Dynamics and Control of a Disordered System In Space[1]

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Abstract

In this paper, we present some ideas regarding the modeling, dynamics and control aspects of *granular spacecraft*. Granular spacecraft are complex multibody systems composed of a spatially disordered distribution of a large number of elements, for instance a cloud of N grains in orbit, with $N>10^3$. These grains can be large (Cubesat-size) or small (mm-size), and can be active, i.e., a fully equipped vehicle capable sensing their own position and attitude, and enabled with propulsion means, or entirely passive. The ultimate objective would be to study the behavior of the single grains and of large ensembles of grains in orbit and to identify ways to guide and control the shape of a cloud composed of these grains so that it can perform a useful function in space, for instance, as an element of an optical imaging system for astrophysical applications. This concept, in which the aperture does not need to be continuous and monolithic, would increase the aperture size several times compared to large NASA observatories such as ATLAST, allowing for a true Terrestrial Planet Imager that would be able to resolve exo-planet details and do meaningful spectroscopy on distant worlds.

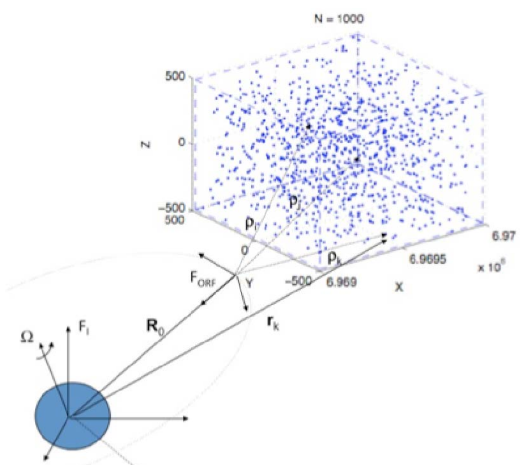
In the paper, we address the modeling and autonomous operation of a distributed assembly (the cloud) of large numbers of highly miniaturized space-borne elements (the grains). A multi-scale, multi-physics model is proposed of the dynamics of the cloud in orbit, as well as a control law for cloud shape maintenance, and preliminary simulation studies yield an estimate of the computational effort, indicating a scale factor of approximately $N^{1.4}$ as a function of the number of grains. A granular spacecraft can be defined as a collection of a large number of space-borne elements (in the 1000s) designed and controlled such that a desirable collective behavior emerges, either from the interactions among neighboring grains, and/or between the grains and the environment. In this paper, each grain is considered to be a highly miniaturized spacecraft which has limited size and mass, hence it has limited actuation, limited propulsive capability, limited power, limited sensing, limited communication, limited computational resources, limited range of motion, limited lifetime, and may be expendable.

The modeling and dynamics of clouds of vehicles is more challenging than with conventional vehicles because we are faced with a probabilistic vehicle composed of a large number of physically disconnected vehicles. First, different scales of motion occur simultaneously in a cloud: translations and rotations of the cloud as a whole (*macro-dynamics*), relative rotation and translation of one cloud member with respect to another (*meso-dynamics*), and individual cloud member dynamics (*micro-dynamics*). Second, the control design needs to be tolerant of the system complexity, of the system architecture (centralized vs. decentralized large scale system control) as well as robust to un-modeled dynamics and noise sources. Figure 1, top left, shows the kinematic parameters of a 1000 element cloud in orbit. The motion of the system is described with respect to a local vertical-local horizontal (LV-LH) orbiting reference frame (x,y,z)=F_{ORF} of origin O_{ORF} which rotates with mean motion Ω and orbital semi-major axis R_0. The orbital geometry at the initial time is defined in terms of its six orbital elements, and the orbital dynamics equation for point O_{ORF} is propagated forward in time under the influence of the gravitational field of the primary and other external perturbations, described below. The origin of this frame coincides with the initial position of the center of mass of the system, and the coordinate axes are z along the local vertical, x toward the flight direction, and y in the orbit normal direction. The assumptions we used to model the dynamics are as follows: 1) The inertial frame is fixed at Earth's center. 2) The orbiting Frame ORF follows Keplerian orbit. 3) the cloud system dynamics is referred to ORF. 4) the attitude of each grain uses the principal body frame as body fixed frame. 5) the atmosphere is assumed to be rigidly rotating with the Earth. Regarding the grains forming the cloud: 1) each grain is modeled as a rigid body; 2) a simple attitude estimator provides attitude estimates, 3) a simple guidance logic commands the position and attitude of each grain, 4) a simple local feedback controller based on PD control of local states is used to stabilize the attitude of the vehicle. Regarding the cloud: 1) the

[1] This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautic and Space Administration.

cloud as a whole is modeled as an equivalent rigid body in orbit, and 2) an associated graph establishes agent connectivity and enables coupling between modes of motion at the micro and macro scales; 3) a simple guidance and estimation logic is modeled to estimate and command the attitude of this equivalent rigid body; 4) a cloud shape maintenance controller is based on the dynamics of a stable virtual truss in the orbiting frame. Regarding the environmental perturbations acting on the cloud: 1) a non-spherical gravity field including J0 (Earth's spherical field) zonal component, J2 (Earth's oblateness) and J3 zonal components is implemented; 2) atmospheric drag is modeled with an exponential model; 3) solar pressure is modeled assuming the Sun is inertially fixed; and 4) the Earth's magnetic field is model using an equivalent dipole model. The equations of motion are written in a referential system with respect to the origin of the orbiting frame and the state is propagated forward in time using an incremental predictor-corrector scheme.

A representative cloud with varying number of grains is simulated to identify the limitations in computation time as the number of grains grows. We derive a control law to track a desired surface in the ORF (equivalently to maintain a reference cloud shape) by defining an error from a desired surface shape, and designing a control law that is exponentially stable and reduces the tracking error to zero. Figure 1 (top right) shows a comparison of various requirements for simulation of single spacecraft vs. granular spacecraft, indicating the high degree of complexity that needs to be taken into consideration. The ORF components of control force required by one of the grains is, for this particular case, in the micro-Newton range. However, no attempt has been made yet to reconfigure (or re-orient) the cloud configuration internally, for which forces in the milli-Newton level are expected, depending on the time required to do the reconfiguration. Figure 1, bottom, shows the computation time as a function of the number of grains, indicating an order $N^{1.43}$ scaling on a 8Gb, 1067 MHz RAM MacOSX computer with a 3.06 GHz Intel Core 2 Duo processor. With this metric, the same simulation for a system of N=1000 grains would take 5.4 hours, and 146 hours (i.e., 6 days) for a system with N=10,000 grains. Therefore, efficient ways to simulate this complex system, where not only the time scales of natural system dynamics, but also the sampling times of the Guidance, Navigation, and Control are included, remain to be explored. Additional details on the cloud modeling, dynamics, and control will be described in the paper.



	Single SC	cloud
Propagation model	Serial	Distributed/parallel
Workspace volume	Small	Very large
Input data structure	Small	Very large
Output data structure	Small	Very large
Significant digits	Many	few
Spatial scales of motion	Orbital/attitude/flex	Orbital/micro/meso/macro
Temporal scales of motion	Orbital/attitude/flex	Orbital/micro/meso/macro
Disturbance frequency	Orbital period	Orbital/micro/macro
Controller bandwidth	ACS+DV	ACS+DV+reconfiguration +containment
Computation on GPU	Not needed	Recommended

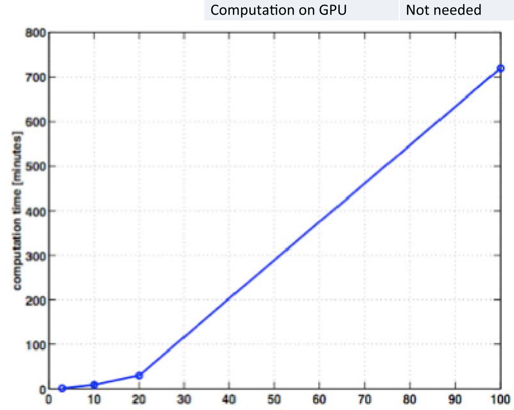


Figure 1. Top Left: Orbital parameters of cloud in orbit. Top Right: Comparison of requirements for simulation of single spacecraft vs. granular spacecraft. Bottom: Computation time as a function of the number of grains.