TOM: 3D SURFACE IMAGING BY A FORMATION OF 3 NANO-SATELLITES

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Abstract—The Earth observation mission TOM, composed of 3 satellites, uses self-organization principles in orbit as basis for photogrammetric methods to generate 3D-images from the different perspectives. A typical baseline distance between the TOM satellites is about 10 km. Challenges concern in particular the related attitude control to orient the cameras in parallel towards the joint observation target. The mission is currently in final implementation stage and has a planned launch date end of 2022.

1. INTRODUCTION

Miniaturization approaches enable increasing capabilities even for satellites at the mass of just a few kilograms, offering interesting new potential for efficient Earth observation missions [6], [7], [9], [15]. In particular, distributed systems address innovative approaches by small satellites in form of constellations (where each satellite is individually controlled from ground) and of self-organizing formations in orbit [1], [3], [5], [11], [13]. Such satellite formations offer capabilities to track a target on the surface of the Earth from different satellites by exchanging via inter-satellite links networked control information for attitude adaptation to enable coordinated joint observations. This objective will be demonstrated by the TOM formation composed of three satellites to generate 3D-images of the Earth surface by photogrammetric methods [12], [14]. This contribution provides further details about the TOM mission and the related satellite design.

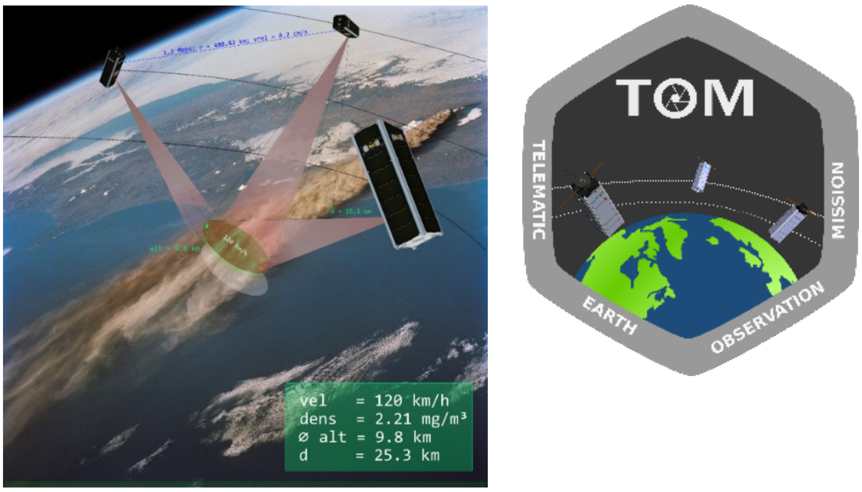

Figure 1: Artist's view of the TOM Formation

Crucial in realizing this formation are networked control algorithms, using inter-satellite links and relative navigation approaches. In particular, the implemented miniature 3-axes attitude determination and control system to enable an appropriate pointing accuracy will be presented. As complement for fine pointing feature extraction and visual servoing from observation data will be characterized.

The 3 TOM satellites are the German contribution to the "Telematics International Mission (TIM)", where partners from 5 continents contribute small satellites and ground infrastructure for joint Earth observation objectives. Three-dimensional surface maps are then generated by photogrammetric methods and application of sensor data fusion approaches. This will offer a broad spectrum of application potential to characterize ash clouds from volcano eruptions [14], damages after Earth quakes, growth of city limits, or ships on sea.

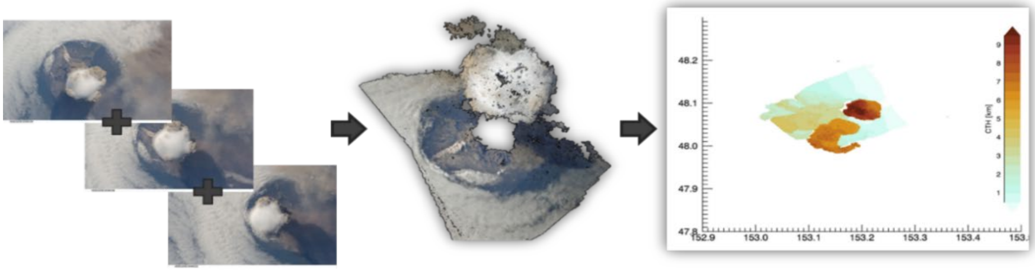

Figure 2: Multiple pictures taken of a volcano eruption from ISS. Due to the relative velocities different viewing angles result during the observation period, which can be used for processing to a 3D-image.

2. TOM MISSION CONCEPT

Three nano-satellites compose the formation of the "Telematics earth Observation Mission (TOM)". TOM is a continuation in Earth observation application of the formation demonstration of the NetSat mission (launched September 2020) [8], [10]. In TOM three nanosatellites, carrying cameras in the visible range as payload, track and perform simultaneous measurements of the same target area on the surface of the Earth from different perspectives. These observations form the basis to apply photogrammetric approaches for sensor data fusion to generate three-dimensional images [14]. The satellite platform will be based on a 3U-Cubesat design, using the UNISEC Europe standard (http://unisec-europe.eu/standards/bus/) for electrical interfaces. This modular design supports fast and flexible integration and testing.

3. TOM SATELLITE DESIGN

The nano-satellite system design of each TOM satellite is based on a 3U-CubeSat and is displayed in Figure 3. The main payload will be a redundant optical camera with the properties

- Resolution: 2464 (H) × 2056 (V) (5.1 Mpixels)
- @600km: GSD: 20.7 m; Swath width: 50.6 km
- Field of view: 4.8°
- Global shutter

This is appropriate to measure the vertical speed of ash clouds from volcano eruptions.

The payload data are downlinked in S-Band, providing a data rate of up to 1 Mbps. The UHF Band is used for TT&C and low speed data transfer. The inter-satellite link (ISL) will also operate in UHF.

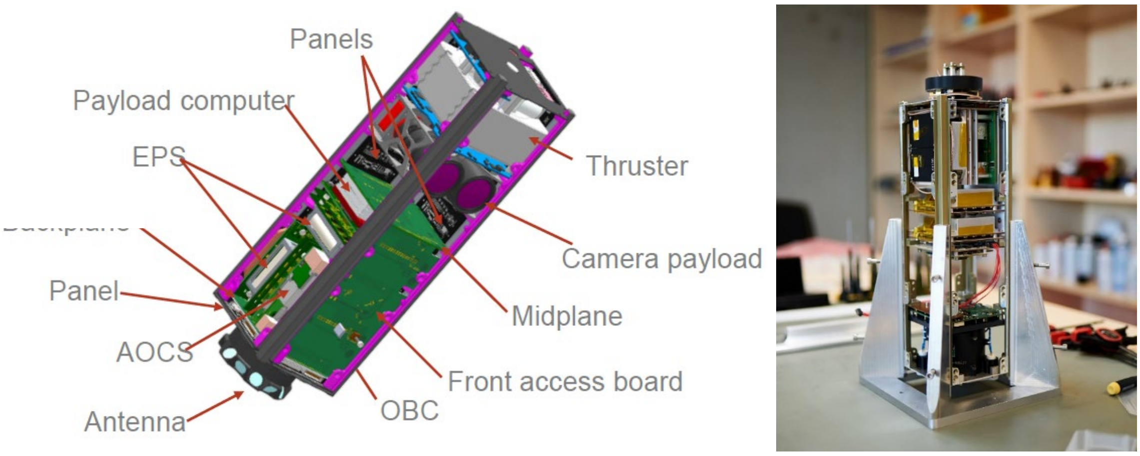

Figure 3: TOM satellite design

One of the main challenges of TOM are the formation flying technologies for the coordination of the three satellites to perform joint observations. The technology base focusses on networked control algorithms, using inter-satellite links and relative navigation approaches. In this context, the attitude and orbit control system is implemented at the size of a 3U-CubeSat to realize appropriate pointing accuracy. For formation maintenance an orbit control system is required. Here the propulsion system based on a single thruster system using nitrous oxide (N_2O) and propene (C_3H_6) generates a total Δv of about 100 m/s.

For attitude control, miniature reaction wheels have been developed with specific high rotation speed up to 19.000 rev/min. The sensor input for attitude determination uses high precision Sun sensors, while position information is contributed from GPS/Galileo receivers integrated into the side panels.

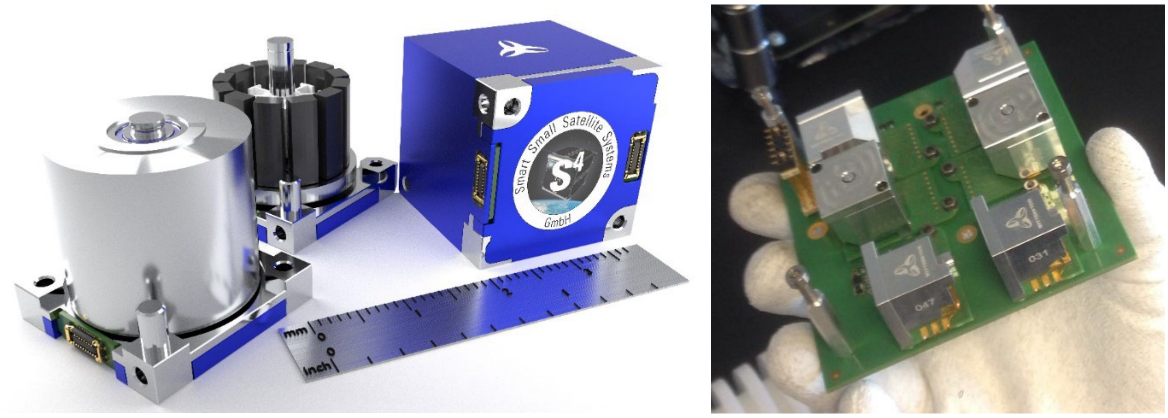

Figure 4: The miniature reaction wheel flown on NetSat at the left side, while the fully redundant three-axes control system composed of 6 wheels is on the right side.

4. ORBIT AND FORMATION DESIGN FOR TIM/TOM

The three TOM satellites form a triple pendulum formation with a baseline distance of about 100 km. The out of plane separation is about 50 km in order to improve the coherence of the imagery data. The quality of results depends mainly on the ratio between baseline distance and satellite altitude. Such triangle formation provides more stable results than a string of pearls in across track direction.

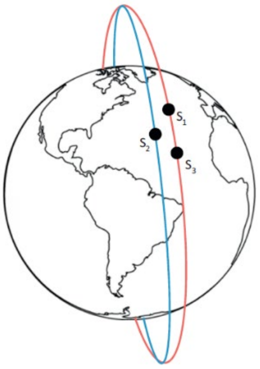

Figure 5: Triple pendulum orbit configuration in the TOM formation

5. VISUAL SERVOING

An additional TOM technology demonstration objective is characterisation of visual servoing with camera images on-board for improvement of satellite attitude control [2]. It contributes further sensor input data to the control system for instrument fine pointing. One of the 3 satellites will be configured as the master. Its task is to detect, describe and continuously track features. It will also transmit this information in form of descriptors to the slave satellites to detect the features as well. Then a matching between slave and master descriptors is initiated and matched features are tracked by all satellites (cf. Figure 6). The temporal synchronisation procedure is outlined in Figure 7.

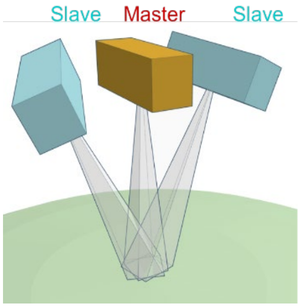

Figure 6: TOM satellite formation for visual servoing

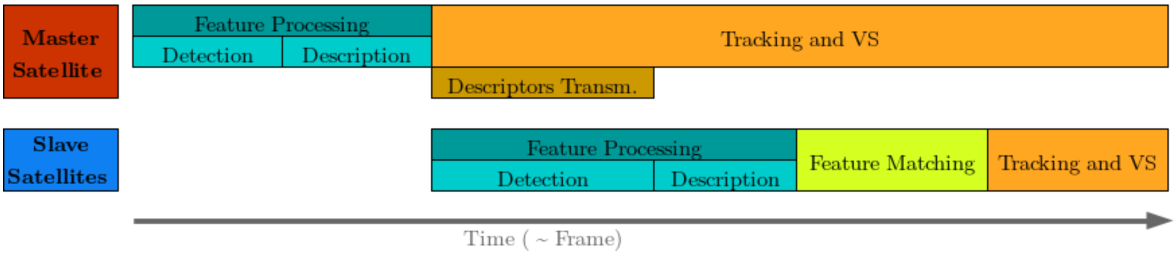

Figure 7: Visual Servoing tasks allocation between master and slave satellites

6. GROUND STATION NETWORK

International collaboration and technology exchange is in focus of TIM. The TIM partners foster collaboration and resource sharing in a Ground Station Network (GSN) to increase observability and availability of ground resources for payload and telemetry data. The GSN based on Internet of Things (IoT) and web technology concepts is realized [4]. It uses integration of heterogenous software and hardware as well as sophisticated scheduling algorithms for data fusion of Earth observation measurements.

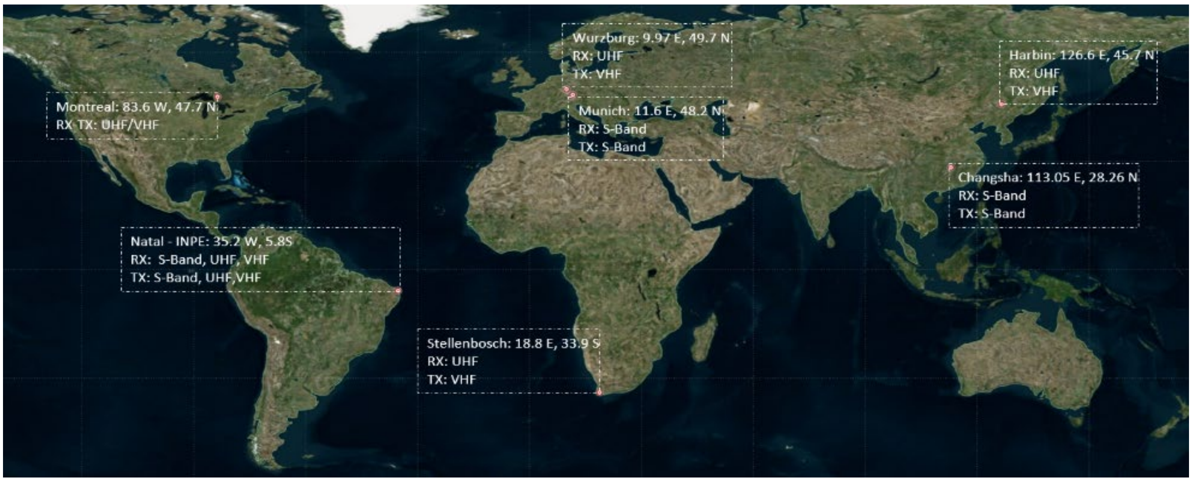

Figure 8: Ground station network used in the TIM mission

6. CONCLUSIONS

Objective of the TOM mission is to characterize distributed measurement concepts for Earth observation by nano-satellites. Here photogrammetric methods will be applied to generate 3D-images of the Earth surface from the different viewing perspectives of the three TOM satellites, flying in formation. Challenging control tasks will be addressed by a 3-axes attitude control system based on miniature reaction wheels and orbit control with a chemical propulsion system. Thus TOM will provide a sensor network in orbit demonstration for Earth observation by a distributed multi-satellite system.

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REFERENCES

[1] Alfriend, K. T., S. R. Vadali, P. Gurfil, J. P. How, L. S. Breger, *Spacecraft Formation Flying. Dynamics, Control and Navigation, Elsevier Astrodynamics.* 2010

[2] Dauner, J., L. Elsner, O. Ruf, D. Borrmann, J. Scharnagl, K. Schilling; *Visual Servoing for Coordinated Precise Attitude Control in the TOM Small Satellite Formation* ; Proceedings 72th International Astronautical Congress, Dubai. 2021, IAC-21 C1.8.2

[3] D'Errico (ed.), M. *Distributed Space Missions for Earth System Monitoring*. Springer Verlag 2012

[4] Kleinschrodt, A., T. Horst, E. Jäger, A. Freimann, S. Dombrovski, R. Haber, K. Schilling; *Extended Ground Station Concept and its Impact on the In-Orbit Communication with the Four-Nano-Satellite Formation NetSat* ; Proceedings IEEE Space Hardware and Radio Conference (SHaRC), 2021.

[5] S. Mathavaraj, and R. Padhi, Satellite Formation Flying – High Precision Guidance using Optimal and Adaptive Control Techniques", Springer Nature Singapore 2021.

[6] Millan, R., R. Steiger, M. Ariel, S. Bartalev, M. Borgeaud, S. Campagnola, J. Castillo-Rogez, R. Fléron, V. Gass, A. Gregorio, D. Klumpar, B. Lal, M. MacDonald, J. H. Park, V. S. Rao, K. Schilling, G. Stephens, A. Title, J. Wu, Small satellites for space science: A cospar scientific roadmap, Advances in Space Research 64 (2019), p. 1466–1517.

[7] Sandau, R., Nakasuka, S., Kawashima, R., Sellers, J. (eds) , *Novel Ideas for Nanosatellite Constellation Missions*, IAA Book Series 2012.

[8] J. Scharnagl; F. Kempf, S. Dombrovski, K. Schilling; *NetSat – Challenges of a Formation Composed of 4 Nano-Satellites* , Proceedings 72th International Astronautical Congress, Dubai 2021, IAC-21-B4.7.8

[9] Schilling, K., Design of Pico-Satellites for Education in System Engineering, *IEEE Aerospace and Electronic Systems Magazine* 21 (2006), pp. 9-14.

[10] Schilling, K. (2009), *Networked Distributed Pico-Satellite Systems for Earth Observation and Telecommunication Applications,* Invited Plenary Paper in Proceedings of IFAC Workshop Aerospace Guidance, Navigation and Flight Control Systems – AGNFCS, *2009, Samara*

[11] Schilling, K.; Perspectives for Miniaturized, Distributed, Networked Systems for Space Exploration, *Robotics and Autonomous Systems* Vol. 90 (2017), p. 118–124.

[12] Schilling, K., Tzschichholz, T., Motroniuk, I., Aumann, A., Mammadov, I., Ruf, O., Schmidt, C., Appel, N., Kleinschrodt, A., Montenegro, S., Nüchter, A., *"TOM: A Formation for Photogrammetric Earth Observation by Three CubeSats",* IAA Conf. on University Satellite Missions, Roma 2017, IAA-AAS-CU-17-08-02

[13] K. Schilling, Formations of Small Satellites, in: *J. Estela / R. A. de Carvalho (eds.), Nano-Satellites: Space and Ground Technologies, Operations and Economics,* Chapter I-3d, John Wiley & Sons 2019. p. 327-339.

[14] Zakšek, K., James, M.R., Hort, M., Nogueira, T., Schilling, K*., "Using Picosatellites for 4D-imaging of Volcanic Clouds: Proof of Concept Using ISS Photography of the 2009 Sarychev Peak Eruption",* Journal Remote Sensing of Environment, Vol. 210 (2018), pp: 519-530

[15] Zurbuchen, T. H., R. von Steiger, S. Bartalev, X. Dong, M. Falanga, R. Fléron, A. Gregorio, T. S. Horbury, D. Klumpar, M. Küppers, M. Macdonald, R. Millan, A. Petrukovich, K. Schilling, J. Wu, and J. Yan; "*Performing High-Quality Science on CubeSats*", Space Research Today, Vol. 196 (August 2016), pp. 10-30.