BMSTU-Sail Space Experiment

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(Received 1st Dec, 2016)

The paper is about the history and a final design of the space experiment "BMSTU-Sail" in which it is proposed to deploy the prototype of Heliogyro solar sail. The experiment will be conducted onboard the International Space Station during the EVA. During the experiment, the nanosatellite of CubeSat class will deploy two-blade solar sail stabilized by rotation. The length of each blade is 5 meters, width - 4cm. The article describes the structure of the satellite including the structure of solar sail unit. The experiment was conceived in 2009 as a student project. The results of its development are already being used in the educational process in the Bauman MSTU. To date, the experiment "BMSTU-Sail" is on the stage of Production Readiness Review, the ground tests will begin shortly. The results of the experiment will be used in the design of a continuation of BMSTU-Sail space experiment which will be a prospective solar sail unit for deceleration of nanosatellites from Earth orbit

Key Words: Heliogyro, Solar Sail, CubeSat

1. Introduction

The phenomenon of light radiation pressure was predicted by J. Maxwell based on his theory of electromagnetism.[1)] Experimentally this effect was observed by the P. N. Lebedev in the beginning of 20 century.[2)] The first researcher who proposed to use the light radiation pressure as a movement force for space satellite was F. Tsander in his pioneer works in the middle of 1920s.[3)] He invented a conception of a solar sail with a series of large flat mirrors stabilized by rotation – a heliogyro solar sail ("geliorotor").

The ideas of Tsander were popularized by R. MacNeal. He proposed to send an interplanetary station with heliogyro solar sail to Halley's comet.[4)] This conception was rejected due to large technical risk however the conception of heliogyro solar sail is still under consideration by different researchers and engineers. [5-8)] The sufficiently full review of solar sail development and research can be found in the book by C. McInnes.[9)]

The frameless solar sails like heliogyro have major advantages relative to the solar sail with structural frame – they can by scale up easily, the don't need any frame to support their structure, but they are much complex dynamical objects rather than framed solar sails.

One of the main problems of dynamics of frameless solar sails is a deployment process. Several experiments were conducted to create and validate the mathematical models of dynamics of frameless solar sails. One of these experiments were Znamya series of experiments,[10)] two of them were conducted in space with partial success. The first one, Znamya-2, was conducted in 1993 in space near Mir space station on the cargo resupply ship Progress M-15. The disk-shaped centrifugally stabilized solar sail prototype was successfully deployed in this experiment. The second experiment, Znamya-2.5, was conducted in 1999 and it was partially successful because solar sail deployment process was affected by the antenna of spacecraft. The series of Znamya experiments is not finished, two more experiments are under development – Znamya-3,[11)] and Znamya-SB.[12)]

Another solar sail-related experiment in Russia is under preliminary research for S.P. Korolyev Samara State Aerospace University.[13)]

In 2010 Japan Aerospace Agency JAXA launched the interplanetary probe Planet-C with additional payload named IKAROS which was the first interplanetary solar sail ever been successfully launched.[14-16)] The sail on IKAROS spacecraft is also stabilized by rotation. The conception implemented on IKAROS is often called as a Solar Power Sail, because it is planned to utilize both light pressure and an electricity from a thin film solar panels on a solar sail to create thrust.

There were also some experiments with framed solar sail. One of them was Nanosail-D2 spacecraft, launched in 2010.[17-19)] The continuation of this project, the LightSail spacecraft, was successfully launched in 2015.[20,21)]

2. History of BMSTU-Sail space experiment

2.1. Early stages

The development of solar-sail related engineering activities in Bauman MSTU started in 2009 as a student project. It was proposed to create some small student satellite with rotary solar sail, very similar to Heliogyro design, but only with two blades and without any mechanism for changing the orientation of solar sail blades. Early designs incorporated the ideology of CanSat movement.[22)] The first time it was presented at the conference was January 2010, as it shown in 23), in which we introduced the concept of two nanosatellites, one with two-blade solar sail and another satellite with the camera. The sailcraft was ought to spin-up and separate from the larger one, and after the separation, the satellite with the camera had to take images of deployment process of rotary solar sail.

2.2. ISS Experiment

The problem of creation of two satellites was much difficult in comparison with one, so we decided to change the way of providing the non-zero angular momentum of sailcraft. It was considered to use the existing spacecraft or satellite which is large enough to provide feasible unloading of momentum. After analysis, we decided to choose the International Space Station as a base satellite.[24] We proposed to perform an experiment during the extravehicular activity on the Russian segment of ISS in which cosmonaut had to launch the sailcraft with the special deploying device.

At that time the main conception of sailcraft was still derived from CanSat, so it had pressurized container with electronic equipment onboard and two external bobbins with aluminized polyimide films with thickness 12μm,[25] for which we determined the damping coefficient to create the mathematical model of deployment of a solar sail.[26]

After negotiations with Russian Federal Space Agency “Roscosmos” we successfully entered the long-term research program on Russian segment of ISS in 2012.[27,28]

During the development of this satellite, we transited from CanSat design to much common CubeSat[29] design.[30,31] One of the big problems was the influence of uncertainties of the structural parameters of sailcraft on the deployment process, as it was shown in 32,33), and now it is still under great attention from our team, as well as other problems.[34]

The final design of BMSTU-Sail space experiment was ready in 2015.[35]

The process of development of such satellite has strong educational background in Bauman MSTU, it is used as a demonstration material for the lectures, for the laboratory practicum and for student’s research.[36]

3. Current status

3.1. General information

The experiment BMSTU-Sail (“Parus-MGTU”) is included in the long-term scientific program of the Russian Segment of ISS. The experiment passed the Russian analog of Critical Design Review stage and now is on the stage of Production Readiness Review. The development is held in Bauman MSTU Special Machinery department under contract with company RSCE Energia[37] which is the main developer of Russian Segment of ISS. All communications with NASA, ESA, and other agencies related to our experiment (if any) are held by RSCE Energia. RSCE Energia is also performing the independent review of documentation of the Experiment to ensure the safety of ISS crew and its structure, especially in the field of dynamical strength during the launch, and ballistic calculations. The target launch date is the beginning of 2018 because of the tight schedule of extravehicular operations on the Russian Segment of ISS.

As the main developer and investigator, the Bauman MSTU is developing the structure of nanosatellite, designs circuit boards, produces parts, makes final assembly and some tests, writes onboard software, releases documentation about the experiment. The main ground station for BMSTU-Sail nanosatellite is situated in Bauman MSTU.

The producer of thin film is NIIKAM company.[38]

3.2. Experiment goals

The main goals of this experiment are:

1. Verification of a mathematical model of deployment process of a heliogyro solar sail.
2. Testing of electronic hardware made from standard commercial electronic components.
3. Detecting and transmitting of experimental data to the ground stations.
4. Utilizing of nanosatellite as an experimental facility for educational process in Bauman MSTU.

3.3. Experiment sequence

The experiment will start inside the station in pressurized volume. Cosmonauts should check the equipment of the experiment according to instructions, provide necessary observations of an external view of the picosatellite, check the onboard software using special software utility on the laptop in the Russian segment. After this, the nanosatellite will be placed inside the launch container and stored in the airlock.

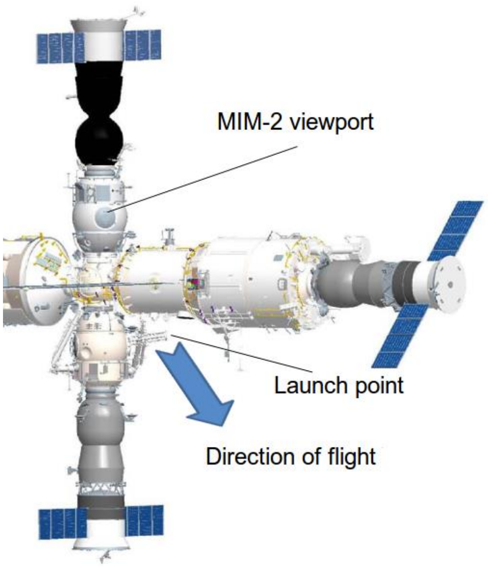

Fig. 1. Zone of the experiment.

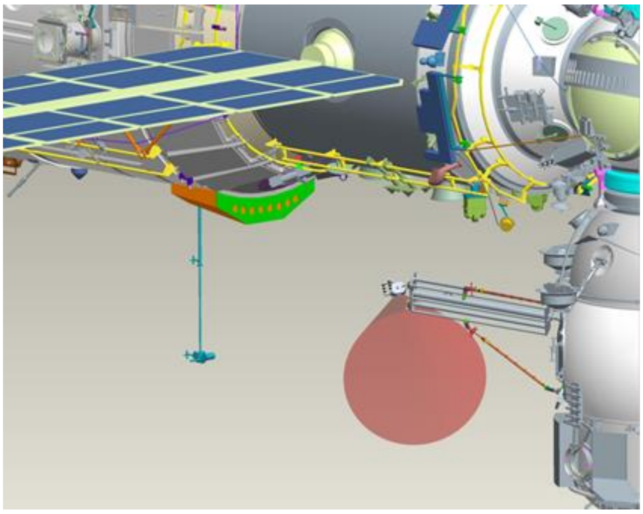

Fig. 2. Zone of the experiment (larger scale). Red cone is the cone of acceptable launch vector.

The main sequence of the experiment will start during the EVA. The launch device will be attached to the external magnetic joint on the Russian segment of ISS. (fig. 1, 2). Then, the nanosatellite will be powered on, the cosmonaut will wait for several seconds until the finishing the initialization of board software. In the case of unsuccessful tests, there are special indicators to abort the experiment and to return it inside the station.

After successful self-tests, cosmonaut will position the launch device into the correct direction and initiate the launch sequence program of nanosatellite, which will spin-up the internal reaction wheel. Then, after commanding from ground control, he will launch the picosatellite into the appropriate direction.

After separation, the nanosatellite will wait for several seconds, because deployment of the solar sail can affect the external structures of ISS. After the delay, the deployment process will start: the internal reaction wheel will slow-down, the bobbins will unroll the sail with precomputed speed, according to a mathematical model of deployment. The whole deployment process will last for two minutes.

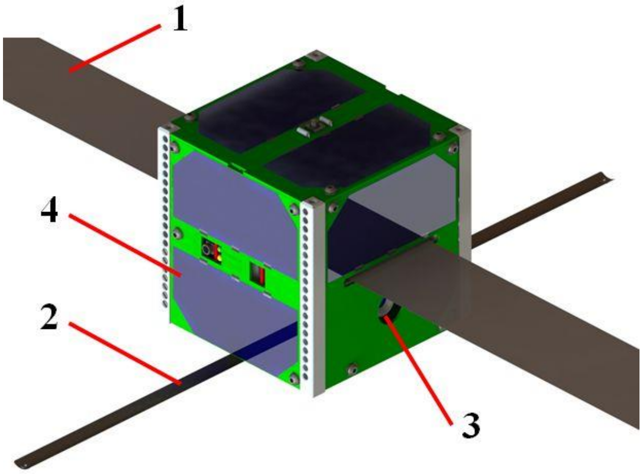

Fig. 3. BMSTU-Sail Picosatellite. 1 – solar sail, 2 – antenna, 3 – onboard camera, 4 – solar cell.

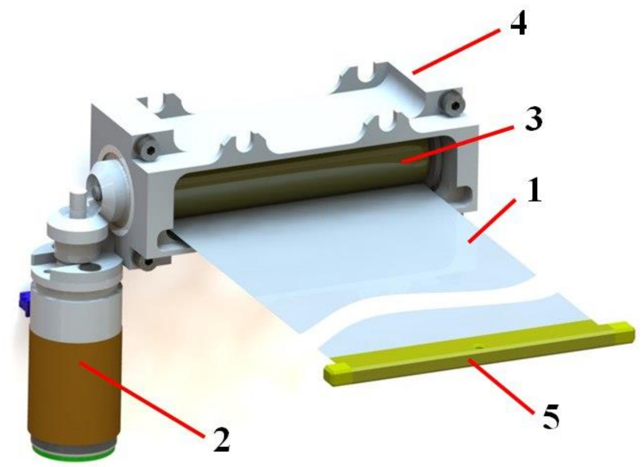

Fig. 4. Bobbin unit. 1 – solar sail, 2 – stepper motor, 3 – bobbin with sail, 4 – bobbin frame, 5 – tip mass.

The deployment process will be documented by cameras inside station through a viewport on the MIM-2 module (fig. 1), from cameras on space suits, from onboard cameras (visible and infrared) of nanosatellite. The nanosatellite will also obtain and store angular acceleration and velocity data of deployment process from onboard sensors.

After the deployment, the nanosatellite will transmit the acquired data to the ground stations. It will transmit data both to the Bauman MSTU ground station as well as to the stations of our collaborators.

There are additional plans to perform the experiment of rolling of deployed solar sail back to the bobbins.

4. Nanosatellite

The external view of nanosatellite structure is shown in fig. 3. The structure of the sail bobbin unit in shown on the fig. 4.

The electronics of the nanosatellite is made from commercially available components. There are two microcontrollers which control the operations of nanosatellite: one of them is Atmel AVR ATmega2560, the other is Milandr K1986BE92QI. The software for these microcontrollers was written in in Bauman MSTU using C programming language, the standard of 1999, with GNU extensions. The ATmega2560 controller is operating under ChibiOS/RT operating system, the K1986BE92QI is operating under RTEMS operating system.

The electronics board were design to be fault-tolerant, the power supply has redundancy protection. The radio transmitter operates in half-duplex mode, it transmits the preamble with callsign “CQCQRS2S” before every transmission so this nanosatellite can also be used by radio amateurs as a radio beacon.

The external view of the BMSTU-Sail nanosatellite electrical mock-up is shown on the fig. 5. The main parameters of nanosatellite are presented in table 1.

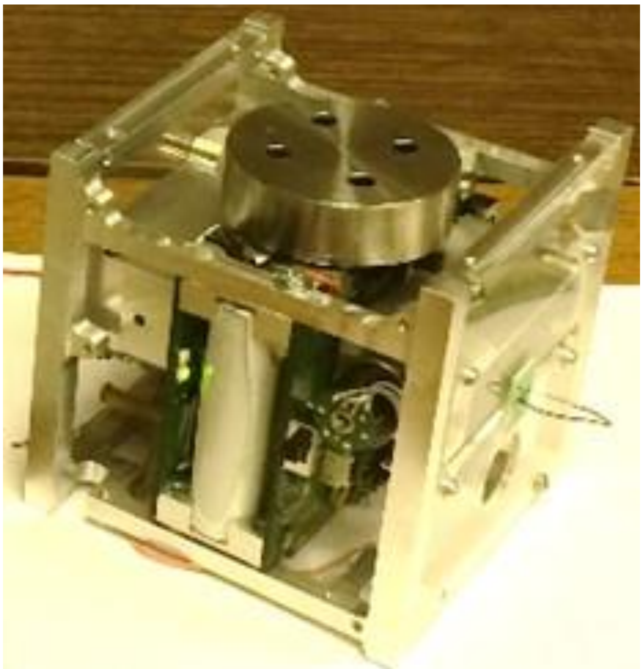

Fig. 5. Electrical mock-up of nanosatellite.

Table 1. Main parameters of BMSTU-Sail nanosatellite.

Parameter	Value
Weight	1.1kg
Lifetime	10 days
Size of the structure	100mm x 100mm x 115mm
Size of the solar sail	2 blades, 40mm x 5m each
Material of the solar sail	one side aluminized polyimide thin film
Thickness of the film	12μm
Radio frequency	433MHz
Callsign	RS2S
Output radio power	1W
Radio baud rate	9600baud
Storage temperature limits	-40ºC to +60ºC
Working temperature limits	0ºC to +20ºC

5. Future development

It was proposed to utilize this technology in the further development of CubeSat constellation in BMSTU. It is possible to separate several nanosatellites in one orbital plane by changing atmospheric drag area in low Earth orbit and by utilization of light radiation pressure in orbits higher than 600km. The possibility of control of orbital parameters of small satellite by changing of drag area was proved during AeroCube-4 CubeSat mission.[39)]

In the beginning, all satellites are situated approximately at the same point of the orbit. Then the first spacecraft deploys the solar sail which changes the drag force resulting in the increasing of the phase angle between satellites. When the phase angle between first satellite and a group of other satellites increases to the appropriate value, the second satellite deploys its solar sail, and so on. After a particular time, all of the satellites can be dispersed along the orbit and all of the solar sail units can be detached from nanosatellites or stored on the bobbins.

6. Conclusion

The experiment BMSTU-Sail is on the late stage of its development. The knowledge we obtain during the development of this experiment is sufficiently enough to allow us to start the development of further projects in the field of solar sails for nanosatellites. The major goal of this technology is the creation of a propellant-less system for formation flying of CubeSats. We post the latest news about the experiment in our website.[40)]

Acknowledgments

Authors would like to thank the NIIKAM company and its CEO Aristov V. F. for volunteer supply of polyimide film for our experiment and other films for testing purposes.

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