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USE OF LASER BEAMS TO CONFIGURE AND COMMAND SPACECRAFT SWARMS

Himangshu Kalita,* Leonard Dean Vance,† Vishnu Reddy,‡ and Jekan Thangavelautham§

The availability of high-performance Commercial Off-The-Shelf (COTS) electronics that can withstand Low Earth Orbit conditions has opened avenue for wide deployment of CubeSats and small-satellites. Utilizing many scores, if not hundreds of these satellites can provide services to end-users on the ground such as position, navigation and tracking (PNT), persistent earth imaging, secure communications and off-grid data storage. Not all these satellites operate as intended in space and some may face premature failure and others may become immobile. This requires effective traffic management. In our approach, a secure laser beam will be used to directly communicate gestures and control one or more spacecraft, including a swarm. Each satellite will have a customized "smart skin" containing solar panels, power and control circuitry and an embedded secondary propulsion unit. A secondary propulsion unit may include electrospray propulsion, solar radiation pressure-based system, photonic laser thrusters and Lorentz force thrusters. Solar panels typically occupy the largest surface area on an earth orbiting satellite. Furthermore, our previous work has shown that commercial space-grade solar panels can be used to detect and distinguish blue and purple laser beams even when exposed to sunlight. A secure laser beam from another spacecraft or from the ground would interact with solar panels of the spacecraft. In a swarm, the secure laser beam would be used to first designate a temporary leader of the swarm, followed by configuration of the spacecraft swarm formation. In this paper we present a low-cost on-orbit mission concept to demonstrate the technology using a pair of 2U CubeSats and a dozen SunCube 1F FemtoSats. Using this low-cost mission we hope to validate the technology in space.

INTRODUCTION

The rapid rise of small spacecraft and CubeSats in Low Earth Orbit (LEO) has increased accessibility, introducing new players to space exploration and enabling new commercial opportunities. At altitude below 450 km, the spacecraft face rapid decay in altitude due to aerodynamic drag and end up burning-up and disintegrating in the atmosphere within 1-2 years. With expected further advancement in electronics and increased congestion at lower altitudes, small spacecraft and CubeSats will begin to occupy higher altitudes in LEO. This is expected to include constellations of CubeSats to perform Earth observation, provide internet access, communications, Position, Navigation and Timing (PNT) and various military services. New approaches are needed to dispose of

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and perform traffic management of these small satellites and CubeSats to prevent congestion, formation of debris fields and rise of the "Kessler Effect."

One commonly suggested strategy to moving or collecting of space debris is the use of specialized servicing/disposer spacecraft to perform rendezvous, capture and manipulation. However, this presents operational complexity and risks when interacting and making physical contact with some of these derelict spacecrafts that maybe damaged, spilling toxic propellants or containing spent radioactive waste.

In this paper, we present an alternative approach to external servicing and space traffic management, where each spacecraft is plated with a "smart skin" containing solar panels, power and control circuitry together with an embedded secondary propulsion unit.[1,2,3] A secondary propulsion unit may include electrospray propulsion, solar radiation pressure-based system, photonic laser thrusters and Lorentz force thrusters. All of these propulsion systems either require minimal fuel or are propellant-less. Solar panels typically occupy the largest surface area on an earth-orbiting satellite. Furthermore, our previous work has shown that commercial space-grade solar panels can be used to detect and distinguish violet laser beams even when exposed to sunlight.[4,5]

A laser beam from another spacecraft or from the ground would interact with solar panels of the derelict spacecraft. The "smart skin" would recognize gestural movements used to encode universal external positioning commands. The laser beam would be used to simultaneously communicate a 'move' and trigger operation of the secondary propulsion unit. The solar-panels in turn will power the smart-skin to permit these communication and command procedures. The laser beam maybe used to guide the movement of the spacecraft, trigger impulse maneuver commands, perform attitude control maneuvers and corrections. Ground and/or space surveillance would be used for verification, to start and stop movement, perform corrections and other such maneuvers. Use of laser beams to perform this external command and control offers some unique security benefits. The laser beams can be readily encrypted and because its directional and focused (i.e. from point to point), it is far less prone to eaves-dropping or hacking from a third-party.

This proposed approach facilitates staged intervention by a space traffic management organization to not only monitor, but also support providing commands to reposition satellites to prevent unwanted collisions or in the extreme case external commandeering of the derelict or damaged satellites to eliminate risks of collisions. This framework may also be applied for human command and control of satellite swarms that need to be maintain close formation while avoiding collisions. The use of human gestures enables intuitive interaction with these spacecrafts and should minimize fatigue and controller confusion after extended, strenuous intervention/commandeering. In the following sections we present background on the use of lasers for space communication, command and control, followed by presentation of the system architecture, description of the gesture control framework, use of laser ranging, external power transmission, presentation of a mission concept to demonstrate the technology followed by conclusions and future work.

BACKGROUND

Laser communication compared with traditional radio frequency communication methods provides much higher bandwidth with relatively small mass, volume and power requirements because laser enable the beams of photons to be coherent over large distances. LADEE demonstrated the advantages of laser communication, providing high bandwidth for a relatively small sized spacecraft.[6] However, LADEE utilized laser system onboard the spacecraft to perform high-speed bidirectional communication and consumes between 50 and 120 Watts. This is too high for spacecraft that typically produce a total power of less than 20 Watts.

Our previous work has shown a bi-directional communication system on a spacecraft without the need for a laser on the spacecraft itself. It has also shown that commercial space-grade solar panels can be used to detect and distinguish blue and violet laser beams even when exposed to sunlight. In our current approach, a laser beam will be used to directly communicate and control a derelict or inactive satellites and structures floating in orbit. With a customized “smart skin” containing solar panels, power and control circuitry and an embedded secondary propulsion unit onboard a spacecraft we can trigger a maneuver by sending a laser signal in the form of a gesture command from a ground station or another orbiting spacecraft.

Sending stroke gesture commands using a simple pointing device is common in various computer applications like marking menus with a pointing device.[7] Stroke gesture recognition is also used to send instructions to robots,[8] develop robotic interface by free hand stroke.[9] Laser pointers has also been used extensively to send gesture commands to computers such as point-and-click or drag-and-drop.[10,11] It has also been used to tell a robot which object to pick up,[12] which button to push[13] and also been used to specify target objects and give commands to robots to execute accordingly.[14]

Satellite formation flying using environmental forces has also been studied extensively. Use of differential aerodynamic drag for satellite formation flying using drag plates has been studied by many researchers.[15] Similarly, satellite formation control using differential solar pressure with the help of solar flaps has also been studied.[16] Moreover, the use of geomagnetic Lorentz force as a primary means of spacecraft propulsion for satellite formation flying is also a well-studied area.[17] Techniques for detecting on-orbit satellites using laser ranging with centimeter accuracy has been shown.[18] These techniques will be used to identify the on-orbit derelict satellites and send maneuver control commands. Moreover, solar panels have also been used as a simultaneous wake-up receiver and for power harvesting using visible light communication.[19]

SYSTEM ARCHITECTURE

The proposed communication architecture consists of a customized “smart skin” containing solar panels, power and control circuitry and an embedded secondary propulsion system. A laser is beamed from a ground station or another spacecraft towards the satellite and the onboard photovoltaics acts as a wake-up laser receiver (Figure 1). Alternately the communications maybe uni-directional as seen in Figure 3. This approach enables a laser ground station or a spacecraft to broadcast commands to the spacecraft in times of emergency that would trigger operation of the secondary propulsion system to perform impulse maneuvers, attitude control maneuvers and corrections. Moreover, adding an actuated reflector to the spacecraft will enable laser ranging and a two-way communication between ground station and the spacecraft, but without the laser diode being located on the spacecraft.

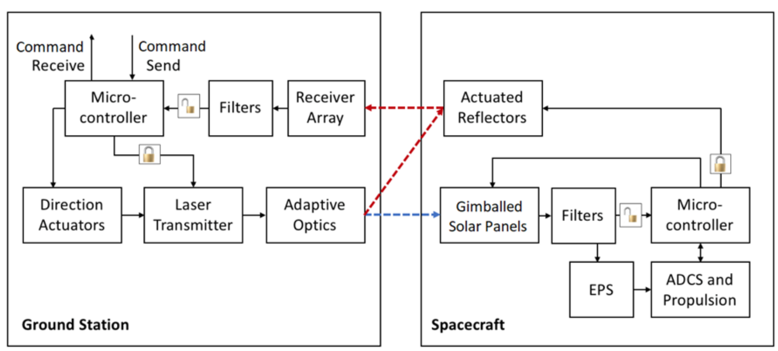

Figure 1. Secure communication between ground station and spacecraft using a bi-directional architecture.

Figure 2 shows the general systems architecture that is extended from, between a ground station and an orbiting spacecraft. The key difference is that the array of receivers can detect spatial information, particularly what cell the laser beam has hit. The ground station is equipped with a microcontroller, a laser transmitter, an adaptive optics system, an array of laser receiver, a series of filters and a series of direction actuators. To mitigate the effect of atmospheric turbulence, the adaptive optics system, together with a reference laser beam is used to measure the beam's distortion when going through the atmosphere and compensate for the distortion by adjusting in the deformable mirror of the adaptive optics system. Direction actuators are used to point the laser transmitter and the receiver array towards the target spacecraft. The laser transmitter can send modulated laser beam to the target spacecraft. The receiver array receives the reflected laser beam and then filters it to gain maximum SNR using the micro-controller.

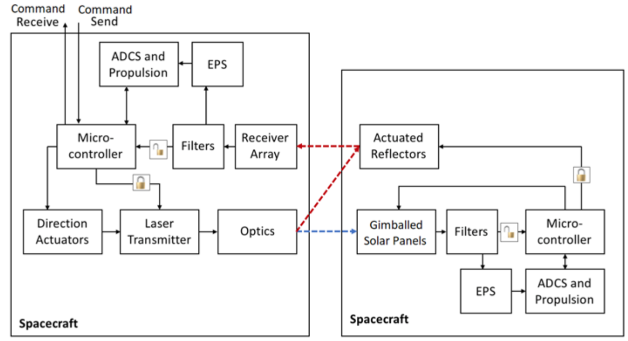

Figure 2. Secure communications between spacecraft to spacecraft in a bi-directional architecture.

On board the spacecraft, the solar photovoltaic panels act as the laser beam receiver. The received signal is then processed through the filters and the DC component and the communication signal is separated using a bias tree. The DC component is transmitted to the onboard EPS system for power harvesting. The communication signal is processed through the microcontroller to gain maximum SNR and the telemetry data is processed to trigger the onboard ADCS and propulsion system. Figure 2 and 4 shows the system architecture (bi-directional and uni-directional) between two orbiting satellite. Spacecraft 1 is equipped with a microcontroller, a laser transmitter, an adaptive optics system along with a series of direction actuators to send a gesture command through a laser signal while spacecraft 2 is equipped with a microcontroller and gimballed solar to identify the gesture command and trigger a maneuver.

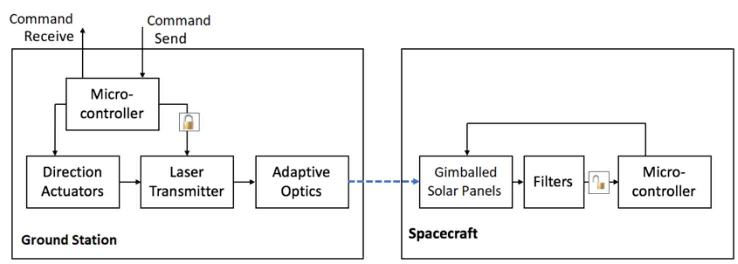

Figure 3. Secure communications between ground station to spacecraft using a uni-directional architecture.

Moreover, an encryption layer is added for data and commands just before being sent to the laser transmitter. Decryption is performed after the signal is filtered and ready to be interpreted by the micro-controller. Through this encryption/decryption process access to the spacecraft is only possible thanks to the

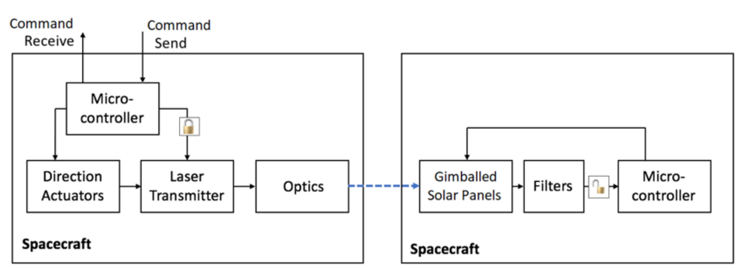

Figure 4. Spacecraft to Spacecraft System Uni-directional Architecture.

right set of passcodes shared between ground control and spacecraft. The passcode for encryption and decryption maybe one or a few gestures prompted at the beginning of a message/command or passed through as a modulatory signal. The passcode would then be used to decrypt the message and perform verification. When verification fails, the commanded message/communication is ignored, or systems goes into safe-mode after too many wrong tries.

GESTURE CONTROL

Gestures are increasingly becoming a predominant mode of human-machine interaction. This is principally due to them being intuitive, requiring minimal training. Stroke gestures also sometimes called "pen gestures" represents the movement trajectory of one or more contact points on a sensitive surface. The most significant advantage of using stroke gestures to input commands in that the user can specify several kinds of commands using just a simple pointing device. In our case, a laser beam would be used as a pointing device with the "smart-skin" acting as the sensitive sensing surface. A laser beam from another spacecraft would interact with the solar panels of the derelict spacecraft.

The laser beam would be used to communicate a 'move' which would then trigger operations on the derelict spacecraft. The laser beam maybe used to guide the movement of the spacecraft, trigger impulse maneuver commands, perform attitude control maneuvers and corrections. This method of gesture control will be used to control a cluster of closely flying satellite and execute satellite formation flying. One of the most important challenges of the satellite formation flying involves controlling the relative positions of the satellites in the presence of external disturbances, i.e., gravitational perturbation including the Earth's oblateness (J_2 effect), aerodynamic drag, and solar radiation pressure.

These issues can be addressed by the use of environmental forces including differential aerodynamic drag, differential solar radiation pressure, and Lorentz force. The satellite formation flying system comprises of a leader and follower satellites equipped with either drag plates, solar flaps or Lorentz actuation system. The orbital equations of motion for the leader satellite and the relative equations of motion of the follower satellites are as follows:

$$\ddot{r}_c = r_c\dot{\theta}^2 - \frac{\mu}{r_c^2}, \qquad \ddot{\theta} = -\frac{2\dot{\theta}\dot{r}_c}{r_c} \tag{1}$$

$$m_f\ddot{x} - 2m_f\dot{\theta}\dot{y} - m_f\left(\dot{\theta}^2 x + \ddot{\theta}y\right) + m_f\mu\left\{\frac{(r_c + x)}{r^3} - \frac{1}{r_c^2}\right\} = f_x + f_{dx} \tag{2}$$

$$m_f\ddot{y} + 2m_f\dot{\theta}\dot{y} + m_f\left(-\dot{\theta}^2 y + \ddot{\theta}x\right) + m_f\frac{\mu}{r^3}y = f_y + f_{dy} \tag{3}$$

$$\ddot{z} = -\frac{\mu z}{r^3} + f_z + f_{dz} \tag{4}$$

The leader satellite is in a reference orbit that is assumed to be planar and defined by a radial distance r_c from the center of the Earth and a true anomaly θ. The follower satellite moves in a relative trajectory about the leader satellite, in a relative frame xyz fixed at the leader satellite as shown in Figure 5. In the (2), (3) and (4) m_f denotes the mass of the follower satellite, f_{dx}, f_{dy}, and f_{dz} are the disturbance forces and f_x, f_y and f_z are the control forces.

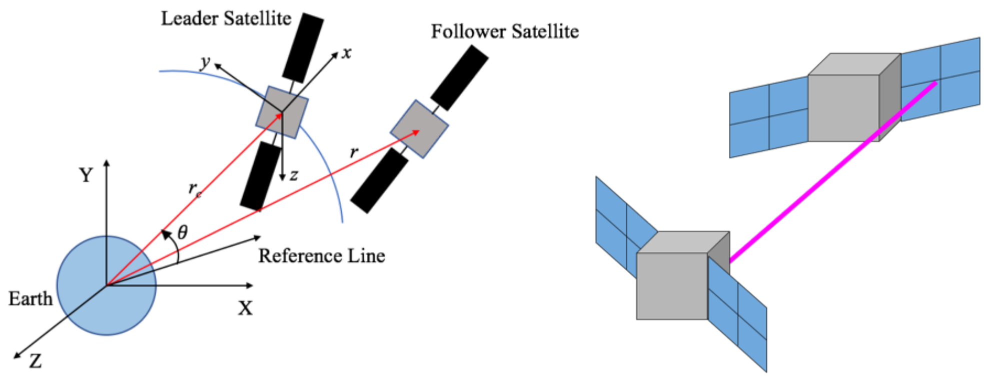

Figure 5. (Left) Leader and Follower satellite reference frames. (Right) Leader satellite sending a gesture command to a follower satellite using laser beams.

Three different types of desired formation trajectories are considered for this paper.

Along Track Formation Flying (AF). The follower shares the same ground track as the leader satellite. It has to keep a constant desired along track separation of r_d and the desired trajectory is defined as:

$$y_d = r_d \tag{5}$$

Projected Circular Formation Flying (PCF). The leader and the follower satellite maintain a fixed relative distance only on the yz plane and the formation is defined as $y^2 + z^2 = r_d^2$. The desired trajectory is defined as:

$$\begin{Bmatrix} x_d \\ y_d \\ z_d \end{Bmatrix} = \left(\frac{r_d}{2}\right) \begin{bmatrix} \sin(\dot{\theta}_m t + \varphi) \\ 2\cos(\dot{\theta}_m t + \varphi) \\ 2\sin(\dot{\theta}_m t + \varphi) \end{bmatrix} \tag{6}$$

Circular Formation Flying (CF). The leader and the follower satellite maintain a constant separation from each other, and the formation is defined as $x^2 + y^2 + z^2 = r_d^2$. The desired trajectory is defined as:

$$\begin{Bmatrix} x_d \\ y_d \\ z_d \end{Bmatrix} = \left(\frac{r_d}{2}\right) \begin{bmatrix} \sin(\dot{\theta}_m t + \varphi) \\ 2\cos(\dot{\theta}_m t + \varphi) \\ \sqrt{3}\sin(\dot{\theta}_m t + \varphi) \end{bmatrix} \tag{7}$$

Where φ is the in-plane phase angle between the leader and the follower satellites, and $\dot{\theta}_m = \sqrt{\mu/a_c^3}$ is the mean angular velocity. We have identified command methods as single-stroke gestures for performing different satellite formation maneuvers. Figure 6 shows stroke gestures representing along track formation flying (AF), projected circular formation flying (PCF), and circular formation flying (CF). The laser pointer on the leader satellite is mounted on a head that can move with fine precision using a SMA or piezoelectric actuation mechanism. The "smart-skin" can identify the laser hitting individual solar cells and hence identify the gesture stroke.

When the leader satellite draws a straight line along the solar panels, the along track formation flying (AF) maneuver is triggered, a clockwise circle triggers the projected formation flying (PCF) maneuver while a clockwise circle with a line along one of its diagonal triggers the circular formation flying (CF) maneuver. In addition to that, gesture strokes to cancel, undo and redo a maneuver is also identified as shown in Figure 7. The lower row of gestures could be used by the spacecraft to record a sequence of gestures strokes into a macro. This includes the record macro, play macro and stop macro recording command.

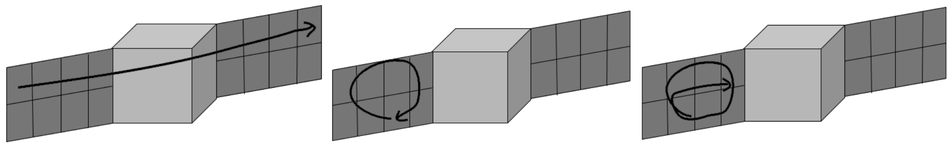

Figure 6. Gesture command strokes for, a) Along track formation flying (AF), b) Projected Circular Formation Flying (PCF), c) Circular Formation Flying (CF).

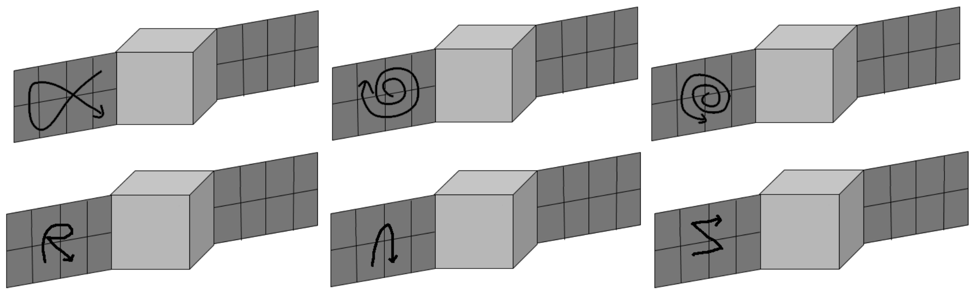

Figure 7. Gesture command strokes (upward row from left to right) to a) Cancel, b) Redo and c) Undo a maneuver and (bottom row, left to right) d) Record Macro e) Play Macro f) Stop Macro.

Ground and/or space surveillance would be used for verification, to start and stop movement, perform corrections and other such maneuvers. The entire move maneuver would be made possible without operation of the Command and Data Handling Computer onboard the derelict satellite. Thus, the laser beam would act as a ‘remote control’ for the spacecraft.

Formation Flying. For formation flight, a leader spacecraft is selected using gestures (Figure 8 top left) and this is followed by identification of the remaining spacecraft in the group Fig. 8 (top center) followed by locking the relative position of each spacecraft Figure 8 (top right). After the group of spacecrafts are locked in relative position and attitude, then gestures movements applied to the leader spacecraft will result in the remainder of the spacecraft following the leader in tandem, maintaining fixed distance and attitude. Finally, Figure 8 (bottom) shows a gesture to unlock a spacecraft in terms of relative position and attitude from the group.

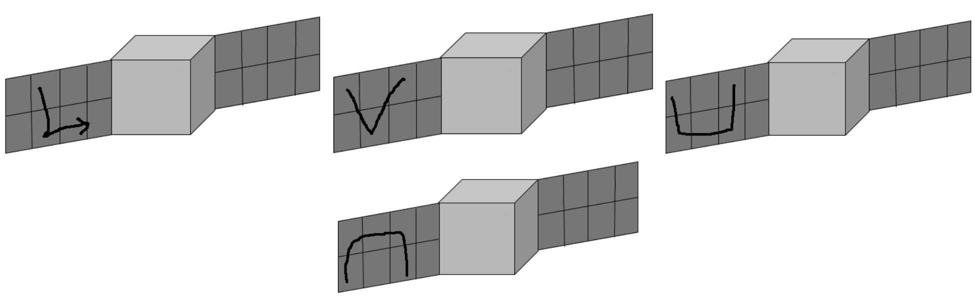

Figure 8. (Top Left) Gesture command strokes to select leader amongst a flock of spacecraft. (Top Center) Gesture to identify other spacecraft that are part of the current group. (Top Right) Gesture to lock relative position and attitude of each current group member spacecraft to the leader. (Bottom) Gesture to unlock relative position/attitude of a spacecraft from a group.

Alphabet of Gestures. Using this general approach, an alphabet of gestures representing symbols and high-level commands can be represented. The limits on the number of gestures is dependent on the solar-cell packing density (analogous to pixel density on a flat panel display) and signal processing frequency (to recognize speed of gesture movement). A third factor can be modulation of the signal.

Modulation. The laser beam maybe used to encode a signal through modulation. This modulation maybe used to encode for "intensity" without having to allocate a symbol in the alphabet. Applied with the gesture shown in Figure 6, the intensity maybe proportional to the linear or angular velocity of the spacecraft. Applied with the play macro gesture, this may determine the replay speed.

LASER RANGING AND POWER TRANSMISSION

Identifying the orbiting derelict satellites from ground in a key requirement to start or stop a movement, perform corrections and for verification. Laser ranging from ground will be used to identify these satellites and perform maneuvers. The radar link equation for satellite laser ranging gives the number of photoelectrons expected to be received for a single laser pulse.

$$n_e = \eta_Q \left(E_T \frac{\lambda}{hc}\right) \eta_T G_T \sigma \left(\frac{1}{4\pi R^2}\right)^2 A_R \eta_R T_A^2 T_C^2 \quad (5)$$

Where, E_T is the energy of the laser pulse, h is the Plank constant, c is the speed of light, σ is the target's optical cross section, A_R is the effective area of the telescope receive aperture, T_A is the one-way atmospheric transmission, and T_C is the one-way transmissivity of cirrus clouds. Assuming that the number of detected photoelectrons is Poisson distributed, the probability of detecting at least k electrons from a single pulse is

$$p(k|n_e) = 1 - e^{-n_e} \sum_{m=0}^{k-1} \frac{n_e^m}{m!} \quad (6)$$

The number of detections per second d follows the binomial distribution with $p = p(k|n_e)$ as follows

$$p(d|f) = \binom{f}{d} p^d (1-p)^{f-d} \quad (7)$$

Where f is the repetition rate in pulses per second. Thus, the probability of receiving at least n pulses per second is as follows $p(n|f) = 1 - \sum_{d=0}^{n-1} p(d|f)$

For the target to be detectable from ground, we assumed a threshold value of 2 photoelectrons per pulse and set a minimum detection rate of 6 pulses per second. The zenith angle of the target is fixed at 30^0, the repetition rate is $f = 2kHz$ and the pulse energy is $5mJ$. The effective area of the receive telescope aperture $A_R = 1m^2$. Figure 9 shows the minimum target cross section required for an 85% detection probability as a function of altitude.

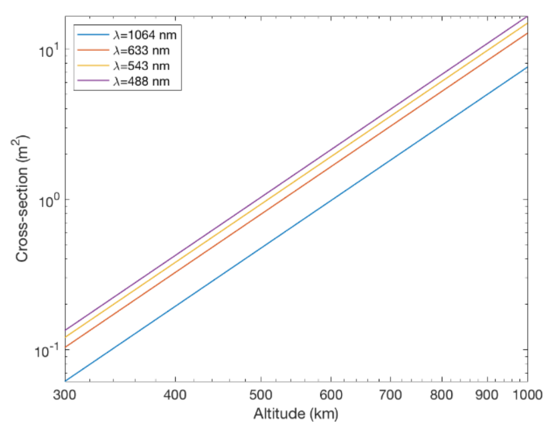

Figure 9. Minimum target cross section required for an 85% detection probability as a function of altitude.

In addition to sending laser commands and performing gesture control maneuvers, the smart-skin can also be used to transmit power from ground while performing maneuvers in case of emergencies. Figure 10 shows the system architecture of the onboard "smart skin" for simultaneous communication and energy harvesting.

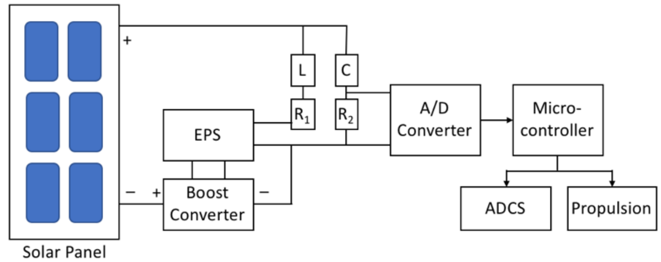

Figure 10. Smart-skin system architecture. Solar panel self-reverse biased receiver circuit for simultaneous communication and energy harvesting.

HARDWARE DEMONSTRATION

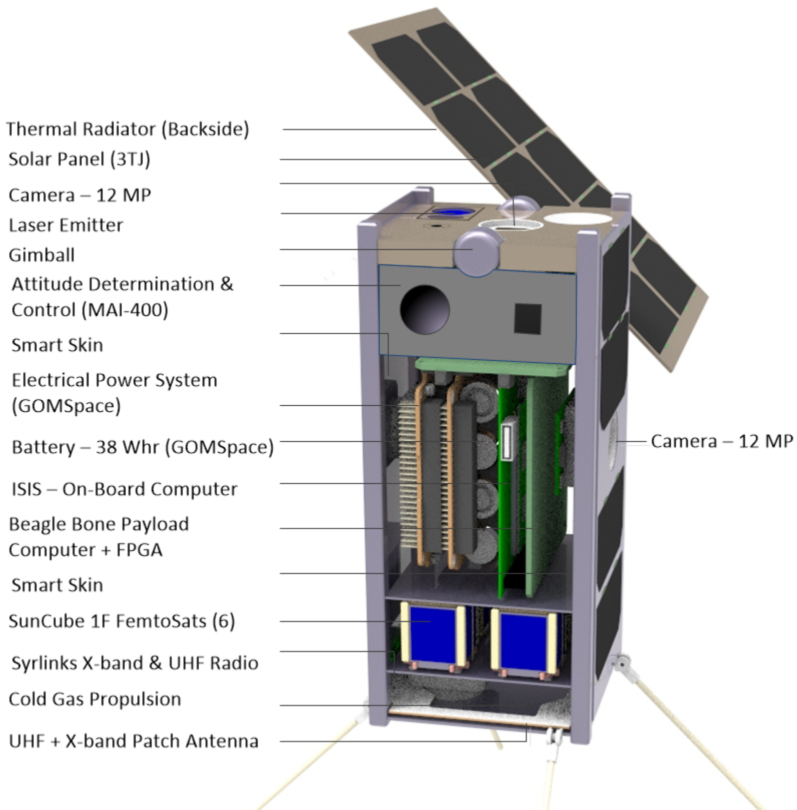

Figure 11. Layout of a 2U CubeSat that will be a FemtoSat carrier to perform swarm experiments.

The proposed technology demonstration mission will contain a pair of 2U CubeSats (20 cm × 10 cm × 10 cm) spacecraft (Figure 11) with a mass of 2.6 kg each. The 2 CubeSats will be launched into Low Earth Orbit (LEO). The 2U spacecraft will be equipped with laser transmitters to perform secure formation-flight command and control from space. Placing the spacecraft at LEO simplifies design and operation and it's relatively easy to obtain a ride at this altitude. Each CubeSat will after commissioning, deploy 6 SunCube FemtoSats[20] that are 3 cm × 3 cm × 3 cm each. Use of the FemtoSats will enable formation flying demonstration for low-cost and complexity. The laser "smart skin" technology will be implemented on the FemtoSats in addition to the 2U CubeSats. The demonstration may also be observed and controlled with ground based laser systems. Each 2U spacecraft will be powered using two sets of Spectrolab solar panels containing triple junction cells providing up to 20 W of power. One set will be deployed using a deployable that provides 1 DoF gimbaling, while a second set is body mounted. The system will charge a 38 Whr Gommspace Lithium Ion battery. Depth of discharge will not exceed 50 % to maximize battery capacity and life. Preliminary power subsystem design suggests that is sufficient margin for mission needs. The mission requires the solar panels be deployed.

FemtoSat Development. Details on the SunCube FemtoSat 1F[21] are given here (Figure 12). The SunCube FemtoSat 1F is a standard being developed at the SpaceTREx Laboratory. The spacecraft has dimensions of 3 cm × 3 cm × 3 cm and has a total mass of less than 35 grams. Each SunCube FemtoSat is equipped with a 32-bit ARM microprocessor, UHF communication system with an expected range of tens of kilometers, 3 MP camera and triple junction solar panels. A baseline design would use magnetorquers for attitude control. These miniature spacecraft can match the capabilities of first generation 1U CubeSats launched during the 2003-2005 timeframe. Using the baseline SunCube FemtoSat 1F design, modification will consist of adding a pair of deployable solar panels that will increase the footprint of the spacecraft so that its detectable by the Air Force and be actuated using shape memory alloys. Secondly, the FemtoSat will be fitted with a custom design electrospray unit to augment solar radiation pressure (SRP) [22] propulsion.

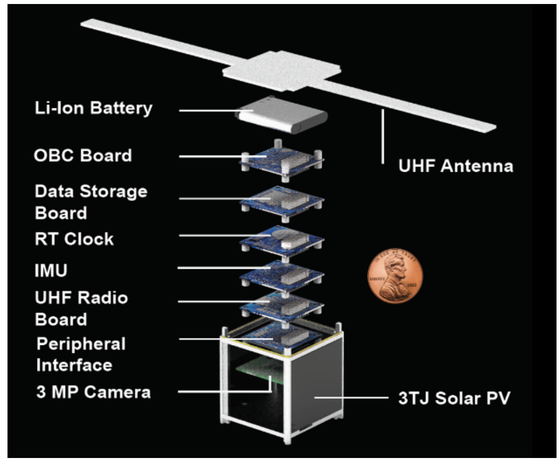

Figure 12. SunCube 1F FemtoSat[21]. It would be modified to include gimballed 'wing' solar panels that would increase footprint to 10 cm × 10 cm and electrospray propulsion.

Concept of Operations

A concept of operations for the proposed mission is shown in **Figure 13**. The pair of CubeSat spacecraft needs to be launched into Low Earth Orbit. The first month will be spent calibrating the instruments and testing all subsystems to ensure the system is fully operational. This will be followed by deployment of the 12 FemtoSats. In turn, another month will be required to commission the FemtoSats. After commissioning of all the satellites, the technology demonstration will proceed for 8-10 months.

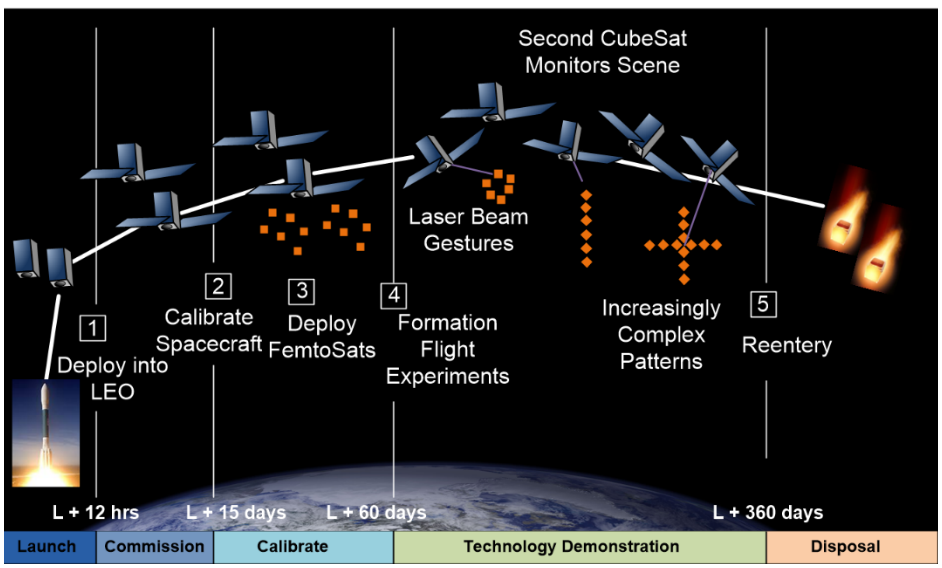

Figure 13. Concept of Operations

Technology demonstrations will be enhanced with timely observation using Univ. of Arizona's ground telescopes. During the primary mission, the 2U CubeSats will generate a laser command signal to organize the FemtoSats. The FemtoSats in turn will confirm reception of the laser-based coordination commands. This will be followed by the FemtoSats attaining a particular formation, followed by maintaining the formation over several weeks. As part of the secondary objectives, new laser commands and gestures will be used to reorganize the FemtoSats into different configurations. The test will be performed to fully validate the "smart skin" technology, followed by validation of the laser gestures commands. During the tertiary mission, the FemtoSats will demonstrate a persistent observation of a ground target and show enhancement possible due to them flying in formation. Further experiments may be performed by directly signaling the spacecraft using ground based lasers mounted on Univ. of Arizona telescopes. These series of demonstrations will validate the principal feasibility of the technology and provide a pathway for wider application of the technology and preparation for implementation on a future operational system.

CONCLUSION

In this paper, we presented a new systems architecture for external position control and traffic management of on-orbit derelict satellite by using a laser beam. We have further proposed a low-cost mission to demonstrate the technology. In our approach, a laser beam will be used to directly communicate and control a derelict or inactive satellites and structures floating in orbit. The same approach maybe also used to actively command and control one or more satellites in a swarm. The satellite will have a customized "smart skin" containing solar panels, power and control circuitry and an embedded secondary propulsion unit. A laser beam from another spacecraft or from the ground would interact with solar panels of the derelict spacecraft in the form of gesture commands. The on-orbit satellite will recognize the gesture command and then would trigger operation of the secondary propulsion unit. The laser beam maybe used to guide the movement of the spacecraft, trigger impulse maneuver commands, perform attitude control maneuvers and corrections.

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