Artificial Gravity for Humans in Space: Philosophical and Methodological, Historical, Technological, and Futurological Aspects

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The article presents the research materials and results on artificial gravity for humans in space. We analyse several important and interrelated aspects of the development and application of artificial gravity in manned spaceflights and providing permanent safe, dignified human life in outer space from an interdisciplinary perspective and in the context of theory and practice. The article introduces philosophical foundations of artificial gravity from the perspective of praxeology and space biospheres environment management to ensure human life, safety, and development in space. A brief description of the conceptual model of outer space applications of artificial gravity for humans is made. The definitions are given. The main methods of creation and influence and modes of artificial gravity application for humans in outer space are systematized. This article reviews the global evolution of ideas, technologies, and artificial gravity projects in the 19th-21th centuries; it presents periodization, general classification and important examples. The article studies advances, issues, limits and perspectives of the research and application of artificial gravity for space exploration. The key conclusions are formulated.

Keywords: artificial gravity, human, life, philosophy of gravity, space, space biosphere, spaceflight

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Introduction

Let us briefly run through some key and interrelated aspects of the artificial gravity problem (gravity) for humans in space biospheres[1] from an interdisciplinary perspective and in the context of theory and practice of space exploration by humans and humanity within the expansion paradigm.[2]

Research, development, and application of artificial gravity technologies are essential to process and conduct human spaceflights and ensure humans' safe and dignified long life in outer space. It is due to the demand for further space exploration given the achieved limits and restrictions while ensuring permanent safe, dignified human life and operation in outer space in prolonged weightlessness (microgravity), taking into account 60 years of experience in manned flights and the life of cosmonauts, astronauts in outer space, starting from first human spaceflight of Yuri Gagarin on April 12, 1961.

There is a long history of researching and solving the artificial gravity problem. We will consider setting and solving the artificial gravity development and application for humans in space as a brief history and evolution of ideas, technologies and projects in the 19th-21th centuries in the paradigm of space exploration, expansion, longtime and permanent life of a human and humanity in outer space.

125 years ago, in 1895, Konstantin Tsiolkovsky, in the book "Dreams of the Earth and the Sky," proposed using rotation to create artificial gravity; he described it in the story "Out of the Earth" 100 years ago, in 1920.[3]

In the 20th and 21st centuries, the leading space countries (USSR / the Russian Federation, USA, EU) have developed theoretical foundations, ideas, technologies, and projects to develop artificial gravity in spaceflights. Paradoxically, people have been flying into space without artificial gravity systems for 60 years. Moreover, the space use of the first artificial gravity systems in the form of centrifuges has begun since the 1970s in the USA, USSR / the Russian Federation and other countries on board automatic biosatellites for researching terrestrial biological objects (plants, animals, et cetera), simulation, studying the effects and consequences of artificial gravity, for developing and applying artificial gravity systems for humans in outer space.[4]

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[1] See (Adamovich & Gorshenin, 1997; Krichevsky, 2021a; Krichevsky & Levchenko, 2021; Noordung, 1935; Sternfeld, 1949; Tsiolkovsky, 1920; 1961; Website of NASA).

[2] The article uses research materials and findings of the methodological, historical, technical and other aspects of artificial gravity, carried out by the author at the S.I. Vavilov Institute for the History of Science and Technology, RAS in 2018-2021. In abridged form, they were published in Russian, first in the article (Krichevsky, 2020b), then in the monograph, Chapter 8 (Krichevsky, 2021: 211-222). Herein a new and complete version of the text is published, and for the first time in English. The author is a former professional military pilot and test cosmonaut. He is experienced with working under artificial gravity in centrifuges and Hydro Labs, in flights on fighter aircraft, laboratory aircraft within preparation for spaceflight. The author has been researching the problem of artificial gravity since 1991. The first publication was "A manned spacecraft with zones of weightlessness and artificial gravity as a means to promote the effectiveness of the cosmonauts' occupational activity" at the International Scientific and Practical Conference (October 1993) at the Yu. A. Gagarin Research&Test Cosmonaut Training Center, Star City (Zvyozdny Gorodok), Moscow Oblast, the Russian Federation. See (Krichevsky, 2012: 126-127).

[3] See (Tsiolkovsky, 1961: 38–112; Tsiolkovsky, 1920; Shipov, 1997: 127).

[4] See (Adamovich & Gorshenin, 1997; Artificial Gravity, 2007; Kotovskaya et al., 1996; Kotovskaya, 2017: 5-21; Orlov & Koloteva, 2017; Shipov, 1997: 148-149; Website of NASA).

The limits of safe extended human stay in space under conditions of weightlessness (microgravity) have been reached: 1.0-1.5 years in near-Earth space at the Mir Space Station and the International Space Station (ISS).[5]

To overcome these limits, it is necessary to introduce artificial gravity, starting with a short-arm centrifuge (SAC)[6] in flights up to 1 year, followed by the transition to full-fledged artificial gravity systems to provide the human life cycle in outer space. The artificial gravity problem has theoretical and practical aspects knowledge, research and experiments experience have been accumulated. Therefore, artificial gravity is of particular importance for safe, dignified human life and effective performance in outer space in long-term near-Earth and interplanetary flights, for providing successful human expansion into space, reproduction, and the creation of space human and humanity.[7]

Since the 1990s and especially in the 21st century, the number of publications on artificial gravity, new ideas, technologies and projects has been growing. Still, there is also criticism of artificial gravity, significant opposition to its implementation for structural, biomedical, technical, economic, and other reasons.[8]

"For some specialists, weightlessness in space is an advantage. One can continually plan and carry out, for example, medical research and preventive measures, dealing with weightlessness without artificial gravity systems. But the time has come to live a normal life and work effectively in space, so we must finally switch over to a new phase by creating manned spacecraft with zones of weightlessness and artificial gravity, bringing the habitat as close to the terrestrial one as possible while preserving and using the space properties important as regards to scientific and technological terms (weightlessness, et cetera). It is necessary to create a healthy artificial environment in space." In the long run, other approaches are also possible, including those based on the methodology of "environmental health," evolutionary biospherology, management of the biosphere and technosphere evolution, as applied to artificial space biospheres and human life in them.[9]

We are referring to the paradigm shift: the transition from human adaptation to long-term weightlessness in space to a new paradigm of using artificial gravity for ensuring "normal" safe, dignified human life in outer space.

In recent years, new results have been obtained worldwide on the influence of the long-term spaceflights factors on the human body.

"Of particular importance are the results of recent years: the project "NASA Twins Study" (2019)[10] and comprehensive analysis (2020).[11] The study of twins is a multivariate analysis of a long-term manned spaceflight according to the unique project "NASA Twins Study," in which two US astronauts participated – twin brothers Scott and Mark Kelly (the first stayed ~ 340 days in flight to the ISS in 2015–2016, the second stayed on the Earth) gave new important information. A comprehensive, in-depth analysis of 59 astronauts and hundreds of samples sent into space reveals that "mitochondrial stress is the biological node for the

[5] See (Kotovskaya, 2017; Krichevsky, 2020a; 2020b; 2021; Orlov & Koloteva, 2017).

[6] See (Kotovskaya et al., 1996; Kotovskaya, 2017; Orlov & Koloteva, 2017).

[7] See (Krichevsky, 2020a; 2021).

[8] See (Artificial Gravity, 2007; Krichevsky, 2020b; Tsygankov, 2013; Website of NASA).

[9] Citation (Krichevsky, 2012: 126-127); see also (Krichevsky, 2020b; Krichevsky & Levchenko, 2021) hereunder in clauses 4 and 5.

[10] See (Garrett-Bakelman et al., 2019).

[11] See (Silveira et al., 2020).

effects of spaceflights and provides insight into the fundamental biological mechanisms that are influenced by spaceflights, and highlights mitochondrial dysregulation."[12]

Thus, a new crucial and challenging issue involving mitochondrial stress has been identified, to a large extent, due to the long-term effect of weightlessness on the human body. It seems that the issue cannot be solved without the application of artificial gravity systems and other new technologies for protecting humans in space.

It is necessary to reconsider our methods, knowledge, research experience and solutions of artificial gravity problem, and experience, possibilities and prospects of spaceflights and human life outside the Earth, to develop new approaches to the artificial gravity problem, including the foundations of "artificial gravity philosophy" in the context of praxeology, and to give a fresh impetus to the development of theory, education and practice for human space exploration using new environment-friendly technologies.[13]

Further, let us take a brief look at the philosophical and methodological (section 1), historical, technological and futurological aspects (sections 2-5) of the discussed subject.

1. Philosophical Foundations of Artificial Gravity and Praxeology

Let us consider the foundations of "artificial gravity philosophy" in the context of human survival, safety and development in spaceflights to space, in space, as well as return from space to the Earth. We will give the basic concepts and definitions, characteristics of the gravity nature and properties (with the emphasis on "natural" and "artificial" gravity in the context of the article topic); we will make a brief analysis in the context of praxeology.

Gravity, its nature and its properties are the research priority in physics, astronomy, cosmology, et cetera. The knowledge gained, new hypotheses, theories, facts rank high for the modern scientific worldview in a wide range – from mechanics and Newton's law of universal gravitation to the general theory of relativity, gravitational waves, quantum gravity, et cetera.[14] They have widespread influence on the development of science and technology, education and practice, including research and space exploration. However, modern knowledge about gravity is incomplete and contradictory. New technological breakthroughs are possible in the cognitive process of the gravity nature and properties for practical application.

Gravity (attraction, gravitation, universal gravitation) is a universal fundamental interaction between material bodies with mass. This well-known general definition refers to natural gravity, natural attraction.

It has been established that natural gravity (attraction, gravity) in nature depends on the masses of interacting material bodies. The index (value) of celestial body natural gravity (g) depends on its mass and is calculated as the ratio of the gravitational acceleration on its surface to the gravitational acceleration on the Earth's surface. On the Earth = 1.0 g, on the Moon ~ 0.16 g, on Mars ~ 0.38 g, on Venus ~ 0.8 g, Jupiter ~ 2.5 g.

According to the laws of physics (mechanics, et cetera), "artificial gravity"[15] ("artificial" attraction, "apparent" gravity, pseudo-gravity) can be created; it requires special knowledge, technologies and techniques.

[12] See (Krichevsky & Levchenko, 2021: 51; Silveira et al., 2020).

[13] See (Krichevsky, 2021).

[14] See (Panov, 2017).

[15] The term "artificial gravity" is widely used in modern science and technology, especially in English, to describe the nature and properties of artificial gravity. This term is also used in the article. See the definition below.

Artificial gravity (simulated gravity, gravity) is an artificially created force in spaceflight, in outer space, which is close to the gravitational force (gravity) by its action.

This definition refers to the article topic in the context of special purposeful creation and application of artificial gravity to ensure a safe and favourable living environment for humans in space.

Various combinations of natural and artificial gravity exist, appear and are used in science and practice, in human life and activity.

The nature and properties of natural and artificial gravity are different. It should be noted, especially in the context of the article, that it is the nature of humans, their body and psyche, through physiology, senses and consciousness, that manifests and reflects the complex effects, interrelationships and contradictions of natural and artificial gravity both on the Earth and in space.

There are three ranges of gravity (attraction, gravitation, force of gravity) in natural and artificial aspects, specified relative to the Earth's surface, different in the magnitude of gravity, the force of gravity:

(1) Reduced gravity (much less than on the Earth's surface, i.e., <1.0 g);
(2) "Normal" gravity (close to that on the Earth's surface, i.e., ~ 1.0 g);
(3) Increased gravity (much greater than on the Earth's surface, i.e.,> 1.0 g).

Of special interest and importance for human life and safety in space is the long-term weightlessness (microgravity) ~ 0.0 g on manned spacecraft and stations, in flights around the Earth – in near-Earth space.[16]

We shall focus on the gravity range (1), which is critical on the current stage prospects for human space exploration in the 21st century and beyond and is specific to near-Earth space and the nearest celestial bodies to our solar system – the Moon and Mars.

It should be noted that artificial gravity as a phenomenon and technology exists and is widely used on the Earth in daily living, in the industry (especially during centrifugal separation), transportation, energy, medicine, sports, military sphere, et cetera.

Artificial gravity arises during manned spacecraft maneuvers, beginning with the launch vehicle startup, the launch, changing flight trajectory, deceleration when returning to the Earth in nominal and off-nominal situations. It is used to select and train cosmonauts and astronauts for spaceflights (under the influence of significant g-force from +5.0 to +9.0 g) on terrestrial centrifuges, in training flights on highly maneuverable fighter planes and other aircraft, as well as in special laboratory aircraft in the Earth's atmosphere – for short-term simulation (up to 30-40 s) of conditions close to weightlessness, while moving along a parabolic path (Kepler curve).[17]

G-force is the conditional value of the ratio of the magnitude of artificial gravity (gravity) to the magnitude of natural gravity (gravity) on the Earth's surface or the ratio of

[16] As opposed to the short-term exposure of artificial gravity (from several seconds to several minutes) on astronauts, cosmonauts while centrifuges training on the Earth, manoeuvring on airplanes with excessive g-force, creating "simulated" weightlessness (~ 0.0 g) on flying laboratories in atmospheric flights, during the launch and injection of manned spacecraft, manoeuvring and return to the Earth. And also when simulating weightlessness in Hydro Labs (up to several hours) and immersion baths (up to several days). See (Adamovich & Gorshenin, 1997; Artificial Gravity, 2007; Kotovskaya, 2017; Kotovskaya et al., 1996; Orlov & Koloteva, 2017; Shipov, 1997; Website "Yu. A. Gagarin Research & Test Cosmonaut Training Center"; Website of NASA).

[17] Astronaut training began in 1960 while preparing for the first human spaceflights in the USA and the USSR. See (World Manned Cosmonautics, 2005; Website of NASA; Website "Yu. A. Gagarin Research & Test Cosmonaut Training Center").

the corresponding accelerations arising under the influence of artificial gravity and natural Earth's gravity.[18]

Depending on the direction (vector) of gravity, the g-force in flights can have positive, near-zero (weightlessness), and negative values. The sensation, perception and g-tolerance by a human, their effects and consequences, including remote ones, for human life and health, the equipment status and operation depend on the directions and time (exposure) of g-force relative to the position of the human body, its parts, and design elements, including the dynamics of g-force, and transients, et cetera.

Artificial gravity in space (within the article topic) is a way to compensate, neutralize, and minimize the adverse effect and consequences of spaceflight and space, prolonged zero-gravity state (microgravity), on human life, health, performance, as well as in the context of functioning, reliability and safety of the equipment, technical systems that ensure human life, and motion in space, et cetera.[19]

Paradoxically, natural conditions and the environment are simulated, synthesized and recreated, which are closely resembling (partially, or "ideally," completely) the usual and natural habitat – human life on the Earth in the context of the natural force of gravity, gravity, gravitation on our planet through new "artificiality" of the environment, its conditions and parameters.

However, a human travels from the Earth into space, lives and carries out activities in space, due to the development and application of technologies (transport, life, et cetera).

The human exposure to the artificial environment in cosmic biospheres in outer space results in a set of complex contradictions and conflicts with the terrestrial human nature, their body, and psyche arises and grows. The longer a human stays outside the Earth under the spaceflight and space negative exposure, the more combined and dangerous the effects and consequences for human health, life, performance, and social relations are. A complex of preventive measures has been developed and used in flights outside the Earth to ensure safety, minimize adverse effects and consequences, maintain the biological and social status of a human, including for a successful return prolonged flight and readaptation to its conditions. These are biomedical technologies, devices, customised suits, food rations, et cetera, daily training on simulators lasting 2-3 hours, et cetera.

However, without technologies and artificial gravity systems in space biospheres, the biomedical prevention system has limited capabilities with a significant investment of time and resources, and in fact, reduces the overall efficiency of human space activities. Moreover, it does not eliminate, but only slows down the processes of body degradation in space under exposure to prolonged weightlessness, when combined with other negative factors (high levels of radiation, electromagnetic fields, et cetera). The problem of mitochondrial stress attests to it.[20]

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[18] G-force is understood to be an acceleration rate affecting a human during his/her movement, as the ratio of the net force to their body mass. G-force is measured in (g) multiple of the mass on the Earth's surface. For a person at rest, standing on the Earth's surface, the vertical g-force is +1.0 g. There is also an area of negative g-force (<0.0 g), arising, for example, when performing inverted aerobatic manoeuvres.

[19] In the long term, when exploring and mastering the giant planets of the Solar System, et cetera, for example, Jupiter, which natural gravity is ~ 2.5 times higher than on the Earth, the inverse problem have to be solved: protecting humans, not from weightlessness, but increased gravity, using customised exoskeletons and other technologies, including disruptive innovations.

[20] See (Silveira et al., 2020; Krichevsky & Levchenko, 2021: 51), as well as the description above, in the Introduction.

Modern conditions and the quality of life in space are very far from a decent favourable environment and standards adopted on the Earth.[21] Besides, under exposure to prolonged weightlessness in space, the reliability, safety and efficiency of equipment are greatly reduced.

Thus, in the discourse of the artificial gravity philosophy and praxeology, applied to theory and practice, we refer to the gravity control, which has a long-term and constant negative effect on the human body, and on the technology and infrastructure of space biospheres, which provide human living in outer space.

Artificial gravity is a control method for preserving human nature and abilities by creating and maintaining a new sustainable balance with the artificial environment in space: a human must preserve their "core," be and remain human, both biologically and socially.[22] This will ensure the safety and efficiency of human activity in space and the organization and activity of society in artificial space biospheres, and interaction with society on the Earth and in the context of expansion prospects.

Alongside, artificial gravity systems have special aspects: side and effects on the human body when creating artificial gravity with prolonged rotation, especially with high angular velocities, et cetera. (See section 2). Special artificial technologies should be created and applied for their minimizing.

That is, the application of artificial gravity to protect against the effects of prolonged weightlessness at a new level of space biospheres development will result in a new "summa of technology" and a new balance of natural and induced factors to provide earth-like human life, human communities in space in the context of gravitation.

The presented foundations of artificial gravity philosophy in the context of praxeology contain a brief description of artificial gravity for humans in the conceptual space model.

In the full model – the "gravitational" narrative and the general "gravity philosophy," which have yet to be created (as well as the new general theory of gravity and the theory of artificial gravity), we need to consider all the options and aspects of natural and artificial gravity, including the nature of gravity and human nature, and the options: technologies for gravity creation and control, transient processes, et cetera. But this goes beyond the topic and format of this article.

2. Purpose, Methods of creation, Effects and Modes of Artificial Gravity

Artificial gravity is necessary to reduce and prevent the adverse effects of weightlessness on human safety, health, life, and performance in space and the functioning, reliability, and safety of technology – technical devices, systems, infrastructure that ensure human life in space. The application of artificial gravity "is the most drastic protection means against weightlessness ... eliminates the very factor of weightlessness, its influence ... extends to all systems of the human body, while eliminating many everyday inconveniences: pollution of the spacecraft atmosphere with fine dust particles, eating, and using water challenges, et cetera."[23]

[21] On modern spacecraft and stations, the routine personal hygiene is impossible, for example, during the entire flight (as a rule, on the ISS it lasts half a year, sometimes up to a year), one cannot take a shower, the washcloth is used, there are peculiarities of nutritional needs and sleep, et cetera. See (World Manned Cosmonautics, 2005; Website of NASA).

[22] See (Krichevsky, 2021; Krichevsky & Levchenko, 2021).

[23] (Kotovskaya et al., 1996: 9).

Main methods of artificial gravity creation

1. The rotation of an object and the creation of artificial gravity (gravity) due to centrifugal force. Description, formulas, possible schemes for the implementation of artificial gravity, technical objects designs, details are given in several sources. The level of artificial gravity (g) depends on the radius and angular velocity of the rotation around the object's centre. The greater the angular velocity of rotation, the greater the damage of the vestibular system, the larger the rotation radius (size of the structure), the more complex and expensive is the system. For example, to create artificial gravity +1.0 g in space in zero gravity, i.e., "terrestrial" conditions, a rotating object radius should equal 100 m and make ~ 3 rpm.[24]

2. Prolonged acceleration and deceleration in spaceflight, "gravitational astronautics" (according to Vladimir Yurovitsky, 2010).[25] There will be a constant acceleration in flight, half the way, for example, to the Moon or Mars, and then constant deceleration. The total flight time and the level of artificial gravity will depend on the acceleration and deceleration. They are determined by the properties of the flying object (manned spacecraft), conditioned by the technologies used: the method of movement in space, energy, i.e., the type, engine power, fuel supply, et cetera.

3. Through high-frequency vibrations, oscillatory systems, et cetera, it targets the human body, parts, and organs.[26]

It is possible that there will be fundamentally new methods, technologies of artificial gravity based on new knowledge about the gravity nature and technologies.

The artificial gravity effect on humans in space

1. Positive: artificial gravity "is the most drastic protection means against weightlessness,"[27] prevention and "gravitational therapy," recovery, including recovery of damage – fractures, et cetera.

2. Negative: vestibular and other disorders, prolonged rotation induced psychological discomfort; cumulative effects of frequent and long-term use of SAC; adaptation-disadaptation conflict due to rotation of weightlessness and artificial gravity zones, frequent and rapid change of zones; the personal response of the body and psyche to artificial gravity, et cetera.[28]

Basic modes of artificial gravity

The critical task while the research, creation and application of artificial gravity is to define the optimal modes of overload conditions from the tolerance and effectiveness perspective.[29]

A large amount of research has yet to be done on the ISS and new manned objects with the SAC and other artificial gravity systems to determine the optimal modes, the minimum effective levels of artificial gravity, duration, et cetera.

The optimal modes of artificial gravity can be formalized, for example, in the form proposed by the author, which includes four main modes:

First, allowable time of human exposure to complete weightlessness (microgravity), the absence of gravity (~ 0.0 g), is limited: a) under normal conditions, for up to 1 month

[24] See (Adamovich & Gorshenin, 1997: 178; Kotovskaya, 2017; Kotovskaya et al., 1996; Orlov & Koloteva, 2017; Sternfeld, 1949; Shipov, 1997: 128-146).

[25] See (Cosmonautics of the 21st century, 2010: 110).

[26] See (Patent RU 2160692 C2, 2000; Valeev et al., 2011).

[27] See (Kotovskaya et al., 1996: 9).

[28] See (Shipov, 1997; Kotovskaya et al., 1996; Kotovskaya, 2017; Orlov & Koloteva, 2017; Tsygankov, 2013).

[29] See (Kotovskaya, 2017: 18).

(30 ays); b) for scientific experiments and tests; c) in emergencies (complete artificial gravity systems failure) in interplanetary flights, for a period of up to one year.

Second. Reduced levels of artificial gravity (from 0.1 to 0.9 g), specific values and duration (time) should be set individually, considering age, diseases, other factors and characteristics.

Third. Constant artificial gravity ~ 1.0 g (as of the Earth) – during human reproduction in space, from conception to birth, and for the further development of a child under 5 (?) years old,[30] and in some human diseases, et cetera.

Fourth. Increased levels of artificial gravity (from 1.1 to 2.0 g), specific values and duration (time) should be set individually, considering age, diseases, other factors and characteristics.

3. A Brief History of Ideas, Technologies, Projects

In the 19th and 21st centuries, there were published a set of ideas, technologies, projects, patents on artificial gravity for spaceflights and human life in outer space, in near-Earth space, on the Moon, for interplanetary spacecraft, et cetera. Among the authors are writers, scientists, engineers, biologists, doctors: Konstantin Tsiolkovsky, Hermann Oberth, Herman Noordung (Potočnik), Ary Sternfeld, Wernher von Braun, David Cardús, Arthur C. Clarke, Gerard K. O'Neill, Sergei Korolev, Boris Adamovich, Oleg Gazenko, Adilya Kotovskaya, Aleksandr Mayboroda, Oleg Orlov, Aleksey Shipov and others.[31]

Periodization of the history and prospects of the artificial gravity problem

We present the evolution of research and work on the gravity problem, the development of ideas, technologies, projects in the form of three main periods:

First. Theoretical studies of the artificial gravity problem from the end of the 19th century.

Second. Development and ground tests of the artificial gravity systems for humans from the 1970s.

Third. The use of artificial gravity for human life in space: a) local, "internal" systems – SAC ~ from 2025-2030; b) transition to full-featured "external" systems at prospective rotating space stations, settlements in near-Earth space, interplanetary flights, on the Moon, including clause a), ~ from the 2030-the 2040s (strategic vision).

Classification of ideas, technologies, and projects of artificial gravity

There are many ideas, technologies, projects, patents devoted to artificial gravity for humans in space (see examples in section 4). General classification can be presented as follows:

1. Objectives.

1.1. Local and periodic compensation of weightlessness adverse effects and consequences;

1.2. Complete and permanent protection against exposure to weightlessness.

2. Physical and technical methods of creating artificial gravity (see section 2).

3. Design of artificial gravity systems:

3.1. On-site, internal, "local" (SAC, oscillatory, and other systems);

3.2. Full-featured, "external" systems: with the spinning of the whole object or its parts; with constant acceleration and deceleration ("gravitational astronautics");

3.3. Combination of clauses 3.1 and 3.2. See also sections 2 and 4.

[30] Author's preliminary assessment. The specific time frame and the possibility of its reduction are to be determined based on the research findings and life in space.

[31] See (Adamovich & Gorshenin, 1997; Kotovskaya et al., 1996; Krichevsky, 2020b; Mayboroda, 2019; Noordung, 1935; Sternfeld, 1949; Tsiolkovsky, 1961; Tsiolkovsky, 1920; Website of NASA).

4. Examples of ideas, technologies, and projects

Here are some significant examples in chronological sequence with brief descriptions (clauses 1-17); in most of them (clauses 1-8, 11-17), artificial gravity is created by the rotation of the entire object (space station, et cetera) or by using the SAC inside the main object (clause 9).

1. The idea of creating artificial gravity on a rotating object consisting of two hemispheres connected by chains, Konstantin Tsiolkovsky, Russia (1895).[32]

2. Manned space station with artificial gravity, Hermann Oberth, Germany (1923).[33]

3. The space station "The habitat wheel" with artificial gravitation (habitat – rotating toroid (doughnut), Herman Noordung (Potočnik), Austria (1929).[34]

4. A rotating wheel space station with artificial gravity, Wernher von Braun, NASA, USA (1952).[35]

5. Hexagonal inflatable rotating space station. NASA concept, USA (1962).[36]

6. "Artificial Gravity," Sergei Korolev, USSR (1963). Development of Konstantin Tsiolkovsky's idea (see clause 1 above). Spinning up two objects connected by a cable system to create artificial gravity in space using the spacecraft Voskhod, but the project was not implemented.[37] In 1966, NASA astronauts successfully conducted the 1st experiment in space, creating artificial gravity by spinning Gemini-11 connected by a 30 m tether to the Agena.[38] The idea was developed in the Russian Federation; see the patent on a manned tether complex (1993)[39] and a new space station concept in near-Earth space, see below, in clause 14.

7. Space settlements – rotating cylinders "Islands" (Island One, Island Two, Island Three), with artificial gravity, at the Earth-Moon libration points, G.K. O'Neill, USA (1974–1977).[40]

8. The Stanford Torus with artificial gravity, Stanford University, USA (1975).[41]

9. The short-arm centrifuge (SAC). Throughout the world, design development was started in the 1960s. In the USSR, the first ground-based SAC was designed upon the project of Boris Adamovich and others (1978).[42] In the early 1990s, in the USSR / Russian Federation, there was an idea of creating a module with a SAC at the Mir Space Station, but it was not implemented. According to the well-known plans, a new module with a SAC to provide artificial gravity was to be created on the ISS. It has been developed since 2020 by the Institute for Biomedical Problems of the Russian Academy of Sciences and the Rocket and Space Corporation Energia, the Russian Federation (2016), though its development and space launch has been postponed for financial and organizational reasons.[43]

10. Method of reduction of the adverse effect of zero-g on living organisms, the Russian Federation (1995, 2011).[44]

[32] See (Sternfeld, 1949: 34).

[33] See (Krichevsky, 2020b; Website of NASA).

[34] See (Noordung, 1935).

[35] See (Website of NASA).

[36] See (Website of NASA).

[37] See (Syromyatnikov, 2003).

[38] See (Website of NASA).

[39] See (Patent RU 2088491 C1, 1997).

[40] See (Website of NASA).

[41] See (Morozov, 2018: 33).

[42] See (Kotovskaya et al., 1996: 71-73).

[43] See (Orlov & Koloteva, 2017: 16; Krichevsky, 2020b).

[44] See (Patent RU 2160692 C2, 2000; Valeev et al., 2011).

11. Rotating wheel space station Nautilus-X with artificial gravity, NASA, USA (2011).[45]

12. Centrifuge GraviCity for the base on the Moon, Aleksandr Mayboroda, AVANTA-Consulting LLC, the Russian Federation (2014).[46]

13. A mushroom-shaped space city with artificial gravity in outer space, NASA, USA (2015).[47]

14. The concept of a new Russian space station Mir-2 with artificial gravity, a project of a group of authors, the Russian Federation (2016).[48]

15. Space Homeostatic Ark, Asgardia, Sergey Morozov (2018).[49]

16. The Von Braun Space Station is a hotel with artificial gravity in outer space, Gateway Foundation, USA (2019), renamed the Voyager Station (2020).[50]

17. "EcoCosmoDom" with artificial gravity in outer space (the General Planetary Vehicle (GPV), a global transport system megaproject), Anatoli Unitsky, Belarus (2019).[51]

The list could go on. Based on the research findings, over 100 technology patents and projects worldwide are dedicated to developing and applying artificial gravity systems for humans in space. Concurrently, the vast majority of them have not been put into practice, and none of them has yet been implemented in space. The advantageous aspect is that they continue the mission as analogs and impetus for the further evolution of ideas, technologies, and projects in the form of patents and food for creative thinking and discussion among professionals and supporters of space exploration.

Realities and Perspectives

The development and implementation of artificial gravity systems for human use in space have been lengthened out. This not only hinders technological development, the transition to new technologies but discredits and destroys the motivation and desires of people and society to explore space and live there, as it is impossible to provide a productive, safe, dignified and comfortable life in space without artificial gravity, as well as solving the problems of mitochondrial stress,[52] expansion into space, creation of an "absolute" space human, possible reproduction, raising and socialization of children born outside the Earth, in space biospheres in near-Earth space, on the Moon, et cetera.[53]

The time has come to change the outdated paradigm of adaptation to prolonged weightlessness, exceed the limits and continue space exploration, expansion into space within a new ("synthetic") paradigm – the use of artificial gravity combined with the methods and technologies of weightlessness adaptation.

Moreover, the artificial gravity problem has been relevant since the beginning of long-term manned spaceflights in the 1970s and 1980s. However, the radical practical solution has been left in limbo for more than 40 years (!). It is critical the uphold and implement the decision. We have to define goals, deadlines and create "game rules."

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[45] See (Website of NASA).

[46] See (Mayboroda, 2019: 36-43).

[47] See (Website of NASA).

[48] Information on the project is available on the Internet. See also (Krichevsky, 2020b: 16-17).

[49] See (Morozov, 2018: 28-37).

[50] See (Krichevsky, 2020b: 18).

[51] See (Yunitskiy, 2019: 56).

[52] See (Silveira et al., 2020).

[53] See (Krichevsky, 2020a, 2021; Krichevsky & Levchenko, 2021).

Further human expansion into space requires directed implementation of artificial gravity systems combined with other known countermeasures,[54] starting with the overdue application of the SAC on the ISS and new space stations,[55] including flights up to 1 year, with a further transition to full-fledged artificial gravity systems for permanent human life in outer space.

There is a set of challenging biomedical, engineering, technical, economic and other issues that need to be researched and solved during artificial gravity systems development and application in space.

It is necessary to create a space environment favourable for human life and work, combining zones of weightlessness, artificial gravity and natural gravity in outer space and on celestial bodies: artificial gravity in near-earth space and during interplanetary flights; natural and artificial gravity on the Moon, Mars, asteroids, et cetera.

It's time to move from long-running research on the Earth only to the study and applications of artificial gravity to humans in space. Twenty-five years ago, RAS academicians Oleg Gazenko and Anatoly Grigoriev wrote in the preface to a fundamental monograph on the biomedical aspects of artificial gravity, "we should not be unprepared if the absence of Earth's gravity will interfere ... with the development of manned cosmonautics in the 3[d] millennium."[56]

The time to apply artificial gravity to humans in space has come.

It is necessary to gain experience in the development, use, application, and operation of artificial gravity systems in artificial space biospheres, first in near-earth space, to protect against hazardous exposure and adverse effects of weightlessness, to provide permanent safe, and dignified life in outer space for humans and human communities.

The practical application of the human artificial gravity systems will fuel the introduction of new technologies (radiation protection, et cetera) and designs of manned flying objects, homeostatic arks in near-earth space, moonbases, et cetera, will open up new opportunities for the development of manned interplanetary navigation, space biospheres and extraterrestrial society, will start expansion into space.

Key Conclusions

1. The analyses of the philosophical and methodological, historical, technological and futurological aspects and challenging issues of the creation and application of artificial gravity to process and conduct human spaceflights, and ensure humans a safe and dignified long life in outer space from an interdisciplinary perspective and in the context of theory and practice.
2. The philosophical underpinnings of artificial gravity in the praxeology context and environmental management of space biospheres to ensure human life, safety and development in space exploration are presented. The definitions are given. A brief description of the conceptual model of outer space applications of artificial gravity for humans is made.
3. The main methods of creation and influence and modes of artificial gravity application for humans in outer space are systematized.
4. This article reviews the global evolution of ideas, technologies, and artificial gravity projects in the 19th-21th centuries; it presents periodization and general classification and important examples.

[54] See (Kotovskaya et al., 1996; Kotovskaya, 2017).

[55] See (Orlov & Koloteva, 2017).

[56] See (Kotovskaya et al., 1996: 5).

5. The article studies advances, issues, limits and perspectives of the research and application of artificial gravity for space exploration. It introduces the transition from human adaptation to long-term weightlessness in space to a new paradigm – the artificial gravity application combined with the methods and technologies of weightlessness adaptation.
6. Safe and effective space exploration, expansion into space, creation of a "space" human and humanity, productive long-term, and permanent safe and dignified human life in outer space, are impossible without artificial gravity. It is proposed to stimulate and set up the introduction of technologies and artificial gravity systems, (a) to carry out long-term human spaceflights since the 2030-the 2040s (optimistic scenario) only with artificial gravity systems; (b) to set the absolute priority of expansion – to achieve permanent human outer space life in the 21st century, including reproduction, with the full application of artificial gravity.
7. It is essential to develop new requirements and standards for human outer space life with the mandatory application of artificial gravity.
8. It is suggested to create an International Centre (Institute) for Artificial Gravity Research for People in Space involving national space agencies, space agencies and other communities and researchers.
9. It is advisable to continue the research and use the knowledge of the ideas, technologies, artificial gravity projects history for the development of science, education and space exploration.

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