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Development of a High-Performance Low-Cost PPU for an Electrospray Colloid Electric Propulsion System for Small Satellite applications

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Abstract

The current state-of-art Electric Propulsion (EP) systems can provide impressive system performance but are associated with both significant volume requirements and high direct cost. These technologies have not been shown to be capable of being effectively scaled down in size, whilst retaining system performance. As a result, such technologies are not an established solution for nano- and micro satellites, which represent a rapidly increasing share of the market due to the advent of large constellations.

Recognizing that the overall cost of an EP system is largely driven by the cost of the Power Processing Unit (PPU), a tailored low power, low cost and high performance PPU was designed targeting the CubeSat Market. By studying the periphery and interfaces, a straight-forward architecture was devised, containing 4 high voltage generators and 12 high voltage switches, all controlled by a microcontroller. The architecture is suited to drive two colloid thruster heads at opposite polarity, omitting the need of a neutralizer to keep the charge balance. The PPU is powered from a 5V and 12V power bus and communicates via I^2C.

The PPU is designed using low cost COTS (Commercial Of The Shelf) components, which were selected for high efficiency and high accuracy. To achieve high voltage accuracy, 4 calibrated, fine-tune regulation loops are implemented.

The high voltage switch needed in this architecture requires a breakdown voltage of > 6 kV and needs to carry 3mA of current. Transistors for such a switch with breakdown voltages in the range of 6 kV are not available on the market. SystematIC is developing a high voltage stackable integrated circuit to provide a solution for the 6kV switch and enable implementation of the PPU architecture.

During the bread board model testing we have verified that the maximum output power of a PPU with a volume of ¼ CubeSat cube is 20W. At full load the electrical efficiency of the overall PPU system is estimated to be about 80%. For an output power of 6W the overall efficiency drops to 66%. The high voltage fine-tune regulation can set the output voltage with an accuracy of 3 kV ± 5V. The high voltage switches have been verified to have a > 6 kV breakdown voltage and properly conduct 1 mA of current without significant voltage drop across the drain source voltage.

Our thruster technology opens the door for small CubeSats to fly new and exciting missions.

Acronyms/Abbreviations

ADC	Analog to Digital Converter
CTH	Colloid Thruster Head
COTS	Commercial Of The Shelf
DAC	Digital to Analog Converter
ECEPS	Electrospray Colloid Electric Propulsion System
EP	Electric Propulsion
EPS	Electric Power System
HiperLoc	High performance Low cost
IC	Integrated Circuit
OBC	On Board Computer
PPU	Power Processing Unit
PS&FS	Propellant Supply and Feed System
PWM	Pulse Width Modulation
TH	Thruster Head

1. Introduction

In response to the European Union's call for the development of market-disruptive electric propulsion technologies, a consortium was formed between Queen Mary University of London (QMUL), Airbus, Nanospace (NS) and SystematIC, which is developing such as system. The focus of the project is to develop a low-cost electric propulsion system which also achieves the high performance typified by conventional electric propulsion technologies. The project name, HiperLoc-EP, captures this essence, standing for High performance Low cost Electric Propulsion. In this project we are developing an innovative approach to electrospray colloid electric propulsion systems (ECEPS) with low cost as a critical design driver.

SystematIC is responsible for the design and development of the electronics needed for the ECEPS. The electrical subsystem, called the Power Processing Unit (PPU), will control the Colloid Thruster Head (CTH), the Propellant Supply and Feed System (PS&FS) and communicate with the On Board Computer (OBC). The time span of the HiperLoc project is 2 years and at the end of this period the PPU is integrated with the CTH and PS&FS to verify the thruster performance summarized below:

- high thruster efficiencies (50%)
- high specific impulse (>1000s)
- capable of providing about 500 m/s of DV for small CubeSat platforms

This paper presents the HiperLoc PPU design strategy and summarizes the most important design targets, explains major design decisions and presents measurement results of the PPU prototype.

2. Design strategy

The HiperLoc architecture design started with the analysis of its predecessor the FP7 Microthrust PPU design and test results [1], [2], followed by making a compilation of system requirements and key performance parameters in the HiperLoc proposal. The thruster grounding and charge neutrality were discussed with consortium partners QMUL and Airbus DS. The operation conditions and PPU peripheral subsystems are analysed leading to a more comprehensive list of requirements. Then a PPU architecture is proposed and broken down into several subsystems of which the feasibility is verified.

Then the full PPU system is designed, manufactured and tested.

3. Objectives

The HiperLoc-EP project targets TRL4. Table 1 summarized the key design targets for the PPU subsystem.

Table 1: Key design targets

PPU Key design target:	Value:	Unit
Conversion Efficiency @ 10W	> 70	%
Acceleration voltage	± 3	kV
Extraction voltage	± 2.1	kV
HV accuracy	± 5	V
HV ripple	10	V_{PP}
Volume	0.2	dm^3

4. PPU architecture

HiperLoc architecture design started with the analysis of the FP7 Microthrust PPU design and test results. The Microthrust PPU design showed strengths and weaknesses. The strength of the Microthrust PPU is found in the basic high voltage generation circuit, which has the potential to reach high conversion efficiency with only a small component count. The Microthrust PPU test results showed that the full efficiency potential of the high voltage conversion circuit was not reached. Within the HiperLoc project the efficiency of the high voltage generation circuit is given highest priority.

The weakness of the Microthrust PPU design is that large circuit parts are only used 50% of the time. Mass, volume and cost can shrink considerably if we could realize a system architecture in which we make full use of every circuit. In addition, the Microthrust PPU architecture is not compatible with the charge neutrality strategy selected in the new design philosophy.

To maximize the output of the HiperLoc project it was decided that the PPU architecture definition would start from a blank piece of paper, while taking the basic high voltage generation circuit and the charge neutrality principle into consideration.

4.1 Charge neutrality

Electrical propulsion generates thrust by accelerating charged particles into space that permanently leave the spacecraft. In colloid thrusters, when the supplied propellant (effectively the propellant tank) is at a negative potential, negative ions are propelled. This effectively charges the satellite relative to the ambient plasma, which is neutral and nominally at zero volts. To maintain the charge neutrality of the satellite a thruster head as discussed below for the ECEPS, contains two tanks, biased at opposite potentials. The positive tank propels positive ions and the negative tank propels negative ions. If both positive and negative ions are propelled in equal flux, the satellite maintains its neutral charge. The method used to equalize the positive and negative beams is described in [3].

While thrusting the positive ions are extracted from the positive tank and the negative ions are extracted from the negative tank. Consequently, both tanks are charging until the tank potential is so high that it is no longer possible to extract any ion from the tank even though there is still plenty of propellant mass available.

This issue is solved by implementing a switch matrix. Before the tanks are charged significantly the polarity is reversed, making sure that all available propellant mass can be propelled, and the tank charge is kept low.

During the reversal of the polarity both thrusters are kept in the off position, to ensure that the thruster only works in its designated operating point.

4.2 Driving the CTH

The colloid thruster head consists of two thrusters (TH1 & TH2) operating on opposite electrical potentials. The positive and negative thrusters are identical, see Figure 1. The extraction and acceleration of the ions are controlled by 3 high voltage electrodes called:

- Accelerator (ACC1 & ACC2)
- Extractor (EXT1 & EXT2)
- Propellant (TANK1 & TANK2)

The voltage between the TANK and the ACC electrodes is designed to accelerate the propelled mass and is typically ±3 kV. The voltage between the TANK and the EXT electrodes controls the propellant flow rate and beam composition and is typically ±2.1 kV.

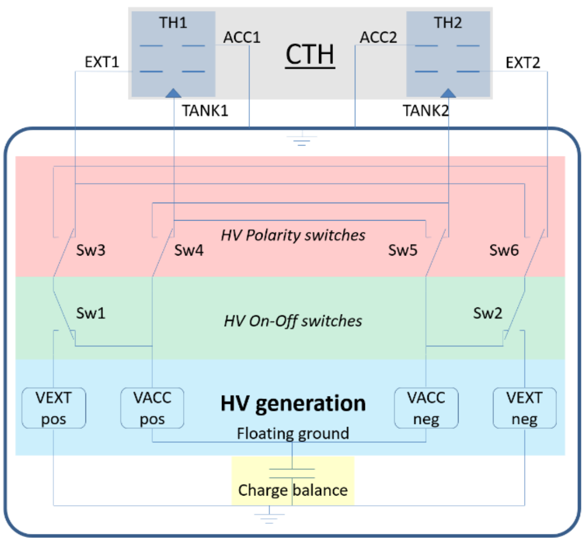

Fig. 1. Simple representation of the PPU architecture

4.2.1 CTH voltage generation

The CTH needs to be biased with a total of 4 high voltages, the extractor and accelerator voltage for positive thrust and the extractor and accelerator voltage for negative thrust. All four high voltage supplies in the PPU are based on the same circuit, depicted in Figure 2.

At the core of the high voltage generation is a Royer oscillator. The LC-resonance tank consists of the primary winding of the high voltage transformer and a low ESR ceramic capacitor. The oscillation frequency is tuned to operate the transformer in its most efficient region. At the secondary side of the transformer the high voltage is rectified. The output voltage and current are monitored by differential amplifiers. For accurate voltage regulation, the monitored output voltage is fed back to a regulation circuit that controls the amplitude of the Royer oscillation.

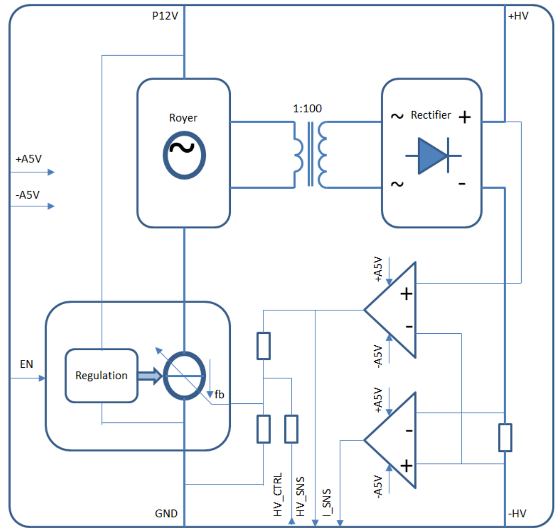

Fig. 2. High voltage generator

Regulating charge neutrality requires floating high voltage outputs with respect to the satellite ground. The high voltage and current monitors must therefore monitor differentially and refer the output to satellite ground. The monitored output voltage and current are readout by the ADC on the PPU microcontroller.

The microcontroller can fine-tune the high voltage output by controlling the voltage on the HV_CTRL input on the Royer circuit. See Figure 2.

4.2.2 High voltage fine tuning

The requirements for the accuracy and stability of the negative feedback regulation loop are very demanding. The inaccuracy of the high voltage (3 kV) must be better than ±5V, hence, it cannot be larger than 0.16%. This level of inaccuracy is not readily available by using DC-DC conversion ICs. These ICs have references with an inaccuracy of no better that ±1 % over the temperature range. To achieve the required accuracy, we need a dedicated reference IC with a specified inaccuracy over the full temperature range better than 0.16% and use it to monitor and control the high voltages. The voltage accuracy is needed for the control of the CTH. Therefore, the best location for accurate voltage monitoring is after the switch matrix.

The voltage after the switch matrix reverses polarity regularly and is therefore impractical for the use in an analogue negative feedback regulation loop. We can however measure all four of the high voltages at the CTH with a microcontroller and use it in combination with the polarity information to regulate to the required voltage. This process is rather slow and places stringent requirements on the microcontroller performance. Microcontroller hiccups and interrupt handling might disrupt the voltage regulation control and cause instability.

The HiperLoc PPU uses a combination of an analogue negative feedback regulation loop and a microcontroller fine-tuning principle. With readily available DC-DC conversion ICs it is possible to make accurate and stable DC output voltages with good line and load regulation performance. To improve the accuracy, we monitor the realized outputs at the CTH with a microcontroller and use a dedicated highly accurate reference IC to calculate the adjustment to fine tune the high voltages. The fine-tuning principle does not only improve the high voltage accuracy but also the precision as all accelerator and extractor voltages are referred to one and the same bandgap reference. The adjustment to the extractor voltages is implemented with a DAC and the adjustments to the accelerator voltages are by PWM control signals. Most microcontrollers contain DAC and PWM hardware periphery, this means that the microcontroller can write the desired value to the hardware peripheral in question and the peripheral handles the task autonomously, leaving the microcontroller free to carry out other tasks.

4.2.3 High voltage switch matrix

The high voltage switch matrix is responsible for periodically reversing the polarity on the thrusters to keep the tank charge low. It will also ensure that the thrusters are only firing when desired.

Figure 3 shows typical CTH waveforms. The voltages in the red waveform are connected to TH1 and the voltages in the blue waveform are connected to TH2. Note that the TANK and EXT electrodes are kept at the same potential while the polarity is reversed effectively preventing the CTH from firing.

4.2.4 High voltage switches

A switch in the switch matrix needs to be a small-sized, high-voltage, low-current transistor which is not available as a COTS component on the market at present. SystematIC decided to develop a high voltage switch in a high voltage IC technology and stack switches to increase the overall break down voltage to meet the requirement.

In an IC technology, electric components are made on a silicon substrate. For every IC technology the maximum node voltage with respect to the substrate is specified. The technology we are using to design the high voltage switch in, is the ultra-high voltage process XU035 of XFAB. This process specifies a breakdown voltage of 700V.

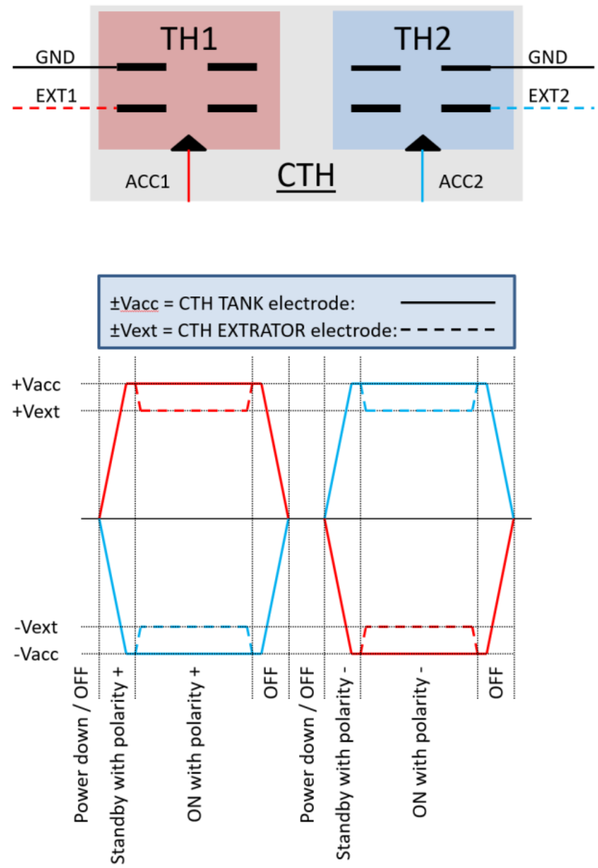

Fig. 3. CTH voltages

The breakdown requirement of the high voltage switch is 6kV, considering 80% derating the design needs to be able to handle voltages up to 7.5 kV. This breakdown voltage is achieved by stacking several high voltage chips.

4.3 Driving the Propellant supply and feed system (PS&FS)

The PS&FS consists of two identical, electrically isolated from each other, propellant tanks, one for each polarity. There is no high voltage connection between the tanks and the PPU. The high voltages on the CTH make an electrical connection to the tanks via the propellant liquid. The propellant liquid flows from the two liquid tanks in the PS&FS to the CTH via two isolation valves.

The thrust performance is dependent on the temperature of the propellant and is regulated to the proper temperature with tank heaters.

4.4 *Interface to the satellite platform*

The PPU is designed to interface directly to the most commonly used Electrical Power Systems (EPS) and On-Board Computer (OBC) on a CubeSat platform. A standard CubeSat EPS provides various regulated voltage buses. The most common voltage buses are the regulated 12V, 5V and 3V3 bus. Some smaller power EPSs provide the raw battery voltage instead of the regulated 12V bus. The HiperLoc PPU is designed to work well with both a battery as well as the regulated 12V voltage bus.

The battery and regulated 12V bus have overcurrent protections to protect the EPS against overloading. The PPU inrush current is designed to stay below the protection thresholds commonly found on CubeSat EPSs.

CubeSat OBCs provide various data buses like I2C, CAN, SPI and UART. The HiperLoc PPU communicates via the I2C data bus as it is the most commonly used data bus in small satellites. It is anticipated the future thrusters are going to be equipped with the CAN data bus as well as I2C.

5. PPU measurement results

The measurement results presented in this paper are obtained with a standalone PPU in air. See Figure 6. The CTH is modelled by 2 load resistors and 4 load capacitors.

5.1 *Conversion efficiency*

The complete PPU subsystem includes two accelerator voltage generators set to ± 3 kV and two extractor voltage generators set to ± 2.3 kV. Figure 4 shows the overall power efficiency vs output power plot of the PPU subsystem in which all power is delivered by the two accelerator generators.

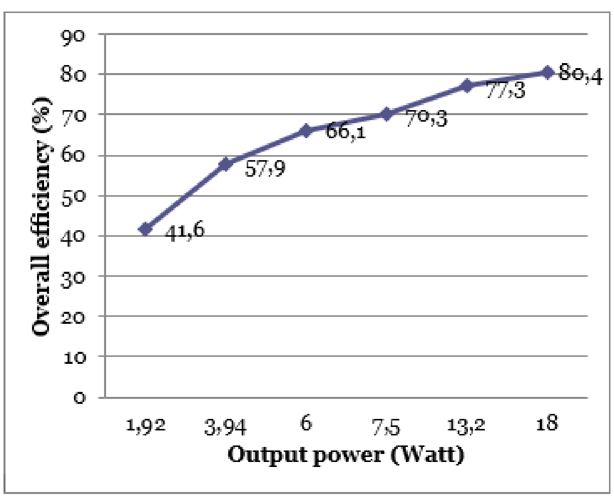

Fig. 4. Efficiency vs output power

Figure 4 shows that the efficiency at 10W is 74%.

5.2 *High voltage accuracy*

The acceleration and extraction voltages can be programmed by the PPU microcontroller between 1.8kV to 3kV. After calibration, the high voltage accuracy at room temperature is better than ± 3V. The high voltage output ripple measurement shows 7.2 V_{PP}. These measurements were carried out with all 4 high voltage generators enabled simultaneously.

5.3 *CTH voltage waveforms in thrust mode*

The required CTH voltage waveforms in thrust mode are explained in paragraph 4.2 and shown in figure 3. In the following measurement the complete HiperLoc PPU BBM depicted in figure 6 is commanded by an OBC to thrust 6W into two resistive dummy loads. Figure 5 shows the scope plot with the following traces:

- positive accelerator voltage(red)
- positive extractor voltage (purple)
- negative accelerator voltage (blue)
- negative extractor voltage (green)

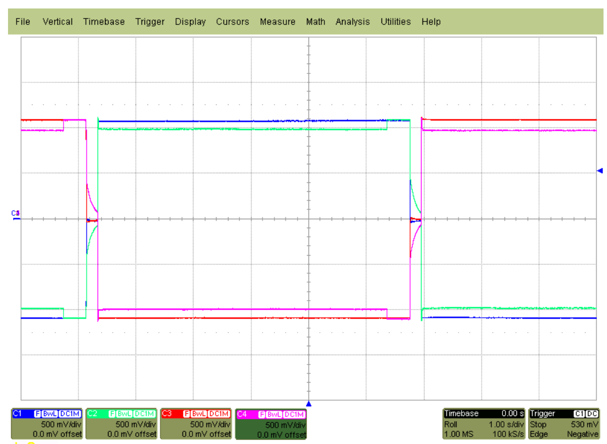

Fig. 5. CTH voltage waveforms in thrust mode

The probes of the oscilloscope have an attenuation of 2000x. The scale of the plot is 1kV/div.

The stages the switch matrix is going through while reversing polarity are: "OFF", "Standby with polarity" and "ON with polarity".

The CTH voltages programmed for this measurement are less than the specified ±3 kV for acceleration and ±2.1 kV for extraction. The reason for this is that the spacing between high voltage lines on the switch matrix prototype PCB is insufficient. Patching the spacing errors with Kapton tape allowed us to verify the proper behaviour of the high voltage switches in the matrix. A redesign of the switch matrix PCB has been made and the new boards are in fabrication at the moment of writing.

6. Conclusions

The HiperLoc PPU is designed to be a high performance low cost solution for nano- and micro satellites with propulsion requirements.

The high performance of the HiperLoc PPU is reflected in the conversion efficiency number as well as the CTH voltage accuracy. The CTH designers can individually program the 4 CTH voltages with a resolution of 1 V. This and the thermal control of the propellant tanks allow them to find the best possible operation point and tailor the HiperLoc thruster according to the targeted thruster specifications.

The dedicated high voltage switches in the switch matrix have shown to be on specification in a typical 6W thrust measurement.

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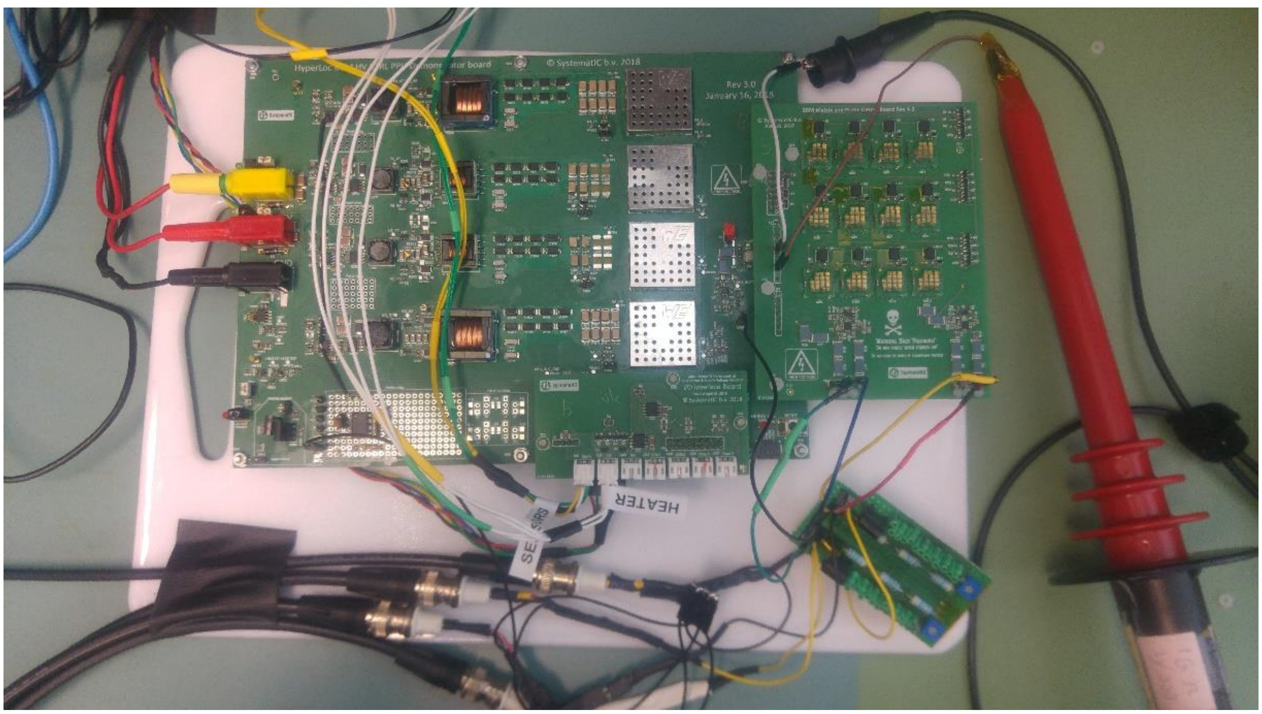

Fig. 6. HiperLoc PPU BBM