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# Investigation of Orbital Controllability Conditions for Small Satellites Taking Into Account the Parameters of Electrostatic Engine

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## Abstract

*The requirements for an electrostatic engine as an actuating element of a small satellite orbit correction system are investigated. It is shown that the already developed engines are too large in size, weight and power consumption to be installed on a nano-satellite even of the U10 format. It is recommended to focus on the construction of controlled small satellites for a mass of 20-30 kg and the corresponding dimensions, similar to the already well-proven satellites of the NorSat series.*

*The desire to build and launch a group of small satellites of the Cube-Sat format (Cubsat) with a controlled configuration is used already two decades because of the well-formulated motivation and the real comparative cheapness of implementation. But the development of this idea takes place mainly for orbitally unguided satellites and without describing the features of their design.*

*This publication explains the methodology for choosing the size of the satellite and recommends increasing the mass of the satellites under consideration to 30 kg, which will create conditions for placing a full set of electrostatic engines on board with all the necessary attributes for their effective operation during the orbital relative correction of the satellites in their formation.*

**Keywords:** Mall Low-Orbit Satellites, Nano-Satellites, Orbit Correction, Miniature Electrostatic Thrusters, Satellite Constellation Configuration Control

## 1. Introduction

The rapid development of small satellites is due to the efficiency of their use, primarily in the problems of monitoring the surface from low orbital altitudes. The presence of video cameras on board even nano-satellites is not an intractable problem, neither in terms of weight and size, nor in terms of energy, nor in terms of angular orientation. Powerful advertising and prototype testing of cheap Cubsets as university and even school satellites has worked well and has already launched thousands of cheap Cubsets.

However, attempts to solve communication problems based on Cubsets were not so successful. It turned out that the Cubsets lack neither the capabilities of orbital control based on electrostatic engines (ESE), nor the dimensions for narrowly directed antennas, nor the power of solar batteries [1,2]. It is important to evaluate what minimum dimensions of a satellite can allow solving communication problems and performing other missions that require configuration control of a group of satellites on its basis, and after such a study it is reasonable to make a decision on choosing the weight and size parameters of small satellites.

The authors consider keeping two satellites at a given distance from each other, not exceeding some known value D, among the complex tasks of controlling the configuration of a constellation of satellites [3]. For example, at $D \leq 100$m, a simple and reliable WiFi wireless communication system will work between two satellites. If, in addition, each satellite has its own communication channel with the ground, it becomes possible to organize communication and data transmission between two remote ground points with virtually no "transport" delay according to the scheme command post - the first low-orbit satellite - the second low-orbit satellite - a remotely controlled robot. A task comparable in complexity (important for space meteorology) is to keep 4 satellites at the vertices of the square. To do this, the impulses of force that correct the orbits are necessary.

At the same time, a formal correction of the satellite's orbit is also a rough increase in its height, often shortly after the separation of the satellite from the carrier, which makes it possible to form the desired satellite orbit, which does not coincide with the orbit of the launch vehicle. In addition, the reusable need to raise the height of the satellite's orbit by its own means periodically arises due to the gradual deceleration of the satellite in a rarefied atmosphere. Increasing the orbit allows you to extend the term of successful operation of the satellite.

We emphasize that there are no special requirements for the accuracy of the implementation of the specified corrective force impulse. It is desirable that the direction of this corrective force vector be close to the vertical, even if with significant errors due to cross-links between the angular and orbital channels. Therefore, all the results obtained in the article for satellite engines are not applicable to the simplest tasks indicated in the previous paragraph, for which the number of engines can be very different.

The article discusses the concept of a certain multi-criteria optimization of the satellite size for an orbital constellation (minimum two satellites), rather than minimizing to Cubset size at any cost. The main condition for the orbital controllability of a small satellite is the placement on it of the required number of ESE, which make it possible to form a corrective force impulse of the required direction and magnitude. Note that the minimum number of such engines on board is 6, not three, if the possible reversal of thrust direction is provided by switching, and not by a bipolar static characteristic of the engine. Of course, in principle, only one engine can be dispensed if during the preparation of each power pulse, the satellite and the axis of the engine rigidly fixed on it are reoriented in the desired direction.

Another important requirement for the control system is the absence of cross-links of the orbital and angular correction channels of the satellite. Angular correction is usually performed by three or four gyro-flywheels capable of generating any necessary corrective torque (with a sufficiently large intrinsic moment of inertia of the gyro-flywheel). If this moment also depends on the corrective force impulse due to cross-coupling, then the constant operation of the corrective angular control loops will be required, an excessive load on the computer and all controls. There is only one way to avoid cross-links - by ensuring that the orbital correction vector passes exactly through the center of gravity (CG) of the satellite. This should be a reasonable constructive solution, possible only with sufficiently large satellite sizes.

## 2. Control with a Minimum Number of ESE on Board

In this case of setting the minimum number of ESEs on the satellite, there is only one axis of the engine (for two reversible engines it is one) and before turning on the engine this axis must be oriented in the required direction to form a given thrust vector. The rotation of the satellite necessary for this is carried out by gyro-flywheels (sometimes elements that control the magnetic or gravitational field of the Earth). The central axis of the engine is initially set to pass through the satellite CG. Therefore, there can be no cross connections between the channels of angular and orbital stabilization. But it is necessary to spend the resource of the angular channel during the formation of each impulse of force correcting the orbit. This makes it mandatory to install a full set of gyro-flywheels on board, usually 4, which is not only in terms of size, but also in terms of power supply.

The feasibility of the described simplest solution largely depends on the specific technical and economic indicators for all onboard executive elements and, of course, should decrease with the reduction in cost and improvement of miniature ESE. Unfortunately, open information about this is limited and inconsistent.

As described in, serious studies of the problem have been carried out by Elon Musk's SpaceX, which intends to launch thousands of Starlink controlled satellites, not yet announced in the Kubset format [4].

Another small satellite with one engine is shown in Fig. 1, but the CG obviously does not lie on the central axis of the engine. Two other examples of ESE are given in Fig. 2 and Fig. 3.

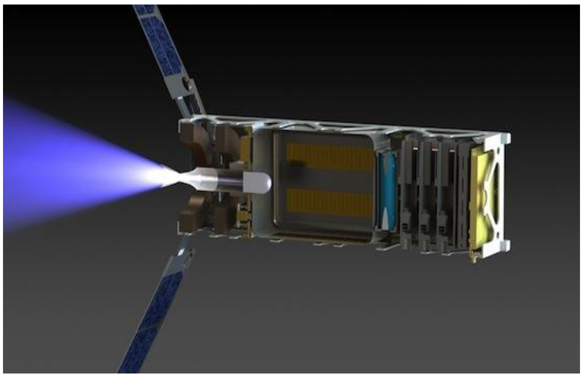

**Figure 1:** Experimental Small Single

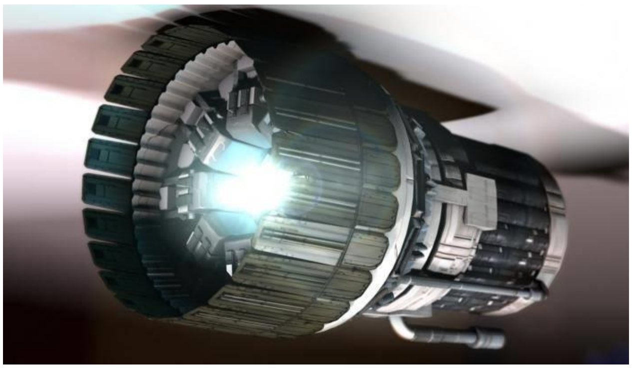

**Figure 2:** Possible View of One ESE Satellite with One ESE

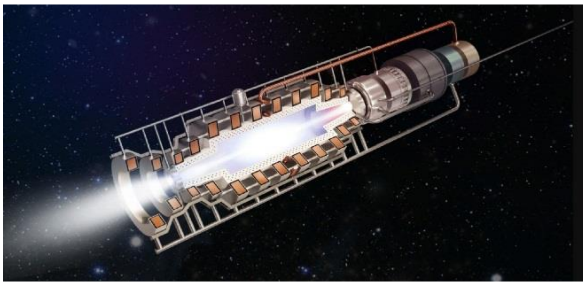

**Figure 3:** Appearance of ESE, Developed at the Samara University

**Figure 4:** ESE ID-200, Developed in Keldysh Center

SpaceX continues to expand its Starlink constellation of communications satellites. Its final composition should reach an unprecedented number of satellites with some simplified orbital control capabilities [4]. The total number of satellites in the system will reach several tens thousands of units.

The experimental single satellite is a panel with a mass of 260 kilograms and corresponding dimensions. The satellites are equipped with a single solar panel, and a krypton-based ESE as the working fluid. Satellites are equipped with various types of antennas to perform their primary mission of communication.

The energy on board the spacecraft is limited, they chose the engine that had the lowest cost of thrust (the ratio of electrical power consumed to thrust). ESE in this parameter proved to be better, therefore, the main efforts were focused on their development.

Fire tests of a new ion engine have been successfully carried out in Russia (Fig. 4). The power of the unit called ID-200 is up to 3 kW with a specific thrust impulse of up to 4,500 seconds (45 km / s). The Keldysh Center, where it is being developed, promises that the ID-200 can be used not so much for satellite orbit correction, but for deep space exploration missions [6]. The bet on ESE for spacecraft is now being made all over the world. For example, such engines are installed on Starlink satellites.

The French company ThrustMe has tested iodine propulsion in space for the first time. The NPT30-I2 engine was installed on the Cubset satellite and confirmed the efficiency of its operation in 11 inclusions in near-Earth orbit [5]. The mass of one engine with fuel is 1.2 kilograms. ThrustMe's NPT30-I2 is a fully integrated propulsion system based on gridded ion thruster technology. It comes in U1 and U1.5 sizes. However, it is not clear whether their production is mass-produced.

Samara University and the interuniversity department of space development by students and postgraduates under the guidance of prof. I.V.Belokonov developed and launched the SamSat-ION nano-satellite with an electrostatic colloidal microengine.

At MSTU named after N.E. Bauman (Russia) found successful design solutions not only for the nano-satellite, but also for its fuel tank [8]. Typically, thin-walled spherical structures are used in nano-satellites. However, as the inventors emphasize [8], such tanks do not occupy the entire internal volume of satellites having a square cross section. At the same time, a larger supply of fuel would mean greater resources for maneuvering in orbit to create large constellations of such vehicles and their relative positioning. The developers note that the proposed tank, although heavier than spherical ones, due to the larger volume, gives more opportunities to change the parameters of the satellite's flight. However, from this publication it is not clear what maneuvers the nano-satellite should perform and how much fuel is needed for this.

The most informative on the research topic are European publications, in particular, within the framework of several IFAC Aerospace symposiums, in which the authors also participated. Our colleague prof. Klaus Schilling from the University of Würzburg (Germany). Their fourth nano-satellite, UWE-4, has been orbiting the Earth since 2018 for the sole purpose of practicing orbital control. The design of the UWE-4 is clear from Fig. 9. Each of the 4 miniature ESEs are located along the ribs of the satellite structure. The condition for the resulting axis of the ESE to pass through the CG of the satellite can be satisfied only if the thrust of each of the ESEs is the same, but it is obvious that for the tasks solved by this satellite, the presence of cross-links of channels gives relatively small errors. Note that each of the ESE is really miniature (length 10 cm, cross-sectional diameter about 1 cm). It is not clear whether this miniaturization is the result of technical progress or whether a significant part of the ESE power had to be sacrificed for this. The volume of fuel in the tank (or tanks) from Fig. 9 is not clear, but the tasks solved by the UWE-4 are clearly described. There are two main ones: a sharp decrease in the height of the orbit to get into the zone of self-destruction (the fight against space debris) and an increase in the height of the orbit to increase the durability of a successfully functioning satellite. These are really the simplest typical tasks, so it is not entirely correct to call a satellite controlled. The term "partially controlled" is more appropriate. The UWE-4 cannot solve complex control problems for orbit correction in a formation of several satellites. But these two simple tasks are completely solved,

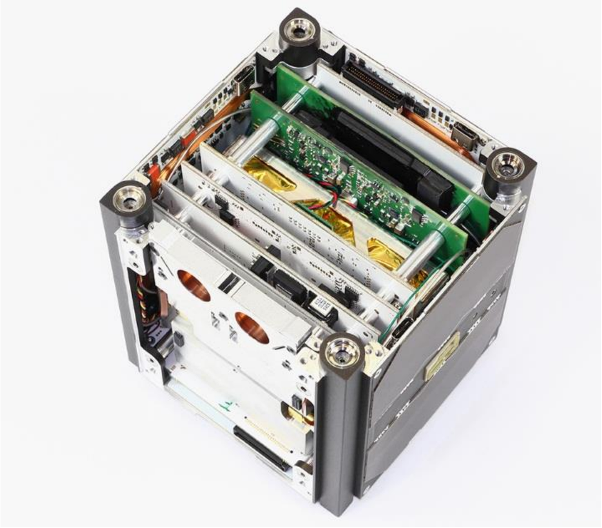

**Figure 5:** UWE-4 Satellite Design (Würzburg's University Experimental)

In order for the spacecraft to move in space and perform various maneuvers, such as entering orbit or trajectory correction or maintaining the required configuration of satellites in the constellation, each satellite needs a propulsion system, the design of which depends on the tasks of the device. In them, electric and magnetic fields are used to accelerate the working substance. Electrostatic thrusters are installed not only on near-Earth vehicles, but also on many interplanetary stations, such as SMART-1, Dawn or Hayabusa-2. Engines for interplanetary stations, as heavier ones, have already been brought to a more perfect state than miniature ones for nano-satellites.

Since the available electrical power on spacecraft is limited, electrostatic propulsion systems must have a maximum ratio of generated thrust to power, which requires a working fluid with a low ionization threshold and high atomic mass. Xenon is by far the most commonly used, however, it is a rare gas that requires special storage conditions, leading to an expensive manufacturing process and specialized equipment to use. With the development of large satellite constellations, the demand for xenon in the space industry is expected to exceed supply within the next ten years.

The energy on board the spacecraft must be economical, therefore, in a specific solution, they chose the engine that had the lowest cost of thrust (the ratio of electrical power consumed to thrust). The ESE showed itself better in this parameter, so the main efforts were directed to its development. It is clear that an engine has not yet been created that could be installed in the amount of 6 copies on board the U10 nano-satellite. This forces us to consider larger satellites. For example, like NorSat [7].

## 3. Substantiation of the Scheme for Placing a Complete Set of Executive Units at a Small ESE

Let's take a simplified geometric model of the ESE in the form of a segment of a cylinder with a diameter d and a length $L$. The shape and dimensions of all 6 engines are the same. For a typical example, we first take the dimensions $L$=12 cm, $d$=3cm.

The central axes of all 6 engines must pass through one point, which is the center of gravity (CG) of the satellite. This is possible only when all engines are shifted away from the CG. In this case, each engine will not physically touch other engines and interfere with the passage of their axes through the CG. Then the cross-links of the orbital and angular correction channels will be excluded.

The above is illustrated by Figure 6 of the location of 4 ESEs in a horizontal plane. End-faced in shape, the engine boundary closest to the CG is removed from it by a distance r. The distance of the other end of the engine from the CG is $R= L+ r$. There are no engines in a circle with a diameter of 2$R$, but the condition of intersection of all central axes of engines (shown by dotted lines) in the CG is strictly fulfilled. This unused volume of the engines can accommodate any equipment or fuel supply necessary for the operation of the satellite. Naturally, when the engine is running, charged particles are released into the free space outside the ESE. The emission directions are shown in Fig. 6 arrows with double lines.

However, in this case, the outer boundary of the satellite will reach a diameter of 2($r$+$L$). At $r$=10 cm, this overall size (diameter) of the satellite will be 2(10+12) = 44 cm, which is significantly (almost five times) larger than the nano-satellite's overall size of 10 cm. Such is the price of eliminating cross-links. In principle, there is no more “cheaper” option for complex cases of high-precision orbit correction. The mass of the enlarged satellite can be roughly estimated using the cubic growth factor $(44/10)^3$ = $4.4^3$ = 77.44, which, when multiplied by the nanosatellite's mass of 1 kg by this coefficient, gives 77.44 kg.

In addition to the above, we note that it is really expedient to fill the “saved” space of a complex shape between the internal ends of the engines with a tank for the working fluid of engines with a large number of sensors empty-full, which, with known geometric and kinematic models of the design, makes it possible to calculate the new position of the CG after the start of consumption of the working fluid. bodies and significantly reduce errors in orbital correction due to cross-links.

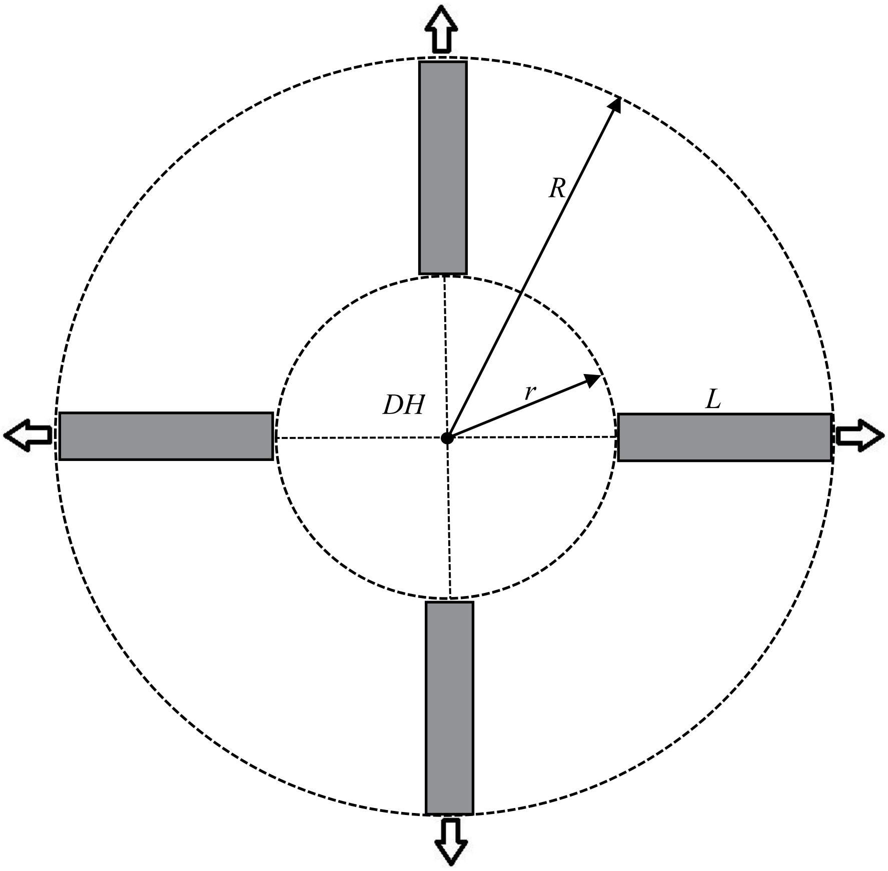

**Figure 6:** Location of Four ESES in the Horizontal Plane

However, in this case, the outer boundary of the satellite will reach a diameter of 2(r+L). At r=10 cm, this overall size (diameter) of the satellite will be 2(10+12) = 44 cm, which is significantly (almost five times) larger than the nano-satellite's overall size of 10 cm. Such is the price of eliminating cross-links. More "cheap" option, in principle, does not exist. The mass of the enlarged satellite can be roughly estimated using a cubic growth factor of 4.43 = 77.44, which, when multiplied by the nanosatellite's mass of 1 kg by this coefficient, gives 77 kg.

If we take an extremely small (hard to implement constructively) value r= 3 cm, then we get 2(3+12) = 30 cm, which is three times the dimensions of the nano-satellite. The weight of the enlarged satellite in this case will be approximately 1 × 33 = 27 kg. This is the true limit of satellite mass reduction. Other values of geometric parameters will only increase the allowable size of the satellite.

In fact, we have solved the problem of two-criteria optimization of the satellite mass. An extremely light satellite with cross-links between channels is a nano-satellite with a mass of 1 kg. To eliminate cross-links between the channels of angular and orbital control, the satellite must weigh at least 27 kg.

In general, the requirements for the size of a satellite with 6 electrostatic engines can be determined по легко выводимой формуле

$$M_{2R} = \left(\frac{2R}{10}\right)^3 = \left(\frac{r+L}{5}\right)^3, \qquad (1)$$

where $M_{2R}$ is the mass of the satellite, 2R is the diameter of the satellite (overall size, numerically coinciding with the mass, since the specific density of the structure is assumed to be 1 kg / dm), r is the distance from the to the inner end of the engine to the outer end of the engine, $L$ is the distance from the to the inner end of the engine, $r$ and $L$ are given in centimeters, $2R$ is given in kilograms. Dimensional factor 5 is measured in m/kg$^{1/3}$.

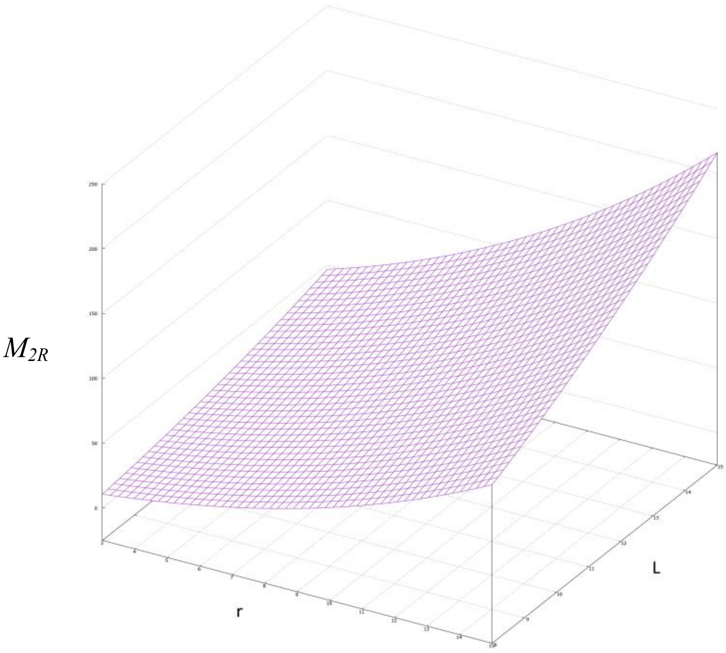

**Figure 7:** Dependence of the Overall Size of the Satellite on Distances *r* and *L*

Scheduled ependence of $M_{2R}$ on r and L is given in Figure 7 at ranges $r$=3-5 cm and $L$= 8-15cm.

From Fig. 7 it can be seen that the possibilities for accommodating 6 electrostatic engines are very limited and do not fit with the cubeset concept even in U12 format.

The arguments for the creation of small satellites of increased dimensions are becoming clear, for example, similar to the successfully functioning small Norsat satellites with a mass of 16 kg or, in the latest version, 35 kg [8]. Another promising way is to reduce the size of the ESE while maintaining their thrust. This is a difficult task that has not yet been fully solved. Engines with increased mass and power are developing faster, useful for interplanetary flights, and not for correction of near-Earth orbit.

The business concept of building a small satellite is to choose its size and mass.in strict accordance with the real needs for the placement of on-board equipment. Particular attention should be paid to the location for solar panels and relatively large antennas. Any additional requirements for their placement and dimensions often make it unreasonably difficult to design a satellite.

As already noted, it is advisable to use the free space between the 6th ESD, which determine the dimensions of the satellite, to accommodate tanks with the working fluid for the ESD, taking measures for its uniform consumption, in which the position of the CG will change slightly. This task for weightless conditions is very complicated and usually involves the controlled ejection of liquid from the tank by neutral gas pressure and control of the liquid remaining in the tank by a special system of sensors.

The total capacity of tanks of acceptable dimensions for the satellite design geometry shown in Fig. 6 can be roughly estimated as follows.

The area of a circle with radius R will be $\pi R^2$. Consider each tank as a segment of a cylinder with a certain base area and height $L$. When estimating the base area, the circular inner boundary with radius r is not taken into account, subtracting its area $\pi r^2$ from tank capacity calculations. The areas of rectangular projections of the 4dL ESD on the base area should also be subtracted, but adding half to the "base" area for two ESDs in a perpendicular plane. As a result, for the base area of 6 tanks $S_b$ we get

$$S_{bg} = \pi(R^2 - r^2) + \pi(R^2 - r^2)/2 - 6dL = 1.5\,\pi(R^2 - r^2) - 6dL. \qquad (2)$$

The "height" of each of the tanks is Sv = L.
As a result, the total capacity of the tanks will be

$$V6b = (1.5\,\pi(R^2 - r^2) - 6dL\,)L. \qquad (3)$$

Substitution in (2) and (3) of the numerical values of the parameters in decimeters gives

$V6b$ =(1.5 $\pi$($R$2 – $r$2) - 6dL )L = ( 1.5×3.14×1.5×(1.52 - 0.32) - 6×0.3 × 1.2) × 1.2 = = 15.5 $dm^3$.

For the considered small satellite with a mass of 27 kg, the volume of the working fluid of 15.5 dm3 can be quite acceptable for performing simple operations in the "partial" controllability mode. For example, as follows from [11], in 2009 ESA launched the GOCE satellite, which was able to perform several maneuvers to raise the micro-satellite's orbit due to an ion engine with a xenon reserve of several tens of cubic decimeters (about 40 kg) and as a result received a very accurate gravitational model of the Earth.

All other elements of the onboard equipment of the satellite must satisfy the limitation of approximately 27-15.5/2 ≈ 19.2 kg (assuming the specific gravity of liquefied xenon is approximately equal to 0.5 kg/dm$^3$). This is quite enough for all the onboard elements necessary for the mission to be carried out, which, among other things, ensure the complete controllability of the satellite.

Let us analyze the composition of equipment for performing 2D surface monitoring.

## 4. The Minimum Composition of Equipment for Surface Monitoring

Let us list the composition of the equipment on the satellite, which is necessary for performing stereo-monitoring of the surface. The use of two video cameras makes it possible to significantly increase the recognition of the features of objects and areas of the underlying surface, especially with a fixed and acceptable in size base between the cameras. Keeping the distance between the cameras is achieved by controlled movement of two satellites in order to maintain the size of the base. In previous works, the authors considered a base of 50-100 m, and a satellite control algorithm that does not allow satellites to “scatter” over a greater distance. Two satellites with antennas and WiFi wireless communication between themselves also allow organizing two-way communication between two ground points (a mobile robot and a command post). All the above requirements are canceled when implementing single-chamber monitoring.

The video camera on board the satellite can be used for both surface monitoring and relative satellite navigation. This is easy enough to do, especially given the rapid improvement and cheapening of video cameras. The receiver of a satellite navigation system is useful for improving the accuracy of navigation as the most important element of an integrated meter [10], but its noise immunity is low.

Gyrowheels solve the problem of controlling the angular position, their number is usually 4, introducing structural redundancy into the system. Under certain conditions, angular stabilization in a certain position may be aerodynamic-gravity [1]. This solution is simpler than gyro-flywheels, but it is not universal. The required power supply is in the order of 8 watts - which is not easy to provide with a small satellite size.

Six ESEs are required for a full orbital correction of the satellite. Small engines are not yet a market product.

Let us separately analyze the case of the simplest satellite maneuver to increase the altitude of its orbit. This requires the formation of a thrust vector directed vertically upward relatively approximately. Errors of several degrees are permissible when setting the axis of the ESE. In this case, the source of information about the actual angular position of the satellite can be, for example, a simple and cheap magnetic field sensor, and not options with video cameras. Descriptions of many nano-satellites include the characteristic “controllable”, meaning the simplest orbital correction described above, and not the extremely precise formation of a corrective force vector. The difference between fine (requiring a full set of ESE) and coarse maneuvers should be understood.

Solar panels should be extremely large area for the chosen size of the satellite, because the energy shortage really exists. During the passage of the shadow part of the orbit, control is impossible without a battery charged in the light part of the orbit.

There are other mandatory elements for installation on the satellite that are not related to ensuring the functioning of the ESE.

## Gratitude

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## 5. Conclusion

The construction for controlling the angular and orbital motion of a small satellite is proposed, which excludes the cross-links between channels due to the organization of the passage of corrective force actions exactly through the center of gravity of the satellite. The properties of the ESE and the geometry of placement of their three pairs on the satellite as actuating elements in the satellite's orbital correction channel are considered. The full composition of the onboard equipment of the satellite was analyzed and it was found that nano-satellites, even in the U10 format, cannot geometrically accommodate all the necessary elements of the angular and orbital motion control systems. More promising are managed small satellites of the NorSat type with a mass of 20-30 kg, convenient both for monitoring and for certain communication tasks. It is possible that by reducing the size of the ESE, the mass of satellites could be reduced.

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