Autonomous Small Spacecraft Missions

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Abstract

The launch of small satellites a little more than a decade ago represented a significant chapter in the history of space exploration. New industry segments have been created, new opportunities emerged for education and research, and successful launches confirmed the technologic and scientific merit of these missions around the Earth.

Here we consider small spacecraft missions beyond the Earth's orbit. We start discussing the benefits and challenges of such projects, including total cost, development time, public access to space experiments, educational tools, miniaturization, minimal redundancy requirements, etc. Furthermore, we explore how autonomous navigation systems can be implemented in small self-propelled spaceships and we present proof-of-concept designs for these missions.

1. Small Spacecraft

1.1 RIT SPEX – overview, goals and current projects

1.2 Small spacecraft - classification based on mass and volume: nano (1 – 10 kg; max. launch volume ~30x30x30 cm^3); pico (0.1 – 1 kg; max. launch volume ~10x10x10 cm^3, with cubesats being the most popular and widely known). Note that this classification is not standardized.

1.3 Spacecraft NASA classification based on the scientific goal of the mission: flyby, orbiter, atmospheric, lander, rover, penetrator, observatory, communications spacecraft; small spacecraft has only been used so far in Earth orbits as an orbiter and communication satellite.

1.4 Impact on education: can be developed for less than $100K by 1-3 faculty and 10-30 students in a timeframe of 1-3 years from concept to launch readiness.

1.5 Impact on research: Earth remote sensing and proof of concept technologies.

2. Autonomous Navigation System

2.1 Implies: position/velocity determination (star based; other) and position correction, using on-board propulsion

2.2 Hardware Triple Modular Redundancy (TMR) processing system based on three microcontrollers; only the arbiter needs to be radiation hardened

2.4 Software based redundancy

2.5 Error Detection and Correction Codes used for data storage and transfers

2.6 Not ONE BIG processor, but several small microcontrollers (<$10/unit) running C or assembly code routines => small and fast code; may result in longer software development time, but this is the trade-off;

2.7 Inter controller communications – serial: CAN, I2C, SPI, or RS-232.

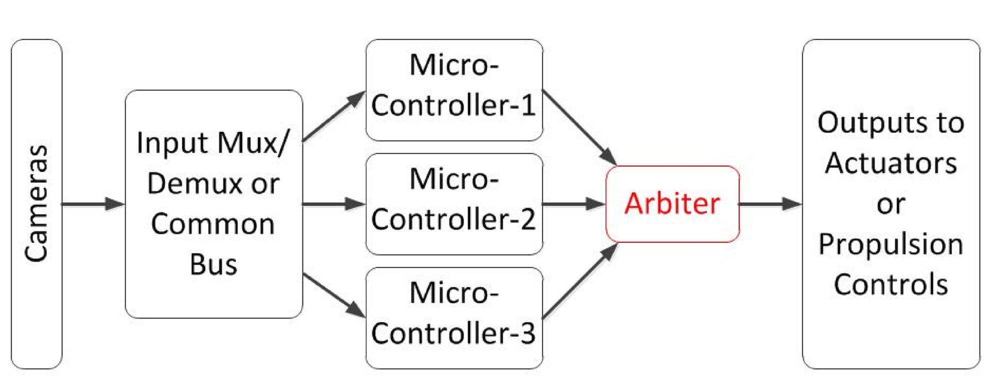
2.8 Same multi-core arrangement for all other functions, i.e. one microcontroller per one complex function

2.9 Small, still picture cameras on all sides of the spacecraft to cover the entire space; no moving parts; star based navigation;

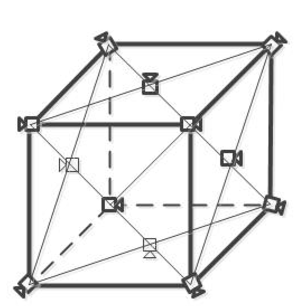
2.10 Accurate on board real time clock

2.11 Component miniaturization accomplished TRL_9;

system miniaturization possible – TRL_6



Triple Modular Redundancy in the Autonomous Navigation System.
The Arbiter is radiation hardened by design.

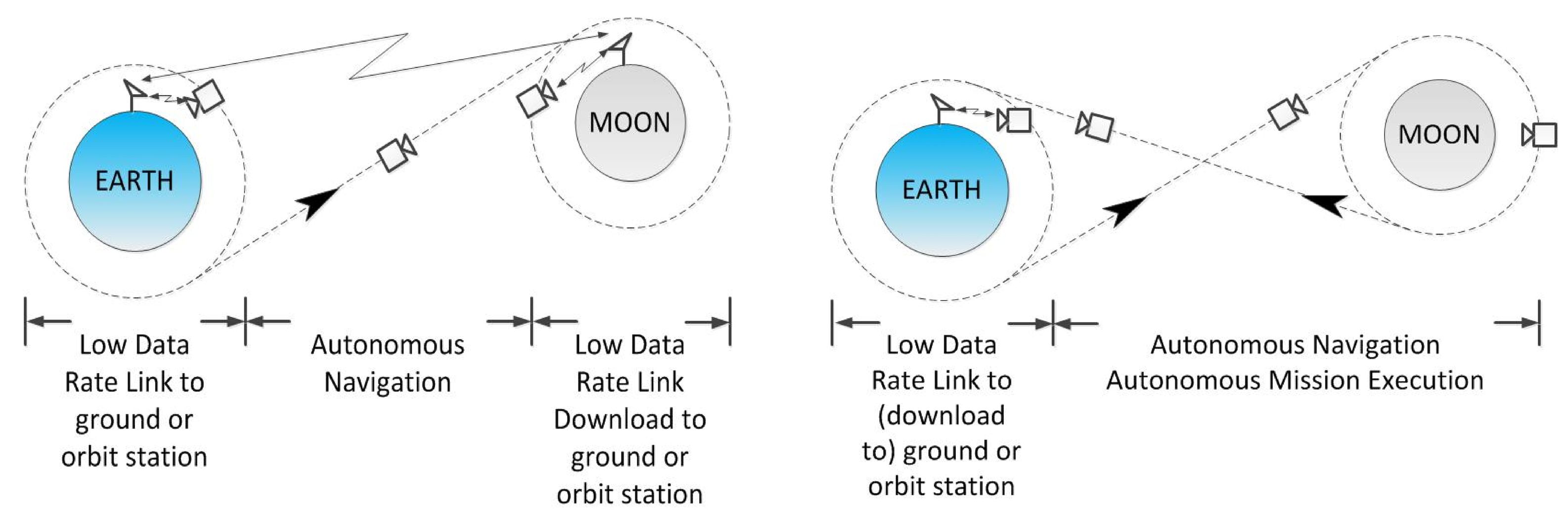


Position of 14 small, non-movable, still picture cameras to cover the entire space around the spacecraft for star based navigation. Their arrangement is similar to the center faced cube crystal structure.

3. Types of small spacecraft missions beyond Earth orbit

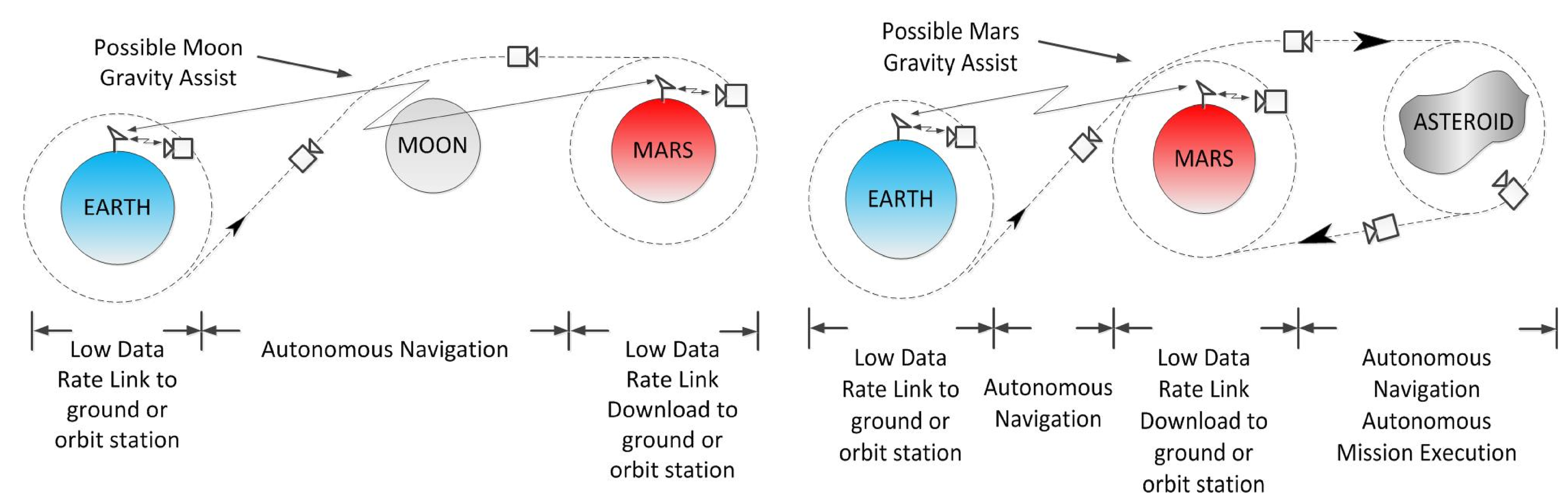
3.1 Earth-Moon: with no return to Earth orbit (WNREO) and
- download to lunar ground or orbit station from Lunar orbit (LOD)
- download to Lagrange point "station" at Lagrange point (LPD)

Earth-Moon with return to Earth orbit (WREO) and download to Earth ground or orbit station from Earth orbit (EOD)



3.2 Earth-Mars: WNREO to Mars and then download to Mars ground or orbit station from Mars orbit (MOD); possible Moon gravity assist.

3.3 Earth-Asteroids: return to Mars to download data, i.e. MOD.



3.4 Mars-Jupiter – similar to 3.2 or 3.3; use MOD or JOD; possible Moon and/or Mars gravity assist.

3.5 Mission characteristics: cost except launch ($ 50 – 200 K), **development time** (1 – 3 years from concept to launch readiness), **development team** (1 – 3 faculty and 10 – 30 students), **operational costs** (only during download phases => minimal). Variability is a function of the scientific goal.

3.6 System requirements for operation of small spacecraft beyond Earth orbit: low data rate link; high data rate link; autonomous navigation for navigation primarily when not in orbit around a celestial body; on board propulsion (chemical – for short duration, high delta v changes; electrical/Ion – for long duration, low delta v changes); attitude control.

Conclusions: the use of small spacecraft beyond Earth orbit require technological innovations that offer tremendous opportunities for education and R&D, while at the same time enhancing our assets to explore the inner solar system. Autonomous navigation and autonomous mission execution are mandatory capabilities in this expanded space environment.

References

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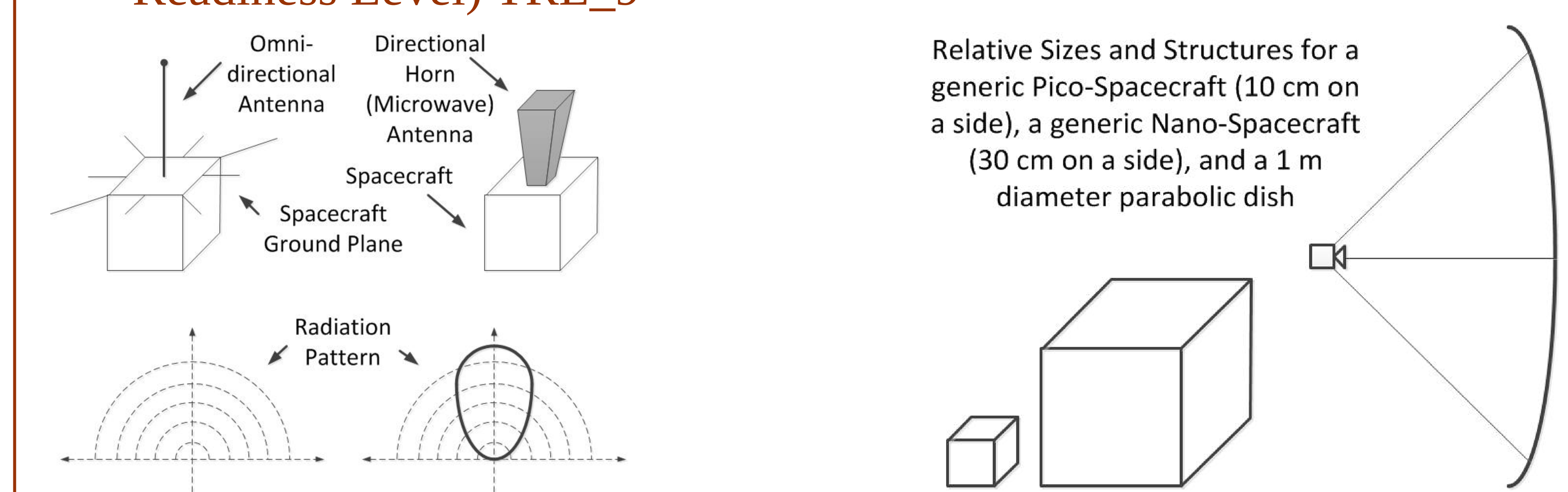
4. Communications

4.1 Low data rate link – feasible for small spacecraft: VHF, UHF, or Microwave – RF; 100 – 10K Bytes/second; used almost exclusively for telemetry; low transmit power 0.1 – 10 W; small size antennas.

- omni-directional -VHF and/or UHF; approximate length: 10 – 50 cm; foldable; used in orbit; spacecraft forms the ground plane = essential; - directional horn (Microwave 1 – 10 GHz); approximate maximum volume 10 x 10 x 30 cm; used outside of orbit; gain = 3 – 7 dB.
- component and system miniaturization accomplished; (Technology Readiness Level) TRL_9



4.2 High data rate link:100K – 1G Bytes/second (used for example to download images); **RF Microwave** – not feasible for small spacecraft because it requires high transmit power; **large size antenna – parabolic dish** (not foldable – max. diameter ~30 cm; foldable – max. diameter ~1 m; miniaturization is not possible; **optical** – may be feasible; not yet tested on small spacecraft - still requires high transmit power, but the "antenna size" is small and could use the attitude control system to help pointing in the right direction.

4.3 Small spacecraft: can only afford low data rate link used when in orbit around a celestial body on which there's a ground station available, and therefore have to be able to navigate autonomously between orbits.

5. Propulsion

5.1. Chemical based: **solid fuel and solid oxidizer** (reasonably efficient, but risky; easy to implement; miniaturization possible; cost of maintaining safety requirements may outweigh the benefits; no throttle possible; may need several "cartridges"); **hybrid** (solid fuel and liquid or gaseous oxidizer; reasonably efficient, low risk; throttle possible; relatively easy to implement; miniaturization demonstrated); **liquid fuel and gaseous oxidizer under pressure** (kerosene and oxygen, resp.– reasonably efficient; minimal risk; the cost and complexity of on board storage is manageable); **hypergolic** (efficient, but very risky; cost of maintaining safety requirements outweighs the benefits); **cryogenic liquid fuel and cryogenic liquid oxidizer** (hydrogen and oxygen, respectively - very efficient, but risky; the cost and complexities of on board storage outweigh the benefits); **Pros**: TRL_9; TRL_6, as it refers to the use in small spacecraft. **Cons**: storage tanks under pressure; nozzle – relatively large for expansion in vacuum.

5.2. Electrical/Ion based: fuel is a gas stored under pressure; gas needs to be ionized; electrostatically accelerated. **Pros:** most efficient per mass of fuel; can be widely throttled. **Cons**: complex system; requires a constant source of electrical energy; gas availability; pressurized gas at launch.