The Wandering Sponges

by Alberto Orioli

e-mail address: iiiiiii@tiscali.it

mailing address: via De Gasperi, 36 - 60027 OSIMO AN - Italy

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Concept paper written for the challenge of small space debris.

Abstract: This is my proposal for remediation of small space debris, in terms of the challenge description and guidelines. So I adopt the preset structure, although some properties of the solution can't fit well into that form; in such cases I consciously prioritize the objective of a feasible remediation over the objective of winning prizes.

The proposed solution is based on two fundamental concepts: aggregation and simulation.

Overview

The Wandering Sponges are space objects; each wandering-sponge is substantially composed of two main subsystems: aggregator and navigator.

The aggregator operates mechanically, like a common "spherical" sponge when a small solid object impacts it... That is, when the relation between the shape of the solid object and the porous structure of the sponge allows, with high probability of happening, that the object becomes constrained inside the volume of the sponge. Analogously, the aggregator changes its velocity as a consequence of each collision with small space debris and increases its mass if the result of that collision is debris trapped inside it. To maximize the probability of this wanted result heavy simulation work is required, by which making the optimal choices of materials and structures of the aggregator; materials and structures must also allow easy tracking of aggregators (for example by means of RADAR or other techniques).

Most of the time a wandering-sponge operates in "passive-mode"; that's a sort of "free fall" whose velocity (magnitude and orientation) depends on gravitational and atmospheric factors, but also depends on the effects of rare collisions with debris.

The navigator subsystem is mechanically constrained to the aggregator and is provided so that the wandering-sponge can be guided remotely, for example from a space center on Earth, via radio (digital) communications. When in this "active-mode" it can change its velocity by activating onboard tiny engines.

Description of the Concept

A fundamental concept in this proposal is aggregation. If we can aggregate many small space debris within one traceable large solid object (the aggregator) then we remediate their dangerousness. In the proposed solution the aggregation phase is of the "passive" type; no algorithm implementations are involved; aggregation occurs directly according to the "rules of nature".

It is a known fact that porous materials can constrain into their structures, under given geometric conditions, other material objects. At "the pore scale" this happens according to rules of mechanics. Unfortunately we need "to constrain inside" a large number of small objects and I don't know a theory that describes this context in terms of equations; but statistics and simulations can help very much to predict what we want to know.

The concept of simulation is widely adopted in mechanics... Its adoption very often results in reduced costs of research and development. For the remediation of space debris proposed here simulation is definitely fundamental and, perhaps, the most challenging part of the solution.

The simulation infrastructure must provide two main components... an advanced simulation-software and a testing-lab. Their activities are strongly interrelated; in the testing-lab a physical object with the characteristics of the (porous and spherical) aggregator is hit with solid objects of various shapes, materials, masses and velocities... and all the possible data describing the effects of the collision are captured, collected and reported... including, of course, translational and angular velocities of the aggregator after the event, damages and modifications to its structures, and momentum of the hitting object, after the event, if the aggregation failed.

Collected data must then be analyzed to improve modeling and parameterization in the simulation-software. A statistical analysis of the results of many simulations may demonstrate our ability (or inability) to predict effects of real collisions by means of the simulation-software... This may imply setting up a new context in testing-lab and comparing the collected new data with predictions... thus getting other "suggestions" on how to improve the simulation-software.

That is, the simulation infrastructure operates in a sort of "circular improvement" between its two main components: the simulation-software and the testing-lab.

High-Level Concept of Operations (CONOPS)

SIMULATING AGGREGATION

In practical terms the first thing to do is to set up a testing-lab and a simulation-software.

The testing-lab includes a room where different "atmospheric conditions" can be reproduced, starting simply with that of air at very low pressure. A synthetic sponge of common material is in the room; its shape approximates a sphere with a radius of 10 meters. The room and the sponge are equipped with all the necessary detectors.

The first experiment to do is to let the sponge fall freely "from top to bottom" of the room and hit it (while falling) with a "projectile" of aluminum, 1 millimeter in size (in the same meaning as space debris of 1 millimeter in size). We are just setting up testing and simulation tools, we don't need to shoot a projectile at 10 kilometers per second now; the speed is enough when, at the end of the experiment, the projectile results aggregated in the sponge... the aggregator.

On the other side the simulation-software is set up to virtually perform the same experiment.

By analyzing the data collected from the real experiment (the evolving velocities of both colliding objects, the angular velocity of the aggregator, its resulting mass and many others), and comparing with the data representing the simulated one, we have a measure of the accuracy of the simulation-software and its aggregator model.

If accuracy "appears to be enough" many experiments can be conducted virtually; some of which can also be reproduced in the testing-lab, to evaluate the predictive ability of the simulation-software. The new real experiment will give further indications on how to improve the simulation-software... which will then able to virtually perform other experiments... and so on. I've already referred to these iterations as "circular improvement".

The simulation infrastructure operates under the control of a team with various skills, including expertise in materials engineering and materials science. The "circular improvement" will soon introduce experiments with the aggregator made of different materials (with respect to the common sponge), because in the test room the target temperatures will be reproduced and the projectile characteristics will resemble the space debris expected speeds, masses, compositions and shapes. The goal is to find an optimal compromise between porous structure robustness, geometries also suitable for constraining larger debris (up to 100 millimeters in size), small mass and great operational volume (the proposed radius of 10 meters is for the simulation beginning only). It would also be desirable, to minimize the transportation volume, that materials and structures of the final version of a wandering-sponge maintain, at least partially, a property of a common sponge... the possibility of reducing its volume when not in use.

ATTACHING NAVIGATOR

The design and production of the navigator subsystem is essentially an engineering work. The current knowledge about spacecrafts is sufficient to build a device that, under remote radio control, can change its own velocity (magnitude and orientation) and that of the aggregator to which it is mechanically constrained.

When in active-mode a wandering-sponge can be seen as a remote-controlled spacecraft with the engine subsystem attached to a "payload" (the aggregator). Of course, the local engine control software implements algorithms that allow automatic maneuvers to approach the new desired trajectory before returning to passive-mode. That is... a space center is allowed but not required to interact, from Earth, with the engines; it can simply communicate the new course data to the wandering-sponge, when necessary.

Modeling of an object composed of a navigator attached to an aggregator is necessary in the simulation-software, because the last phases of the simulation work inevitably concern the wandering-sponge as a whole (not the aggregator alone).

SENDING INTO ORBIT

Transportation of a wandering-sponge in space to the desired altitude (up to 2000 kilometers) can be made in the "usual" manner. Its first orbit is intended to cross (soon or late) the presumed orbit of a "cloud of debris".

As simulations are expected to demonstrate, aggregation at very high relative speeds presents different dynamics (and risks) than aggregation at low relative speeds... Thus it will be a desirable approach to first place the wandering-sponge into an orbit such that the expected impact with debris to be aggregated occurs at low relative speeds and at angles previously studied by the simulation-software. To minimize the probability that the first impact occurs with "falling debris" destined to destroy themselves, instead that with the presumed orbiting ones, it would be a good choice to operate at higher altitudes first... and "navigate" to lower orbits when the wandering-sponge can't (for various possible reasons) aggregate more debris at the higher ones.

The wandering-sponge in passive-mode is expected to change its angular velocity and translational velocity after each impact with debris, which determines its new trajectory. If the "new course" is not useful for approaching (sooner or later) other debris to be aggregated then it "switches" to active-mode, and the navigator maneuvers (by controlling the engines) toward a new useful orbit.

SELF-DESTRUCTION

When a wandering-sponge becomes "saturated" (a condition, previously studied through simulations, for which the aggregation capability is too reduced) it is time for self-destruction.

Current orbital parameters are checked; if the saturated wandering-sponge is destined for a destructive fall in Earth's atmosphere then it is left in passive-mode; if it is destined to escape Earth's gravity then it can be left in passive-mode, too... the gravity of Sun will "guide" it to a better self-destruction. (Even other "destinations" are safe.)

Instead, if the saturated wandering-sponge maintains an orbital trajectory then its navigator can change that, to follow a "self-destruction path".

Challenge and Physics-Based Justification

It seems to me that the challenge about remediation of small space debris can't fit in usual recovery practices, whose costs appear too little scalable or justified only by the value of the recovered objects. Perhaps we have to look at the issue in a way totally oriented towards its peculiarities; first of all in consideration that debris (under 100 millimeters in size) destruction, if possible, is not an economic loss... indeed it is a potential saving for other space missions in general.

I don't know a physical theory by which to predict all we need to predict in my proposed solution. We are facing large amounts of collisions between debris and a solid but porous object, composed of relatively elastic materials (or of structures with elastic properties)... Physics provides us equations to describe what happens when a small solid object, with a given momentum, impacts the solid structure of a spherical sponge... It can impact the structure under the surface of the sphere, and lose its kinetic energy by slightly breaking the structure or causing a temporary elastic modification in it (the loss of kinetic energy decreases the probability that the small object escape in a reverse path); or it can hit "a perimetral part of a pore" directly exposed at the surface, with different consequences... The overall result of interest, after each collision, is that the small object remains, or does not remain, constrained in the volume of the sphere; knowing that, in any case, both colliding objects will proceed at velocities that are different with respect to the ones they had before the collision. All the significant physical quantities regarding this single collision can be processed by equations; but this possibility, alone, does not represent a predictive capability with respect to a wandering-sponge behavior, because too many variants, also dynamic ones, must be taken into consideration when it actually impacts, in a small interval of time, many debris of different shapes and masses... and with different "saturation levels" at each collision.

All that pushes away the idea of describing wandering-sponge behaviors only through deterministic laws. But for sure (we could all say for direct experience) "sponges aggregate debris"; and if we want to take advantage of this evidence we need to master empiricism and statistics... and develop our own application.

Statistics implies "large numbers"; large numbers are reasonably achievable only through virtual experiments; virtual experiments involve advanced simulation-software, whose improvements in accuracy require testing-lab experiments.

On the other hand, the concept of simulation is widely adopted in mechanics; its adoption very often leads to a reduction in research and development costs.

Effectiveness of the System

To estimate the potential effectiveness of a wandering-sponge, reliable simulation-software is a must. Through long running simulations it is possible to produce a report about the effectiveness on an annual basis, including the number of debris the solution can address for any given range of their size.

This solution for remediation of small space debris is markedly scalable... it includes the possibility of leaving in orbit concurrently more than one wandering-sponge; with identical or different aggregation characteristics; so that effectiveness on different targets can be maximized with respect to costs... Again, simulation is the key tool to evaluate if some possibilities should be exploited or should not; also because if a wandering-sponge reaches the saturated condition, or the energy reserve for its engines runs out, then it is no longer fully effective, so accurate predictions of these eventualities are needed.

I don't have experience with space programs... and I could not involve such an expert in this proposal. I suppose that costs of past space missions are known to space program experts and that the operations I described in the subsections "ATTACHING NAVIGATOR", "SENDING INTO ORBIT" and "SELF-DESTRUCTION" have costs comparable to those of similar operations in previous space programs.

Instead, true unknowns are the costs associated with the operations described in the subsection "SIMULATING AGGREGATION". The simulation infrastructure, as a whole, requires very advanced hardware and software, and a very skilled team... To a careful look, the costs associated with the "first implementation" of all this are the only ones actually risky. In fact, the costs associated with the subsequent phases may be approved, or not, with the aid of a "progressive approach", based on the actual improvements achieved by the simulation, which lead to the best compromise in the choice to face each subsequent step cost.

Discussion of Key Technical Risks

A good simulation of mechanics involving objects constituted by porous materials (or objects with very complex structures) is an ambitious goal, with many important returns in other future applications. But difficulties in its realization may arise during the development; in the worst case the development could be suspended indefinitely.

This risk can be accepted considering that the costs of sending into orbit are (virtually) canceled, as well as the costs of remotely controlling the device wandering in space.

When in space, the risk of damages leading to a permanent deactivation of the navigator subsystem must be taken into account, too. In this case the capability of remote control is lost; however, tracking a wandering-sponge, thanks to its materials and to its volume, does not rely on communications with the navigator; therefore, in this bad case, it represents a new traceable debris.

The worst risk I can now foresee would be from collisions (in space) that, unexpectedly, break off small pieces of the wandering-sponge structures, so small that they can't be tracked.