CompanionCube

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Mission Statement

CompanionCube is designed to support deep space missions. It can orbit and take pictures of deep space spacecraft during events of interest. Support by monitoring large spacecraft (visual from outside), manual or automated control.

Mission Keywords

Deep space exploration, low magnetic field strength, vacuum, gyro.

Design Principles

The CompanionCube is a standardized picosatellite, based on the CubeSat layout. A basic CubeSat unit consists of a 10 cm cube with a mass of up to 1.33 kg, 1U. During launch stages, the CubeSats are into so-called P-PODs, each P-POD holds three units (1U).

A CubeSat is divided into subsystems. Depending on the mission, these subsystems will be different, but every CubeSat has to have at minimum the following subsystems:

- Structure system; the purpose is to maintain the integrity of the CubeSat with a mass optimization to support loads of up to 10 G's and provide easy access to all other subsystems.
- Power subsystem; the purpose is to produce, store, manage and distribute power to the systems that need it.
- Telemetry and communication subsystem; the main objective is to transmit the data from the onboard stored data to the ground station or nearest spacecraft as well as a communication link with the host spacecraft for control issues.
- Payload; in the case of the CompanionCube it contains a camera to observe other spacecraft.

Design Requirements

1. Mass shall be less than 1.33kg.
2. Satellite shall be 10(cm) x 10(cm) x 10(cm) in size.
3. CompanionCube shall have a propulsion system to orbit the spacecraft.
4. CompanionCube shall have a camera to observe spacecraft.
5. CompanionCube shall have a docking system for connecting with spacecraft for refueling or recharging.
6. CompanionCube shall work autonomously for at least 45 hours.

Materials and Structure

The designed structure meets the following requirements:

Requirement	Description

Fabrication method	An aluminum frame with six aluminum or composite sheets fastened together
Material	Aluminum 7076 or 6061
Weight	1.2 kg
Additional characteristics	Structure shall contain frame in the center to hold flying wheel unit

Hardware Assumptions

- iESP is fully developed and ready to use.
- Sufficiently low flywheel bearing friction, so that dissipated mechanical energy does not cause system to overheat.
- Constituent materials withstand thermal fluctuations.
- Thermal expansion does not interfere with cube rotating mechanism or flywheel operation.

Components Layout

Subsystems:

- Propulsion subsystem. Contains ion thruster. (20% of volume)
- Attitude control subsystem. Contains reaction weel, accelerometers. (12.5% of volume)
- Power subsystem. Contains battery, inductive copper wires. (30% of volume)
- Thermal control subsystem (4% of volume)
- Communication and telemetry subsystem. Contains communication board, antennas, onboard computer (22% of volume)
- Payload. Contains Camera (15% of volume)

Picture below shows component layout of satellite.

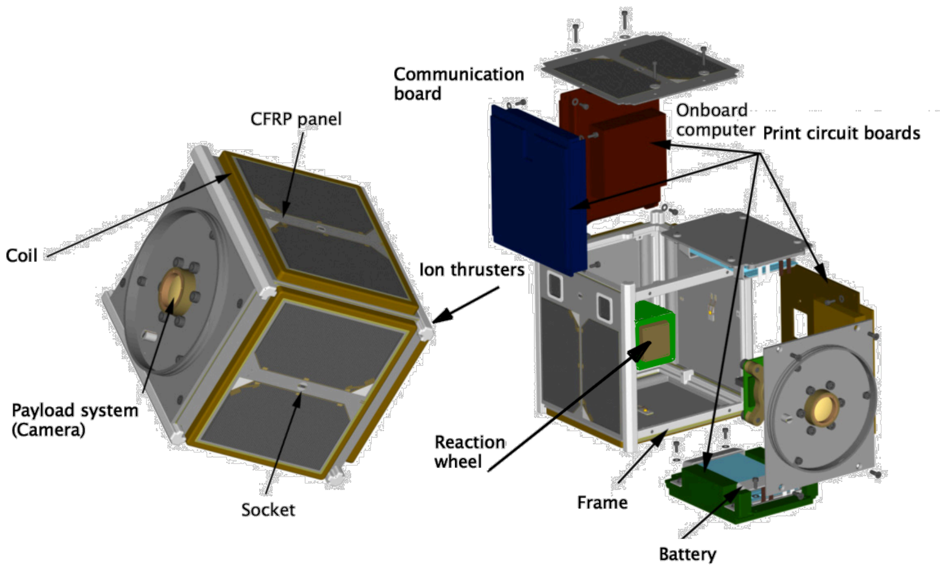

Fig. 1. CubeSat subsystems layout. Unmodified source: http://www.davidreneke.com/wp-content/uploads/2012/06/inside.jpeg

Propulsion

An essential part of CompanionCube is its propulsion and stabilization capabilities. We took the following options into consideration, and subsequent sections further expand on our design considerations.

- Thrust: Rocket engines, compressed cold gas propulsion, ion thrusters.
- Rotation: Magnetorquers, flywheels.

Thrust Subsystem

A rocket engine is generally a bulky system and becomes feasible on larger satellites (e.g. Rockedyne engines for CubeSats: https://www.rocket.com/cubesat). At this large scale, it offers a Δv on the order of 1000 m/s for a 1U CubeSat. In order to increase this value, refueling at the spacecraft is the typical approach, but would complicate the docking procedure and would require the spacecraft to carry the refueling infrastructure as well as the propellant itself.

Directional release of compressed gas puts similar constraints on the docking and refueling. The size and complexity of the engine can be reduced significantly compared to those of rocket engines, but at the cost of lower exhaust velocities and therefore a lower total Δv.

Ion thrusters are still in development, but are widely regarded as a viable near-future option for cube satellites. The use of electricity for acceleration of the ions to effective exhaust speeds between 10 and 100 km/s allows for operation with less fuel consumption compared to rocket engines.

The ion Electrospray Propulsion System (iEPS) project at MIT proposes thrusters which, according to current estimates, can produce a force of 0.5 N / m^2 . One iEPS module has the size of 12x12mm^2. Covering a side panel of a 1U CubeSat therefore produces a thrust of approx. 5mN, corresponding to an acceleration of 5 mm/s^2 for the CompanionCube. This value is quite low, but on the other hand allows for very precise control of velocity as well as slow, smooth drift maneuvers past the spacecraft. A great benefit of this method is its achievable Δv, which surpasses 10000m/s with only 150g of propellant. According to MIT estimates, this kind of propulsion system would make up around 20% of the volume of a 1U CubeSat. Our choice for thrust therefore is the iEPS.

Stabilization System

Additionally, a system to control the thrust vector and orientation of the satellite needs to be implemented. At the most basic level, this is possible by selectively activating modules of the ion thruster to establish a torque on the CubeSat. A disadvantage of this method is the continuous fuel usage for simple rotations in order to capture different areas with the imaging system, in addition to limited maneuverability in the first place. Therefore, a torque-exerting system is highly desirable.

Magnetorquers use existing magnetic fields to apply torque to a structure by generating opposing magnetic fields of its own. This is a very promising approach, because it removes the requirement of moving parts inside the cube. A constraint is the existence of any external, homogeneous magnetic field. Homogeneity can be disturbed by nearby materials and electric currents. In addition, rotation requires the magnetic field strength to be sufficiently large. This is no issue for earth-orbiting satellites, when only minimal adjustment is required. On the other hand, when quick rotation is desired, a much stronger magnetic field is needed. Therefore, celestial body magnetic fields may be insufficient, or practically nonexistent, when exploring deep space.

Another option would be to artificially generate a magnetic field on the spacecraft itself, but this would require constant current, which consumes considerable amounts of energy. Additionally, strong local magnetic fields might damage other components onboard the cube.

Our stabilization system of choice is flywheels. When set into motion, these rotating discs or rings have a high angular stability in space. Due to conservation of angular momentum, when torque is applied perpendicularly to their axis of rotation, a resulting force tilts the axis of rotation into the third direction. The resulting motion of the flywheel can be described as some kind of precession along its rotational axis. The higher its angular momentum is, the smaller the observed precession becomes.

Using this idea, one can create a reference coordinate system in space, which stays fixed once the flywheels have been set into motion. Using 2 or 3 flywheels fixes the system against any kind of rotation – assuming the exerted torque is sufficiently small. These flywheels are at the heart of our CamSat. They are placed in a gimbal, as illustrated in the CAD drawing, to allow arbitrary rotations of the CamSat using stepper motors, which are located in the two joints of the gimbal.

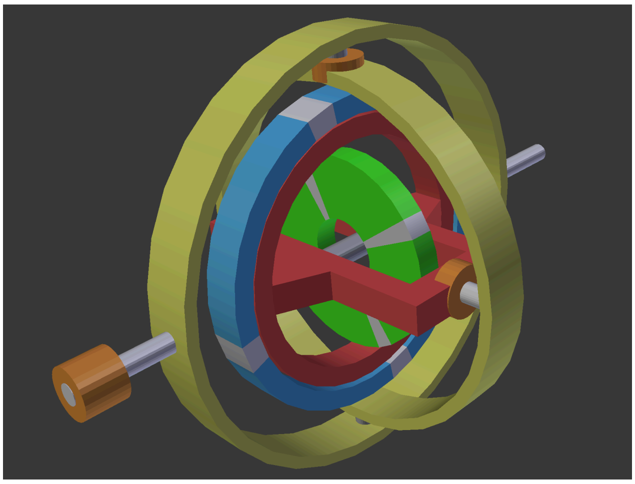

Fig. 2. CAD model of flywheel within gimbal.

Existing flywheel systems do not use the gimbal and intersecting revolute rings, which have the advantage of fewer moving parts. On the other hand, their system results in larger occupied volumes. We decided to use this design to allow accommodation in a 1U cube. In case the cube encounters any sort of unexpected external torque, the cube exterior can adjust (rotate), without taking considerable damage. This is not true for a system without a gimbal, where the flywheels have to change velocity to rotate the cube – a sudden shock may significantly damage the system because the flywheels would be forced to change orientation. Being able to rotate freely around a fixed point in space allows the thrust to be directed in an optimal direction, which is also true for the camera positions.

In the docked state the flywheels are at rest. Just before launch, they are spun up to their target rotational speeds onboard the primary spacecraft. This exerts a torque on the entire spacecraft. Placing flywheels on the spacecraft aligned with the cube flywheel in the satellite, and spinning them in the opposite direction to maintain zero net angular momentum can counteract this torque. Then, the satellite detaches and can use its fixed reference. This launch is also facilitated by the stabilizing effect of the flywheels. If, for some reason, a significant torque is applied during the detachment, it will only affect the outer layer of the cube, and the core will not begin rotating. Thus, it will be straightforward to realign the thrust vector and perform corrective maneuvers. A satellite without this kind of stabilization will have more trouble regaining control, might drift away too far, or become lost in space.

After docking with the spacecraft, the flywheels will be slowed to a halt and their energy recuperated by using the gimbal motors as generators. This step is not necessary but is interesting in order to prevent constant energy loss due to continuous friction in the flywheel bearings.

Friction in the bearings should also be considered during CamSat operation – the motors used for accelerating the flywheel need to supply the flywheels with the energy lost due to friction. Otherwise the CamSat core will slowly start to spin and precess, resulting in less controlled behavior as well as mechanical stress on the core structure.

Power Subsystem

While designing power system for CompanionCube, the recharging process shall be taken into account. According to the requirements, the CompanionCube shall work autonomously for at least 45 hours. To illustrate this performance, a power consumption calculation was conducted. The table below shows energy consumption of all electrical parts of the satellite.

	Power Consumption
Propulsion system	720 mW

Camera		360 mW
Onboard computer		200 mW
Communication board	Transm. mode	1700 mW
	Reciev. mode	200 mW
Reaction wheel		500 mW
Accelerometer + gyroscope positioning system		400 mW
Total power consumption		3180 mW

Table 1. Power consumption calculation.

For the communication board we can assume that it works in recieve mode most of the time. It switches to transmit mode in order to send images to host spacecraft. Thus average power consumption of communication board can be considered as 200mW.

For the calculation of the battery capacity, the maximal power consumption has been assumed:

$$P_{battery} = Time \cdot P_{consumption} = 50(h) \cdot 3.180(W) \approx 160Wh$$

According to requirements, the satellite shall be charged on the host spacecraft. As ion thrusters panel was chosen as propulsion system, the CompanionCube shall be charged with electric power. Thus wireless inductive charging from the spacecraft using the QI protocol was selected. Typically, wireless charging uses a magnetic field between two coils to transfer the energy from one system to the other, which is also known as resonant inductive coupling. The energy is transferred from the energy source to the receiver, where it is typically used to charge the battery in the device. The system is essentially a flat form of a transformer - flat because this makes it easier to fit into the equipment in which it is to be used.

The picture below shows charging process with a coil on each side, although one is already sufficient.

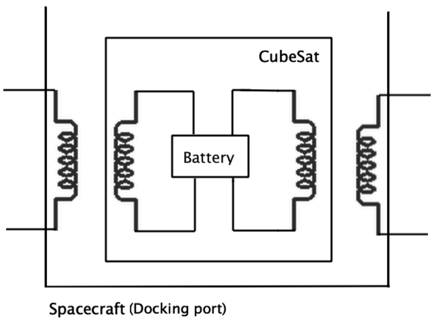

Fig. 3. Recharging process.

There are two inductive copper wires inside the docking port on the host spacecraft. After landing in the docking port, alternating current is applied to the coil of the spacecraft and the energy transfer begins, the battery starts charging. After signaling a fully charged status, the transfer is stopped.

General properties of the transmission system:

- Frequency: 110 – 205kHz
- Transmitted power up to 120 W
- Maximum distance between inductive wires is 8 cm
- Power consumption on heating is 30%

This method gives several advantages:

- no need to constantly plug and unplug satellite connectors.
- no need to use a precise docking mechanism.

And disadvantages:

- losses in board of satellite on heating(not more than 20%)
- longer charging process (charging speed is at the order of 50W/h)

According to calculations, charging will take 4 hours.

Thermal Control Subsystem

Thermal control is important for any satellite, in a small volume we need to integrate many subsystems that must be kept in operative range. Due to space and energy constraints we try to limit the implementation of active control systems such as heaters. Instead we use passive systems like surface finishes, radiators and heat pipes. While in space, satellites are exposed to harsh conditions that can lead to catastrophic failures. From the thermal point of view, the main challenge is to cope with the strong temperature variation between the direct sunlight and eclipse phases (from 100 ºC to -130 ºC in a tenth of a second). Thus, different materials were chosen for covering the CompanionCube.

Material	Density Kg/m2	Thermal conductivity W/(mK)	Heat Capacity J/(kgK)
FR4 Fiberglass	1900	0.30	1369
Aluminum 6061–T6	2700	201	900

Table 2. Material properties.

Aluminum will be useful during direct exposure to sunlight and high temperatures, while fiberglass can be used in low temperatures. In case of extreme temperatures the satellite can also use its propulsion system to rotate itself. An additional benefit to fiberglass is that it can be permeated by the magnetic field without heating up and thus facilitates the transmission of power during charging periods.

Sensing Capabilities for Docking

Knowledge of CompanionCube's Euler angles plays a significant role in precision thruster control. As with most existing CubeSats, an onboard inertial measurement unit (IMU) would be included to provide the CubeSat with navigation information. IMU's typically consist of an accelerometer, gyroscope, and magnetometer, with many modern devices made via microelectromechanical system (MEMS) fabrication techniques to minimize form factor. Embedded processing enhancements such as an Attitude Heading and Reference System (AHRS) would be used in conjunction with sensor fusion algorithms in order to improve reliability and accuracy when compared to standard gyroscopic flight equipment. Closed-loop PID control of the thrusters would be used to obtain the desired orientations.

AHRS provides the system with orientation data, but three-dimensional position in space is required for docking. A popular solution on Earth is Global Positioning System (GPS), but because the CompanionCube is intended for missions outside satellite range, it is unable to rely on GPS. Therefore, some alternative for dead reckoning is required in order to identify the CubeSat's position relative to the docking mechanism.

Using its onboard cameras, CompanionCube can use template tracking to localize its position. The system will be able to compute homographies that describe the relationship between its camera observations and a priori template images, which describe the affine transformation required to planarly align the CubeSat with the docking mechanism. The optical alignment technique may be insufficient in dark regions of space, but CompanionCube will resolve this issue with onboard light-emitting diodes (LEDs).

In summary, CompanionCube requires three-dimensional orientation and position information to properly align with its docking mechanism. We propose using a combination of IMU measurements and computer vision techniques for alignment. In the next section, we will describe the higher-level procedure that CompanionCube uses for docking.

Docking Procedure

Docking in deep space missions is an interesting ongoing research topic for CubeSats. Although many existing systems are capable of independent orbit, few are designed to fly around a spacecraft. In addition, many current models contain solar panels for sustainability and are intended for near-earth orbit. Controllable, deployable CubeSats could increase a deep space crew's self-surveillance capabilities by permitting use case flexibility.

In this section, we propose a docking procedure. We include a wireless, inductive charging method, eliminating the need for onboard solar panels and further reducing CubeSat mass. Instead, we incorporate the previously described flywheel system that stabilizes CompanionCube and permits trajectory following via ion thrusters. In addition, we propose a mechanical design that allows minor deviations in desired docking orientation and position. In the following subsections, we break the docking procedure into four stages:

A. General Station Alignment.

B. Approach Docking Port.

C. Precision Dock Alignment.
D. CubeSat Capture.

A. General Station Alignment.

CompanionCube begins by orienting itself in three dimensions using its ion thrusters, such that its anticipated forward trajectory in the subsequent phase will intersect with the spacecraft location. This alignment phase is to verify that the cube is moving in the correct direction.

B. Approach Docking Port.

The purpose of this phase is to move towards the docking port. Throughout this phase, controlled thrusters push CompanionCube towards the spacecraft. The flywheel inside the cube maintains stability. This section also uses the template tracking described in the previous section for localization.

C. Precision Dock Alignment.

During the previous approach stage, we expect CompanionCube to experience minor deviations from its desired trajectory due to sensor or control noise and potential environmental disturbances. In addition, the cube would ideally enter the dock backwards, for redundancy in future deployment. Therefore, once the cube has gotten close to the docking port, an additional iteration of orientation correction is beneficial to the cube's positioning. Precision thruster control, by using a subset of the available ion channels, is used in this stage in order to ensure the cube is properly aligned. While facing the dock, CompanionCube exerts a burst of force forwards, then uses its inertial flywheel to spin along its yaw axis and enter the dock backwards. This method allows future releases to use thrusters in case the launching mechanism fails.

D. CubeSat Capture.

At the beginning of this phase, the robot is properly aligned with the docking mechanism and is located just outside the docking port. The port gate opens, and the cube enters the chamber. The chamber entrance would be a few centimeters larger than the cube, and slowly taper on all sides as the cube continues further into the chamber. When CompanionCube has fully entered the docking port, a gate closes and prevents the cube from escaping the hatch. The back of the chamber contains a spring-damper system connected to a platform, which slows the incoming velocity of the cube. The chamber back platform would move along a linear actuator towards the gate in order to compress and store energy in the spring, and also align the cube flush against the chamber back platform for inductive charging. Another purpose of the spring-damper system is for subsequent CompanionCube deployment, which will be demonstrated in the following Release Procedure section.

While inside the port, induction embedded in the chamber back platform is used to recharge CompanionCube. Because inductive charging currently operates over a range of 3 to 8 cm, the alignment system ensures that the cube is within proper charging distance. A high-resolution magnetic gripper mechanism was initially considered for fine-tuning charging alignment, but was later discarded to avoid interference with the inductive charging subsystem.

A physics-based animation, available at tinyurl.com/spaceapps2015companioncube, demonstrates the capture mechanism. The simulation is represented by closed form solutions to the second order mass-spring-damper differential equation.

Release Procedure

The Release Procedure is closely related to the Docking Procedure. Continuing from above, docking is shown in a) in the concept diagram below, where the gate and chamber back platform have aligned and secured the cube. To build up energy, a linear actuator at the base of the docking port further compresses the spring against the gate. In part c), we assume that the gate opens symmetrically and does not impart any moments when launching the cube out of the docking port d), in an effort to minimize energy expenditure.

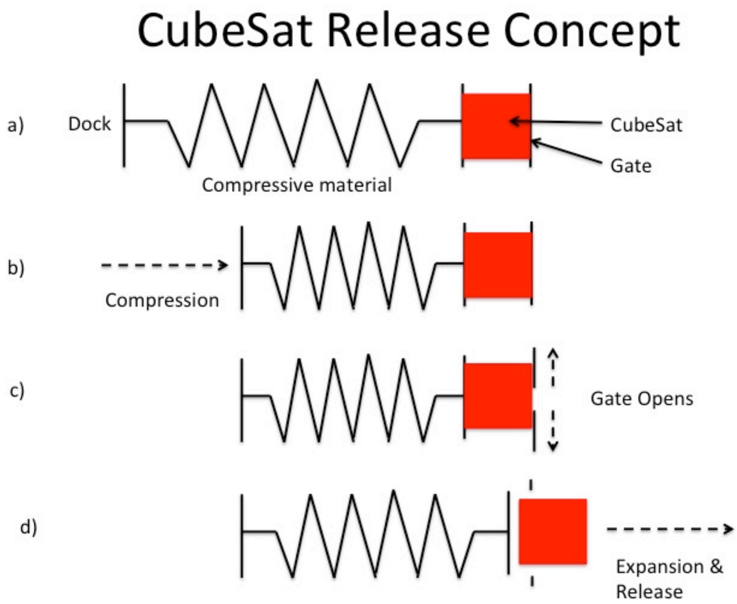

Fig. 4. CubeSat Release Concept.

For an initial release, CompanionCube would be stored in the docking port without the compression material at rest. When ready to deploy, the chamber would initiate the Release Procedure.

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