Наука и Образование
МГТУ им. Н.Э. Баумана
Сетевое научное издание
ISSN 1994-0448

Наука и Образование. МГТУ им. Н.Э. Баумана. Электрон. журн. 2014. № 11. С. 357–370.
DOI: 10.7463/1114.0740118
Представлена в редакцию: 24.11.2014

УДК 621.0+681.5

Возможности механизмов параллельной структуры для ориентации космического телескопа «Миллиметрон»

Артеменко Ю. Н.[1,2], Карпенко А. П.[1,*], Волкоморов С. В.[1]

[*]apkarpenko@mail.ru

[1]МГТУ им. Н.Э. Баумана, Москва, Россия
[2]Физический институт им. П.Н. Лебедева РАН, Москва, Россия

Ключевые слова: гексапод; космическая обсерватория; механизм позиционирования антенны; параллельный механизм

В статье идет речь о проекте космической обсерватории «Миллиметрон». Во введении дана краткая информация о проекте, приведено описание конструкции и основные технические характеристики обсерватории.

Статья делится на три раздела. В первом разделе с позиций управления ориентацией телескопа выделены два направления разработки. Рассмотрены несколько вариантов конструктивных решений телескопа, обеспечивающих заданные технические характеристики.

Во втором разделе статьи представлены четыре модели поворотного устройства телескопа, выполненного в виде многосекционного механизма параллельной кинематики типа хобот. Заданы основные массогабаритные характеристики системы и на их основе выбрана наиболее подходящая модель.Установлены размеры конструкции, удовлетворяющие заданным требованиям.

Третий раздел статьи посвящен планированию траектории перевода антенны обсерватории из текущего в заданное допустимое положение. Для синтеза траектории разработано программное приложение, написанное на языке C++. Приложение обеспечивает решение поставленных в разделе прямой и обратной задач кинематики манипулятора. Рассмотрены используемые в программе итерационный и оптимизационный методы.

В заключении делается вывод о принципиальной возможности создания многосекционного манипулятора для обеспечения навигационных задач орбитальной астрофизической обсерватории «Миллиметрон». Формулируются перспективы дальнейшего развития работы.

Список литературы

1. Baier H., Reindl M. Adaptive structures and mechatronic components for vibration and shape control of satellite payloads // Proceedings of the 10th European Space Mechanisms and Tribology Symposium (San Sebastian, Spain, 24-26 September 2003) / R.A. Harris, ed. ESA SP-524, Noordwijk, Netherlands: ESA Publications Division, 2003. P. 391–396.
2. Kardashev N.S. Radioastron: a radio telescope many times the size of Earth. Research program // Physics-Uspekhi. 2009. Vol. 52, no. 11. P. 1127–1137. DOI: 10.3367/UFNe.0179.200911e.1191
3. Bronowicki A.-J. Vibration isolator for large space telescopes // Journal of Spacecraft and Rockets. 2006. Vol. 43, no. 1. P. 45–53. DOI: 10.2514/1.12036
4. Merlet J.P. Parallel Robots. Springer Netherlands, 2000. 380 p. (Ser. Solid Mechanics and Its Applications; vol. 74). DOI: 10.1007/978-94-010-9587-7
5. Sayapin S.N. Active vibration isolation and pointing system for high-precision large deployable space antennas // Facta Universitatis. Series: Mechanical Engineering. 2001. Vol. 1, no. 8. P. 935–938.
6. Саяпин С.Н. Перспективы и возможное применение пространственных механизмов параллельной структуры в космической технике // Проблемы машиностроения и надежности машин. 2001. № 1. С. 17–26.
7. Саяпин С.Н. Анализ и синтез раскрываемых на орбите прецизионных крупногабаритных механизмов и конструкций космических радиотелескопов лепесткового типа: дис. ... докт. техн. наук. М., ИМАШ РАН, 2003. 446 с.
8. Саяпин С.Н., Кокушкин В.В. Способ подавления помех от колебаний упругой конструкции космической трансформируемой антенны в процессе эксплуатации и устройство для его осуществления: пат. 2323136 РФ. 2008. Бюл. № 12.
9. Smirnov A.V., Kardashev N.S., Baryshev A.M. The space mission Millimetron // Proceeding of 23rd International Symposium on Space Terahertz Technology, Tokyo, April 2012. P. 74.
10. Smirnov A.V., Baryshev A.M., de Bernardis P., Vdovin V.F., Gol'tsman G.N., Kardashev N.S., Kuz'min L.S., Koshelets V.P., Vystavkin A.N., Lobanov Yu.V., Ryabchun S.A., Finkel M.I., Khokhlov D.R. The current stage of development of the receiving complex of the Millimetron space observatory // Radiophysics and Quantum Electronics. 2012. Vol. 54, no. 8-9. P. 557–568. DOI : *10.1007/s11141-012-9314-z* (Перевод из журнала: Известия ВУЗов. Радиофизика // 2011. Т. 54, № 8-9. С. 617–630.).
11. Smirnov A.V., Baryshev A.M., Pilipenko S.V., Myshonkova N.V., Bulanov V.B., Arkhipov M.Y., Vinogradov I.S., Likhachev S.F., Kardashev N.S. Space mission Millimetron for terahertz astronomy // Proc. SPIE 8442, Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave (August 22, 2012). Art. no. 84424C. DOI: 10.1117/12.927184

12. Colafrancesco S. Millimetron cosmology and fundamental physics // 223rd Annual American Astronomical Society (AAS) Meeting. (Washington, DC): Abstracts. January 2014. Vol. 223. Abs. no. 340.05.
13. Stewart D. A Platform with Six Degrees of Freedom // Proceedings of the UK Institution of Mechanical Engineers. 1965–66. Vol. 180, part 1, no. 15. P. 371–386.
14. Wild W., Kardashev N.S. Millimetron — a large russian-european submillimeter space observatory // Experimental Astronomy. 2009. Vol. 23. P. 221–244.
15. Зенкевич С.Л., Ющенко А.С. Основы управления манипуляционными роботами. М.: МГТУ им. Н.Э. Баумана, 2004. 480 с.

Science & Education of the Bauman MSTU
Electronic journal
ISSN 1994-0448

Science and Education of the Bauman MSTU, 2014, no. 11, pp. 357–370.
DOI: **10.7463/1114.0740118**
Received: 24.11.2014

Capability of Parallel Mechanism Used for Attitude Control of "Millimetron" Space Telescope

Artemenko Yu. N.[1,2], Karpenko A. P.[1,*], Volkomorov S. V.[1]

[*]apkarpenko@mail.ru

[1]Bauman Moscow State Technical University
[2]Lebedev Physical Institute, Russian Academy of Sciences

"Millimetron" space observatory project is introduced. Essential technical requirements and capabilities are given. Two possible design approaches regarding telescope position control are discussed. Several designs of a multi-sectional manipulator for antenna position control are considered. Problem of trajectory synthesis for moving the manipulator to the command position is formulated. Forward and inversed kinematics problems are stated. Two methods for solving trajectory synthesis problem are introduced. Programmatic solution is implemented and described. Further development directions are designated.

Keywords: hexapod, space observatory, antenna slewing mechanism, parallel mechanism

Introduction

"Millimetron" is a project currently under development by the Astro Space Center (ASC) in the Lebedev Physical Institute of the Russian Academy of Sciences, the NPO Lavochkin, and the OAO "Information Satellite Systems" n. a. Academician M.F. Reshetnev in cooperation with a number of Russian and international companies [9, 10, 11, 12]. The project is headed by Nikolay S. Kardashev and aimed at building a space observatory with a cryogenic radio telescope functioning in a wavelength range from 20 mm to 20 μm. A diameter of the telescope is 10 m. The observatory is intended for investigating different objects in the Universe at the ultrahigh sensitivity (in the single-dish observatory mode) and the unprecedented high angular resolution (in the ground-space very long baseline interferometry (VLBI) mode) in the infrared and millimeter wavelength ranges [14]. The ultrahigh sensitivity of the space telescope is achieved by cryogenic cooling of the antenna's dish, heat shields, and receiving equipment using liquid helium (Figure 1). The telescope's sensitivity matches the sensitivity of a 100 m telescope without cooling.

The observatory's automatically deploying antenna is 10 m in diameter and consists of three dishes and coaxial active and passive heat shields mounted on the "Navigator" space platform

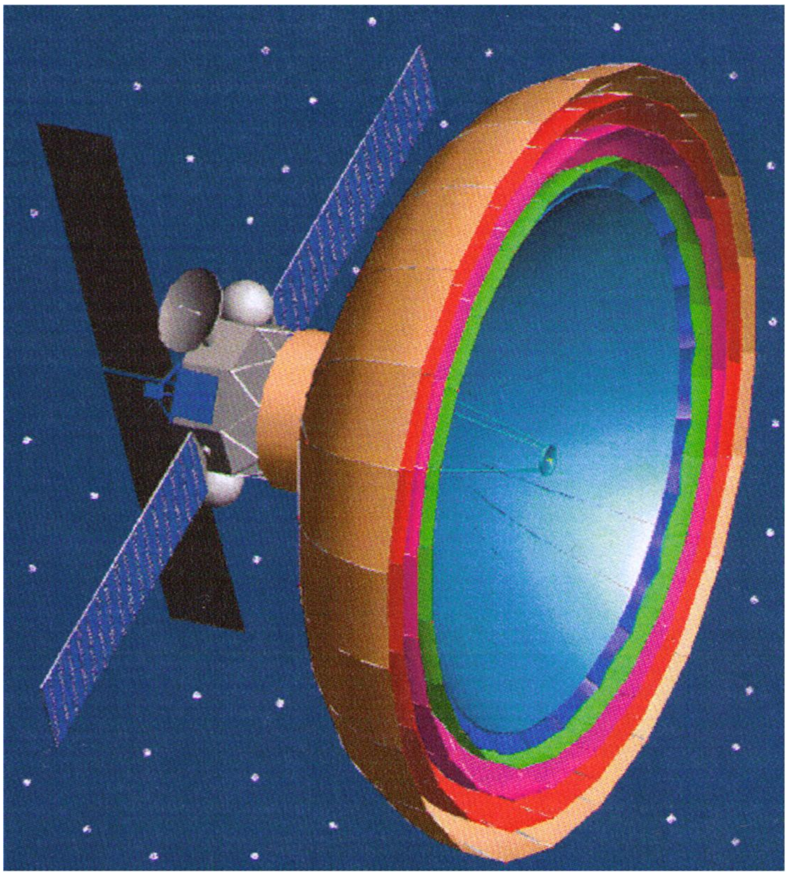


Figure 1: Overall view of one of the versions of the “Millimetron” space observatory

similar to the one used in the “RadioAstron” project [2]. The antenna’s main dish, its adjacent active heat shield and a cryocontainer for the scientific equipment are cooled by liquid helium to the temperature of 4.5K while the receiving equipment is cooled to 0.2 K. The main dish is formed after deployment and locking of rigid high-precision blades with adaptable reflecting surface. The antenna’s subdish is 57 cm in diameter and is located inside the main mirror in the antenna’s primary focus which protects it from zodiacal light and heat radiation of the Earth and the Sun. The subdish is equipped with a hexapod mechanism for adjusting the antenna after its deployment. The third (flat rotary) mirror is located near antenna’s secondary focus inside the cryocontainer and is equipped with a two-degree-of-freedom mechanism used for transmitting the radiation under study to one of the detectors positioned around the mirror.

The natural-vibration frequencies are about 5 Hz for the antenna structure and nearly 3 Hz for the heat shields. An accuracy of functional surface of the antenna’s main dish must be no worse than 10 μm (RMS deviation). The antenna guidance accuracy must be no worse than 1 arcsec and its stabilization accuracy must be no worse than 0.2 arcsec.

The telescope’s unprecedented resolution is achieved as a result of its work in cooperation with large ground-based telescopes in the VLBI mode at distances of up to 1.5 million km away from the Earth. The telescope is planned to be launched into the orbit orthogonal to the ecliptic plane in the region of anti-Sun L2 Lagrangian point to compensate for the gravitational influences of the Sun and the Earth.

In the first part of the paper we examine design versions for the observatory. In the second part we offer several models for the antenna's slewing mechanism implemented with a multi-sectional parallel "trunk" mechanism [4, 6, 13]. The third part is dedicated to planning the antenna movement from its current point to a target position. In the conclusion, the main results of the work and prospects for its development are stated.

1. Design versions

Several constructive decision versions meeting the technical requirements were considered during the development of the "Millimetron" observatory. Regarding the telescope attitude control, there are two directions of development.

The first direction suggests the permanent orientation of the observatory's longitudinal symmetry axis and its radiation screens towards the Sun (Figure 2).

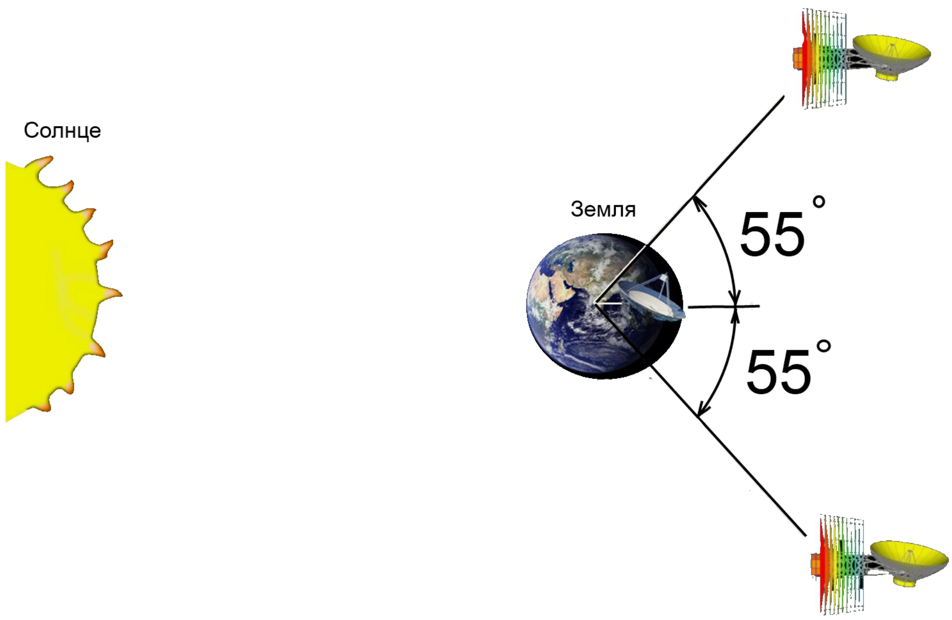
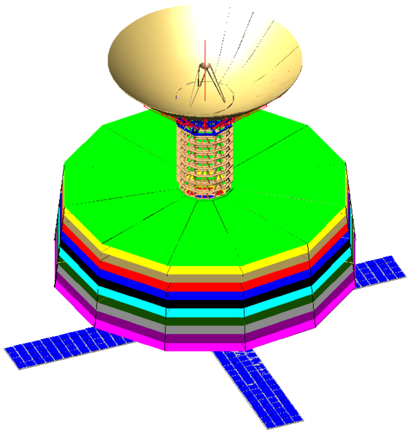


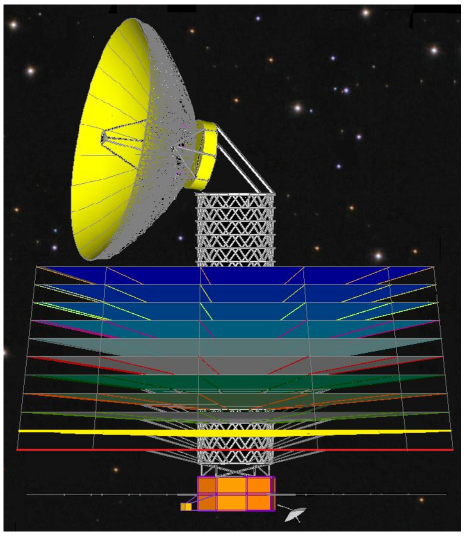
Figure 2: Orientation of "Millimetron" relative to the Sun

In this case it is required to rotate the antenna relative to the service module where reaction-propulsion engines of correction, orientation and stabilization and flywheel-engines are installed. The antenna itself must be moved away from the nearest heat shield to prevent collision when rotated by 90°.

One of these variants utilizes a flexible frame as a supporting device and is shown in Figure 3. A total length of the presented version is 22—24 m; the total mass is about 7 tons, 2.5 tons of



(a)



(b)

Figure 3: One of the design versions

which is due to the masses of the "warm" container and the service module. The mass of the antenna with the cryocontainer is about 2.5 tons, too. The transformable structures of deployable radiation shields and one of the active cryocontainers, as well as the slewing mechanism (with a total length of 12 m and a total mass of 1.5 tons) are positioned between these two sections of the observatory. Thus, the observatory has an oblong dumbbell shape with the telescope on one side and the service module on the other side. Masses of the service module and the telescope are approximately the same and the observatory's center of mass lies approximately in the center of the "dumbbell". The location of the observatory's center of mass in this case strongly depends on location of the telescope's center of mass when it moves, which makes it necessary to compensate for incipient moments by using of the engines of the service module.

In the simplest mechanism for the flat turn of the telescope the cryocontainer is fastened to the edge of the supporting truss (see Figure 3). Practically, though, this mechanism results in a 1.5 m deviation of the telescope's center of mass from the observatory's longitudinal axis of symmetry and in a 1 m deviation of the observatory's center of mass. Compensation of incipient moments by using of flywheel-engines is impossible in this case, and usage of reaction-propulsion engines of the service module is limited by the propellant margin and the required period of unfailing service life of 10 years.

Thus, keeping the center of mass on or near the observatory's longitudinal axis of symmetry is a precondition for the telescope rotation. Apart from minimization of the incipient moments, this requirement is also conditioned by the fact that the telescope needs to be stabilized after rotation to allow receiving the radiation. Depending on the type of the object under observation and the scientific research program, stabilization time varies from 15 min to several hours. Stabilization involves minimization of moments caused by external factors: solar radiation pressure and solar wind. This is achieved by aligning the observatory's center of mass and the geometrical center of the external shield on the observatory's longitudinal axis of symmetry. To meet the above-mentioned requirements the telescope slewing mechanism must be able to maintain the invariant position of the center of mass and to adjust this position.

This paper is dedicated to a different type of slewing mechanism implemented with a multi-sectional parallel "trunk" mechanism [4].

The second direction is based on a traditional layout of space telescopes. The antenna is mounted on the space platform atop the lower transfer frame, the "warm" instrument container, and the upper transfer frame (see Figure 1). The telescope positioning is accomplished by changing the orientation of the whole observatory by flywheel-engines mounted on the service module. Incidentally, to protect the telescope from heat radiation of the Sun and the Earth with shields its slewing angles must not exceed $30°$ of the Sun direction.

This circumstance severely reduces the number of potentially observable objects. Nevertheless, this number is enough to complete the project scientific program. The telescope positioning by observatory rotation results in uneven external shield irradiation relative to its geometric center and the observatory's center of mass. This results in an angular, and a need of continuous work of the stabilization system arises. This, in turn, results in vibration of the observatory structure. Thus, this design version requires a high-performance vibration-absorbing system to be used [1, 3, 5, 7, 8].

2. Design of a multi-sectional manipulator for attitude control of the observatory's antenna

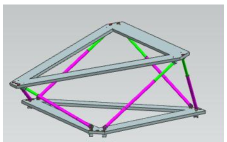
The main mass-dimensional characteristics of our system are as follows:

- the antenna diameter is $10{,}000$ mm;
- total mass of the antenna and cryocontainer is 2500 kg;
- the center of mass of the antenna-cryocontainer system is on the antenna's axis of symmetry and is located at a distance of 3200 mm away from the cryocontainer base.

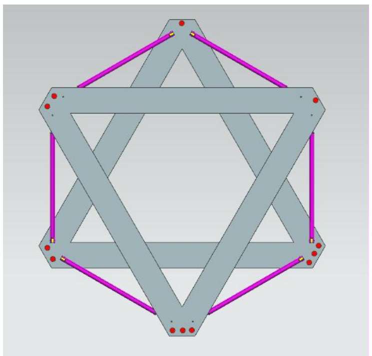
The carrier rocket blister diameter requires that the diameter of the manipulator sections should not exceed 3640 mm. The manipulator length in its folded (transportable) state must not exceed 750 mm.

The manipulator sections are represented by hexapod parallel mechanisms (Stewart platform [4, 13]), and their number must not be more than five on the ground of reliability and simplicity of operation.

We assume that to minimize the manipulator's weight hexapod platforms have the form of equilateral triangles with beveled edges (Figure 4) made of rectangular-sectioned (40×100 mm) carbon-fiber reinforced plastic ($1550\ kg \cdot m^{-3}$) tubes. Hexapod beams are two- or three-sectional and are made of the same carbon-fiber reinforced plastic. Each beam is connected to the base (lower platform) with a Hooke joint, and to the upper platform – with a spherical hinge.



(a)



(b)

Figure 4: Model of a manipulator section

The manipulator must provide attitude control for the antenna within the hemisphere whose axis of symmetry coincides with the longitudinal axis of symmetry of the spacecraft. In all cases the antenna must be at least 500 mm away from the first platform base.

For the sake of simplicity we shall call the center of mass of the antenna–cryocontainer system a manipulator clamp. Let α stand for the angle between the antenna's axis of symmetry and the spacecraft's longitudinal symmetry axis and let $\alpha_{\max}$ stand for its maximum value (Figure 5).

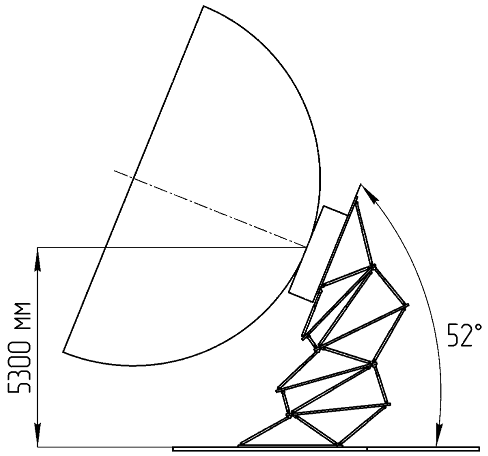


Figure 5: Manipulator model 1a: $\alpha = \alpha_{\max} = 52°$

Preliminary analysis shows that in order to slew the antenna by 1 arcsec, the rotary device elements must displace by 0.3 μm (for displacements from 50 to 75 μm). To provide precision of at least 0.1 μm, the rotary device includes a high-precision piezoengine hexapod. The same hexapod is also used to reduce the antenna's high-frequency oscillations to a value of less than 0.2 arcsec. This hexapod is not considered in this paper.

Four parameterized models were developed using Solidworks:

- manipulator 1a: all the platforms are of the same size, beams have two sections;
- manipulator 1b: all the platforms are of the same size, beams have three sections;
- manipulator 2a: intermediate platforms are smaller, beams have two sections;
- manipulator 2b: intermediate platforms are smaller, beams have three sections.

In all cases beam lengths must allow folding the manipulator to the transport position. Models do not include beam actuators.

Models 1a and 1b. Five-sectional manipulator 1a with $\alpha = \alpha_{\max}$ is shown in Figure 5. The figure demonstrates that a five-sectional manipulator of this type constructed of equal-size sections using two-sectional beams cannot transfer the observatory's antenna to the position with $\alpha > 52°$.

Model 1b in its end position is shown in Figure 6. This model supports the required position of the antenna.

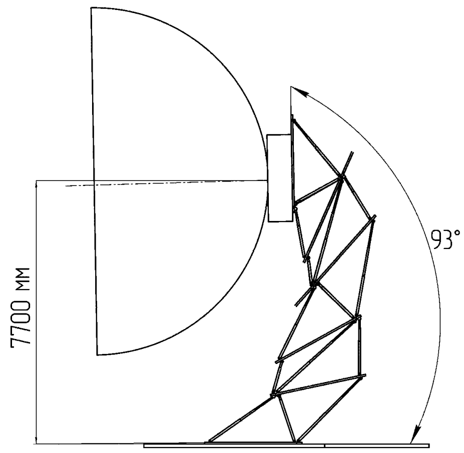


Figure 6: Manipulator model 1b: $\alpha = \alpha_{\max} = 93°$

Models 2a and 2b. Complying with the following requirements, these models are used to create a five-sectional manipulator:

- the first and last platform sizes match the sizes of the manipulator model 1;
- all the intermediate platforms are of the same size.

The problem was set to find the maximum possible diameter of the transfer platforms that will meet the condition that $\alpha_{\max} = 90°$. It was ascertained that the five-sectional manipulator 2a is capable of fulfilling the task when this diameter equals 1721 mm (Figure 7).

Since manipulator 2a is capable of fulfilling the task and is structurally simpler we will not consider manipulator 2b.

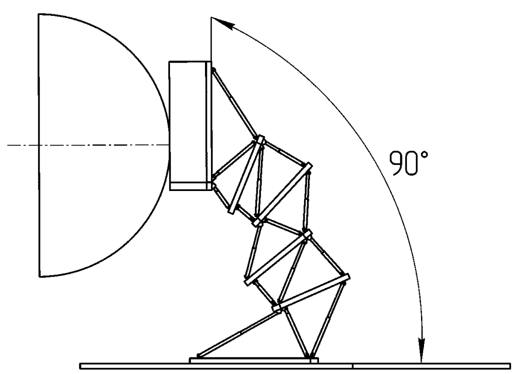


Figure 7: Manipulator model 2a: $\alpha = \alpha_{\max} = 90°$

3. Trajectory synthesis for moving the manipulator to the command position

A computer program to build different manipulator trajectories was created. This application provides solutions to forward and inverse kinematics problems for the manipulator. The forward kinematics problem consists in finding the position and maybe orientation of the manipulator clamp with given beam lengths [4]. The inversed kinematics problem consists in finding the beam lengths of all the manipulator sections ensuring the given position and maybe orientation of the manipulator clamp [4, 15].

We will use the following notation: q_i is the vector of generalized coordinates of the i-th manipulator section; $q = (q_1, q_2, \ldots, q_5)$ is the vector of generalized coordinates of the entire manipulator; Q is the set of possible admissible values of components of the vector q; S is the (4×1)-vector for the clamp position in the fixed coordinate system attached to the base of the manipulator's first section. In our case the vector length of q_i is 6 and the length of q is 20.

The inversed kinematics problem is formulated as follows: find admissible generalized coordinates of the manipulator $q \in Q$ providing the given clamp position S. This problem is a set of six nonlinear trigonometric equations for the vector q in $6(n-1)$ unknowns. This system can have no solutions (the given position is unachievable), a single solution or an infinite number of solutions (the given position can be provided by an infinite number of manipulator configurations). The latter case is typical for a multi-sectional manipulator and therefore we can consider a task of finding a somewhat optimal solution to the inverse kinematics problem.

Two methods were used to solve this problem using the above mentioned computer program.

The optimization method allows taking into consideration additional structural requirements by integrating them into the optimality criterion. This method qualifies as a known method for solving nonlinear equations sets by reducing them to a nonlinear programming problem.

The iterative method as opposed to optimization method makes it possible to obtain not only the sought-for final configuration but also a set of its intermediate configurations constituting step-by-step movement of the manipulator from the initial position(http://freespace.virgin.net/hugo.elias/models/m_ik2.htm). The main idea behind this method is the gradual increment of the generalized coordinates by a value that will bring the manipulator clamp closer to its desired position.

The program has two distinct modes. In the first mode transition starts directly from the current manipulator position. In the second mode the manipulator configuration is preliminary changed in such a way that its antenna's axis of symmetry coincides with the longitudinal axis of symmetry of the spacecraft ($\alpha = 0$). This mode is illustrated in Figure 8 where the clamp is shown as a small filled circle.

The program provides a solution to the problem when the clamp position is fixed and the antenna is pointed in the desired direction relative to the longitudinal axis of symmetry of the spacecraft. This feature allows solving the antenna attitude control task when the clamp is stationary. This approach is preferable from the point of view of spacecraft control because it allows unloading the flywheel-engines. This approach is also shown in Figure 8.

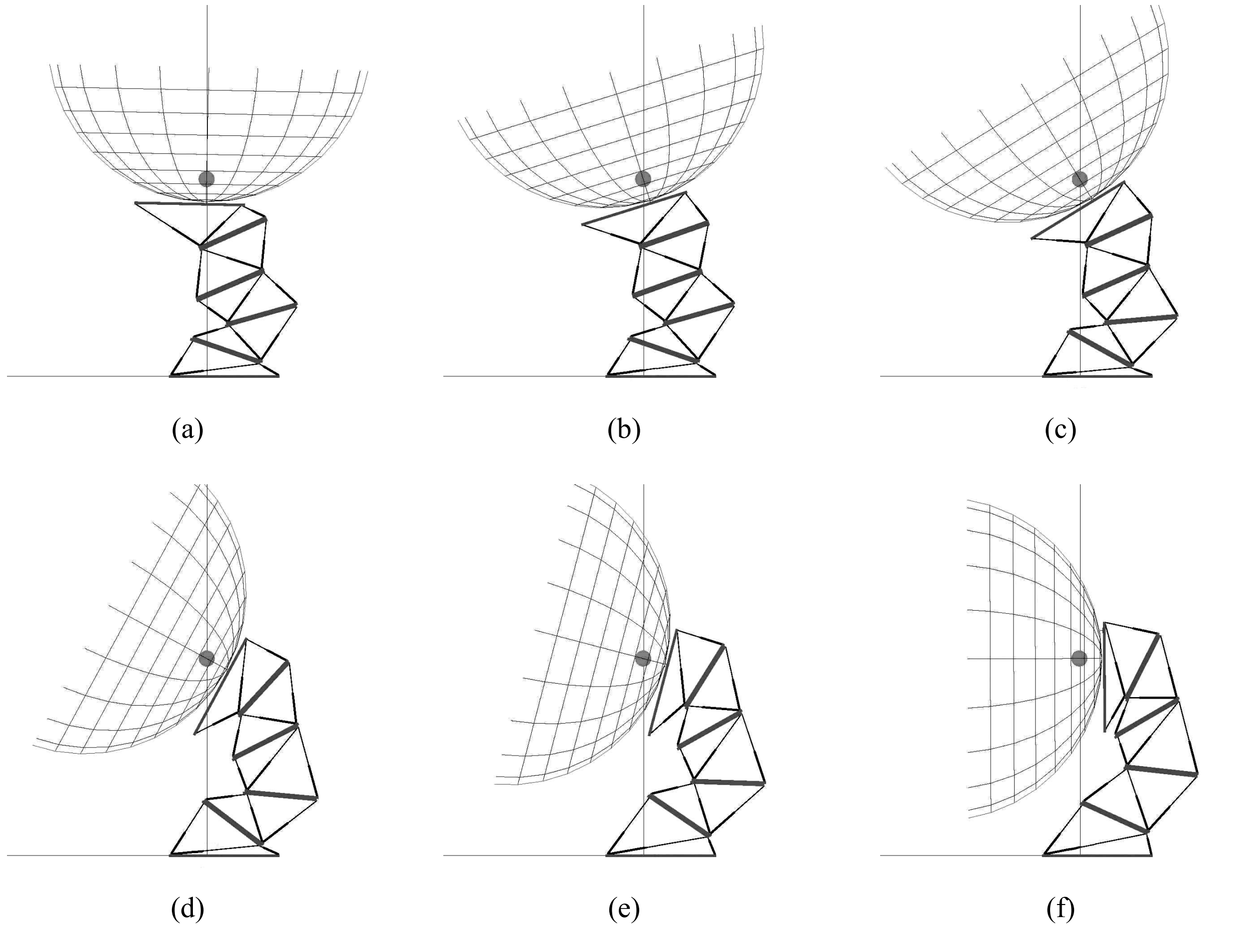


Figure 8: Iterations of mode two of manipulator 2a positioning problem solution

Conclusion

This paper results show that, in principle, it is possible to create a multi-sectional transformable space robot-manipulator to provide navigational tasks of the submillimeter space observatory "Millimetron".

The introduced multi-sectional manipulator solves the following problems:

- transforming the telescope from its folded (transportable) state to its working state;
- pointing the telescope towards any point in the hemisphere bounded by the heat shields;
- preserving invariable positions of the centers of mass of the telescope and the observatory while pointing the telescope;
- correcting positions of the centers of mass of the telescope and the observatory;
- observatory attitude control;
- lowering the stabilizing oscillations of the telescope;
- off-loading the flywheel-engines;
- etc.

Further development involves solving the following problems:

- manipulator stiffness analysis;

• natural-vibration frequencies determination;

• finding the moments of inertia to compensate for work of flywheel-engines during the antenna reorientation;

• synthesis of optimal trajectories for antenna movement with consideration for possible failure of one or several beam actuators;

• synthesis of classical and neural network based manipulator control systems for the antenna reorientation with consideration for the above mentioned failures.

References

1. Baier H., Reindl M. Adaptive structures and mechatronic components for vibration and shape control of satellite payloads. In: Harris R.A., ed. *Proceedings of the 10th European Space Mechanisms and Tribology Symposium*, San Sebastian, Spain, 24-26 September 2003. ESA SP- 524, Noordwijk, Netherlands, ESA Publications Division, 2003, pp. 391–396.
2. Kardashev N.S. Radioastron: a radio telescope many times the size of Earth. Research program. *Physics-Uspekhi*, 2009, vol. 52, no. 11, pp. 1127–1137. DOI: 10.3367/UFNe.0179.200911e.1191
3. Bronowicki A.-J. Vibration isolator for large space telescopes. *Journal of Spacecraft and Rockets*, 2006, vol. 43, no. 1, pp. 45–53. DOI: 10.2514/1.12036
4. Merlet J.P. *Parallel Robots*. Springer Netherlands, 2000. 380 p. (Ser. Solid Mechanics and Its Applications; vol. 74). DOI: 10.1007/978-94-010-9587-7
5. Sayapin S.N. Active vibration isolation and pointing system for high-precision large deployable space antennas. *Facta Universitatis. Series: Mechanical Engineering*, 2001, vol. 1, no. 8, pp. 935–938.
6. Sayapin S.N. Prospects and the possible use of spatial mechanisms of parallel structure in space technology. *Problemy mashinostroeniya i nadezhnosti mashin = Machinery Manufacture and Reliability*, 2001, no. 1, pp. 17–26. (in Russian).
7. Sayapin S.N. *Analiz i sintez raskryvaemykh na orbite pretsizionnykh krupnogabaritnykh mekhanizmov i konstruktsiy kosmicheskikh radioteleskopov lepestkovogo tipa. Dokt. dis*. [Analysis and synthesis of the disclosed on orbit precision large-dimension mechanisms and designs of space radio telescopes petal type. Dr. dis.]. Moscow, Keldysh Institute of Applied Mathematics (Russian Academy of Sciences), 2003. 446 p. (in Russian).
8. Sayapin S.N., Kokushkin V.V. *Sposob podavleniya pomekh ot kolebaniy uprugoy konstruktsii kosmicheskoy transformiruemoy antenny v protsesse ekspluatatsii i ustroystvo dlya ego osushchestvleniya* [A method of suppressing the interference from vibrations of elastic design of transformable outer space antenna during operation and device for its implementation]. Patent RF, no. 2323136. 2008. (in Russian).

9. Smirnov A.V., Kardashev N.S., Baryshev A.M. The space mission Millimetron. In: *Proceeding of 23rd International Symposium on Space Terahertz Technology*, Tokyo, April 2012, p. 74.

10. Smirnov A.V., Baryshev A.M., de Bernardis P., Vdovin V.F., Gol'tsman G.N., Kardashev N.S., Kuz'min L.S., Koshelets V.P., Vystavkin A.N., Lobanov Yu.V., Ryabchun S.A., Finkel M.I., Khokhlov D.R. The current stage of development of the receiving complex of the Millimetron space observatory. *Radiophysics and Quantum Electronics*, 2012, vol. 54, no. 8-9, pp. 557–568. DOI: 10.1007/s11141-012-9314-z

11. Smirnov A.V., Baryshev A.M., Pilipenko S.V., Myshonkova N.V., Bulanov V.B., Arkhipov M.Y., Vinogradov I.S., Likhachev S.F., Kardashev N.S. Space mission Millimetron for terahertz astronomy. In: *Proc. SPIE 8442, Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*, 22 August, 2012, art. no. 84424C. DOI: 10.1117/12.927184

12. Colafrancesco S. Millimetron cosmology and fundamental physics. *223rd Annual American Astronomical Society (AAS) Meeting Abstracts*, Washington, DC, January 2014, vol. 223, abs. no. 340.05.

13. Stewart D. A Platform with Six Degrees of Freedom. *Proceedings of the UK Institution of Mechanical Engineers*, 1965–66, vol. 180, part 1, no. 15, pp. 371–386.

14. Wild W., Kardashev N.S. Millimetron — a large russian-european submillimeter space observatory. *Experimental Astronomy*, 2009, vol. 23, pp. 221–244.

15. Zenkevich S.L., Iushchenko A.S. *Osnovy upravleniia manipuliatsionnymi robotami* [Bases of controlling of manipulators]. Moscow, Bauman MSTU Publ., 2004. 480 p. (in Russian).