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Formations of Small Satellites to Realize Sensor Networks for Earth Observation

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Abstract **– At the level of small satellites with a mass of a few kilograms all capabilities of self-organizing sensor networks for Earth observation can be realized. Photogrammetry methods enable sensor data fusion to generate 3-dimensional images of a target area. Here appropriate satellite position information in combination with attitude determination and control provides precision pointing accuracies to generate suitable input for subsequent data processing. This way, on small satellites efficient methods for distri-buted sensor systems in orbit can be implemented.**

I. INTRODUCTION

Miniaturization technologies enable realization of satellites at the mass of just a few kilograms, in particular in the form of so called CubeSats, being composed of multiples of 10 cm cubes [5], [12]. While in the beginning around the year 2000, CubeSats were mainly used in academia as educational tool for applied systems and space technology, today several hundreds of such CubeSats are launched every year, in majority for commercial constellations in Earth observation. Here each satellite is individually controlled from a ground control center, providing its observation plan and related attitude and orbit control activities.

Recent technology development progress enabled miniature attitude and orbit control systems, as well as inter-satellite communication links. This provides the basis for self-organizing satellite formations in orbit [6], www.telematik-zentrum.de/netsat . These technology breakthroughs in formations of very small satellites allow as next step to realize in a cost-efficient way advanced sensor networks supporting innovative Earth observation approaches [2], [6], [8], [11]. Thus there are currently opportunity for technology transfer of terrestrial sensor network technologies for new applications into challenging space application context.

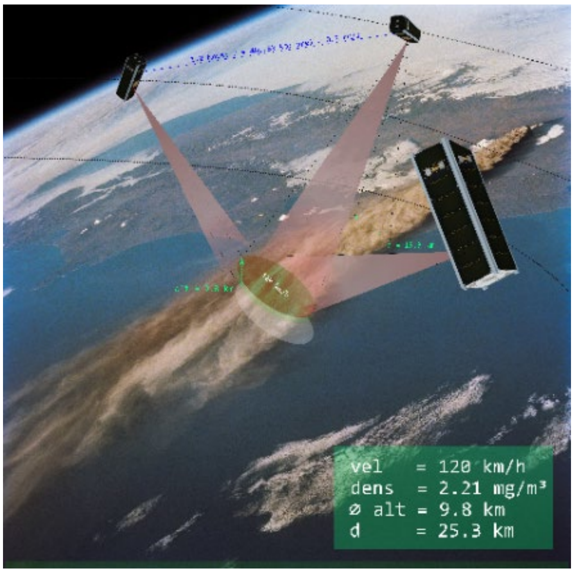

Fig. 1. The 3 cooperating TOM satellites [8] for three-dimensional characterization of ash clouds from volcano eruptions.

II. SMALL SATELLITE DESIGN

A broad spectrum of sensors is available at very small sizes, such as detectors for electromagnetic fields and waves, radio waves, plasma and particles, as well as photometers and imagers [5]. Those miniature sensors are appropriate payloads for small satellites.

In parallel, miniaturization of electronic components supports also significant reduction of satellite mass and related launch costs. In particular, typical CubeSat developments are based on commercial-of-the-shelf electronics, but still need to be adapted to the harsh space radiation environment. Here deficits of miniaturization are to be compensated by appropriate redundancy and software concepts, in particular fault detection, identification and recovery (FDIR) algorithms [6]. Thus, in the field of small satellites, there is a shift of efforts from hardware to software and control engineering observed, in order to counterbalance deficits of miniaturization.

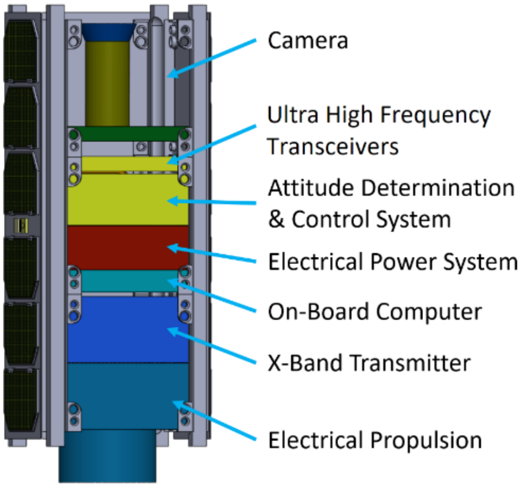

Fig. 2. Typical small satellite design with camera payload in form of a 3Unit CubeSat (mass about 4 kg and dimension 30x10x10 cm)

Particular progress was achieved in precision satellite pointing by development of miniature reaction wheels at very low nominal power consumption level of nominal just 150 mW each. Thus, by combination of at least 3 reaction wheels, within the available limited resources of a small satellite, a 3-axis attitude control systems is able to orient the satellite into any desirable direction with appropriate precision below 1°. Further pointing accuracy is achieved by nested control loops in the sensor system itself.

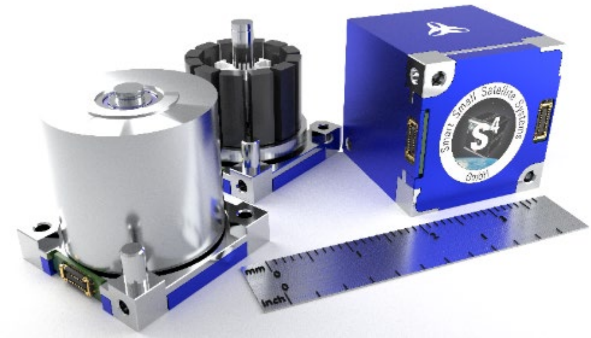

Fig. 3. Miniature reaction wheel for satellite high precision pointing capabilities: in the background the brushless motor, at left the rotation mass on top of the motor, and at right the system finally sealed in its housing of a 2 cm cube.

Thus, by the impulse conservation law from physics, an acceleration/deceleration of the reaction wheel induces a rotation of the whole satellite in the opposite direction. In case the maximum rotation speed of up to 19.000 revolutions per minute is reached for a reaction wheel, a desaturation by using magnetorquers is to be initiated in order to gain again all degrees of freedom for sensor pointing.

III. JOINT SATELLITE OBSERVATIONS

Satellite positions are acquired from GNSS information, by example from GPS measurements and shared via inter-satellite links within the network. Each satellite's attitude is determined from Sun sensor, horizon sensor, and magnetometer measurements in combination with models of the Earth's magnetosphere and of the satellite orbit. For higher precision also a star sensor can be integrated. Distributed control algorithms coordinate pointing of all satellite payloads to the same target area (cf. Fig. 1) based on this position and attitude determination by taking advantage of reaction wheels (cf. Fig. 3) as actuators.

Here combination of attitude and orbit data from the complete satellite network must provide appropriate accuracies in order to apply suitable sensor data fusion methods to the measurements. Fine tuning of the camera orientation control towards the target area is realized in a second step by using visual servoing methods [10], transferred from mobile robotics. Visual servoing is a technique encapsulating feature extraction to control in a feedback loop. It comes in two variants: Image Based Visual Servoing (IBVS) and Position Based Visual Servoing (PBVS). IBVS computes the control values on the basis of image features directly. This eliminates the delay related to image interpretation and inaccuracies caused by camera calibration. In PBVS features are indirectly obtained from image measurements and are used in conjunction with known or computed 3D model of the target to estimate the pose between the camera and the target. Obviously, PBVS is not an option here and thus, IBVS in a eye-in-hand (EiH) configuration is considered. EiH is represented by a camera being mounted directly onto the end effector -which is the satellite in our case- where attitude is controlled. Visual servoing tasks are described by minimization of an error value between a current and a desired set of image features. Classical IBVS considers 6 degrees of freedom, i.e., it computes a instantaneous linear velocity and an instantaneous angular velocity, and assumes perspective projection, i.e., a pinhole camera. Visual servoing provides a direct link to control the satellite solemnly based on data from the camera. But it is only as good as it's partial components: feature detection and tracking that provides, the sets of current and desired features, and the Geometric Jacobian that links the end effector frame to the satellite.

Photogrammetric problems are inherently depending on the multiplicity of related images or the image stream. For precise pointing of a single satellite, one detects features in an image and tracks them in the continuous stream of image data that follows – first detect, then track. Harris&Stephens [3] or Shi&Tomasi [9] have proposed slightly different methods to robustly detect features for such a purpose, based on the minimization of sum of square differences of an image patch (cf. Fig. 4)

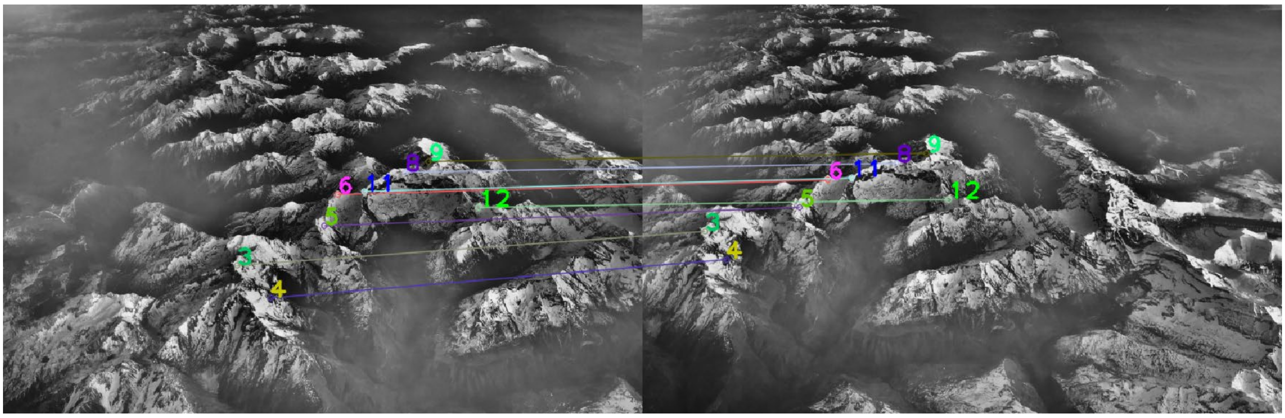

Fig.4. Example of a feature tracking, i.e., feature matching.

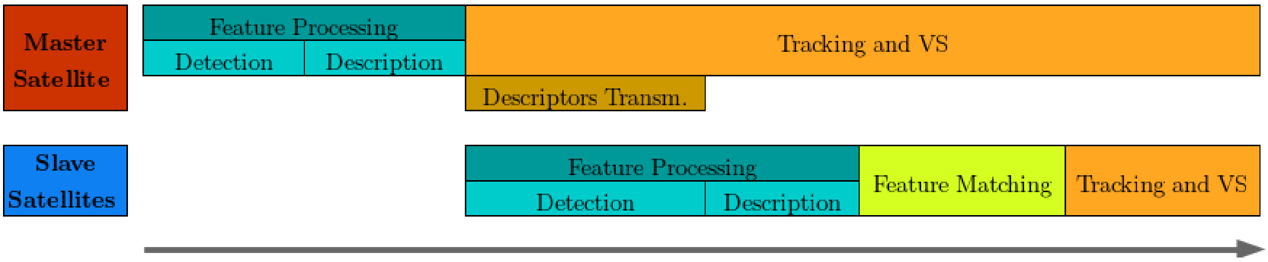

Fig. 5. Image processing pipeline for target tracking and image based visual servoing.

After having acquired a list of features in an image, it is interesting to observe their apparent motion in the image stream. This process is called Feature Tracking. A well-know method was first introduced by Lucas&Kanade [4], with the widely-used pyramidal implementation [1]. Please note: Detection and tracking are correlated problems: good features are those that are easy to track, and vice-versa. The Lucas&Kanade tracker is sufficient for tracking features, that change only in a limited way. More extended models are needed for more complicated cases with a clear rotation or affine transformation. Features are detected only in the first frame, later on, the difference between two neighboring images is analyzed. This can lead to a significant change in the features character, practically turning them into outliers. Shi et al. propose a measure of dissimilarity, that takes into account changes with respect to the first frame [9].

In a multi satellite configuration, one needs to detect features in images of all satellites, as well as searches for the correspondences and matching them based on their local appearance. Fig. 5 shows the overall image processing pipeline: The master satellite acquires an image and does the feature processing, i.e., the detection and description. Afterwards, it transmits the descriptors to the slave satellites and starts its tracking. After receiving the descriptors at the slaves, the images from the slaves are processed. The descriptor of the detected features is matched with the received descriptor. The tracking and visual servoing starts there as well.

Detected image features are used for fine pointing across the complete satellite formation. Thus via inter-satellite links feature maps are exchanged and further processed by matching algorithms.

IV. THE TOM MISSION FOR PHOTOGRAMMETRIC 3D-OBSERVATIONS

A specific example using a camera payload is provided by the "***T***elematics earth ***O***bservation ***M***ission" (TOM) [8] using a formation of 3 small satellites to observe a target area from different directions (cf. Fig. 1), and to use photogrammetric methods for generation of 3D-images [11]. Planned launch is 2021. It includes an intersatellite link as well as a high bandwidth optical downlink capability by the OSIRIS payload (cf. Fig. 6, 7).

Here simultaneously acquired camera data are used to characterize vertical extension of ash clouds, moving with significant speeds of about 100 km/h. Thus time synchronization in imaging is essential to avoid parallax phenomena implying decreased image quality. While the 3D-image data processing is using the extensive computer facilities on ground, accurate position and pointing information is an essential input to be acquired in orbit by the satellite formation.

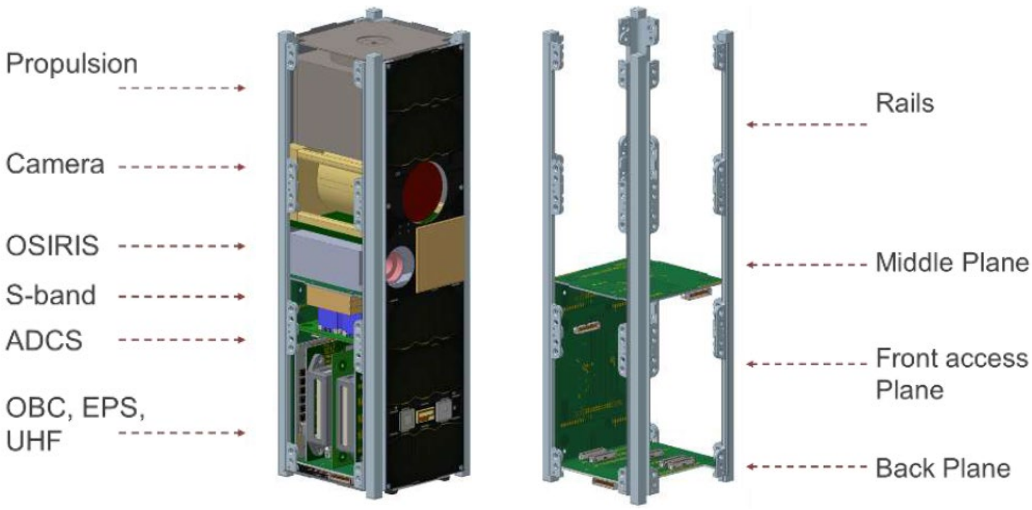

Fig.6 The set-up of each of the 3 TOM satellites with the structural components at the right, and the included subsystems and payloads at the left.

Fig. 7 TOM satellite with deployed solar arrays for power generation.

Additional five small satellites from international partners join TOM by providing further observation perspectives in ***T**elematics **I**nternational **M**ission* (TIM) [7]. Every additional satellite joining the initial formation increases image quality.

V. EXPERIMENTAL TESTING

In preparation of TOM, the photogrammetric methods were tested in a first step with camera data from space station [11]. In a second step, high precision turntables at the "Zentrum für Telematik" (Würzburg) are used to simulate payload pointing in orbit by hardware-in-the-loop tests in the laboratory (cf. Fig. 8, 9). The setup includes 3D-structures as moving targets simulating orbit motion, while cameras mounted on the two turntables track the target and generate images for subsequent processing and image data fusion.

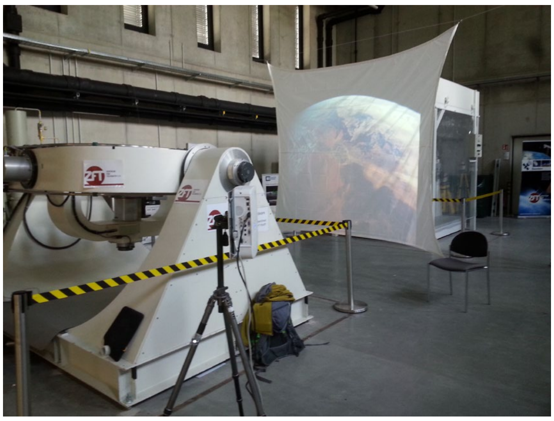

Fig. 8. Simulating Image Based Visual Servoing of a single satellite with a precision turntable.

Fig. 8. Cameras mounted on the two precision turntables to simulate the orbit motion in imaging the 3D-object on the ceiling.

VI. SUMMARY

In the framework of "New Space" very small satellites of a few kg of mass are placed in orbit at moderate costs. Technology breakthroughs in miniature attitude and orbit control systems allow to realize suitable sensor networks in orbit. This distributed observation system takes advantage of significant controlled relative distances between different satellites. Challenges in realization of such multi-satellite formations concern relative attitude and orbit determination, distributed control, inter-satellite data exchange and synchronization. The concrete example of the TOM mission (to be launched 2021) is used to illustrate in this context 3D-imaging of ash clouds from volcano eruptions by photogrammetric methods.

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