INNOVATIVE CAMERA POINTING MECHANISM FOR STRATOSPHERIC BALLOONS

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ABSTRACT

Quality of video recordings from stratospheric balloons is poor for a reason of motions of balloons gondolas. This paper presents new low-cost and innovative camera stabilization and control system (3-DOF pointing mechanism) that is designated specifically to be used on the stratospheric balloons. Prototype of this system was launched on BEXUS 11 balloon as a student's experiment called Stabilized Camera Observation Platform Experiment (SCOPE). Although experiment did not fulfil all its objectives it proved that selected concept of the pointing mechanism is correct and system can work in extreme conditions at the height above 30 km. Test flight also allowed to identify main issues and complications that occur while designing such systems.

1. INTRODUCTION

Earth-orbiting satellites are used for remote sensing, but in recent years various studies show that remote sensing performed from platforms operating in the stratosphere has some advantages in comparison to satellite observations (e.g. [1]). Stratospheric altitudes are reachable by High Altitude Long Endurance Unmanned Aerial Vehicles (HALE UAVs) or by stratospheric balloons. It seems, that such balloons (equipped with video cameras) can be used for many valuable terrain observations, for environment monitoring and, in some cases, in crisis management. Moreover, cameras could be mounted as a secondary payload on balloons sent for investigations of the atmospheric conditions or with other scientific equipment. Such secondary-payload cameras could significantly increase mission's output, provided that image quality is high enough.

During the flight balloon's gondola moves and rotates in uncontrolled manner causing serious problems with smooth video recordings. Changes in gondola's attitude make observations of the Earth's surface very difficult, especially during flights in windy conditions or in cases of relatively small and light-weight gondolas, which are more susceptible to disturbances. When one considers using video camera on stratospheric balloon it is important to be able to compensate changes of gondola's orientation while keeping camera turned towards desired direction. Such ability would allow making continuous observations of chosen areas on the ground not directly below the vehicle (balloon route cannot be controlled and, therefore, targets interesting for observations may not lie directly below the balloon). Pointing mechanism could also be used to capture terrain mosaic or for pointing directional antenna to the ground station (it might be useful for balloon-borne experiments which require large data transfer for data analysis during the flight).

Commercially available camera stabilization systems for UAV applications are very expensive and are not entirely suited for stratospheric balloons (i.e. required ability to compensate unlimited rotations of the gondola around the vertical axis, ability to work in low temperatures and near-vacuum conditions of high altitudes). While engineering community and numerous companies are focused on complicated, multi-applicable and highly accurate systems, which are also capable of vibration dumping (e.g. SPEKTROP project [2]), we propose simple system made from COTS components which is designated specifically to be used on the stratospheric balloons. Designed three DOFs video camera stabilization and control system (pointing mechanism) is capable of compensating changes in balloon's gondola attitude and allows camera to track selected ground targets during the flight. First prototype of the system was constructed and tested under the Stabilized Camera Observation Platform Experiment (SCOPE) as a part of the Balloon Experiments for University Students (BEXUS) 2010 programme.

The paper is divided into seven sections (including the introduction). In the second section objectives of proposed camera stabilization and control system are defined and system requirements are presented. Section three contains detailed description of system design. Pre-flight tests and analysis are presented in section four, while final in-flight verification of the prototypic realization of this system (performed during BEXUS 11 flight) is described in section five. Lessons learned and recommendations for future balloon-borne experiments are listed in the section six. Section seven contains conclusions, summary of presented work and considered scenarios of future development of the system.

2. OBJECTIVES AND SYSTEM REQUIREMENTS

Main objective of designed innovative and low-cost video camera stabilization and control system is compensation of balloon's gondola attitude and ability to keep camera tracking ground targets (selected by the Ground Station (GS) operator during the flight or read automatically from on-board memory). Proposed system is a 3DOF pointing mechanism that is specifically designed to be used on stratospheric balloons, but after some minor modification, could also be mounted on HALE UAVs or other aerial vehicles.

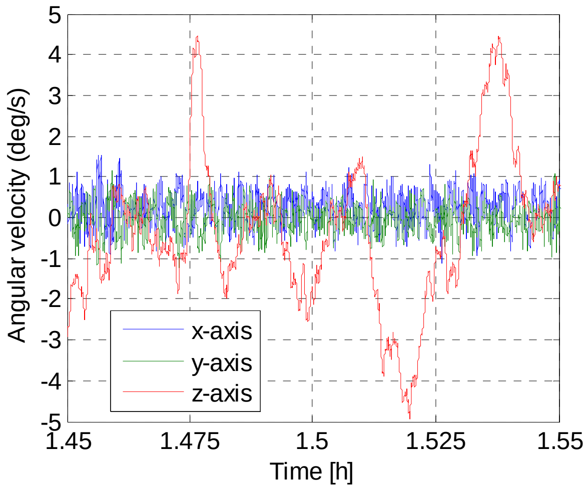

Figure 1. Angular velocities of the stratospheric balloon gondola during ascent (based on Low.Co.I.N.S. data obtained during BEXUS 6 flight in 2008)

Data from various flights of stratospheric balloons was analysed in order to formulate system requirements that would establish basis for detailed system design. Video recordings from balloons flights BEXUS 6/7 and BOBAS 3, as well as quantitative data of gondola's attitude obtained by the Low.Co.I.N.S. experiment (Low Cost Inertial Navigation System tested during BEXUS 6 flight [3]) were used to identify the nature of gondola's motion during the flight and to define requirements for motor velocities of the stabilization system. There are no significant vibrations during balloon's flights, but changes in gondola's attitude might be fast. Three major phases of flight, i.e. ascent, level flight and descent, are characterized by different velocities of attitude changes. Maximal gondola's angular velocities around vertical axis recorded during ascent were below 10 deg/s, during level flight were around 1 deg/s and during descent were up to 60 deg/s (for horizontal axes values were smaller). Presented values were recorded for medium-weight (about 100 kg) gondola during BEXUS 6 flight in steady weather conditions. For heavier gondolas and larger balloons those velocities are expected to be significantly smaller. It is also important to note that rotations around the vertical axis are infinite regardless of gondola's mass and slip ring should always be used on the last joint.

Presented camera stabilization system was designed to compensate changes in gondola's attitude during first two phases of similar flight (ability to compensate changes in gondola's attitude that are not faster than 30 deg/s), to compensate unlimited rotation around vertical axis and to withstand 10g vertical acceleration in the final phase at the end of flight. Another driving factor for the design were extreme environmental conditions at the maximal height reached by the balloons (around 35 km): temperature below -60°C and pressure below 5 mbar (such conditions have significant influence on convection), which impose severe requirements for thermal design. Such conditions are also very problematic for all mechanical systems with moving parts (motors, bearings) due to issues like friction and several others.

Apart from the educational aspects of the student project, main objective of SCOPE was realization of a prototype of proposed system and in-flight verification and assessment of its performance during BEXUS balloon flight. Developed prototype is slightly simplified version of proposed design: no slip ring was used on the third joint and, therefore, rotations of this joint are limited to 310 degrees, but special measures were implemented for the purpose of post-flight evaluation of its performance. In prototypic realization an additional video camera was used to record motions of the pointing mechanism during the flight for such post-mission analysis.

3. SYSTEM DESIGN

3.1. General overview

Main element of the system, mounted to the structure, is called Platform Orientation Mechanism (POM). POM consists of three frames connected by rotational joints actuated by stepper motors. Video camera is mounted to the last joint. Motion of joints is provided by three motor drivers, controlled by the Interface Board (IB). Encoders data is used as a feedback signal. PC/104 is used as On-board Computer (OBC) and it is responsible for gathering data, computations and communication with the Ground Station (GS). Electronic box (containing: electronic boards, PC/104 and power control subsystem) and power supply system with battery box are mounted on the structure above POM. GPS receiver gives information about gondola position. Inertial Measurement Unit (IMU), which is mounted on a long boom outside the gondola to minimize electromagnetic disturbances from other gondola's payloads, provides actual gondola attitude. Basing on these data, PC/104 computes joints positions that are needed to achieve desired camera orientation. Data flow between PC/104 and other sensors (except IMU) is carried out via IB. No antenna is used and communication must be provided externally. Schematic overview of the system is presented in the Fig. 2 and basic parameters of the prototype tested during BEXUS 11 flight are shown in the Tab. 1.

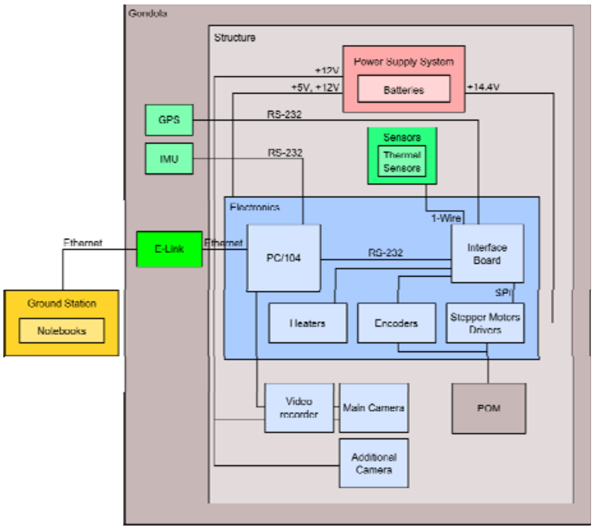

Figure 2. Overview of the camera stabilization and control system

Table 1. Basic parameters of the camera stabilization and control system.

Total mass	21.87 kg
Mass of POM's moving parts	5.76 kg
External dimensions	466 x 550 x 538 mm
Camera maximal deflection from vertical axis	45^{o}
Rotations around vertical axis	Unlimited (limited to 310^{o} in the prototype)
Compensated changes in gondola's attitude	30 deg/s
Camera resolution	540x576 px
Operational time (available power)	12
Minimal operational temperature (confirmed)	-70^{o}C
Minimal operational pressure (confirmed)	1 mbar

3.2. Software design

Software running on the PC/104 is responsible for: controlling the entire experiment, receiving telecommands from the GS and sending telemetry to GS, gathering data from sensors (IMU, GPS, thermal and voltage sensors) and storing this data on on-board memory, computing camera attitude that should be obtained in order to point toward selected target and sending computed joints positions to IB. The source code of PC/104 control software is written in C++ and run on Linux OS.

OBC software can control POM in one of three modes:
(i) Desired joints positions are send directly via telecommands – manual POM control by GS operator.
(ii) Camera is stabilized to point directly downwards – Joints Positions Determination Algorithm (JPDA) is used and on the basis of gondola's actual attitude (measured by the IMU) calculates joints positions that would keep camera pointing directly downwards.
(iii) Camera tracks selected ground targets – on the basis of gondola's current position (from the GPS data) and selected target's geographical coordinates (provided by GS operator via telecommands or read from on-board memory) Target Tracking Algorithm (TTA) calculates desired camera attitude for pointing to the target. Then, taking into account gondola movements, JPDA on the basis of desired (computed by the TTA) and gondola's actual attitude calculates joints positions that would keep camera pointing to the target. Working of these two algorithms is shown in the Fig. 3.

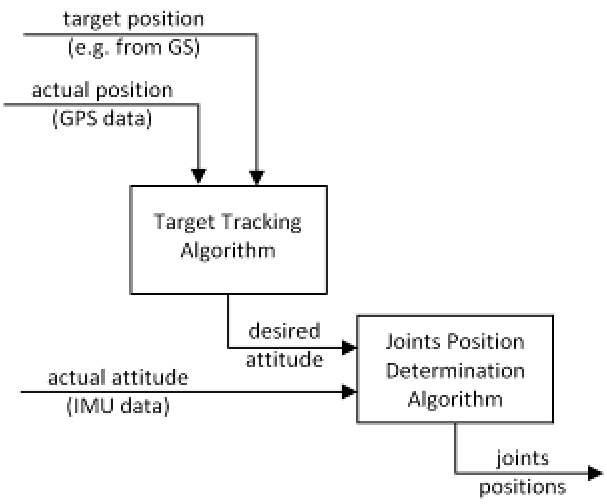

Figure 3. Control algorithms for tracking ground targets

Besides aforementioned main modes of operations, system can also be used to perform pre-programmed sequence of motion (e.g. capturing terrain mosaic or performing test sequences of motions). Changing between modes is performed via telecommand from GS or, in case of no-communication, performed automatically by OBC software according to pre-programmed sequence (in such case system can also automatically select ground targets from pre-defined list).

GS software used to operate the stabilization system is running on a netbook. Communication between OBC software and GS must be provided externally (in case of BEXUS flight it was E-link system belonging to balloon's providers – Esrange). GS is responsible for:

sending telecommands, receiving telemetry, real time presentation of all telemetry data received from the experiment (also on the graphs) and storage of all received telemetry data for after flight evaluation of system's performance in case of on-board data loss (it was especially important during test flight of stabilization system prototype during SCOPE experiment on-board BEXUS 11). Special procedures are implemented for auto-check of all telecommands and for telemetry data analysis. Screen from main panel of GS software is presented in the Fig. 4 .

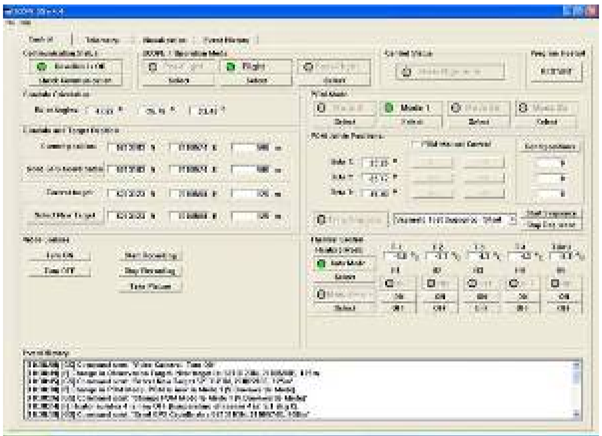
Figure 4. Screen from main panel of GS software

3.3. On-board computer and electronics

Electronic design scheme of the prototypic realization of proposed camera stabilization and control system is presented in the Fig. 5. Main element of on-board electronics is Kontron MOPSlcdLX AMD LX800 PC/104 connected to the IB, on which four controllers are located.

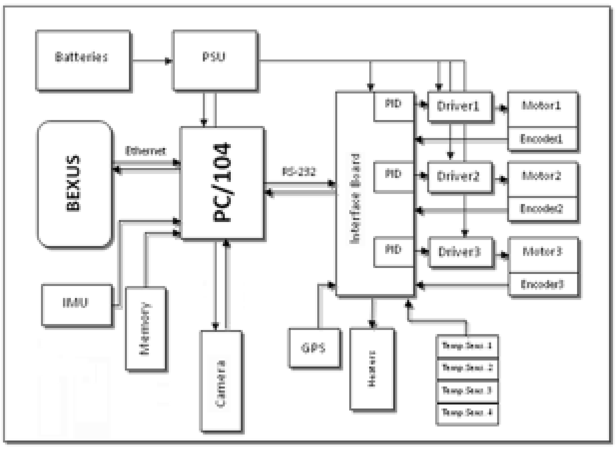

Figure 5. Electronic design scheme

Each controller contained ATmega128 microcontroller and ULQ2003 board as a power stage, which generates Pulse-Width Modulation (PWM) signals (sinus-like function was used as a control signal). These signals are used for powering stepper motors. Voltage control was used, because it is simple, but sufficient. ATmega128 microcontrollers are also used for gathering signals from sensors (positions of POM's joints, temperatures, geographical coordinates). RS-232 communication interface is used to exchange data between IB and PC/104. Incremental encoders (connected to motor drivers) and motors of two first stages are working in the feedback loop (with PID based regulator) to make POM moves smoother (and also faster and more precise). To achieve high quality and smooth shaft rotation of the stepper motors (1/256 microstep), the specialized motor controllers were designed.

3.4. Video camera and sensors

LC-1/3 Sony 520TVL board analog camera with 520 TVL resolution and Sony CCD 1/3'' sensor was used in the prototypic realization of the camera stabilization and control system. The main advantage of this camera is low weight (7 g) and small size (30×30×20 mm excluding optics). There was used LCMTV 25 mm objective. The camera was mounted on a board frame grabber A/V which allows to record with a resolution up to 1280x720 pixels and up to 30 frames per second. Recordings were stored on a micro SDHC card. Dimensions of this system are very small: 60×60 mm main board. The strong advantage of this system is that it is autonomous and can work even if any malfunctions of other subsystems occur. On the other hand recordings were not available on GS during the flight. Moreover this solution allows to use a slip ring.

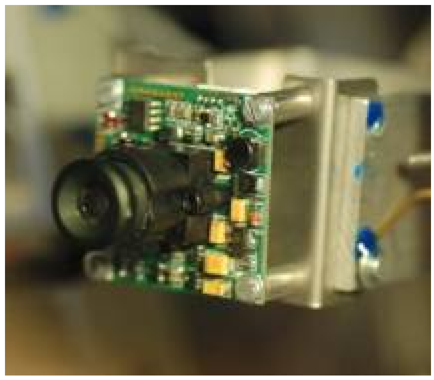
Figure 6. Video camera mounted on the POM

To stabilize camera in the desired orientation data of actual gondola's orientation is provided by IMU. MicroStrain 3DM-GX1 was chosen. It has nine sensors: three accelerometers, three gyros and three magnetometers. All of them are provided with full temperature compensation which highly increases accuracy of its readings. High accuracy assured by the producer (+/-0,5° for static and +/-2° for dynamic conditions) is extremely important in the proposed stabilization system. IMU is calibrated before flight upon receiving telecommand from GS (quality and precision of stabilization depends strongly on IMU accuracy).

Garmin GPS 18x LVC receiver was chosen, because it can work above the altitude of 60 kft (18 km), while majority of commercially available GPS receivers cannot work above this level.

Four DS18B20 temperature sensors were used in the experiment, which provide actual value of temperature in crucial points: IMU and GPS box (this part of experiment was independent of other parts and was only heated by itself), on Styrofoam wall (to check of gradient temperature), in battery box (capacity is sensitive to temperature changes) and in the electronic box (the hottest part of the experiment). These sensors are connected to IB and can measure temperatures in range from -55°C to +125°C.

3.5. Mechanical design

The main element of the stabilization system, Platform Orientation Mechanism (POM), is mounted to the aluminium structure. Structure frame is integrated by angle bars and self-locking screws secured by glue. Upper part of the structure, separated from POM by the internal panel, holds electronics box and battery box. Structure is closed from all sides: internal components are covered by aluminium body-mounted panels (20 mm layer of Styrofoam and layer of the space blanket is applied outside for insulation) and polycarbonate plate is mounted below POM for safety reasons. A small hole was drilled in this plate to minimize the risk of vapour condensation which may obscure camera view during the flight. Overview of the structure is presented in the Fig. 7.

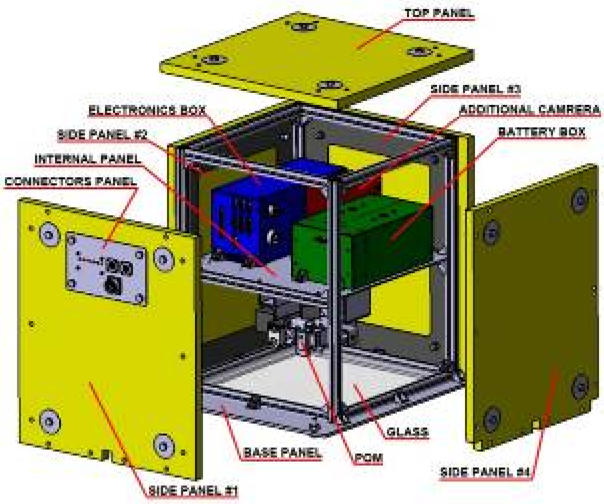

Figure 7. Schematic view of the prototypic realization of the camera stabilization and control system

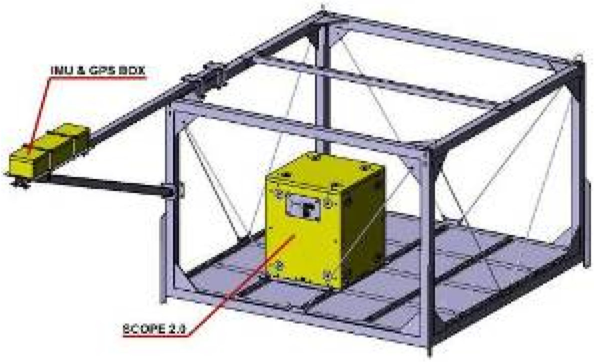

Figure 8. Position of the prototype of proposed camera stabilization and control system (SCOPE) in the BEXUS 11 gondola (IMU/GPS box is located on a boom)

IMU and GPS are mounted in a box located on a 1.5 m aluminium boom outside the gondola to minimize disturbances from other payloads and electronic devices located inside the gondola (Fig. 8). Such distance was selected after tests with other experiment that was on the gondola and consisted a strong magnet. In fact every use of IMU with magnetometers should be preceded with proper interference tests.

3.6. Platform Orientation Mechanism

POM is divided into three aluminium-made stages. Frames are connected stiffly without clutches and gears. Moments of inertia for particular stages are very small and counterweight is used on the last stage for balance. POM's motion is realized by three stepper motors. Encoders provide rotation data about shafts position for two first joints to improve control (moment of inertia of the third stage is so small that data about shaft position given from the stepper motor is adequately accurate in this case). Transmissive Optical Sensors are used to determine the resting POM position (camera pointed vertically downwards), because selected encoders do not provide absolute position. Picture of the prototypic realization of that mechanism is presented in the Fig. 9, while schematic view of proposed POM design is presented in the Fig. 10.

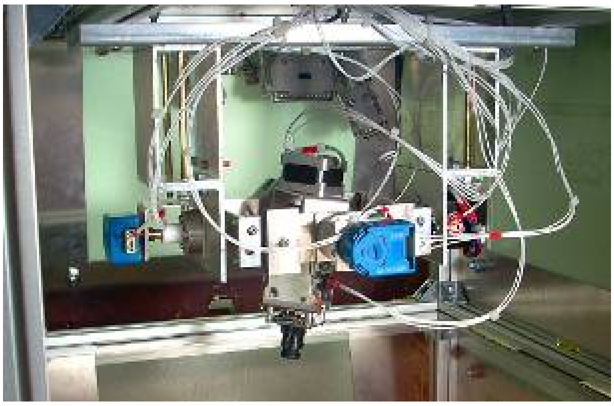

Figure 10. Prototypic realization of Platform Orientation Mechanism (POM) for BEXUS 11 flight

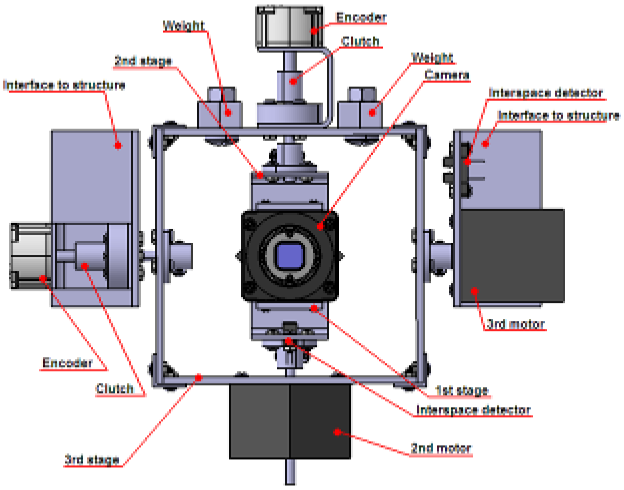

Figure 9. Schematic view of the Platform Orientation Mechanism (POM)

4. PRE-FLIGHT TESTS AND ANALYSIS

During preparations for the BEXUS 11 flight campaign tests of particular components and assembled POM were performed in thermal-vacuum chamber in wide range of temperatures (to -100°C) at pressure of 1 mbar. These tests proved that the system works well for a long period of time in the internal temperature -70°C, even though microcontrollers and other electronic components were specified to temperatures higher than -40°C.

Extensive thermal analysis were made in ANSYS Fluent 6.3. Convection and radiation models were used to cover wide range of operational pressure. It turned out that radiation can be omitted in modelling, because its influence on total temperature is less than 10%. In case of balloon-borne experiments risk of too low temperature exists on low altitudes, while risk of too high temperature exists on high altitude and, therefore, both cases were investigated (external temperature 200 K and 280 K respectively). Some sample results of thermal analysis of the electronic box is presented in the Fig. 12. This result shows that the temperature of PC/104 will be much higher than others PCB.

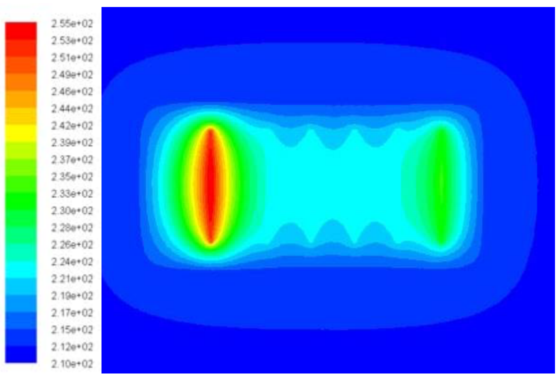

Figure 12. Thermal analysis of the electronic box

Data obtained in thermal-vacuum chamber tests and performed computer analyses were used to design thermal control system which will ensure that during the entire flight temperatures will be within the range defined for all components (-40°C ÷ 70°C for the electronic box, -10°C ÷ 40°C for the battery box). It turned out that passive thermal control system consisting of Styrofoam insulation panels is sufficient and such system was used.

Just before the flight reduced ground tests were performed. Those tests proved that the selected concept of the system is correct and 2-axis stabilization works satisfactorily, but some problems were detected in compensation of motions around vertical axis due to lower than expected accuracy of IMU.

5. PARTICIPATION IN BEXUS 2011 CAMPAIGN

SCOPE experiment flown on BEXUS 11 from Kiruna (Sweden) on the 23rd of October 2010. Although not entirely successful due to problems with on-board software and in communication with the GS, this flight proved that the constructed system can work in every phase of flight, withstand landing and operate without disturbing other systems on-board the gondola. However, flight preparations showed that designed system should be more ergonomic and modular. Picture of SCOPE mounted inside the BEXUS 11 gondola is presented in the Fig. 13.

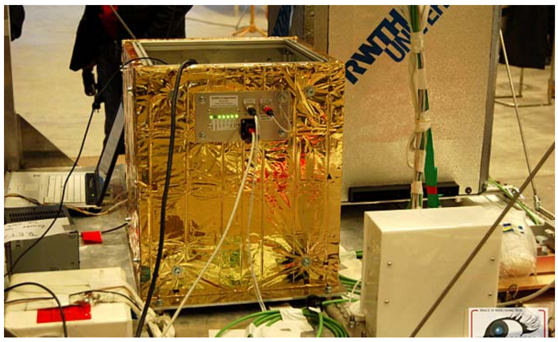

Figure 13. SCOPE mounted inside the gondola of BEXUS 11

The flight was steady and the gondola, on which SCOPE was mounted, was very heavy. This resulted in only small changes in gondola's attitude and no much work for stabilization system. Quality of the video recorded during entire flight by the main camera is very good and allows recognition of some surface features like trees and roads. Unfortunately balloon's flight was over inhabited area and not many interesting things were to be seen. Frame of the video from the main camera captured during ascent (23 minutes after the launch at the height of 7 600 m) is presented in the Fig. 14, while frame captured during steady level flight at height of 31 000 m is presented in the Fig. 15.

Figure 14. Frame capture from the main camera showing Earth surface from the height of 7 600 m

Figure 15. Frame capture from the main camera showing Earth surface from the height of 31 000 m

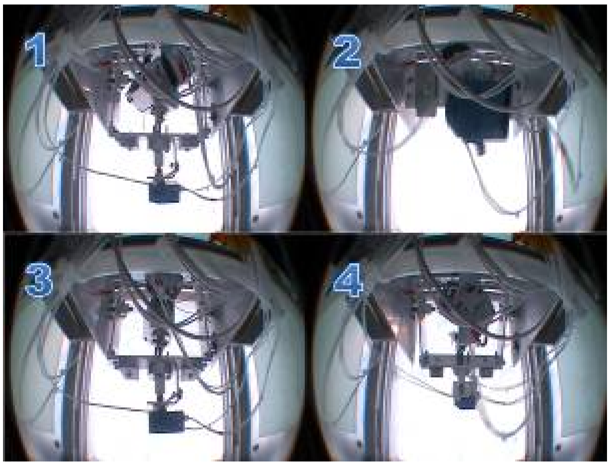

Figure 16. Pre-programmed test sequence of motion performed at the height of 16 000 m (pressure: 93mbar, external temperature: -53 ^{o}C)

Video recording from the additional camera shows that POM was nominally performing pre-programmed test sequence of motion at all altitudes (these sequences were performed to unblock the mechanisms in case of possible blocking due to low temperature and they could also be used to assess the performance of the mechanism). During such sequence all joints are moved to extreme positions with the maximal velocity. Sequence performed at the height of 16 000 m is presented in the Fig. 16.

6. LESSONS LEARNED AND RECOMENDATIONS

During all the work on the experiment there appeared many aspects and issues, smaller and greater, that should have been changed. Despite the fact that they were identified before the flight campaign, they could not be improved due to time restrictions.

Among these major issues, one of the greatest is that related to IMU sensor. The model chosen for SCOPE happened to have not enough accuracy in computing yaw angle. In fact readings of this value were useless and could not be taken into account during the flight. Possible improvements include using different model of IMU or using an external, independent system computing yaw angle (e.g. using inclinometers, accelerometers or separate magnetometers) or linking data from IMU and GPS to determine gondola trajectory and on this base calculation of north direction. However, it must be noted that increasing accuracy by choosing better IMU would results it significant increase of system's overall cost.

Another issue concerns OBC software. Identified failures include: loss of communication, slow data flow between OBC and IB, problems with telemetry storing data. These should be improved in future projects. Main reason of these problems were last-minute modifications performed before the flight.

Point Grey Chameleon CCD 1/3" Colour Camera was chosen for the experiment in preliminary design phase. After Critical Design Review it turned out that this camera (which relies on USB 2.0 standard) cannot be used with slip ring, because USB 2.0 has too small frequency for selected slip ring. Therefore, it was decided not to use slip ring in the prototype prepared for the BEXUS campaign and flight version of POM was designed and constructed without the slip ring. However, in the last phase of SCOPE project, it appeared that selected camera cannot at all work with PC/104 and new analogue camera was chosen: LC-1/3 Sony 520TVL. In this camera USB 2.0 standard is not used for data transfer and it could work with slip ring. Unfortunately it was too late to change POM design and, therefore, in the prototype of the camera stabilization and control system tested during BEXUS 11 flight rotations of the third joint were limited, although finally selected camera could have been used with slip ring.

Finally during work, improvements and applying changes to the experiment it appeared that it should be more ergonomic. This include software (e.g. possibility to update software via telecommand from GS), mechanics (e.g. easier access to important parts, modularity in design) and electronics (e.g. easier way to recharge batteries).

7. FINAL REMARKS AND FUTURE DEVELOPMENT

New camera stabilization and control system designed specifically for stratospheric balloons was constructed and thoroughly tested. Innovative design allows high camera deflections from vertical axis (up to 45 degrees) and unlimited rotations around vertical axis, although in prototype rotations were limited. Ability to track ground targets selected by the operator during the flight may significantly enhance possibilities to use stratospheric balloons for various ground observations. Design based on COTS components ensured low price of the prototype – its overall cost was below 5500 EU. This cost could be even lower, because during construction of the prototype many ESA recommended components (specified for harder conditions than those at the height of 35 km) were used.

Final test flight on the BEXUS 11 stratospheric balloon did not fulfil all its objectives, but proved that selected concept of the pointing mechanism is correct and system can work in extreme conditions at the height above 30 km. This flight also allowed recognition of certain issues (e.g. fatal IMU yaw angle accuracy, software problems with communication with GS and slow data flow between OBC and IB) that must be resolved. It should also be noted that in cases when balloon's gondola is very heavy and flight is smooth (as it was in case of BEXUS 11) changes in gondola's attitude are slow and only compensation of rotational motion around vertical axis becomes important. However, during such flights, ability to point camera in the desired direction is still very important.

Pre-flight preparations showed that easy access to all parts of the experiment is essential. All future versions of proposed system should be more ergonomic and modular. This general rule is important for all balloon-borne experiments.

Designed system, after some minor modifications and further miniaturization, can be used on UAVs for various observations. Infrared camera can be used instead of visible light camera. One could also think of using proposed system as a pointing mechanism for a directional antenna, which needs to be precisely pointed in the direction of a ground station. Such solution might be useful for balloon-borne experiments that transmit high amounts of data.

Quantitative measurements of system's accuracy are to be done in coming months. Next test flight of the constructed system is considered on-board of one of experimental stratospheric balloons flown in Poland by teams of students and amateurs or on-board a small plane. It is also possible that dedicated balloon project will begin in the Students' Space Association at the Warsaw University of Technology and proposed camera stabilization and control system (after some modifications and miniaturization) could be used as a payload.

8. ACKNOWLEDGMENTS

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