ICEPS: Compact, all-purpose, USB 2.0 based small satellite system core

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Abstract

ICEPS (Irvine-Class Electrical Power Supply) is the system core that EXA designed for the 1U IRVINE-03 satellite, currently in construction and in the late stages of development for the Irvine Cubesat STEM Program under a 12-year plan to provide satellite parts. It was designed based on Ecuador's first satellite NEE-01 PEGASUS's PCEPS launched in 2013, and its newer counterpart has modernized capabilities including an EPIQ Z2 Sidekick OBC (On-Board Computer) running Linux IIOS, 2 SDRs (Software Defined Radio) with a frequency range from 70 MHz to 6 GHz being able to adapt to any communications network or application, 512GB of storage, 50 W power delivery up to 100W peak power for 2.5 seconds and able to operate in temperatures between -50 C and +125 C. It has an IMU (Inertial Measurement Unit) with a 6-axis Motion Tracking Device for ADCS precise operations, includes 4 UMPPT channels, each one with 16 V @ 2 A and with a total of 20 internal sensors for data collection and system monitoring purposes. It has been designed to be on the cutting edge of modern mission requirements, with a total height of 25 mm and a total mass of 100 grams in a single board. The native architecture of the entire digital system is USB 2.0. Due to the high mission requirements of IRVINE-03, this enables the use of more modern devices and components, with a much faster data transfer rate than traditional cubesat digital systems. The system core includes the capability to mount a 2W communication laser with a speed of 10Mbps and supports a 5W laser at 100 Mbps, which enables cubesats to perform previously unattainable communication goals and data download requirements, previously impeded by slow data download rates. Its first technological readiness test will be IRVINE-03, and has become the default system core of all the next IRVINE cubesat missions. In addition, ICEPS will also be used in the upcoming Spacebit's Asagumo robotic walker, as a payload on Astrobotic's Peregrine lunar lander on 2021. This paper will describe all the features and characteristics of ICEPS, along with all electrical and dimensional specifications, as well as its potential for expansion and improvement.

1. BACKGROUND (PCEPS) (IRVINE)

In 2011, the NEE-01 Pegasus was officially presented and was launched on April 25, 2013. The technology for this satellite was built and developed completely by the Ecuadorian Space Agency, this included a power core named “PEGASUS CLASS ELECTRICAL POWER SUPPLY”, henceforth the name PCEPS. The Power Supply was successfully tested in space and worked as expected. At that time the power delivery was 100 W and the battery bank on board was able to deliver up to 104 W.

In 2015 EXA was contacted by the Irvine Cubesat STEM Program (ICSP) to work together in a 12-year project meant to send a total of 12 cubesats on various student-training missions. For the first mission, EXA provided solar panels and batteries. Due to the very high-power gain of the solar panels and the large battery capacity, not all the entirety of the available power was properly managed and delivered. The solution to this problem lay within the power supply, which was originally developed for a satellite with similar power demands. This power supply was actually used for the IRVINE-01 and IRVINE-02 mission, but for IRVINE-03 a new and modernized version of PCEPS was then completely redesigned and upgraded for that mission. It is also used for all the other following missions into what now is called ICEPS standing for “IRVINE CLASS ELECTRICAL POWER SUPPLY”.

2. DESIGN

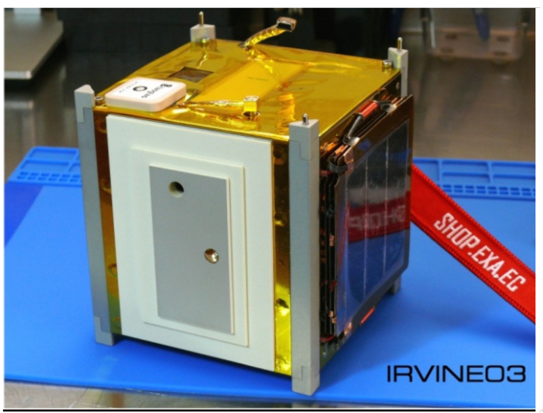


Fig. 2.1.1.- Fully built final model of IRVINE-03 CubeSat

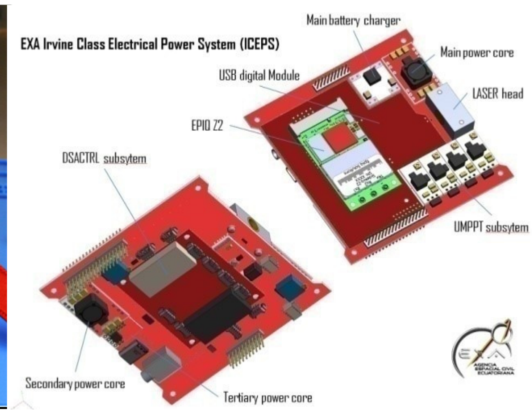


Fig. 2.1.2.- ICEPS components schematic

2.1 USB architecture

In general, the standard protocols for nearly every CubeSat have been I2C or SPI for some time now, and while those are sufficient for normal applications that do not need a high bandwidth data transfer rate, due to the nature of the IRVINE-03 (*see figure 2.1.1*) mission, said protocols cannot handle the payload data generation rate. A bottleneck forms between the payload and the high-speed communications laser (*see section 2.3*) if using I2C protocol. By incorporating USB 2.0, not only is this protocol compatible with modern payloads and protocols, but it is also able to handle substantially higher data rates internal to the spacecraft, through use of an integrated USB hub.

This USB hub has 14 ports. Not all of them are available for use because 6 of them are used by ICEPS devices themselves, which means 8 ports are available for external use. For example, one of these internal USB ports enables the use of a DSA-CTRL daughter card mounted directly on ICEPS, which can manage up to 6 actuation ports (*see section 2.7*).

ICEPS has a standard USB-C connector on the side of the board to externally connect, access, and program the Epiq Z2 OBC directly from a normal computer USB port. However, it is important to note that this USB-C connector is backwards compatible and normally uses USB 2.0 protocol.

2.1.1 USB bus resilience against radiation

Some of the concerns about using USB bus technology in space applications arises from the radiation environment in LEO. To mitigate the impact of SLEs and SSEs in the OBC and other sensitive components, specially due the high speed of them, the ICEPS board is encased between 2 BA01/S battery packs, this batteries made by EXA have excellent radiation shielding properties and act as radiation attenuators, effectively shielding the ICEPS board with 14 millimeters of low electron number masses (7 mm on each side) and the second radiation protection is the SEAM/NEMEA [2] shielding MLI that protects all the sides of the cubesat.

The Space Environment Attenuation MLI (NEMEA) is an MLI of 27 layers that has spaceflight heritage since 2013 and has been demonstrated very effective in regulating temperature and plasma environments, but most importantly in this case are its radiation shielding properties, which can greatly block or attenuate Alpha, Beta, X-ray, Gamma and neutrons.

2.2 Solar charge using Unified Maximum Power Point Tracking

The power generation architecture of IRVINE-03 includes 2 Deployable Solar Arrays (DSA), each one with two nanomorphodynamic actuator sets [3], these DSAs have two sides and each one is equipped with solar cells, hence the need of four UMPPT channels, in order to harness as much power as possible without sacrificing the other partially lit side. The UMPPT bus to which the channels are connected feed the charging circuit to which the battery arrays are directly connected, and at 50W of onboard power this also creates the need to handle all this power input using several power cores. (*see section 2.4*)

2.3 Laser Communications Module

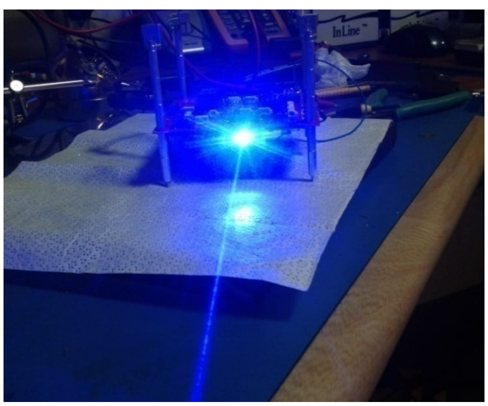


Fig. 2.3.1.- PLM-02 module mounted on IRVINE-03

The ground station used to receive signal and payload data only has line of sight and contact with IRVINE-03 for approximately 10 to 15 minutes. This situation is similar for all CubeSats in LEO and creates the problem of downloading large amounts of data in a potentially unachievable short time, this creates a bottleneck in payload missions and it is potentially solved through the use of laser communications because these modules have higher data transfer rates that can handle large payload data sizes and can potentially achieve downloads in 10 to 15 minutes.

In case that the payload generates even larger amounts of data this excess can be stored in the local storage card which has a minimum size of 256 Gb and a maximum of 512 Gb, reducing the bottleneck mentioned earlier.

The frequency of the communications laser is 450nm or 405nm, this result in a visible deep blue laser (*see figure 2.3.1*). While the atmospheric extinction rate for this frequency is higher than traditional lasercomm frequencies, the energy level per photon and the intensity of the emitter is much higher while the accuracy is lower. The laser has an intensity of 2W and a nominal beam aperture of 20 degrees. This is a CubeSat friendly solution since highly accurate pointing equipment is bulky and expensive and this approach is the reverse situation, brute-forcing power instead of brute-forcing accuracy. [4]

The laser module in ICEPS is called PLM02 (Pulsed Laser Module 02), operating at a maximum data rate of 10Gbps, which is the second generation of PLM01. This initial laser module (PLM01) was installed and tested in IRVINE02 launched in 2018 on board a SpaceX Falcon 9.

In order to test PLM02 and ensure that the expected frequency meets actual hardware capabilities, we first tested the intensity of this laser module using a Hyperion Argentum laser power meter. The laser was tested before the beam aperture was modified to a larger angle in order to make the beam fully hit the intensity sensor. It should be noted that during integrated testing, any flammable materials such as white paper or foam had to be removed because during initial standalone tests of the laser, misfiring could cause a small portion of these materials to burn. This is not the case while the laser is calibrated to larger beam apertures. The intensity readings are displayed below in Fig 2.3.3.

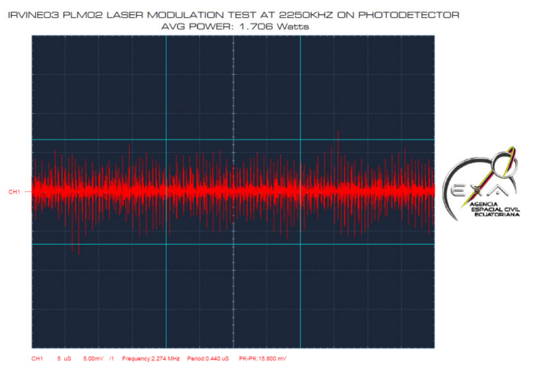


Figure 2.3.2.- Laser modulation of 2.25Mbhz observed at 1.7W

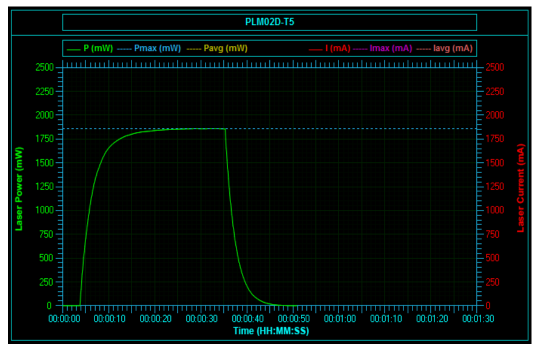


Figure 2.3.3.- Power plot of figure 2.3.2 captured while modulating at 1.7W

Next, the laser was calibrated to the requested beam aperture of 20 degrees. In order to test that the correct aperture is actually in the engineering model, we measured the distance to the aligned test matrix, and using the formula in Fig. 2.3.3, we estimated the footprint diameter that corresponded to the aforementioned beam aperture. The lens was adjusted until said value was achieved.

$$\alpha = 180 - 2\left(\tan^{-1}\frac{x}{f/2}\right)$$

Figure 2.3.4.- Experimental beam aperture calculus based on physical data

Where α is the beam aperture, is the distance to the test matrix and is the footprint diameter.

2.4 Power Supply

There are many features integrated in this hardware due to the fact that the power supply circuitry does not occupy too much space in the board, however, the core function of ICEPS is the power supply itself. ICEPS has several power rails including one 5V@3A, one adjustable 12V@3A rail, two redundant 3V3@3.6A rails, one unregulated 4.2~3.6@12A rail and one auxiliary APU port.

This represents an advantage because CubeSats systems can have low power inputs and high-power inputs for flexible hardware requirements. Some of these rails are adjustable which means that any payload or system with a particular power requirement would have no problem using ICEPS. The board uses a standard PC104 connector bus architecture for ease of integration with other boards.

2.5 Epiq Sidekick Z2 OBC

During the IRVINE-03 design process the need arose to use an EPIQ Z2 Sidekick because it is a flexible, programmable and highly customizable digital platform. It runs Linux IIOS which is known across the programming industry as a preferred operating system that is easy to work with and it also includes a watchdog device. (*see figure 2.5.1*)

2.6 Software Defined Radio

The EPIQ Z2 includes 2 receivers and 1 transceiver, all of them SDR (Software Defined Radio). This means that a CubeSat can connect to any communications network operating between 70 MHz and 6 GHz by defining the frequencies as a variable function within the OBC. This opens up many possibilities such as relaying signals through the CubeSat or establishing small CubeSat swarms operated in orbit. This also means that there is no need to use a dedicated radio or communications card since it is all integrated within ICEPS and it is only required to connect the actual antenna.

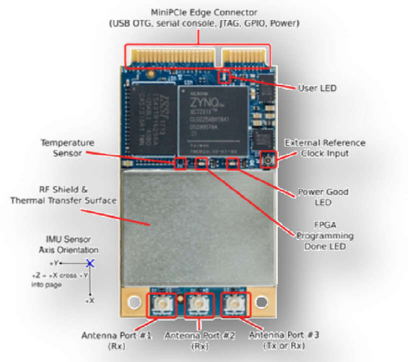


Figure 2.5.1 The Epiq Z2 OBC

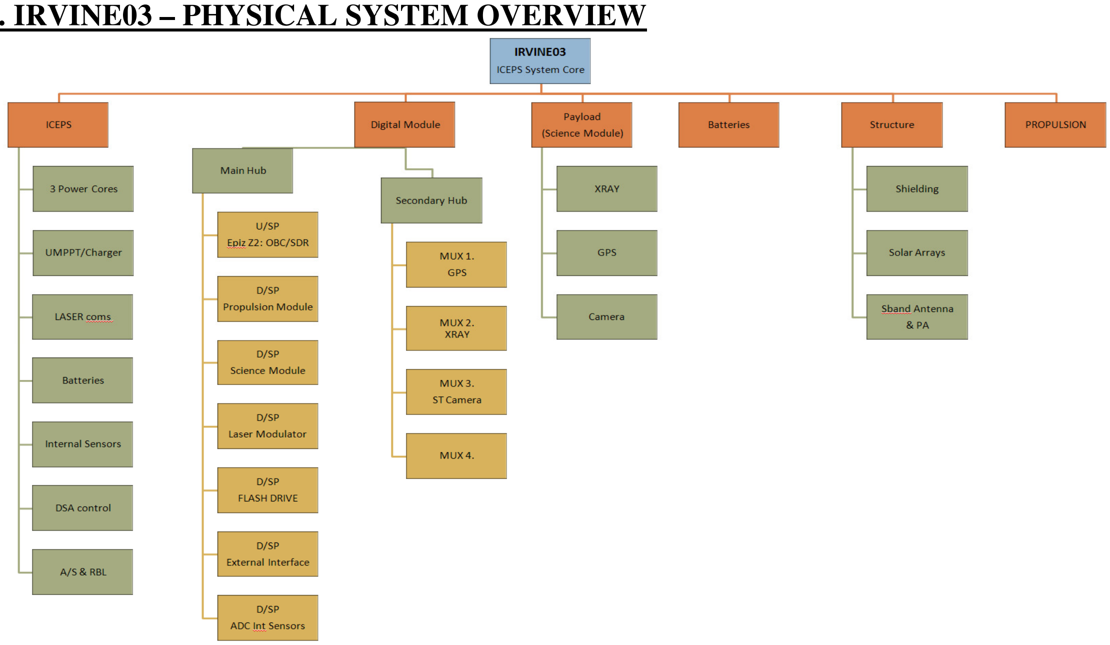
2.7 DSA Deployment Control

The DSACTRL (Deployable Solar Array Control) card is a daughterboard mounted on the back of ICEPS that serves as an actuator control hub. Commands are relayed from the OBC into the respective ports. Although IRVINE-03's two DSA panels use only four, there are two extra channels for redundancy, with a total of 6. This means that a CubeSat may operate actuator systems or any other mechanical operations through ICEPS' own circuitry.

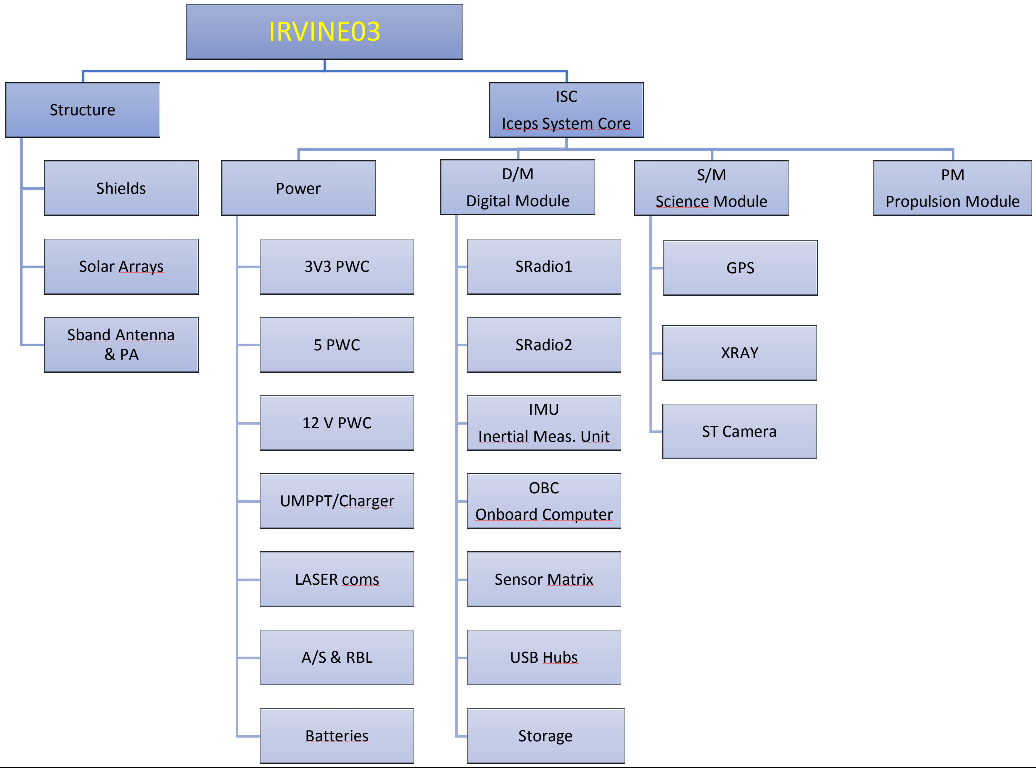
2.8 Sensors and actuators

The board has 20 sensor slots incorporated into the board's capabilities, available for any kind of telemetry and internal data gathering. One of these slots are used for measuring the board's temperature for example, but other kinds of sensors can also be used. The DSAs have mechanical sensors to indicate and signal deploy/release operation, this sensor inputs are basically a voltage that is tied into 2 ADC to I2C chips, who are tied into a I2C to USB controller forming and internal network that can be expanded up to 32 slots. The actuators are slots into the same network that receive a TTL signal to activate devices like the antenna power amplifier or the DSACTRL activation signal.

3. IRVINE03 – PHYSICAL SYSTEM OVERVIEW



3.1 IRVINE03 – FUNCTIONAL SYSTEM OVERVIEW



4. SYSTEM DESCRIPTION TABLE:

Bus type:	USB 2.0
OBC:	Xilinx Zynq XC7Z010-2I System-on-Chip: Programmable Logic (PL) Specification: -28K Logic Cells -2.1 Mbits Block RAM -80 DSP slices Processor System (PS) Specification: -Dual-core ARM Cortex A9 CPU running up to 733 MHz -Linux 4.11 • 512 MB of DDR3L RAM • 32 MB of QSPI flash storage for uboot boot loader, Linux kernel, and root file system Temperature Sensor: TMP103AYFFR Accuracy: -40 deg C to +125 deg C (+/- 1 deg C typ), Resolution: 1 deg C
OBC/OS:	Linux computer running IIOS
Radio:	SDR from 70Mhz to 6GHz
EIRP	28.5 dBm integrated LNB
Sensitivity:	-110 dBm
Antenna ports:	2 RX and 1 Transceiver (TX/RX)
System Storage	256 or 512 Gigabytes
Number of ports:	14 total: 8 external, 6 internal; USB2.0 60MB/s r/w
High Speed Laser communications	400nm or 450 nm solid state laser, temperature stabilized, 10 Mbps, variable beam aperture, variable focus. Integrated temperature sensor range -50C to +125C
Power rails:	5V@3A; 12V@3A(adjustable), 3v3@3.6A(2 redundant); 4.2 ~ 3.6 (unregulated) @ 12A ; 1 auxiliary APU port
Battery packs	One or two at 3.7@6A, 50W nominal

Power delivery	50W Nominal (continuously) , 65W Maximum, 100W peak for 2.5 sec.
Solar mgmt:	4 UMPPT channels 16V@2A max each
Solar charger:	Based on TP5100 2A continuously, 1S, 2S,3S
Internal sensors:	20 internal sensors; integrated IMU
Actuators:	Integrated automatic management of Release/deploy mechanisms ; integrated automatic LNB/PA switching
Built in protection	RBL; 10A Activation switch w/ MTBF>1000, 2A and 7A resettable fuses
Inertial Measurement Unit:	6-axis Motion Tracking Device: (3-axis gyroscope, 3-axis accelerometer) TDK / InvenSense ICM-20602 - Gyroscope sensitivity error: ±1% - Gyroscope noise: ±4 mdps/√Hz - Accelerometer noise: 100 µg/g/√Hz
Mass	100 grams
Operating temp.	-50C to +125C
Dimensions	96x96x25mm – PC104

ICEPS has been in constant development since 2017, with constant additions and new features added in. Slowly but steadily, it evolved from being purely a power supply to a CubeSat system core. Only recently, in 2019, the first construction and testing of ICEPS started.

5. IN-ORBIT DEMONSTRATION AND FUTURE DEVELOPMENT

Currently, we estimate that ICEPS (*see figure 5.1*) can handle power for up a 6U CubeSat, if fitted with two dual-stack battery banks as the EXA's BA01/D it could handle up to 200W of power in full configuration. With that in mind, this board is the first completed iteration of a modernized power core and its internal circuitry has much room for improvement and fine tuning. Its constituting components can also be improved and optimized to use less space and handle more power, which could make room for more USB ports and larger Laser modules. Because of deadline and mission constraints, ICEPS has not been improved much further than needed.

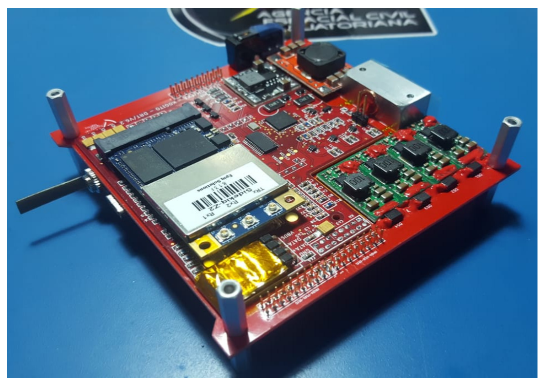


Fig. 5.1.- Fully assembled ICEPS board

The next planned iteration of ICEPS is *TITAN*. Theoretically, it could power a 24U CubeSat in a single, slightly thicker board along with 8 dual battery banks reaching 500W. The function of this board would be the same as ICEPS: A system core that can route power and data inputs and outputs, and include many features that would otherwise require their own card in order to save space and optimize missions.

ICEPS will make its maiden voyage onboard IRVINE03 in Q1/Q2 on an ELaNA launch slot, but other projects are right now considering using ICEPS from many other countries, one of them is the Spacebit (UK) lunar mission[5] to the surface of the moon in 2021, ICEPS will be used onboard ASAGUMO (*see figure 5.1*), a 1U cubesat walker using EXA's IRV03 Spacecraft bus which includes ICEPS and a heavier version of the NEMEA shielding.

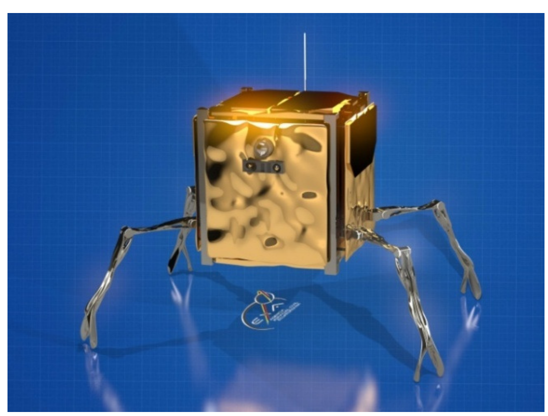


Fig. 5.2.- Early design of QB-Walker ASAGUMO

6. CONCLUSIONS

At the time of writing of this manuscript, ICEPS is the only known satellite system core completely based on USB 2.0 protocol and technology, as well as one of the few system cores (all-in-one) designed for cubesats from 1U to 24U. The main rationale behind the ICEPS design is to take the cubesat community beyond the limitations of the I2C, SPI and CAN-bus protocols, which, while tried and true, are falling behind the computational needs of today's missions. Capabilities such as high throughput, high capacity storage or high speed laser communications are hampered or impossible using said protocols. USB enables cubesats to interface with the millions of devices on the ground that have long since standardized to it.

There are new classes of instruments, sensors and a community of hardware suppliers that suddenly open up to space (from the perspective of the cubesat). While there is always some software configuration or mechanical need to ruggedize non-aerospace hardware, USB bridges the communications and power gap relatively seamlessly as compared to the older protocols or ad-hoc connections that served only a single mission before. With best practices applied to securing cables, standard EMI and related shielding can be applied around many "new" devices, enabling more features per mission in space. This approach takes advantage of the enormous amount of engineering that went into terrestrial USB peripheral devices, making them available to the space industry at lower cost than independently developing such a wide range of hardware.

7. REFERENCES

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