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SOLAR SAIL IMPLEMENTATION USING SMART MATTER

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ABSTRACT

A pathway to a new structural material, Super Miniaturized Addressable Reconfigurable Technology (SMART), has been developed. In this paper we focus on the application of SMART matter to the particular problem of solar sail propulsion, which has its unique challenges for mechanical implementation, navigation, and attitude control. We address how the SMART approach can meet the requirements for advanced solar sail propulsion involving:

(1) areal densities down to grams per square meter,
(2) structural stability during deployment and operations,
(3) dynamic, continuous, fine control & agility, and
(4) reliability and adaptation to faults and failures.

A solar sail implemented with SMART matter is a fine-grained, highly parallel system with tens of thousands of elements. These elements may be addressed and operated as are pixels on an LCD display, except that SMART system elements and actuators feature a broader range of behaviors. The large number of moving elements presents challenges for production and operations but will also provide unprecedented flexibility and the opportunity to adapt to operational requirements and contingencies. The physical shape and the intrinsic reflecting area of the sail may be changed. Continuous or abrupt changes in the structure of the SMART matter will provide the control required to successfully and autonomously operate solar sails.

FULL TEXT

INTRODUCTION

In 2003 a team of researchers from NASA's Goddard Space Flight Center, Langley Research Center, and Glenn Research Center came together with the support of the Revolutionary Aerospace Systems Concepts (RASC) program to determine how a resource atlas of the Main Belt Asteroids (MBAs) could be obtained. The Prospecting Asteroid Mission (PAM) is the mission concept advanced by this RASC project.

Mission Requirements Context Set in the 2020s the goal of the PAM mission is to produce a detailed topographical, gravity, elemental, and chemical survey of hundreds or perhaps thousands of asteroids.[1] MBAs, being parts of shattered planets, objects that were on their way to becoming planets, or loose agglomerations of primordial material are important for our understanding of the origins of planets, planetary systems, and life. Because they are at the transition between small rocky refractory worlds and the volatile rich outer worlds, MBAs are a rich source of materials that may one day be used for supplies or construction on exploration missions throughout the solar system. These resources include high quality sources of Ni-Fe and water and methane ice. MBAs are not large worlds, therefore their gravitational fields are small. They are in interplanetary space therefore their materials are relatively local to space because material transport does not require overcoming the great gravitational wells of the planets. The number of MBAs is not well known, but there are likely hundreds of thousands to perhaps more than a million objects with diameters of more than 1 km. The surface area of the largest thousand would cover about 70% of Mars, and the area of the remainder likely dwarfs that of the Earth and perhaps the other planetary bodies as well. Though we are currently cataloging MBAs and other asteroids at a great rate, we expect that there will be many we do not find in the next two decades. Furthermore we expect that some of the most important asteroids will be the hardest to find: for example we do not know what the smallest asteroids will look like, particularly those whose gravity is too week to retain regolith. The MBAs are an important part of our solar system, we can learn much of the solar system's history there and gain important information about the physical processes governing our origins. They contain the materials we use for our structures and to support our lives. They are, perhaps, the planetary surfaces most accessible to interplanetary space and may be the dominant solid surface region in the solar system.

<u>Mission Challenges</u> MBAs are at present, however, difficult to reach. They are far away from the Earth with round-trip light travel times starting at about 30 minutes. Solar radiation starts at 1/4 the Earth's solar constant at the inner edge of the belt, and drops from there. Considered as a whole, the MBA surface is interesting, but complicated and spread between the orbits of Mars and Jupiter. Individual asteroids with their weak gravity have usually not pulled themselves into spheres and can support odd shapes by balancing mechanical stresses against gravity and their rotation. This gives rise to complicated gravity fields that tumble about as the asteroids tumble. These present important challenges for the mission architecture and the propulsion system for the mission spacecraft.

<u>Mission Architecture</u> The Autonomous Nano-Technology Swarm (ANTS), developed at NASA/GSFC is a multi-spacecraft architecture featuring multiple levels of autonomy inspired by biological insect colony behaviors.[1] ANTS was developed as a means to organize the considerations arising with multi-spacecraft missions. It was realized early on in PAM concept development that multiple spacecraft would be necessary to realize the goal of mapping hundreds or more asteroids within a reasonable mission lifetime. Furthermore, it was realized that the operation of these multiple spacecraft could not be handled using current methods of deep space operations. The number of spacecraft, the number of targets and the rate of encounters and mapping, the communication latencies and bandwidths militate against remote commanding and control. Furthermore, current mission architectures place multiple science mission goals in conflict. This is seen mainly in conflicting requirements and operations of different science instruments. A multi-

spacecraft gravity survey of an asteroid's mass distribution requires a different operational profile than an X-ray spectrometer that is determining an asteroid's surface composition by examining its fluorescence. ANTS removes the constraint that instruments must be attached to the same spacecraft bus and proposes that mission functions are provided by specialized spacecraft that work in a coordinated fashion to achieve mission goals.

Thus we see that the spacecraft required for PAM must have a high degree of autonomy for a number of reasons. These reasons are driven by operational requirements, the complexity of multi-spacecraft operations in deep space, the irregularity and lack of a priori knowledge concerning many target asteroids, among others.

To achieve the goals of PAM, ANTS points towards as many as a few tens of teams simultaneously performing science operations about as many asteroids. Each team is to study as many as ten asteroids a year, leading, potentially to the characterization of more than a hundred asteroids by the entire mission each year. As an aside, the control requirements for such a system of systems led to the development of the Neural Basis Function (NBF) control architecture that provides a self-similar approach to controlling multi-level systems.[4]

This need for spacecraft to visit multiple asteroids a year points towards a fairly high performance propulsion system. It is also important for the spacecraft to transfer themselves from the Earth and deploy themselves to the MBAs in a reasonable amount of time. The spacecraft must be agile because of the complexity of the asteroid gravitational environment. Furthermore, once freed from the need for consensus operations, the individual ANTS/PAM specialist science workers may take on more specialized trajectories.

At the same time, the time scales for inter-spacecraft interaction and encounter and orbital operations about spacecraft remind us of the need for local control. An important way to simplify the problem of autonomous control and planning is to remove the planning and negotiation that are driven by the need to make the most of consumables such as fuel or propellants. For this reason, ANTS/PAM spacecraft are to use solar sail propulsion. Radiation pressure from the Sun is available at all times, excepting eclipses.

There are, however, difficulties realizing the use of solar radiation as the primary means of propulsion. Foremost is that sunlight, though continuously emitted, is very weak. Second, Newton's Second Law points to two methods for realizing significant accelerations using solar sails: reflect lots of light and keep the mass down. These conflict: the larger the structure, the more massive it is. Large structures are also a problem on launch because they must fit within the shroud of launch vehicles. Third, solar sails are the flagship Gossamer structure application: they pose problems of stiffness and stability. Fourth, agility and fine control point towards stiffness and actuation that are problematic for Gossamer structures. Finally, in the quest to drive down mass, reliability suffers because the main way to make systems more robust is to make materials thicker, heavier, stronger, redundant, and so on, going against the requirements for mass reduction. Pushing forward solar sail propulsion technologies requires advances in material technologies. In general, this has been taken to mean the development of materials with enhanced properties such as areal mass, strength, opacity, resilience to the space environment, etc. To these trends we consider the impact that micro- and nano-fabrication technology, coupled with advances in computing and communications may have on the implementation of solar sails.

In this paper we discuss new systems architectures that will provide new ways to construct aerospace structures. We consider a synthesis of trends in micro- and nano-fabrication technologies, computer and communications, and materials technologies that will address all of the problems identified above during our ANTS/PAM studies. These technologies are inspired by and share characteristics with biological systems because they solve similar problems. Indeed, some of structures using the ART and SMART approach detailed here will resemble bodies more than traditional spacecraft buses.[2]

ADDRESSABLE STRUCTURES

Addressable Reconfigurable Technology (ART) is based on a fundamental node-strut unit that contains integrated actuation, control, communications, and feedback sensing. ART nodes are interconnected by the struts to form a truss. The struts are reversibly extensible allowing the geometry of the truss to be reconfigured. Variable geometry trusses have been of interest for aerospace applications for some time, but advances in software and hardware computing technologies as well as wireless telecommunications now make this a scalable technology. The addressability of ART is important because it allows individual nodes to be commanded or directed by existing central control processors. For systems with limited numbers of nodes, centralized control is adequate. With sufficient computing and communications capability, the number of nodes that might be controlled by, say, a Beowulf-style supercomputer could be quite large. NASA/GSFC is currently constructing a Tetrahedral rover based on ART technology. This system has four nodes and six actuated struts and will be controlled by a laptop computer using wireless communication.

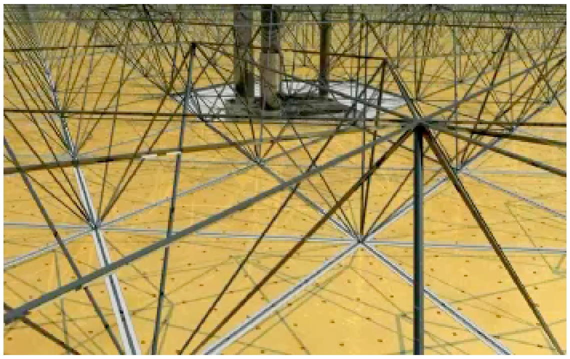

Figure 1. Close up of the back of a SMART solar sail concept.

MEMS/NEMS BASED ART

Super Miniaturized Addressable Reconfigurable Technology (SMART) is the extension of the ART technology using MEMS and NEMS-based devices. For many applications a centralized controller as envisioned with ART will suffice. For systems with extremely large numbers of components, individual nodes and their neighbors must have a more autonomic control capability so that the system, the SMART-truss, can be controlled without referring individually to the potentially vast number of elements making up the truss.[4] Control algorithms may be distributed across logic integrated within the SMART-nodes themselves, which is the fundamental idea behind "smart matter." SMART trusses are inherently multi-functional structures with embedded components and subsystems directly linked with the highly integrated actuated frame.

ANTS/PAM spacecraft would be implemented using SMART trusses (Figure 1). Components would be distributed through a SMART truss and could themselves be constructed using SMART techniques.[3] By placing mass only where it is needed to provide support or tension as required, efficiencies in the use of building materials that are commonplace in large-scale macroscopic structures can be realized in the small, but not quite microscopic regime by the 2020s. Though structures such as nodes and struts may be small, but still visible, they would make full use of MEMS devices, particularly actuators, and relevant NEMS techniques, such as the use of carbon-nano-tube (CNT) enhanced materials. In this way, we can be more careful about the use of mass in the construction of aerospace components and subsystems, and we foresee that these techniques will enable fully functional pico-spacecraft platforms in the sub-kilogram range. As we will now discuss, even though these spacecraft have limited mass, their size may be quite large.

HIGH PERFORMANCE SOLAR SAILS

For kilogram-class spacecraft, a 10^2 m^2 solar sail begins to provide enough reflected sunlight to provide the agility and acceleration required to travel to and between the MBAs. We have found that such spacecraft could travel from Earth's orbit to the asteroid belt in about 2.5 years. Even with the drop in solar radiation pressure as the square of the distance from the Sun, the accelerations of these solar sail propelled pico-spacecraft are more than adequate to move quickly between asteroids. The gravitational pull of individual asteroids will be manageable by these spacecraft, and in fact, radiation pressure pushing the spacecraft onto the asteroids has been a greater concern. With regard to the magnitude of the accelerations involved, a 1 kg spacecraft with a 100 m^2 solar sail is adequate.

This, however, requires that the solar sail propulsion system must have a total areal density approaching or better than 1 g m^{-2}. Coming up with a reflective space flight-worthy material with this areal density is challenging, but it is a recognized problem and progress is being made. The propulsion system, however, must also include the frame and actuation systems for deployment and operations that control the geometry of the reflecting surface and the resulting momentum transfer. For the ANTS/PAM spacecraft, a SMART frame controls the geometry of the solar sail surface. Because the SMART nodes are small and the struts are composed of CNT enhanced ribbons that are stored on spools when retracted, the packing factor for the SMART nodes depends mainly on the size of the nodes. Considering the thickness of the CNT enhanced ribbons on their spools, we estimate that a packing factor for the SMART frame of 100 to 1 for each linear dimension is feasible. The fully deployed SMART frame for the ANTS/PAM solar sail has millimeter-scale nodes connected by 10 cm-long tubular struts that are no thicker than a human hair. The total mass required to hold the reflecting surface is kept to a minimum. More conventional implementation technologies based on macroscopic EMS are possible, and the ART and SMART architectures are compatible with a range of requirements on areal density.

STRUCTURAL STABILITY

Though the struts are thin, they would be relatively stiff. Active damping and shape control by the actuators on the nodes are important topics. For the PAM solar sails, deployment and operations present different challenges. For deployment, the SMART solar sail frame exercises its actuators to move through the 100 to 1 packing ratio mentioned above. It starts from a compact, stowed configuration in which neighboring SMART nodes may physically touch providing additional opportunities for strengthening the structure. It is critical that the extensions of the struts remain compatible, that is, that strut-driven changes in the geometry of the truss do not place undue stress on nodes or struts. For general deployment scenarios, where node-strut extensions lead to geometrically similar configurations, this places important constraints on the quality and repeatability of the extension mechanism. However, even in cases where point defects occur the large number of degrees-of-freedom open the possibility could adjust their deployment to adapt to the problem. The point defect or failure becomes a de facto constraint on the system that is added to the constraints associated with the deployment, e.g. the scaling laws that govern the attainment of the final shape of the solar sail.

Going beyond shape control, the SMART truss, with its integrated actuators, sensors, logic, and communications has the elements required for active control. Point defects as mentioned above, e.g. such as the seizing of a strut actuator, concern the static configuration of the SMART truss. Furthermore, we presume that most changes to the truss structure could occur adiabatically. But because the nodes and struts are light and stiff, vibrations and other oscillations could propagate for a while. Care must be taken to ensure that undesirable modes are avoided and when they occur, that they are damped out. Local and global modes of oscillation might be driven during the dramatic evolution of deployment, various contingencies including collisions or device failures, or they may even be driven during the normal course of attitude control and ordinary operations. The SMART truss offers the controls and actuation that can address these issues, and it is likely that control logic distributed across the system can help solve this problem with essentially local information. In other words, the data from the thousands of nodes from the solar sail need not be collected centrally for the system to maintain its stability. This is a topic of current research for SMART truss structures that draws on progress being made in actively controlled structures, for example in segmented optics. In one sense, the ANTS/PAM solar sail is a segmented “optical flat” serving as a propulsion system.

DYNAMIC CONTROL

Whereas the time scales associated with the motions of the SMART solar sail frame are expected to be relatively fast and are to be controlled on that time scale, the orbital dynamics and low-thrust character of solar sail propulsion present a completely different set of temporal constraints. Recall, traversal from the Earth’s orbit to the MBAs is about 2.5 years; traversal between asteroids occurs over days or weeks; encounter operations about asteroids present a wide variety of time scales ranging from a month to shorter for the ANTS/PAM concept. To meet this wide variety of time scales, the ANTS/PAM spacecraft must have a wide dynamic range of control for its solar sails. Furthermore, because the gravitational environment in which PAM spacecraft traverse is irregular and constantly changing, the PAM spacecraft must be able to continuously adapt. Recall that the trajectories required by the ANTS/PAM science specialist workers are not unhappy compromises and can take advantage of exciting new trajectory possibilities afforded by a dynamic, agile, always-available solar sail. For the solar sail, this means continuous attitude and configuration changes.

Attitude control and the direction of the propulsive force can be affected and controlled by articulating the solar sail. The segmentation of the SMART solar sail frame also provides important capabilities as well. A scientifically important class of trajectories in the vicinity of an asteroid involve long dwell times above the sub-solar point where the Sun is directly overhead on the asteroid. These trajectories have a favorable illumination geometry for many remote sensing applications, of which X-ray fluorescence spectrometry is one. These trajectories include hovering trajectories where spacecraft maintain position over the sub-solar point. A problem faced by solar sail spacecraft in such trajectories is that solar radiation and the asteroid's gravity will tend to force a solar sail spacecraft into the asteroid. The segmented structure of the SMART truss when coupled with a reversibly stretchable sail segments would allow the solar sail propulsion system to be "turned off." One candidate technology for such reflecting segments are dendritic polymers with particular elements added for reflectivity. The molecular structure of such polymeric material is reminiscent of a branching two-dimensional network of Slinky spring toys. Advanced versions of such a material can provide the 100-to-1 stretchability, reflectivity, and resilience to the space environment for the ANTS/PAM solar sail. Struts from the SMART frame would be attached to these segments. Because the nodes of the frame are addressable, like the pixels on an LCD projector or laptop computer display, essentially any combination of reflective solar sail segment "activations" can be contemplated. The sail segments may be stretched fully, partially, or not at all. For the 10^2 m^2 class solar sails contemplated for ANTS/PAM spacecraft, 10 cm segments points to an LCD screen consisting on the order of ten thousand "pixels." Images could be "displayed" on the SMART solar sail frame, but for ANTS/PAM this capability will primarily be applied for continuous and fine control of the spacecraft attitude and trajectory.

RELIABILITY AND ADAPTATION

Space is a harsh environment, and this fact was fundamentally important to the RASC ANTS/PAM study. On the scale of the global constellation or swarm of ANTS systems, there is great redundancy supporting each of the various mission functions: science/engineering operations, communications, and mission control. The ANTS/PAM mission, for example, is designed to be able to field a functioning asteroid science team and complete PAM mission goals even in the event of 95% attrition of spacecraft. This approach of redundancy and reliability shows up across the levels of the ANTS system architectures.

Focusing on the SMART solar sail frame, the analogy with LCD displays can be taken even further. Most LCD displays feature a few faulty or failed pixels and yet maintain acceptable function. The SMART solar sail likewise can adapt to the loss of a number of sail segments and other components. For solar sail propulsion, broken and misaligned segments can provide unwanted reaction forces or other problems, but again, the redundancy in the system provides the freedom to adapt. The adaptation can occur either by controlling the global or local geometrical configuration of the SMART sail, or by changing the pattern of the reflecting segments.

Self-assembly precursor Depending on the capability of the SMART nodes there is the possibility that the structure may be self-healing as well. Describing this self-healing requires that we explain the distinction between the fabrication of the SMART nodes and their assembly into the SMART truss structure.[3] The individual SMART nodes and their struts are individually quite robust, though their trusses are quite Gossamer: even in their packed configuration concerns were raised about whether these MEMS-based sails could survive the launch environment. To circumvent this problem, ANTS/PAM researchers took advantage of a proposed automated research facility (ARF) located at the Earth-Moon Lagrange point that was part of the RASC program exercise. In this concept, SMART nodes and struts are fabricated on the Earth using advanced micro- and nano-fabrication techniques and facilities. The SMART nodes make use of RF identification technology (RFID) that allows nodes to query and communicate with nearby nodes. The struts of these ANTS/PAM SMART nodes are equipped with a grasping or clamping mechanism that allows struts to fasten themselves to a neighboring node. The SMART nodes are packaged and struts are kept retracted during launch and transfer to the ARF. Once on board the ARF, the RFID-enhanced addressability of the SMART nodes comes into play: the nodes are brought to templates that have RFID-enhanced sockets that the SMART nodes can detect and home in onto. A command is sent and the SMART nodes latch onto the templates that then bring a pattern of nodes within the vicinity of a SMART truss or another template. A change in the command stimulates the SMART nodes extend their struts according the design of the truss being constructed. For this advanced self-assembly concept, the SMART nodes must be able to autonomously, or better yet autonomically, guide the struts to their proper destinations. Thus for ANTS/PAM, the individual nodes have some capability to find neighboring, to extend struts out to them, and to fasten themselves together into a truss. This is a challenging capability to implement, but it is one with elements that have been studied by aerospace researchers for some time, as well as some new twists made possible by advances in the commercial world.

<u>Self-healing</u> Many of the features of the self-assembling system just described could be used as the basis for self-healing as well. Like a robotic arm moving about the outside of the space station, a SMART node, a group of SMART nodes, or even a SMART truss could use its struts and fastening mechanism to move about on a SMART structure. These could migrate to where they are needed providing replacement or new “building material” to patch holes or enable the construction of a new structural component. For a solar sail, this capability might allow PAM spacecraft to recover from what would otherwise be catastrophic rends or tears in the SMART frame. Control of this capability is an interesting problem that we are just beginning to study. There could be interesting instabilities to which such systems may be prone. It does seem clear, though, that control strategies for systems with such capabilities will have to be completely scalable with a high degree of autonomic behavior ceded to the individual SMART nodes themselves.[4]

CONCLUSION

Solar sail propulsion is an important technology that progress in materials science is making more and more attractive. The fact that radiation pressure is plentiful but weak presents a cascade of challenges that, if not addressed, limit the applicability of solar sails. In this paper, we have described the results of an analysis which attempts to determine how advances in computing software and hardware and communications technologies may couple with advanced materials and manufacturing methods to enable a new approach to solar sail propulsion. Within the architecture of ART and SMART structures, we find that solar sail propulsion can be a primary means of propulsion capable of interplanetary transfer and asteroid encounter operations. A pathway to areal densities of 1 g m^{-2} has been sketched, with the advanced MEMS-based and CNT-enhanced materials seen as one element of a broad spectrum of reconfigurable articulating trusses based on a fundamental node-strut unit that integrates actuation, logic, communication, and sensing. The approach brings active control to the problems of controlling Gossamer structures and deploying the large areas of solar sail material required to achieve significant accelerations. Continuous adaptations are possible and solar sails of exceptional agility and precise control are within the reach of the SMART truss architecture. We have discussed some of the more interesting reliability and fault-remediation possibilities posed by the SMART architecture. Work on control strategies were mentioned, but are discussed in more detail elsewhere.[1,2,4] The segmented architecture and very large numbers of degrees of freedom lead to excellent resiliency and provide wide avenues for dealing with contingencies including global and local geometrical reconfiguration, the modification of the pattern of reflectivity of the sail, and even the breaking of truss topology to allow the migration of segments of the truss structure. In this work, the ANTS/PAM mission to the Main Belt Asteroids served to provide SMART solar sail frame technology with a mission-oriented focus. Back-propagating from the advanced application architectures to currently available technologies, researchers at NASA/GSFC are constructing the first prototypes of a macroscopic ART truss.

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