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Automated Health Check for SPS Systems

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Abstract

For all space solar architecture concepts, maintaining high efficiency of all reflectors, solar panels, and photovoltaics are important for success. If a reflector, solar panel, or photovoltaic were to be defective or have lower efficiency than expected once deployed, detecting and possibly replacing that part should occur. For a very modular system like SPS-ALPHA Mark II, a system that could detect and report damaged reflectors would be beneficial to the efficiency of the entire system. Using computer vision and robotics for many space solar architectures, an automatic health check could be created. This system could detect defects or anomalies in efficiency that may be caused by micrometeoroids or other unexpected debris. This would allow tracking the efficiency and visual appearance of the reflectors, solar panels, or photovoltaics on-board, leading to insight on when it is appropriate to replace said parts. While tracking the health of 1,000,000 reflectors in the case of SPS-ALPHA Mark II, using a human watching a camera feed would be time-consuming and inefficient. Due to decreasing costs to launch per kg, it may be feasible to dock resupply vessels with the SPS and replace the defective parts robotically. The paper will detail the algorithms and robotic processes necessary to do a health check and part replacement.

Keywords: Space Solar Power (SPS), Automated Health Check

1. Introduction

Creative solutions are required to address the current climate crisis. Space Solar Power (SPS) is one such solution. The SPS concept is simple: build a space satellite that collects solar power from the sun and beams it back to Earth as a laser or RF power. A space-based solar power plant would have many advantages over a terrestrial one: no size constraints, and the elimination of losses due to atmosphere and weather. Although the concept is simple, the implementation is extremely complex and challenging. This paper aims to address one of the many challenges associated with SPS, CO_2 emissions and environmental factors, and will focus on one proposed SPS configuration: NASA's SPS-ALPHA Mark II.

The SPS-ALPHA Mark II concept, shown in Fig. 1, is composed of five main parts: a sunlight reflector system to capture and concentrate light from the sun, photovoltaic modules to convert light from sunlight reflectors into electrical energy, a DC to RF converter, a phased array used to beam the power back to Earth as microwaves, and finally a rectifying antenna to receive the high-power microwaves and convert them into AC power for use in the grid [1].

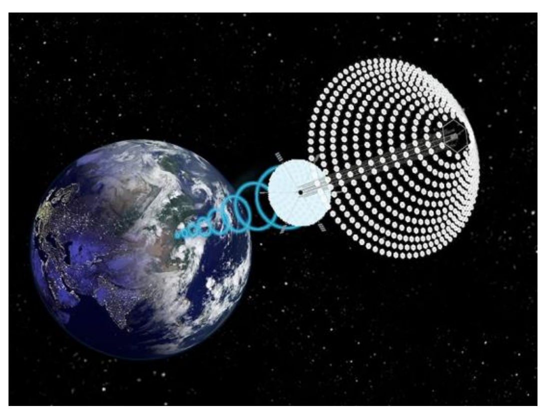


Fig. 1. SPS-ALPHA Mark II Concept [1]

The SPS-ALPHA Mark II utilizes a modular design to limit reliance on any one component for mission-critical tasks and to reduce the total diversity of parts used which helps to ensure no single point of failure for the system. This is especially important in the context of a satellite which is exceedingly difficult to access in the event of a failure or deployment issue. Approximately 5,000 thin-film reflectors will be used to build the sunlight reflector system and over 200,000 solar power generation (SPG) modules which convert the light into DC power. Each SPG module has a corresponding wireless power transmission (WPT) module which composes the DC-RF converter which produces the power eventually beamed back to Earth. Modular push/pull arms installed on the satellite will be used for initial construction and maintenance [1].

2. Need

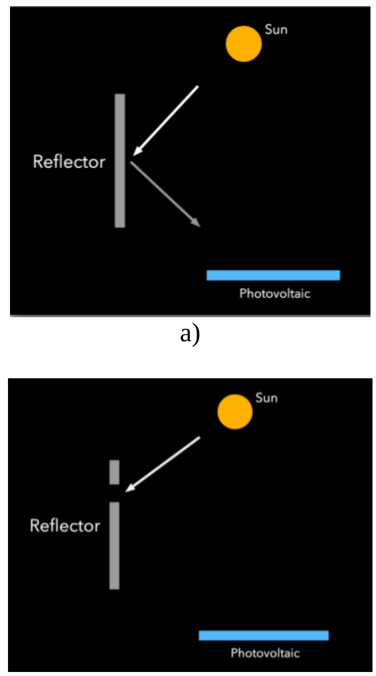
A SPS satellite designed to deliver power to Earth would be stationed in geosynchronous orbit. The United States Department of Defense actively tracks over 27,000 pieces of space debris in Earth orbit [2]. Space debris exists in a wide range of sizes, many of which are much too small to track. At the incredibly high speeds at which space debris travels, even impacts with small pieces of debris can cause serious damage to spacecraft. The large size of any SPS implementation and the fragility of the thin-film reflectors and SPG modules renders the SPS vulnerable to space debris collisions.

A reflector in good health reflects the maximum light possible back towards the SPG modules. Collisions with space debris may penetrate the reflector surface, causing a change in reflectance and a decrease in light concentration illuminating the SPG surface.

Maintenance and resupply missions for orbiting satellites are extremely expensive. Even with lower costs due to the privatization of resupply missions, 30% of NASA's yearly budget for the ISS is allotted to between 20 and 30 resupply missions [3]. Even more so, the environmental costs of resupply missions are staggering. Rocket fuels used to propel cargo into space release harmful gases and soot into the atmosphere which can deplete the ozone layer and pollute the air [4]. In order to lower the environmental costs of SPS satellites, care should be taken to limit the number of cargo resupply missions to the satellite. Consequently, the decision to patch or replace a component after a space debris collision should be strategic and based on defendable evidence.

Similarly, a SPG module in good health is able to convert the reflected sunlight to DC power as efficiently as possible. A micrometeoroid impacting a photovoltaic might compromise the efficacy of the entire panel, not just the affected impact zone. Additionally, it may be more damaging to the overall functionality of the SPS because the ability to convert concentrated light at that point is lost, whereas an equally sized damage area in a reflector loses only that amount of area of unconcentrated light. This means that we should value health checking for equal areas of photovoltaics more than reflectors.

In the event that one of the reflectors or photovoltaics is damaged by space debris, solar flare or other event, the efficiency of the entire system is lowered. Lowered system efficiency limits power yield beamed back to Earth and requires power to be sourced from other, potentially non-renewable, CO_2-emitting sources.



b)

Fig. 2. a) Reflector to SPG module in good health
b) Reflector after a collision with debris

3. Proposed Solution

A system capable of detecting damaged reflectors and photovoltaics and reporting it to be replaced optimally could maximize SPS efficiency and lower environmental costs. This automated health check for SPS systems is proposed, explained, and its potential benefits described.

The primary goal of the proposed automated health check for SPS systems is to monitor SPG and reflector surface health so strategic maintenance is possible.

The system to health check the SPG modules will operate as follows: the DC power generated by any SPG module can be measured directly and compared with the previous day, using data about the amount of power generated stored in a central computer. A large dropoff of power generated indicates a malfunction which can be investigated further with a pan tilt zoom camera mounted on the "backbone" of the SPS. Additionally, we can track the life of a SPG module by taking a picture of it while illuminated and storing it in the central computer. This image can be compared to the previous images and determine if any visual change has occurred. Visual changes to the SPG could be caused by micrometeoroid impacts, thus reducing its power output.

The system to health check the reflectors will operate as follows: A variable power laser and camera receiver will be mounted on the "backbone". Each laser will be responsible for scanning all reflectors in its line of sight. Additional computational power will be necessary to store and process data provided by the laser unit and camera. The laser's beam will scan the surface of the reflectors and the light reflected from the laser beam into the receiving camera lens will be used to determine surface health. If the reflector is in working order, it is expected that a small fraction (around 3%) of the light will scatter off the surface of the reflector and be detected by the camera. Due to the laser being variable power, we can ensure no camera burnout by changing the intensity of the laser to match the expected distance of the reflector that we are trying to measure. To measure a specific point on the surface of the reflector, we only need to turn the laser on for a fraction of a second. At the same time, the camera must open its shutter and take a picture. On the camera, a wavelength filter can be used to isolate the laser's wavelength. This will block out the sun's brightness and allow us to isolate the laser point.

A daily map of the intensity of a bounced laser at any given point on the reflector will be produced for each reflector on the SPS. Data from the laser will be cross-referenced against the previous maps generated in order to determine if the day's results are unusual. For a dysfunctional reflector, such as one with a hole, light would travel through the reflector, into the void of space, and not be detected by the camera.

Each days' data will be stored within a central computer and compared to the previous day. The laser-camera unit can pan, tilt, change focus and zoom. This will allow for a wide range of scanning coverage. Only if a deviation from normal is detected should a given reflector be identified as needing investigation. An investigation would be a picture of the reflector when illuminated by the sun being sent to Earth.

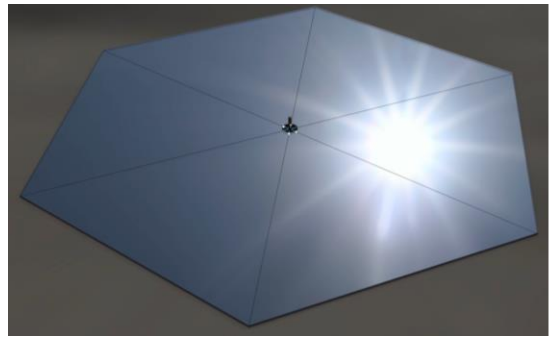


Fig. 3. Example reflector (34 meter diameter)

Once information about the health of individual reflectors and SPG modules has been collected, a decision about how to address problems may be made. Some spare materials for repairs should be kept on the SPS-ALPHA. Repairs will be completed robotically using modular push/pull robotic arms which are already included in the SPS-ALPHA design. These robotic arms may be modified to repair the reflective surfaces as needed. Resupply missions will be necessary once the on-satellite supply of spare parts is exhausted which should only be completed if the environmental cost of a resupply launch is less than the environmental cost of using alternative, Earth-based power systems when the SPS is not performing at its peak power output.

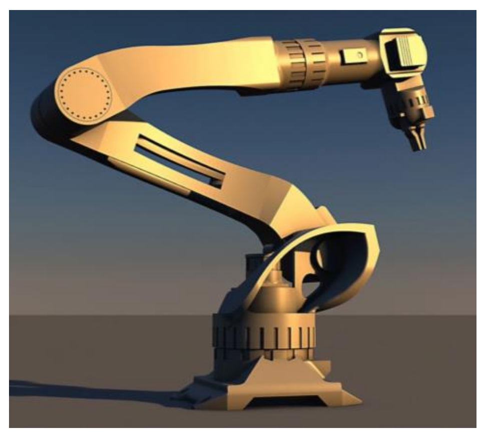


Fig. 4. Push/pull robotic arms for maintenance

4. Proof of Concept

A proof of concept experiment was designed to demonstrate how a reflector would scatter the light back to the camera. Depending on the health of the reflective surface on SPS, the laser will encounter differing levels of reflectivity. A 532 nm handheld laser pointer was shone at two different reflective surfaces to show how the laser scatter varies. The first surface is a generic mirror that is likely to have comparable reflectivity to the implemented material of the SPS reflector. This makes it a good upper bound for testing scatter. In Fig. 5, a black fitted drape is used to simulate "outer space," a place where no scatter will come from, and the mirror is the reflector. The image in Fig. 5, is an example of a reflector in good working condition. The green laser can be seen in the mid-right part of the mirror but a limited amount of scatter was detected by the camera.

Fig. 5. High power 532 nm laser scattering off of a generic mirror

Conversely, the image in Fig. 6 is an example of a reflector in poor condition. Much more scatter from the green laser is detected by the camera. It will be easily possible for computer vision software to classify this image as "damaged" while the first is classified as "healthy."

Fig. 6. High power 532 nm laser scattering off of a metallic, less reflective surface.

In the case where space debris has completely broken a hole through the reflector surface, no light from the laser beam will be scattered by the surface and hence no light will be detected by the camera where scatter is historically expected to be seen.

5. Results and Discussion

The results of the proof of concept experiment show two facts: that a reflector is capable of scattering a measurable amount of light back to the camera, and that it is possible to distinguish different health scenarios based on these images.

The position of the camera and laser, and the angle of the camera and laser can be used to create a map of the reflector surface in terms of health. Using the health of the surrounding area for context clues and a record of what reflected light historically looked like in a given location, a complete picture of the reflector may be formed describing its lifetime health and any events which damaged the surface.

The design choice to use reflectors which include no internal computer, power system, or diagnostics, drives down cost to manufacture reflectors as well as lowers launch weight and subsequent launch costs. A centralized system for diagnostics adds risk to some degree as any failure would endanger the entire health check system, but the gains outweigh the costs, especially since the health check system is not directly required for SPS mission function. Considering that the reflectors could be as thin as 9-micrometers, and have a density of 1.4 g/cm^3, any added mass would be a significant portion of overall weight [5].

6. Conclusions

SPS satellite systems need an automatic health checking plan to ensure they are continuously operating at maximum efficiency and to minimize the environmental cost of maintenance resupply missions.

Once the health check system identifies damage to be repaired, a cost-benefit analysis should be considered. Since the purpose of an SPS system is to increase the availability of clean, renewable energy, any decrease in power output may require power to be supplied from other, non-renewable sources. This means the environmental cost of maintenance must balance the direct impact of resupply rockets with the indirect cost of a lost renewable energy source.

Future work with this project would require further analysis of the materials used in reflector surfaces beyond experiments from the proof of concept discussion. Characteristics of the particular material chosen would impact the development of software to track system health and performance. Additionally, a more quantitative analysis of the environmental cost trade-off of resupply missions should be carried out in order to optimize when maintenance is recommended after a particular debris collision.

Acknowledgments

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References

[1] J. C. Mankins, SPS-ALPHA: The First Practical Solar Power Satellite via Arbitrarily Large Phased Array (A 2011-2012 NASA NIAC Phase 1 Project) Final Report, NASA (2012).

[2]M. Garcia, Space Debris and Human Spacecraft, 26 May 2021, https://www.nasa.gov/mission_pages/station/news/orbital_debris.html, (accessed 29.09.21).

[3] Audit of Commercial Resupply Services to the International Space Station, NASA (2018).

[4] E. Marais, Space tourism: rockets emit 100 times more CO_2 per passenger than flights – imagine a whole industry, https://theconversation.com/ space-tourism-rockets-emit-100-times-more-co-per-passenger-than-flights-imagine-a-whole-industry-164601, (accessed 29.09.21).

[5] Composition of Polyethylene Terephthalate (Mylar), https://physics.nist.gov/cgi-bin/Star/compos.pl?matno=222, (accessed 30.09.21)