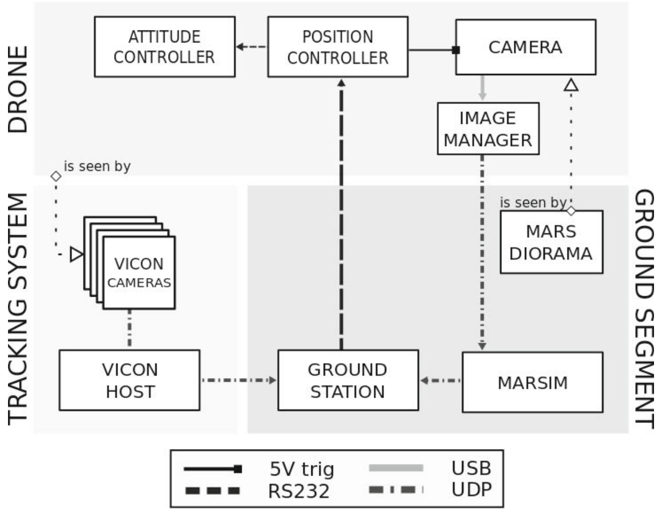


Fig. 1. Functional architecture of the VTNF

2.1 The Tracking System

The purpose of the tracking system is to measure the position and the attitude angles of the quadrotor while it flies inside the tracked volume. The tracking system used in the VTNF is based on the *Vicon Motion Capture System* [14] and is composed by 13 Vicon Bonita infrared cameras, connected together in a PoE (Power over Ethernet) network hosted by a dedicated workstation (*Vicon Host* in Fig. 1) on which the proprietary Vicon Tracker software runs. The infrared cameras are attached on a cube-shaped aluminum structure with 9 m long sides, thus providing an available fully tracked flight volume of approximately 650 m^3, not considering the volume occupied by the diorama. They acquire 0.3 Megapixel images up to 240 Hz and can track a single marker with an accuracy of 1 mm and sub-mm precision. The markers are little spheres covered with an infrared-reflective coating, attached on the body to track. In order to reconstruct without ambiguity the full pose of a rigid body, at least three markers are needed.

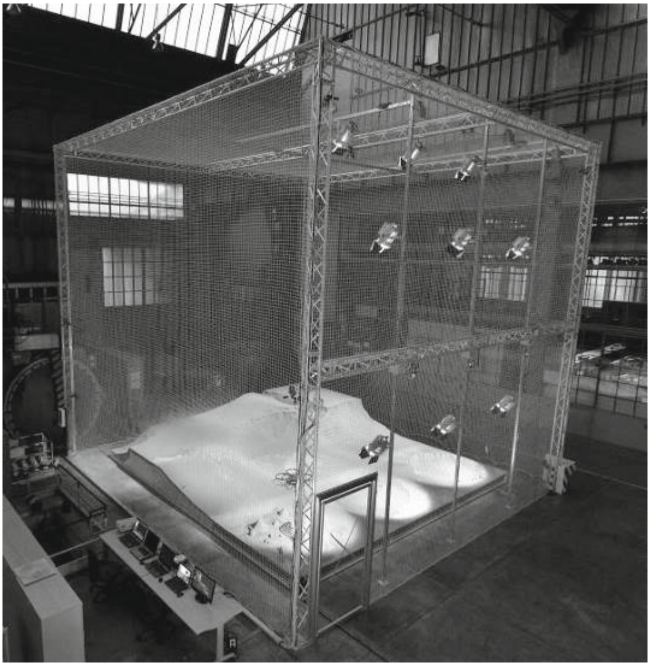


Fig. 2. The Vision-based Terrain Navigation Facility

2.2 The Quadrotor

Among the various solutions considered for handling the camera in the flight volume above the diorama (e.g. robotic arms, blimps, cable cameras) a quadrotor offers high maneuverability, good payload capabilities, simple mechanics and low maintenance. The model used in the VNF is shown in Fig. 3; it has a custom lightweight carbon fiber frame and can bring a payload up to 1 kg heavy with an endurance of about 15 minutes. In our setup the camera (in its gimbaled or fixed version), the position control board, the radio modem and a PC104+ single board computer constitute the payload of the vehicle; its total weight amounts to 2.5 kg.

Fig. 3. The quadrotor used in the VTNF

The intrinsic flight stability of the quadcopter is guaranteed by a *Mikrokopter* Flight Control board [15] that controls its Roll and Pitch angles in order to keep it stable while hovering in the air, or to reach the commanded angular values (attitude controller in Fig.1). The board features an Atmel ATMEGA644 microcontroller running at 20 MHz, a 3-axis accelerometer and three gyroscopes. The firmware of the Flight Control board allows the user to take external control of the UAV (i.e., bypassing the radio controller) by means of a dedicated serial protocol [16] on a UART interface; this link is used to send the *Roll*, *Pitch* and *Yaw* commands to the drone.

The position controller runs on an additional Arduino Mega 1280. The board runs 4 parallel PID controllers, one for each of the remaining degrees of freedom (x, y, z and *Yaw* angle). This board receives on a dedicated wireless-serial link the feedback obtained from the UDP Vicon data stream and sends the commands to the auto-pilot board. The board takes also care of triggering the camera when the MarSim requests a new picture.

A camera and a PC104+ single board computer are used to take pictures of the diorama and to deliver them to the ground segment. The computer features an Intel Atom D510 dual core 1.62 GHz CPU with 2GB RAM. It retrieves the images sent by the camera on the USB link and forwards them to the MarSim. The camera used in the project is the 1312M model by Edmund Optics. It is a CMOS gray level camera (1280x1024 resolution, 8 bits pixel depth) with a rolling shutter. This particular model has been chosen since its characteristics are comparable to the already space qualified camera based on STAR1000 sensor. It can be attached to the drone both in its fixed mount version and in a fully integrated gimbal solution.

A wireless link connects the drone to the ground segment using a couple of identical radiomodems (see Fig. 4) featuring either a standard RS232 serial interface or an IEEE 802.11a LAN wireless link. The former link is used to send every time-critical data to the position controller, i.e. the current attitude of the quadrotor, the target position and the camera-trigger signal; the latter conveys to ground the pictures coming from the camera via UDP.

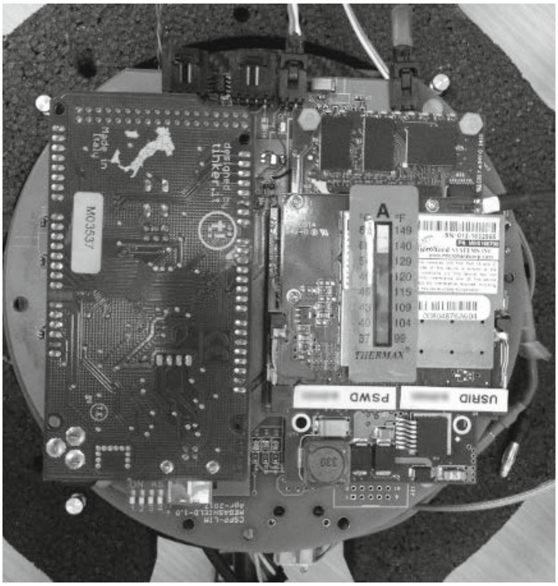


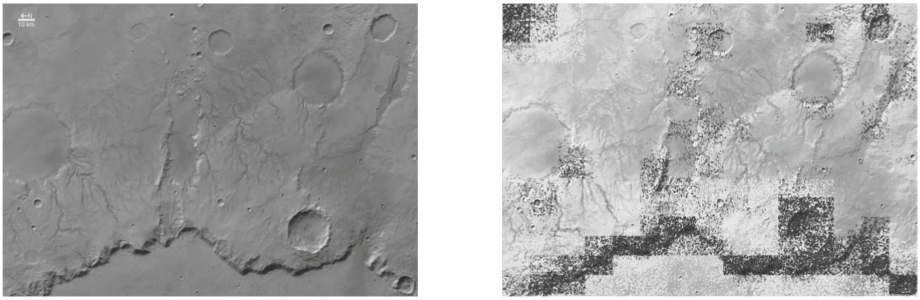
Fig. 4. The Arduino board running the position controller and the on-board radiomodem attached on their carrierboard

2.3 The Ground Segment

The Ground Segment in the VTNF is composed by two software modules (the *Ground Station* and the *Marsim* in Fig. 1) and by a diorama.

The Ground Station. The Ground Station module is a simple module that accesses in real-time positions and angles of the drone, as provided by the Vicon Host on the UDP link, and adapts them to provide a continue pose feedback to the quadrotor position controller. Moreover, this module receives the target position by the MarSim and triggers a new picture when the error is less than a tunable threshold; then it acknowledges the MarSim that it is ready to compute a new target point.

The MarSim. The MarSim is a TASI proprietary module. It embeds both a complete functional and dynamical model of the extra-planetary lander and the computer-vision routines that are the object of the testing activities. The MarSim receives as inputs the pictures triggered by the drone and outputs a succession of Martian geographical coordinates, computed and updated at runtime during the experiment. These are the result of a complex chain of operations performed to simulate the behaviour of a real lander in its EDL phase (image processing, data fusing with on-board sensor, computation of the new nominal trajectory, actuation of thrusters, integration of the dynamic until the new point of interest). The coordinates are then scaled and re-projected in the diorama reference frame and passed to the quadrotor as target waypoints. Figure 5 offers an example of a hazard map generated by the simulator in this stage, starting from a picture of a portion of Martian terrain. Further details about the MarSim can be found in [5].



(a) (b)

Fig. 5. A real image of Martian terrain (5a) and the output of the hazard map algorithm (5b). The dangerous areas for landing have been highlighted.

The diorama (8 m × 8 m, 1.5 m of maximum relief height) accurately reproduces four peculiar geographic details of the Mars surface in 1 : 300 scale:

- Nili Fossae
- Victoria Crater
- Xanthe Terra
- Dilly Crater

Nine mercury-vapor stage lamps provide accurate and homogeneous lighting. Figure 6 shows the good level of resemblance between two actual Martian surfaces, and their equivalent reproduction on the diorama.

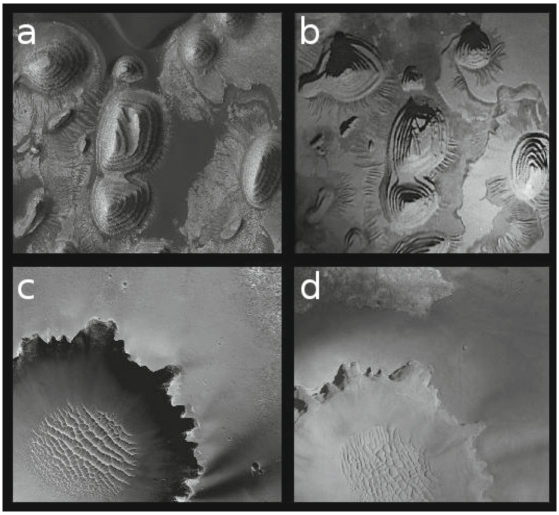


Fig. 6. A portion of Western Arabia Terra (a) and Victoria Crater (c) and the corresponding representations on the diorama (b,d)

3 System Modeling and Control

In the current application, a high dynamic response of the quadrotor does not represent a critical requirement. The drone does not have to perform aggressive maneuvers, nor has it to respect strict dynamical or trajectory constraints. Hence a very simple control architecture, featuring 4 parallel PID controllers (acting on the x, y, z and *Yaw* degrees of freedom of the quadrotor), has been designed in order to move the quadrotor on its target position.

Given the following conditions in the flight of the quadrotor:

- Small *Roll* and *Pitch* angles ($\pm 6\ ^\circ$),
- *Yaw* angle fixed at $\psi = 0\ ^\circ$,
- Low translational velocities,
- Hovering flight (i.e. constant thrust value),

the dynamical model of the vehicle can be completely linearized and the x, y, z and *Yaw* dynamics can be decoupled.

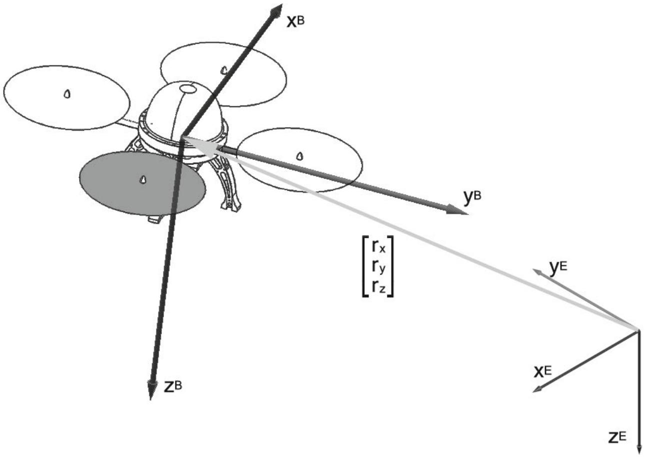


Fig. 7. Body (B) and Earth (E) reference frames

Given the global and local reference frames of Fig. 7, the following simple representation of its translational dynamics can be derived [2], [12]:

$$\begin{bmatrix} \ddot{r}_x \\ \ddot{r}_y \\ \ddot{r}_z \end{bmatrix} = \frac{1}{m} \begin{bmatrix} 0 & \bar{T} & 0 \\ -\bar{T} & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \varphi \\ \vartheta \\ T \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ g \end{bmatrix} \tag{1}$$

With r_x, r_y, r_z being the coordinates of the center of mass of the drone in the earth-fixed frame, m the total mass of the quadrotor, $\bar{T}$ the hovering thrust

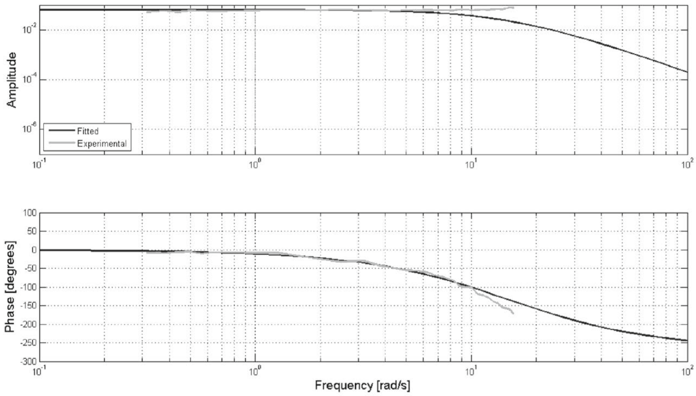


Fig. 8. Roll and Pitch frequency response. Dark grey lines represent the angular frequency response of the angular controller, identified by fitting the experimental results (light grey lines).

value; φ and ϑ respectively are the *Roll* and *Pitch* rotation around x_B and y_B axes.

However, (1) does not completely characterize the description of the dynamics since its angular dynamics is still not known. Unfortunately, Mikrokopter offers very poor documentation about the design of the attitude control loops design [11]. For this reason their dynamics have been experimentally identified.

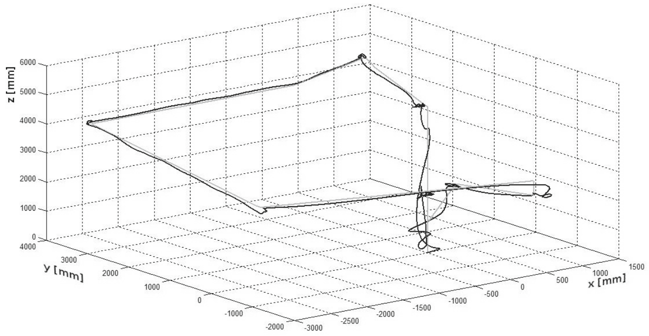
The identified frequency response of the angular controller has been modeled with a third order transfer function described by (2) that has been experimentally found to well represent both *Pitch* and *Roll* dynamics of the system:

$$F_{\varphi\vartheta}(s) = \frac{0.063}{0.0003s^3 + 0.0133s^2 + 0.2s + 1} \tag{2}$$

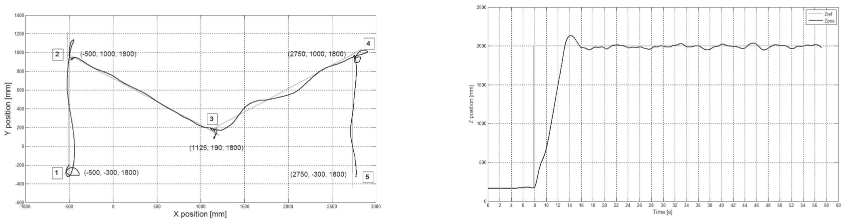
its bode plot is shown in Fig. 8.

An alternative approach to model identification of Mikrokopter dynamical model in time-domain can be found in [11].

The PID controllers have been designed in order to keep the rising time in the order of 2.5 s for a 1 m step reference on x, y, z. Experimental tuning of the PID parameters have been conducted directly on the plant to further adjust the flight performance of the vehicle. Figure 9 shows the experimental results after



(a) *A complete flight in the tree dimensional volume*



(b) *A planar flight through 5 points*

(c) *The dynamic behavior on z axis*

Fig. 9. Experimental results

some test flights. The positioning error causes the drone to hover in a circle of maximum radius 6 cm around the target point while the Z error varies within a maximum range of ±8 cm (Figure 9a and Fig. 9b). The *Yaw* angle is kept within a precision of ±3 °. Dedicated tests have shown that Vicon Tracking System provides, after a good calibration and with optimal camera coverage, 1 mm accurate and 0.1 mm precise position data. The maximum latency in the camera trigger signal has been measured to be 40 ms.

4 Conclusion

In this paper we have presented the Visual Terrain Navigation Facility, a test bed for studying and validating vision-based routines and algorithms to be used during planetary Entry Descent and Landing (EDL) by a lander. We have described the major technical details of the architecture and the design choices in relation with its three main functional components: the Tracking System, the Ground Segment and the Quadrotor. We have finally shown how, in our operation hypothesis, a very simple PID-based control architecture successfully stabilizes the quadrotor and allows basic autonomous navigation functionalities with good performances. The VTNF is currently used in *Thales Alenia Space*'s headquarters in Turin both for the already described purposes and in technological demonstrations. Although the VTNF has been created keeping in mind the validation of specific aerospace-derived image algorithms, it offers noticeable potentialities for a number of applications not strictly related with the original purposes of the project. Moreover our research activities in the facility are not over; experimentation with visual-aided auto-takeoff and auto-landing routines, visual odometry and new control strategies are currently carried out in the VTNF. An outdoor GPS-based version of the facility is also currently under development and will permit image analysis and EDL simulation on larger scale.

Acknowledgments. The VTNF facility has been designed and integrated with the support of the STEPS project co-funded by Regione Piemonte (Project co-financed by EC Platform: POR FESR 007/2013). The work has been carried out in collaboration with Thales Alenia Space Italy. The authors would like to thank Carlo Paccagnini and Corrado Maddaleno for the precious collaboration.

References

1. Augugliaro, F., Schoellig, A., D'Andrea, R.: Dance of the flying machines. IEEE Robotics and Automation Magazine 117 (December 2013)
2. Castillo, P., Dzul, A., Lozano, R.: Real-Time Stabilization and Tracking of a Four-Rotor Mini Rotorcraft. IEEE Transactions on Control Systems Technology 12(4), 510–516 (2004)
3. Hoffmann, G., Rajnarayan, D., Waslander, S., Dostal, D., Jang, J., Tomlin, C.: The Stanford testbed of autonomous rotorcraft for multi agent control (STARMAC). The 23rd Digital Avionics Systems Conference (IEEE Cat. No.04CH37576) pp. 12.E.4–121–10 (2004)

4. How, J.P., Bethke, B., Frank, A.: Real-time indoor autonomous vehicle test environment. IEEE Control Systems 28, 51–64 (2008)
5. Lanza, P., Noceti, N., Maddaleno, C., Toma, A., Zini, L., Odone, F.: A vision-based navigation facility for planetary entry descent landing. In: Fusiello, A., Murino, V., Cucchiara, R. (eds.) ECCV 2012 Ws/Demos, Part II. LNCS, vol. 7584, pp. 546–555. Springer, Heidelberg (2012)
6. Lindsey, Q., Mellinger, D., Kumar, V.: Construction with quadrotor teams. Autonomous Robots 33(3), 323–336 (2012)
7. Lupashin, S., Hehn, M., Mueller, M.: A platform for aerial robotics research and demonstration: The Flying Machine Arena. Mechatronics 24(1), 41–54 (2014)
8. Mellinger, D., Michael, N., Kumar, V.: Trajectory generation and control for precise aggressive maneuvers with quadrotors. The International Journal of Robotics Research 31(5), 664–674 (2012)
9. Michael, N., Mellinger, D., Lindsey, Q., Kumar, V.: The GRASP Multiple Micro-UAV Testbed. IEEE Robotics & Automation Magazine 17(3), 56–65 (2010)
10. Ritz, R., Müller, M.W., Hehn, M., D'Andrea, R.: Cooperative quadrocopter ball throwing and catching. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 4972–4978 (October 2012)
11. Sa, I., Corke, P.: Estimation and control for an open-source quadcopter. In: Proceedings of the Australasian Conference on Robotics and Automation 2011 (2011)
12. Waslander, S.L., Hoffmann, G.M., Tomlin, C.J.: Multi-agent quadrotor testbed control design: integral sliding mode vs. reinforcement learning. In: 2005 IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 3712–3717 (2005)
13. Willmann, J., Augugliaro, F., Cadalbert, T., D'Andrea, R., Gramazio, F., Kohler, M.: Aerial robotic construction towards a new field of architectural research. International Journal of Architectural Computing 10(3), 439–460 (2012)
14. Vicon tracking system homepage, `http://www.vicon.com/`
15. Mikrokopter flight control 2.1 specifications, `http://tinyurl.com/l86k4gf`
16. Mikrokopter serial protocol specifications, `http://tinyurl.com/ltabhnb`