Innovative Vacuum Arc Thruster for CubeSat Constellations

IEPC-2013-306

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

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Abstract: The University of the Federal Armed Forces (UniBwM) is currently developing an innovative electric propulsion system for small satellites with extremly low space, mass and power budget. Satellites with these characteristics were built by the Justus-Maximilians-Universität Würzburg (JMUW) within the international CubeSat project. the Bavarian government UniBwM and JMUW are working together to equip the new pico satellite UWE-4 (Universität Würzburg Experimentalsatellit 4) with a sufficient propulsion system for fine positioning and attitude control. JMUW is responsible for the development of the satellite and the integration of the propulsion system which is currently under development at UniBwM based on the so called Vacuum Arc Thruster. To demonstrate the positioning ability of the system the mission of UWE-4 is to chase another CubeSat and to hold its relative position. Together with the strict restrictions of the CubeSat this gives some serious challenges to be solved.

I. Introduction

CURRENT and future space programs suffer more and more from cost reduction are challenged to deal with budget cuts. On the other hand more satellites for communication, navigation and scientific task are needed. Thus nNew concepts are necessary to solve this contradiction. Several years ago the idea of intelligent dust was established. The idea is to use a swarm of several small specialized satellites instead of one big multitask satellite. In this scenario each satellite may only be able to fulfill a few tasks but due to the cost reduction in development launch such an approach should offer advantages over commonly deployed satellites. Due to the low cost universities and other small scientific institutions can further the development of such satellite formations.

An international standard in this field is the CubeSat by the California Polytechnic State University (CalPoly). The dimensions of one CubeSat are 100 mm x 100 mm x 100 mm at a maximum mass of 1.33 kg[1]. Several CubeSats can be merged to one bigger satellite. CalPoly has also developed an orbital deployer for the integration of

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several satellites into the most common launch vehicles. By this CalPoly has set a standardized design and a list of specifications which can be adapted and modified by other institutions like Justus-Maximilians-Universität Würzburg (JMUW). JMUW has already launched two CubeSats called UWE-1 and UWE-2 (Universität Würzburg Experimentalsatellit 1 and 2) into low earth orbit (LEO). Currently UWE-3 is waiting for its launch[2]. None of these satellites was equipped with a propulsion system for fine positioning and attitude control. Only UWE-3 had magnetorquers for attitude control. Based on the last satellite of this series UWE-4 plans to use an innovative propulsion system to demonstrate the principal ability of formation flying.

This requires a very small, lightweight, robust thruster with a very precise thrust production (1 µNs). Due to mass and space limitations (max. 200 g, 100 mm x 100 mm x 10 mm) chemical thrusters and electric propulsion systems with gaseous or liquid propellants are not practicable. Moreover the bus voltage and the power budget of UWE-4 (approximately 4 V, max. 2 W) require a very sophisticated power processing unit (PPU) and a highly reliable ignition mechanism. The mission analysis showed that only the so called Vacuum Arc Thruster (VAT) may meet all these requirements[3]. While JMUW is responsible for satellite development and integration of the propulsion system the VAT and its components is subject of current research at the University of the Federal Armed Forces in Munich (UniBwM).

Apart from principal issues like reliable ignition process, an improvement of the plume characteristics and the development of a suitable propellant feeding system, this special mission provides additional "technical" challenges. Extreme mass and space limitations require innovations for thruster head design as well as for the PPU. The major issues concerning the PPU design are the low bus voltage and the low power budget. Up to now no propulsion system has dealt with such restrictions. In the following we describe some possible solutions on this subject.

II. Mission Overview

The definition of the mission parameters was integral part of the research at JMUW. Given by the satellite design and its restrictions a suitable task for the satellite was developed and the necessary inputs for the thruster development at UniBwM like propellant mass, number of pulses, thrust and power were derived.

A. The Platform

As mentioned before UWE-4 is based on a modular CubeSat design developed at JMUW. Its mechanical structure consists of four rails on which the six solar panels are attached therefore building a cube-shaped satellite. These four rails are important for the mechanical rigidity of the satellite. Moreover they have direct mechanical contact to the deployment rails of the orbital deploy unit. Therefore they have to be very smooth so they can slip easily out of the deployer. This is very important for the thruster head design which will be described later. To provide good thermal control and easy access to the electronics the outer and inner structure are decoupled from each other. The inner parts contain power management, communication, attitude determination and control modules whereas the outer parts carry solar panels and sensors like sun sensor, magnetometer and rate gyroscopes (Fig. 1)[4].

The whole design was developed for UWE-3 and allows only very limited options for changes. Therefore the implementation of the propulsion system is a real challenge. JMUW developed the necessary interfaces between propulsion system and satellite. Within this process a propulsion architecture with four thrusters mounted on the external rails emerged. With this concept it is possible to control attitude and position very precise without interfering with the solar panels.

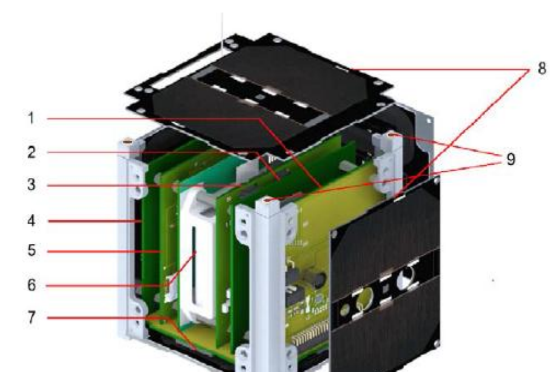

Figure 1. Structural Overview of UWE-4[4].
(1) Front Access Board, (2) PPU, (3) ADCS, (4) Communication, (5) OBDH, (6) EPS, (7) Backplane, (8) Solar panels, (9) Thruster heads.

B. Mission Description

UWE-4 should demonstrate the possibility of formation flying in LEO. This requires – apart from attitude control – the ability for fine positioning within a given orbit. The technical limitations of such a small satellite cause the requirements for formation flight to be kept very simple. One orbital deploy unit can set three CubeSat´s into orbit on after the other without any sophisticated control mechanism in place. This means that these satellites will drift apart over time. This defines the task for UWE-4 and the VAT: To obtain a relative distance below 1500 km between two satellites and to maintain this position throughout a planned mission duration of three months in order to sustain a radio link[4]. For this task several mission models were evaluated. From this analysis follows that a total Δv of 4.5 m/s is required. At an I_{sp} of 1000 s and a thrust of 2 µN the necessary propellant mass amounts to 0.6 g at a life time of 10^6 pulses if the repetition rate is 1 Hz. The actual thruster operation will be bang-bang controlled with a time constant of 1 day. A more detailed description can be found in IEPC-2013-195[5].

C. Requirements and Restrictions

During mission analysis several restrictions emerged. Most of these limitations are stricter than expected at the beginning of the project. Therefore most of the effort is focused onto developing a complete propulsion system. The most critical restriction is the mass limit of 200 g. In addition with a power limit of 2 W and a bus voltage of 3.8 to 4.3 V it turns out to be extremely difficult to build a suitable PPU. The space assigned to the PPU inside the satellite is limited to one PCB of 100 mm x 100 mm with 10 mm distance to the next board. Due to these limitations it is impossible to focus the plasma plume by magnetical or electrical methods. Therefore the only means of enhancing the thrust vector is the geometry of the thruster head. As described above four thruster heads will be installed in the four outer rails of the satellite, which also results in severe constraints for the thruster head dimensions. Since the rails are the main structure any changes which decrease the mechanical stability are not possible. A maximum diameter for the thruster head of 7 mm and a maximum length of 80 mm were determined together with a maximum mass for all 4 thruster heads of 50 g. This leaves only 150 g for the PPU. As mentioned above the total propellant mass necessary for the proposed mission is only 0.6 g assuming an I_{sp} of 1000 s. 1 Hz thruster operation over 10^6 pulses at a precise thrust of 2 µN is another challenge for the reliability of the VAT.

III. VAT Development

The main advantage of the Vacuum Arc Thruster is its simplicity. There are no tanks for gaseous or liquid propellants which consume space and mass and therefore no valves which could freeze or leak. Back in 2001 thrust measurements at JPL have shown that the VAT is a suitable fine positioning system[6]. The most common concept is the coaxial assembly (Fig. 2). A cylindrical cathode is surrounded by tubular insulation which itself is covered by the anode. If a voltage is applied between these electrodes a vacuum arc is formed. Normally this would require a very high voltage to achieve a breakdown in vacuum. Therefore the so called "trigger-less ignition" has been developed[7]: A conductive film is deposited on the insulator surface with a tiny gap between the film and the cathode. This layer is a short circuit between the electrodes if no current is flowing in the circuit thus transferring the full applied voltage. At the tiny gap between the conductive layer and the cathode a high electric field arises at relatively low voltages (some 100 V) until a breakdown occurs and the plasma is initiated by so called cathode spots – Fig. 3 shows a sequence of cathode spots visualized by a high speed imaging system[8]. This leads to a voltage drop across the thin film since its resistance is not zero. The vacuum arc plasma acts in the following as low resistance path between the two electrodes with a burning voltage of about 30 V. During this process the cathode and the conductive film are eroded. In fact it is the eroded cathode material which forms the quasi neutral plasma plume with an inner pressure of about 10^7 Pa leading to an exhaust velocity of the order of 10^4 m/s[9]. As already mentioned the feeding of the cathode material is not important for the proposed mission

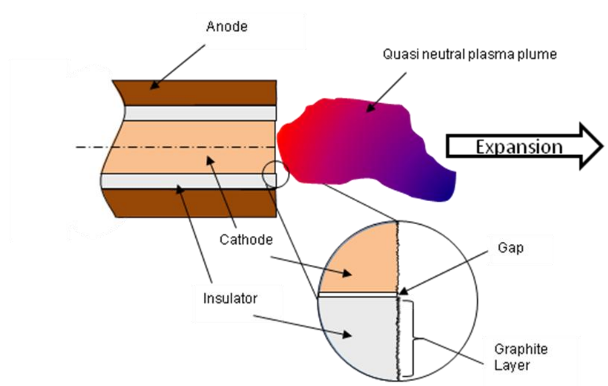

Figure 2. Simple schematic of the Vacuum Arc Thruster.

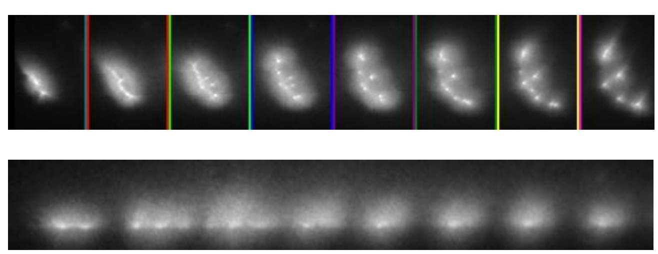

Figure 3. High speed imaging of cathode arc spots. *Chronological sequenz over 300 µs, frontal (top) and lateral view (bottom).*

due to the small amount of propellant required. Nevertheless it is subject of current research as well as the development of a more durable conductive layer.

A. Thruster Head Design

Before all restrictions of the mission analysis were identified several possible design types for the thruster head were investigated. As proposed in earlier work the coaxial VAT was further tested[10]. Although it showed good performance (as proved by NASA) the main disadvantage is that most of the cathode does not get eroded evenly. This means that the major part of the material is of no use at all for the satellite propulsion thus acts as an extra mass which should be avoided. In the first stage of the project a planar type of thruster head was developed. An improved coaxial design was chosen. Instead of a solid rod of cathode material a hollow tube is used. Thus the mass of the system is reduced. Figure 4 and Fig. 5 show a prototype based on this concept

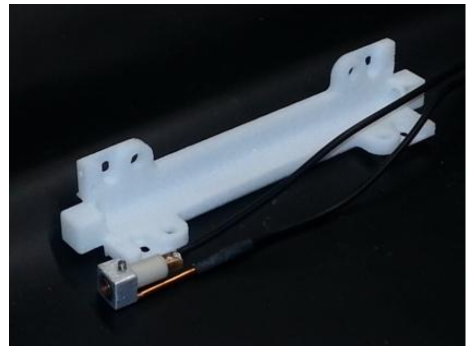

Figure 4. Prototype of thruster head with rapid prototyping model of the outer rail of UWE-4.

The rail which needs to accept the the thruster head is milled from an aluminum block making it possible to be used as anode. To prevent the electronics of UWE-4 from possible damage due to short circuits an insulation is placed between anode and rail. The cathode material should have an I_{sp} of about 1000 s according to the current mission model. Therefore possible materials are titanium (I_{sp} = 924 s) or tungsten (I_{sp} = 1078 s)[9].

B. Improvement of the Ignition Mechanism

A critical subject of this project is the ignition mechanism. To achieve low power discharges a thin conductive layer on the insulation between anode and cathode is necessary. This layer is eroded during thruster erosion and therefore it has to be replaced in some way. It could be observed that during high power vacuum arc operation (e. g. for layer deposition) a re-deposition of the conductive layer by deposition of cathode material occurs. Up to now this effect couldn´t be reproduced reliably at the UWE-4 power regime. Several different solutions are currently under research. In order to overcome this problem current research focuses on the use of other – longer lasting – conductive materials like aluminum, copper, titanium or tungsten and the application of alternative deposition methods. Another possible solution is the use of indium or tin as cathode material. Both elements due to their low melting temperature display a high erosion rate – even at low power – which allows to regenerate the conductive layer by a combination of electrostatic and hydrostatic effects. These effects are currently being quantified. One downside of the use of these materials is the production of macro particles which may contaminate the satellite and a lower I_{sp} which increases the required propellant mass.

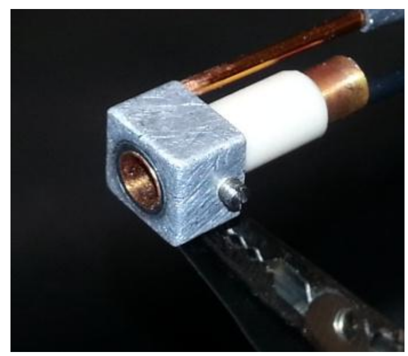

Figure 5. Magnified view on the prototype of the thruster head with a hollow cathode.

C. Propellant Feeding

A propellant feeding system is necessary to replace the eroded cathode material which is used for thrust production, when larger amounts of propellant are needed to achieve mission goals. Several methods have been investigated. One method is the installation of a micro motor directly to the cathode. Since a gear mechanism is necessary to reduce the rotation speed this setup becomes rather complex, space consuming and heavy, criterions of exclusion in this project. A simple spring mechanism would be the most elegant way but up to now no satisfactory solution without any complex byproducts could be found. Another way is the use of low melting point materials like indium or tin as cathode material. The same effects mentioned in the paragraph above lead to self-feeding of the VAT. Unfortunately the achievable I_{sp} may be too low for the current mission model and the production of micro particle may be disadvantageous. In the last stage a piezo electric feeding system was conceived which is currently under development.

IV. Power Processing Unit (PPU)

The power processing of a vacuum arc source for space applications needs to overcome numerous challenges. A laboratory vacuum arc arrangement, e. g. for thin film deposition, can be operated easily with a pulse forming network (PFN). Thereby very high currents at high voltages can be produced. Thus the ignition even without a proper conductive layer is no problem at all. Unfortunately PFNs are heavy and space consuming, Therefore different methods for arc initiation are necessary. At UniBwM the inductive power supply has been adapted as proposed by Schein et al. in 2002[11]. This simple concept consists of a coil which is charged by a source voltage and the discharged into the thruster. The whole process is controlled by a switch, e. g. an IGBT or a MOSFET (Fig. 6). The operation frequency is tunable from single pulses up to 1 kHz. It is important to note that this kind of PPU produces a self-adapting voltage pulse which provides the required electric field. Depending on the condition of the conductive layer this may be achieved at a voltage of 100 V but also voltages up to 700 V can be produced by this system. This initiation last for some ns after which the voltage drops to about 30 V for the rest of the discharge (some 100 µs) as visualized in Fig. 7. Therefore this PPU design represents a kind of an adaptive power source which is controlled by the thruster itself.

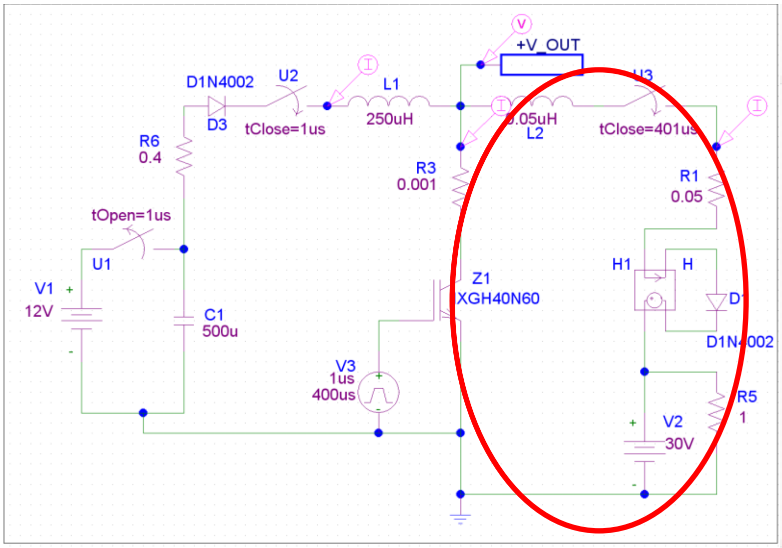

Figure 6. PSpice model of the inductive PPU concept by Schein et al. with a simple model of the vacuum arc (red).

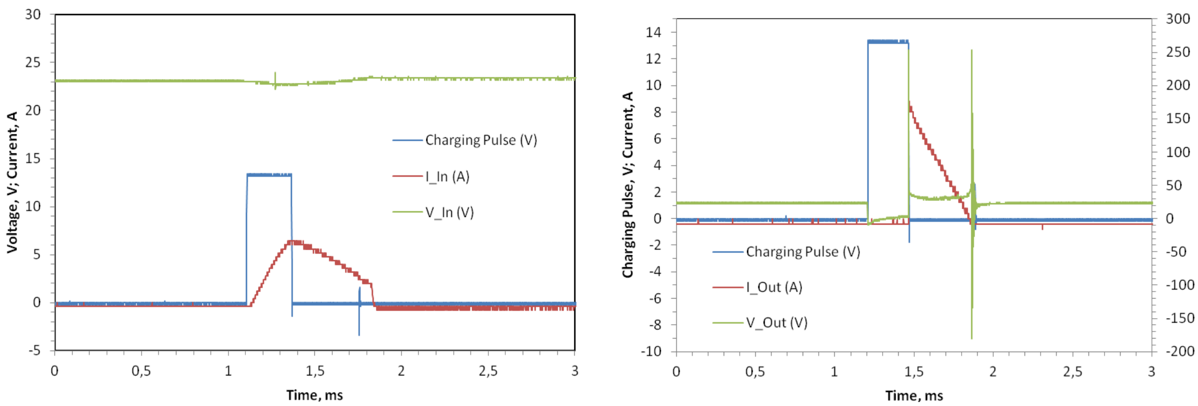

Figure 7. Voltage and current measurements at the PPU prototype. *Input (left) and output (right) at an operation voltage of 24 V, using a copper cathode.*

To protect the electronis of the satellite especially to avoid high return currents in case of a short circuit at the thruster head a galvanic separation is necessary. Therefore the described PPU concept was modified by Apcon Aerospace and Defense GmbH. Instead of a simple coil a transformer will now be used to process the power needed for ignition. The resulting design is more complex but the benefit is a higher safety level for the whole satellite (Fig. 8).

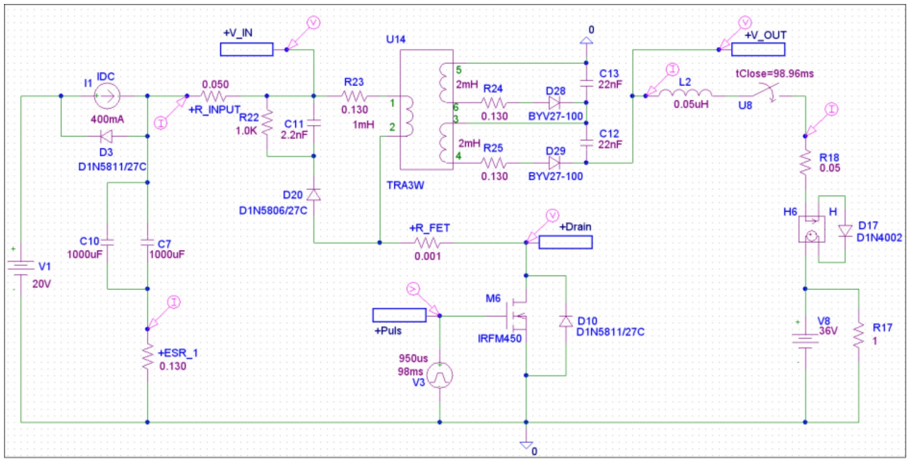

Figure 8. PSpice model of the improved PPU concept for UWE-4.

The initial PPU was designed for bus voltages of 12 to 24 V. Due to the limited solar electric power supply of UWE-4 only 3.8 – 4.3 V are available. Therefore additional electronic stages have been implemented: At first the bus voltage is converted to 12 V which is necessary for the operation of several electronic parts used in the PPU. In a second step the 12 VDC will be transformed to 25V as an input voltage for the PPU described above. Since there are four thruster heads four transformers are necessary. The PPU is operated by a micro controller which is programmed with the mission specific parameters from JMUWs mission analysis. The input commands are transferred by the UWE-4 interface. Currently the PPU has been assembled and is now in the integration phase (Fig. 9). Several teething problems occurred which are now under progress.

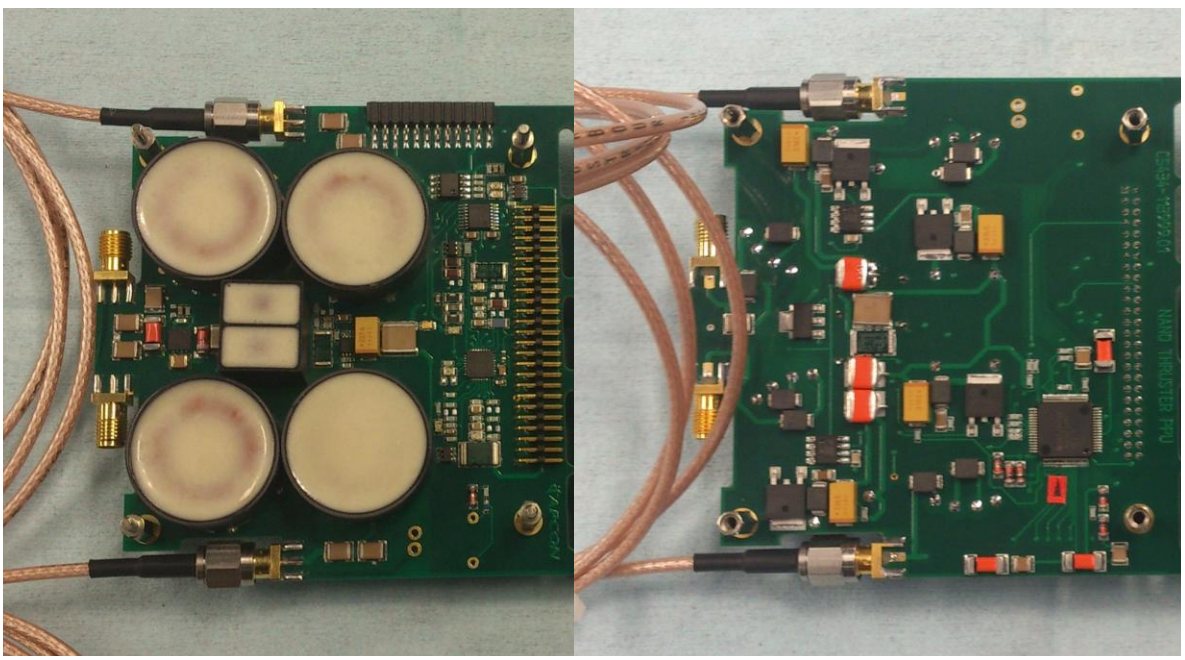

Figure 9. The UWE-4 PPU. *Frontplane with the four transformers on the left, backplane on the right.*

V. Conclusion

We are currently developing an electric micro propulsion system for the UWE-4 pico satellite of Würzburg University. Several design challenges have to be solved within a tight schedule since the satellite is supposed to be launched in 2014. The propulsion system chosen for this task is the Vacuum Arc Thruster which has shown its abilities in previous research programs. NASA measurements indicated a highly reliable, durable propulsion system with thrust to power ratios up to 10 µN/W at different power levels. Since previous VAT systems were designed for higher bus voltages and under less restrictive space and mass limitations several modifications and further developments are necessary. By choosing different materials a large range of I_{sp}, erosion rates and thrust is achievable. This allows a good matching to the UWE-4 requirements. Current research is focused on the improvement of the ignition mechanism and the enhancement of the system life time. The electrical design has been outsourced to Apcon AeroSpace & Defense GmbH as well as the corresponding testing routines. In 2014 the described VAT system will be the first to actually operate in space. Electrical parameters will be monitored as well as an orbital thrust measurement to collect data for future programs. Further research will focus on the cathode physics and the visualization of the cathode processes. Future missions with higher space and mass limits enable the use of a more sophisticated cathode design and the use of different focusing methods for the plasma plume.

Acknowledgments

This research was funded by the Bavarian State Ministry of Economy, Infrastructure, Traffic and Technology within the Bavarian Space Flight Support Program 2012 – 2014 as "Innovative Propulsion System for Satellite Formations based on Vacuum Arc Thrusters" (IASV).

References

[1] "Cubesat Design Specification", rev.12, 2009, Stanford University and California Polytechnic Institute.

[2] Busch, S., and Schilling, K., "UWE-3: A Modular System Design for the Next Generation of Very Small Satellites", Small Satellites Systems and Services - The 4S Symposium 2012, Slovenia, 2012.

[3] Mueller, J., Hofer, R. and Ziemer, J., "Survey of Propulsion Technologies Applicable to Cubesats", URL: http://hdl.handle.net/2014/41627, [cited April 2013].

[4] Kronhaus, I., Pietzka, M., Schilling, K. and Schein, J., "Pico-Satellite Orbit Control by Vacuum Arc Thrusters as enabling Technology for Formations of small Satellites", 5th International Conference on Spacecraft Formation Flying Missions and Technologies, Munich, 2013.

[5] Kronhaus, I., Pietzka, M., Schilling, K. and Schein, J., "Application of Electric Propulsion in Picosatellites from Concept to Reality - the UWE-4 Case", 33rd International Electric Propulsion Conference 2013, Washington, D. C., 2013.

[6] Schein, J. et al., "Vacuum Arc Thruster for Small Satellite Applications", NASA Report: NASA/CR-2001-211323, Dec. 2001.

[7] Anders, A., Schein, J. and Qi, N.: "Pulsed vacuum-arc ion source operated with a ''triggerless'' arc initiation method"; Review of Scientific Instruments, Vol.71, No.2, 2000, pp. 827 – 829.

[8] Schein, J., and Forster, G., "Innovative high-speed camera system diagnostics of plasma torch fluctuations", *Proceedings of ITSC 2008*, Maastricht, Netherlands, 2008.

[9] Polk, J., Sekerak, M., Ziemer, J., Schein, J., Qi, N. and Anders, A.: "A Theoretical Analysis of Vacuum Arc Thruster and Vacuum Arc Ion Thruster Performance"; IEEE Transactions on Plasma Science, Vol. 36, No. 5, 2008, pp. 2167 – 2179.

[10] Schein, J., Qi, N., Binder, R., Krishnan, M., Polk, J., Ziemer, J. and Shotwell, R., "Vacuum Arc Thruster for Small Satellite Applications", NASA Report: NASA/CR-2001-211323, Dec. 2001.

[11] Schein, J. et al., *"Inductive Energy Storage Driven Vacuum Arc Thruster"*, Review of Scientific Instruments, Vol. 72, No 3. Feb. 2002, pp. 925 - 927.