Laser Beam for External Position Control and Traffic Management of On-Orbit Satellites

Himangshu Kalita
Space and Terrestrial Robotic Exploration Laboratory, Department of Aerospace and Mechanical Engineering, University of Arizona
Leonard Vance
Space and Terrestrial Robotic Exploration Laboratory, Department of Aerospace and Mechanical Engineering, University of Arizona
Vishnu Reddy
Lunar and Planetary Laboratory, University of Arizona
Jekanthan Thangavelautham
Space and Terrestrial Robotic Exploration Laboratory, Department of Aerospace and Mechanical Engineering, University of Arizona

ABSTRACT

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. Further improvement and reliability of these satellites will enable them to operate in higher orbits where they may be permanent fixtures. Not all these satellites operate as intended in space and some may face premature failure and others may become immobile. These derelict satellites if left unmanaged can become a space-debris problem. There is a need to develop secondary and backup systems to effectively move these satellites and perform traffic management of these derelict satellites so that collision risks are minimize or eliminated.

Specialized spacecraft to perform moving or collecting of space debris have been suggested and all have life-limitations. 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 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 laser beam from another spacecraft or from the ground would interact with solar panels of the derelict spacecraft. The laser beam would be used to communicate a ‘move’ which would then 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. 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 from ground would act as a remote control for the spacecraft. Use of a laser beam to perform this external control has several important advantages. A laser beam enables secure point to point communication and cannot be eavesdropped, unless if the eavesdropping unit is in the way or close to the derelict satellite. Both scenarios can be used to determine if an eavesdropping unit exists. However, if RF (Radio Frequency) were to be used, then eavesdropping maybe possible without detection. RF signal requires licensing and is congested due to high demand. Use of a laser beam avoids these logistical challenges. This laser system may serve as a secure backup system that can be used to mitigate and take back control of a satellite from cybersecurity threats/hacking using RF communication. A laser beam generated from the ground has the advantage of being extensible, with new and advanced optics, higher power transmission and high data frequency. Ground operation of the laser combined with ground surveillance offers a low-cost, secure approach to operate, keep track of and station-keep spacecraft and structures in space.

1. 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 military services. New approaches are needed to dispose of 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 spacecraft 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. 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 [2].

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 spacecraft 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, discussions, conclusions and future work.

2. 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 [1]. 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 [2]. It has also has 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 [3]. Stroke gesture recognition is also used to send instructions to robots [4], develop robotic interface by free hand stroke [5]. Laser pointers has also been used extensively to send gesture commands to computers such as point-and-click or drag-and-drop [6,7]. It has also been used to tell a robot which object to pick up [8], which button to push [9] and also been used to specify target objects and give commands to robots to execute accordingly [10].

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 [11]. Similarly, satellite formation control using differential solar pressure with the help of solar flaps has also been studied [12]. Moreover, the use of geomagnetic Lorentz force as a primary means of spacecraft propulsion for satellite formation flying is also a well-studied area [13]. Techniques for detecting on-orbit satellites using laser ranging with centimeter accuracy has been shown [14]. 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 [15].

3. 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. 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.

Fig. 1 shows the proposed system architecture between a ground station and an orbiting spacecraft. 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.

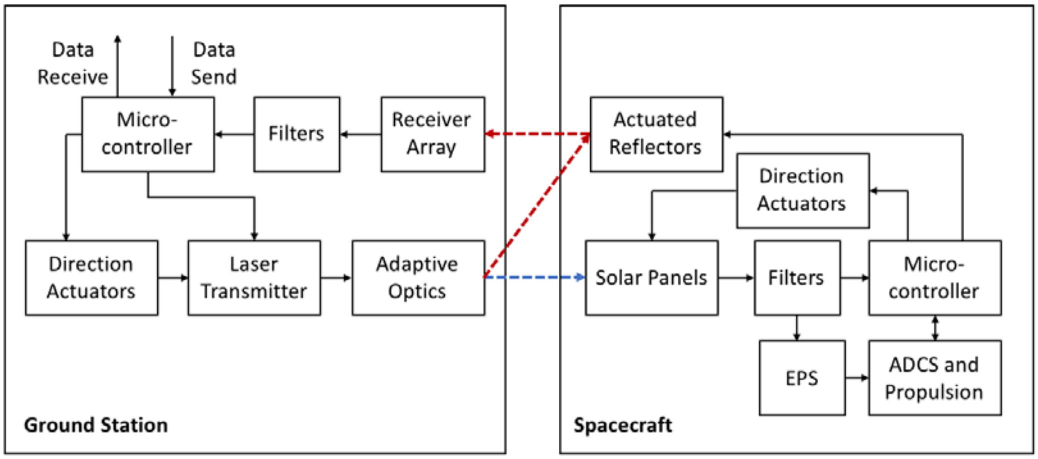

Fig. 1. Ground Station to Spacecraft System Architecture

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. Fig. 2 shows the system architecture 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, solar panels and direction actuators to identify the gesture command and trigger a maneuver.

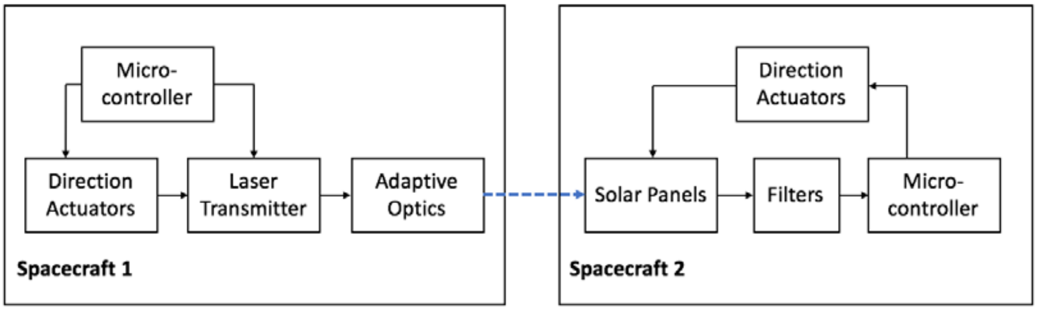

Fig. 2. System architecture between two Spacecrafts

4. 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 Fig. 3. 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.

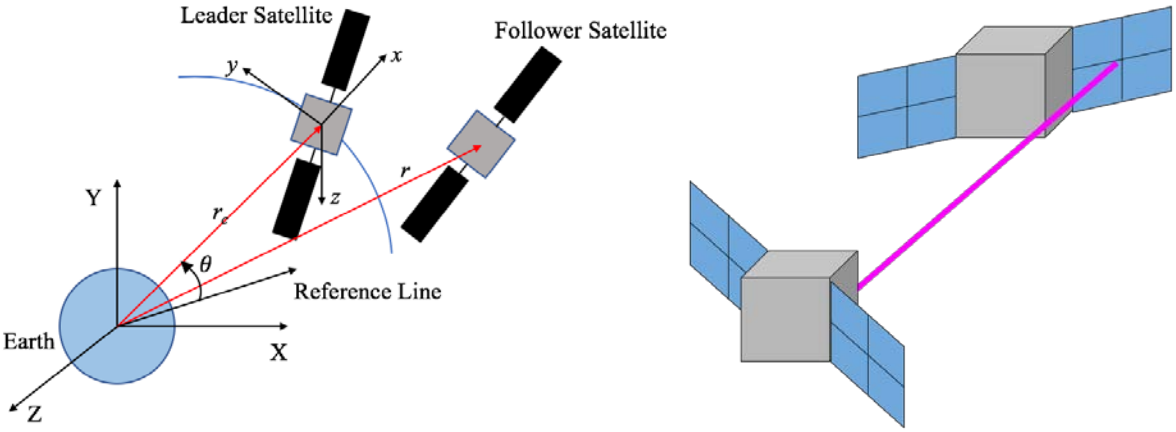

Fig. 3. (Left) Leader and Follower satellite reference frames. (Right) Leader satellite sending a gesture command to a follower satellite using laser beams.

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 inplane 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. Fig. 4 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 Fig. 5.

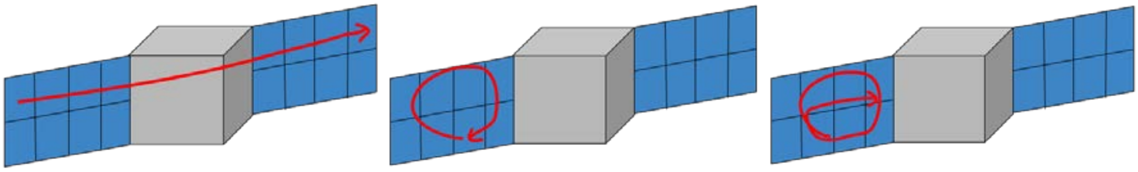

Fig. 4. Gesture command strokes for, a) Along track formation flying (AF), b) Projected Circular Formation Flying (PCF), c) Circular Formation Flying (CF).

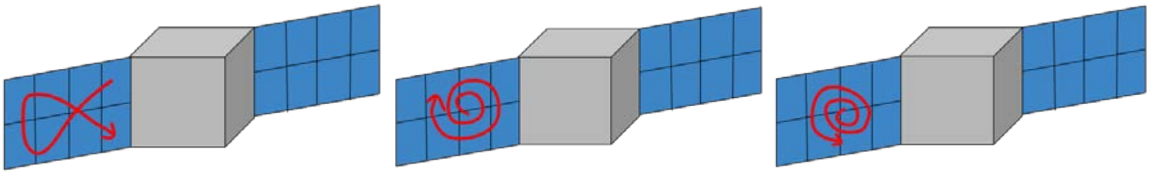

Fig. 5. Gesture command strokes to a) Cancel, b) Redo and c) Undo a maneuver.

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.

5. LASER RANGING

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 to be the following:

$$n_e = \eta_Q \left(E_T \frac{\lambda}{hc}\right) \eta_T G_T \sigma \left(\frac{1}{4\pi R^2}\right)^2 A_R \eta_R T_A^2 T_C^2 \tag{8}$$

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:

$$p(k|n_e) = 1 - e^{-n_e} \sum_{m=0}^{k-1} \frac{n_e^m}{m!} \tag{9}$$

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

$$p(d|f) = \binom{f}{d} p^d (1-p)^{f-d} \tag{10}$$

Where *f* is the repetition rate in pulses per second. Thus, the probability of receiving at least *n* pulses per second is as follows:

$$p(n|f) = 1 - \sum_{d=0}^{n-1} p(d|f) \tag{11}$$

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 $A_R = 1m^2$. Fig. 4 shows the minimum target cross section required for an 85% detection probability as a function of altitude.

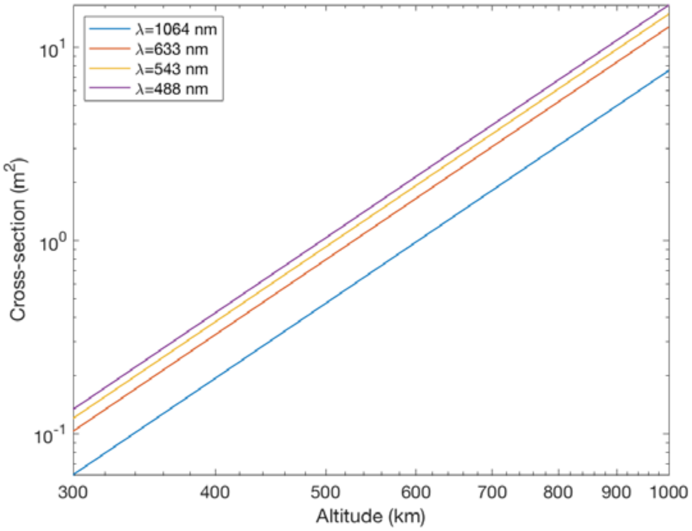

Fig. 6. Minimum target cross section required for an 85% detection probability as a function of altitude.

6. POWER TRANSMISSION

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. Fig. 7 shows the system architecture of the onboard "smart skin" for simultaneous communication and energy harvesting. A self-reverse bias is applied to the solar panel to improve its performance by increasing the number of photo-carriers and improving drift velocity. The energy harvesting branch is connected to the Electrical Power System (EPS) that supplies the rated current and voltage to the battery for charging. The boost converter is connected to the EPS system to supply a high reverse bias to the solar panels. The signal from the communication branch is provided to the analog to digital converted which is processed by the microcontroller for telemetry data. The telemetry data is then decoded to trigger the Attitude Determination and Control System (ADCS) and propulsion.

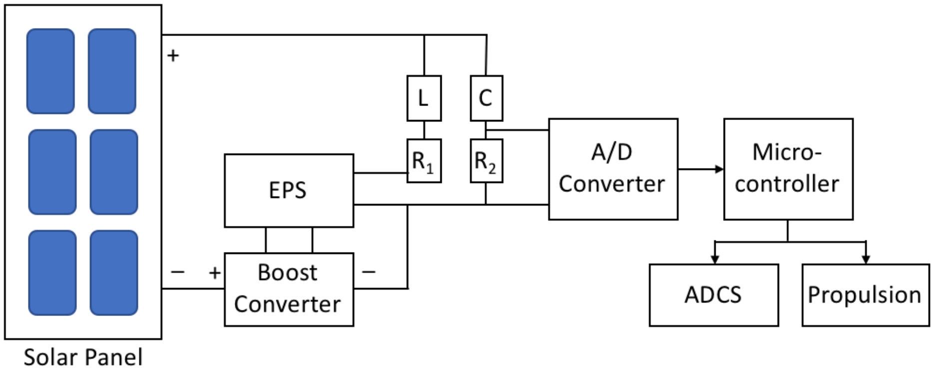

Fig. 7. Smart skin system architecture. Solar panel self-reverse biased receiver circuit for simultaneous communication and energy harvesting.

The frequency response of the receiver circuit (RC) is given by:

$$|H(j\omega)|_{RC} = \sqrt{\frac{(R_1R_2)^2 + (\omega R_1 L)^2}{(R_1+R_2)^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}} \tag{12}$$

The overall frequency response of the system is the product of the frequency response of the solar panel (SP) and the receiver circuit (RC).

$$|H(j\omega)|_{sys} = |H(j\omega)|_{SP}|H(j\omega)|_{RC} \tag{13}$$

The optimal values of the parameters R_1, R_2, C and L is determined depending on the type of solar panel. The minimum spot diameter of a transmitted laser beam is set by its diffraction limit as follows:

$$D_{spot} = \frac{2.44R\lambda}{D_T} \tag{14}$$

where R is the distance from the source to receiver, λ is the wavelength of the laser beam and D_T is the diameter of the lens. The spot diameter is defined as the first zero in the diffraction pattern which contains 84% of the beam energy. However, this limit can only be achieved if adaptive optics are used to eliminate atmospheric beam spread.

Fig. 8 (Left) shows the variation of spot diameter with altitude for lasers with different wavelength for $D_T = 1m$. It can be seen that the spot diameter is ~1m for $\lambda = 1064nm$ and ~0.48m for $\lambda = 488\ nm$ at an altitude of 410km. If the spot size is larger than the receiving array, it is desirable to decrease the wavelength to put more of the power on the array, even at the price of decreasing the efficiency while if the spot size is smaller than the receiving array, the laser wavelength is preferably chosen for optimum solar cell performance.

For monochromatic illumination, existing solar cells have peak response at about 850 nm (for GaAs cells) and about 950 nm (for Si cells). The efficiency decreases linearly with wavelength for wavelengths shorter than the peak. However, for longer wavelengths, the efficiency drops rapidly to zero. The efficiency is zero for photon energies lower than the bandgap E_g, or wavelengths longer than the cutoff wavelength, λ_c as follows:

$$\lambda_c = \frac{1.24}{E_g} \tag{15}$$

Thus, it is important to select a wavelength near the optimum value. The efficiency of a solar cell to monochromatic illumination is much higher than the efficiency produced by the broad solar spectrum near the optimum wavelength. The received power P_R is proportional to the transmitted power P_T, gain of the transmitting antenna G_T, gain of the receiving antenna G_R and inversely proportional to the space loss L_S as shown below:

$$P_R = P_T G_T \eta_T L_P L_A \eta_R G_R \eta_Q / L_S \tag{16}$$

Where, η_T is the efficiency of the transmitter optics, η_R is the efficiency of the receiver optics, L_P is the pointing loss, L_A is the loss in atmosphere due to turbulence and weather, η_Q is the quantum efficiency. Also, $G_T = (\pi D_T/\lambda)^2$, $G_R = (\pi D_R/\lambda)^2$ and $L_S = (4\pi R/\lambda)^2$. Fig. 8 (right) shows the power received with altitude for lasers of different wavelength with $P_T = 10W$.

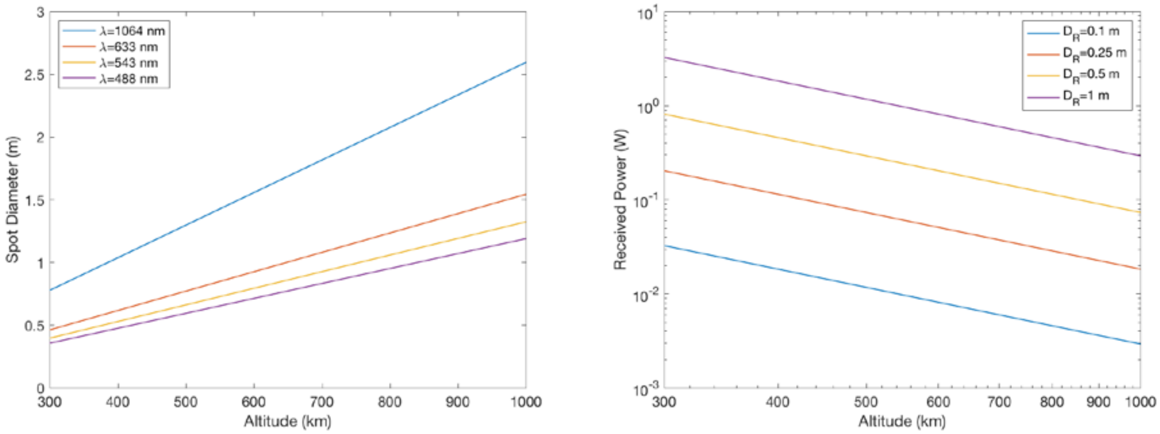

Fig. 8. (Left) Variation of spot diameter with altitude. (Right) Variation of received power with altitude for different diameter of receiving antenna.

7. 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. 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 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.

We have identified simple gesture commands to trigger along track formation flying, projected circular formation flying and circular formation flying maneuvers. Moreover, gesture commands to cancel, redo and undo a particular maneuver are also identified that would allow the laser beam to act as a remote control for the spacecraft. Laser ranging would be used for ground surveillance of these satellites that would allow us to start, stop or verify a maneuver. In case of a need for emergency power, power can be transmitted from the ground or from space by shooting a laser beam and the "smart-skin" operating as the power harvesting module.

The laser beam will enable a secure point to point communication and cannot be eavesdropped, unless if the eavesdropping unit is in the way or close to the derelict satellite. However, if RF (Radio Frequency) were to be used, then eavesdropping maybe possible without detection. RF signal requires licensing and is congested due to high demand. Use of a laser beam avoids these logistical challenges. This laser system may serve as a secure backup system that can be used to mitigate and take back control of a satellite from cybersecurity threats/hacking using RF communication. However, significant advancements are required to make this approach practical and efforts are underway to develop laboratory prototypes to validate the feasibility of our proposed systems architecture.

8. REFERENCES

1. D. M. Boroson, J. J. Scozzafava, D. V. Murphy, B. S. Robinson, "The Lunar Laser Communications Demonstration (LLCD)," 3rd IEEE International Conference on Space Mission Challenges for Information Technology, 2009.
2 X. Guo, J. Thangavelautham, "Novel Use of Photovoltaics for Backup Spacecraft Laser Communication System," IEEE Aerospace Conference, 2017.
3 G. Kurtenbach, W. Buxton, "User Learning and Performance with Marking Menus," SIGCHI Conference on Human Factors in Computing Systems, 1994.
4 D. Sakamoto, K. Honda, M. Inami, T. Igarashi, "Sketch and Run: A Stroke-based Interface for Home Robots," 27th International Conference on Human Factors in Computing Systems, 2009.
5 M. Skubic, D. Anderson, S. Blisard, D. Perzanowski, A. Schultz, "Using a hand-drawn sketch to control a team of robots," Autonomous Robots, 2007.
6 D. R. Olsen, T. Nielsen, "Laser pointer interaction," SIGCHI Conference on Human Factors in Computing Systems, 2001.
7 C. Kirstein, H. Muller, "Interaction with a Projection Screen using a Camera-Tracked Laser Pointer," International Conference on MultiMedia Modelling, 1998.
8 C. C. Kemp, C. D. Anderson, H. Nguyen, A. J. Trevor, Z. Xu, "A Point-and-Click Interface for the Real World: Laser Designation of Objects for Mobile Manipulation," 3rd ACM/IEEE International Conference on Human-Robot Interaction, 2008.
9 T. Suzuki, A. Ohya, S. Yuta, "Operation Direction to a Mobile Robot by Projection Lights," IEEE Workshop on Advanced Robotics and its Social Impacts, 2005.
10 K. Ishii, S. Zhao, M. Inami, T. Igarashi, M. Imai, "Designing Laser Gesture Interface for Robot Control," IFIP Conference on Human-Computer Interaction, 2009.
11 S. Varma, K. D. Kumar, "Multiple Satellite Formation Flying Using Differential Aerodynamic Drag," Journal of Spacecraft and Rockets, 2012.
12 S. Varma, K. D. Kumar, "Multiple Satellite Formation Flying using Differential Solar Radiation Pressure," AIAA/AAS Astrodynamics Specialist Conference, 2010.
13 S. Tsujii, M. Bando, H. Yamakawa, "Spacecraft Formation Flying Dynamics and Control Using the Geomagnetic Lorentz Force," Journal of Guidance, Control, and Dynamics, 2013.

14 J. J. Degnan, “Millimeter Accuracy Satellite Laser Ranging: A Review,” Contributions of Space Geodesy to Geodynamics: Technology, 1993.
15 C. Carrascal, I. Demirkol, J. Paradells, “A novel wake-up communication system using solar panel and visible light communication,” IEEE Global Communications Conference, 2014.