NEED OF SPACECRAFT FORMATION FLYING AND ITS COMPLEXITIES: AN OVERVIEW

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Abstract

The present scenario in space segment is the usage of either single spacecraft for Earth observations like remote sensing (includes cartography, surveillance/military, crop prediction, weather forecasting etc.), communication, interplanetary and scientific missions or a constellation of satellites for global positioning or regional navigation. The future scenario would be the addition of new domain like the spacecraft formation flying to the existing. Instead of a single spacecraft, a group of separated satellites orbiting in space in one particular formation to achieve the intended goal/mission is known as Spacecraft formation flying.

To understand the complex phenomena happening at distant stars or in our own solar system we may need space observatories spanning from few hundreds of meters to thousands of kilometers. The realization of a spacecraft of even few tens of meters long and launching it is practically not
realizable. The idea is to split these complex functional requirements into a number of simple sub functions and placing the electronics required to achieve these simple sub functions in several individual spacecrafts and controlling them to fly in rigid formations thus by forming a virtual huge spacecraft. This is practically realizable. Several remote sensing missions demand the need of complex imaging like 3D imaging techniques which can be realized through optical sensors placed in satellites flying in orbits with particular formations. As this concept of decentralization is involved, the realization time can be significantly reduced through parallel production, assembly, integration, testing and even launching. As replacement of non functioning electronics is easy, the probability of mission failure can be minimized to a great extent.

This paper brings out the need aspect, advantages and the complexity involved in the realization of spacecraft formation flying and also addresses some of the challenges in establishing possible near real time communication link between spacecrafts, development of new class of sensors, control dynamics and navigational algorithms.

Key Words: Formation flying, AFF, KOG VISNAV, SWARMS, TPF, DARWIN, Interferometry, MMS.

1 Introduction

We usually come across aero planes flying in formations and doing maneuvers in air shows. The extended version of this is Spacecraft formation flying. Here more than one spacecraft orbit either in the planetary orbital environments or in heliocentric orbits of deep space with some specific formations to achieve the intended mission objectives. During the period 1960-1970 more research work in the field of relative motion of satellites was being done usually with the sole purpose of docking of two satellites. In 1969, same data pertaining to interaction of the solar flares with the Earth through NASA, ESA and the then soviet satellites orbiting in different nearby orbits were correlated for better understanding of the phenomenon which gave rise to the idea of possibility of spatial sampling through separated spacecrafts - the above mentioned ex-
Experiments proved to be seminal ideas to the later development of the concept of satellite formation flying.

2 Need aspects of spacecraft formation flying from technical point of view and some possible ways of realization

2.1 Deep space ASTRONOMICAL missions

To understand in detail the phenomena like birth of new stars, chemical reactions taking place etc. in the distant galaxies & star clusters or in the search of extra solar Earth like planets which are several light years away we need space observatories (to avoid the influence of atmosphere) with telescopes having apertures ranging between 100-1000m and extending up to few thousand kilometers which can provide better resolutions and minute details. Realizing the space platforms of even few 10s of meters itself is a complex, expensive affair. So the idea is to split the theoretically required large spacecraft into a number of practically possible small separated satellites which are made to act together in tandem to provide a virtual large space platform in deep space which can be used in the study of celestial objects which are several light years away.

Figure 1: separated spacecraft interferometry (Image only for representation) Source- [1]

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In the case of deep space observations, the concept of interferometry is mainly employed usually there will be a number of separated collector spacecrafts (normally 2) and single combiner spacecraft. Mirrors placed in the separated collector spacecrafts reflect the incoming light from the distant source to the combiner spacecraft where the detector (of CCD or photon counting type) is housed and image will be formed. The distance between the separated collector satellites which forms the baseline length plays a vital role in the determining the angular resolution.

Figure 2: TPF mission. (Image only for representation) Source-Internet

Terrestrial Planet Finder (TPF once realized will give a virtual telescope as big as a football ground) and DARWIN are few among the planned deep space interferometry missions which employ the separated spacecraft formation flying techniques in their mission operations.
2.2 Study of the Natural magnetic fields around Earth

Figure 3: MMS mission. (Image only for representation) Source-Internet

Planet Earth possesses a natural magnetic field. At 60,000 to 90,000 kms away from the centre of the Earth in the magneto tail region, phenomenon like breaking and reconnection of these magnetic field lines do occur with the transfer of large amount of energy stored in the magnetic field lines to the plasma particles enclosed by these field lines.

Separated satellites flying in pyramid like formations are more suitable in the study of the magnetic reconnections. NASA's Magnetospheric Multiscale Mission (MMS) is engaged in this task.

2.3 Study of asteroids using the concept of Swarms

An interesting aspect in the field of formation flying is the concept of Swarms. Large number of autonomous satellites (may be few thousands) each weighing between a few 100gms to a kilogram and each assigned with a specific (need not be unique) job to carry out are made and launched towards asteroids at once. Since the mass each satellite is very small, the impact of perturbations (mainly gravitational forces) on them is also less.

Multiple satellites will be assigned with the same task. Before getting destroyed near the asteroids they take the data related to
the task they have been assigned to carry out and transmit the same to Earth. In the process even if we lose a few 50–100 satellites it will not have a major impact in achieving the mission objective.[4]

2.4 3D imaging from space in the Earth perspective

To monitor and assess the rate at which the changes with respect to forest cover, vegetation, mining areas, melting of the ice glaciers is taking place 3D imaging from space would be much beneficial.

Making the spacecrafts to orbit around in near Earth orbits, in specific formations (like tetrahedral formation) will enable the spacecraft formation with optical payloads to produce a 3-D image of the interested geographical locations.

2.5 Surveillance using large SAR antennae from space

Synthetic Aperture Radars (SAR) are more suitable for all weather, day & night critical remote sensing applications like surveillance across the borders. Observations independent of the lighting conditions and cloud cover can be made using SAR antennae. To do radar imaging in L band or lower frequencies the size of the antenna has to be very large.

So the idea is to split the large antenna into a number of small antennae placed in a number of small separated satellites. Making them to orbit in specific formation at the time of radar imaging and thereby making a virtual large antenna of required length and breadth we can achieve the objective.

Aligning the different separated small SAR antennas (so that they are in the same plane) to a few arc seconds range precision in attitude (orientation) is a challenge but with recent technological developments it is realizable. Phase difference among the signals fed to different patch antennas which make the SAR is required to create different antennae beam patterns required for radar imaging in different modes of operation. With proper co-ordination among the member satellites and complex ground data processing algorithms it is possible to simulate the same effect of a large antenna.
One more area is the application of interferometer principle together with SAR antennae in separated satellites to make an interferometric SAR (INSAR). INSAR has great capabilities and can be used to detect the changes even of millimeter scale of a particular topography imaged successively.

3 Need aspects of spacecraft formation flying from economic and mission point of view

Factors like production, testing, launching, realization time; Mission success probability makes formation flying more a necessity for complex missions. The concept of formation flying involves a breaking up of a single complex function performed through a large satellite into a number of simple functions performed through hardware modules housed in small separated satellites. As the approach of decentralization is adopted, parallel production of the functional modules, their assembly into separate small satellites, simultaneous testing of these small satellites followed by parallel launch even with launchers of less capability from multiple launch pads is possible. This greatly reduces the assembly, integration, testing time and there by reducing the implementation time from ground design to onboard realization. One more advantage is the possibility to replace that individual satellite, housing a non functioning hardware with another satellite containing proper functioning module in a very short duration. This reduces the mission criticality to a great extent. This possibility to expand the array and replenish the satellites, creates a new domain of opportunities and new dynamic configurations for new applications.

4 Challenges involved in the realization of spacecraft formation flying

Formation flying involves the separated satellites orbiting in particular formations for the accomplishment of particular mission objectives. Formation may take place near planetary orbital environ-
ments or in deep space as necessitated by the mission. The inter
satellite distance may vary between few meters near Earth and
Earth like planetary orbits to a few hundred/thousands kilometers
in deep space missions. Design of different optimal formations con-
sidering fuel, maximum coverage for a particular application itself
is a big challenge.

4.1 Constraints to the realization of separated
spacecraft formation flying in deep space

In deep space missions where formations are made at distances of
0.1 A.U. (approx. 14.9 million kms.) away from the Earth we
cannot depend on GPS satellites for navigation. Real time commu-
ication between the member satellites of the formation which are
few 1000s of kilometers apart is difficult to realize. Achieving of
the precise relative position (of < 1 cm) and relative attitude (of <
1 arc min) among the member satellites is another herculean task.
The luxury of the availability of a variety of sensors (like Earth
sensor, sun sensor, magnetometers, star sensors, and GPS aided
position tracking sensors) for attitude and orbit determination in
Earth orbits becomes scarce once we reach deep space. Except star
sensor we dont have any other traditional sensor to use.

4.2 Constraints to the realization of separated
spacecraft formation flying in near Earth
orbits

In formations made near earth orbits a different set of problems
arise. Atmospheric drag, always try to deviate the satellites from
there designated orbits. Sometimes there are possibilities of col-
lision among the closely orbiting satellites. Plume (Thruster ex-
hausts after thruster firing) impingement is another potential de-
grading factor which can degrade the imaging capacity of lenses of
the optical payloads, solar panels power generation efficiency by de-
positing a thin film of thruster discharge on their surface. It has to
be considered seriously during the design of closely flying satellite
formations.
5 Possible solutions to overcome the challenges of spacecraft formation flying

5.1 Some of the possible approaches in deep space missions

5.1.1 Design of Autonomous formation flying (AFF) sensor

Deep space formations pose challenges like the need for the design of a new class of sensors, design of algorithms which can make inter satellite real time communication for navigation happen. Scientists of NASA have come forward with a new design Autonomous Formation Flying Sensor (AFF). AFF has 4pi steradian coverage and thus eliminates the unnecessary search maneuvers. Hence reduces the fuel requirement to some extent. AFF works at 30 GHz in the Ka band & makes use of the existing TURBO ROGUE GPS receiver technology (which was designed to work in L-band) with necessary changes to make it act as a transceiver (Both transmitter and receiver). This will be positioned in all the member satellites. AFF not only help in relative navigation but also act as new class of sensor. AFF keeps track of the relative changes in phase of received ranging signals to determine the relative position and relative attitude. With AFF it is predicted that a relative positional accuracy of 1cm and relative attitude accuracy of 1 arc min is possible to achieve among the member satellites having separation in the range of 1m to 1300 kms.

5.1.2 Design of Kilometric Optical Gyro (KOG)

Kilometric optical gyro (KOG) is another new design for precise attitude determination. KOG makes use of the counter propagating laser beams among the member satellites to precisely determine the rotation and rate of rotation of the formation.
6 Some of the possible approaches in near Earth orbiting missions

6.1 Maintaining of fuel balance among separated satellites of the formation

Formations taking place in near Earth orbits have to use much of the fuel for trajectory correction maneuvers. When a formation is made, compared to inner satellite, the outer satellite will be traveling at a higher velocity. When it undergoes corrections, more fuel is required than the one flying in inner orbits. If it continues like this outer satellites may get depleted of the fuel at an early stage of mission. So the idea is to change the positions of the satellites frequently within the formation. Thereby, a balance with respect to the use of fuel in all the member satellites can be achieved. So mission planning involves frequent reorganization of the satellite positions to achieve efficient formations.[2]

6.2 Design of new navigation algorithms

Usually satellites orbiting in the near earth formations will be flying very closely. During maneuvers due to thruster firing the plumes (exhaust of thruster discharge) coming out may impinge on the solar panels or sensitive optical payloads of nearby satellites and degrade their performances. So the need is to design complex algorithms and computer aided mathematical models which take into account the atmospheric drag, solar radiation pressures, gravity related perturbances i.e. all the possible constraints experienced by the individual satellites & also relative attitudes of the possible victims of plume impinge (optics part of optical payloads and solar panels) into account during thruster firing of the individual separated satellite. Designed algorithms must perform all the complex calculations and guide correctly during the attitude & trajectory correction maneuvers.

From the dynamics point of view we need the design of new algorithms/ control laws which take into account the dynamic states, possible sensor Field of view (FOV) occultations of all the member satellites to determine the coupled attitudes and plan the translatory motions. Depending on the magnitude of attitude correction
required we can have cold gas, pulsed plasma thrusters & field emission electric propulsions (more suitable when small thrusts of micro/milli Newton range is required) along with the existing chemical thrusters.

Vision based position and attitude determination (VISNAV) concept for the navigation of member spacecrafts of the formation is a new idea under development. It involves a new position sensing diode (PSD), a wide angle lens and beacons of unique light sources. PSD will be placed at the focal plane of the wide angle lens and connected to 4 electric circuits. Currents proportional to the intensity of beam (light from the beacon) focused by the lens on the silicon area of the diode are generated in four directions. Currents are also proportional to the position of the centroid of the light beam on the diode. With the processing of these currents it will be possible to determine the relative positions of the member spacecrafts.[3]

6.3 Master slave approach

As the number of satellites will be more than one - commanding, tracking and telemetry also demand a new design approach. All the satellites may be given equal authority and can be commanded and tracked just as we command and track the individual satellites. This approach demands the hardware of equal complexity in all the satellites. One more approach is to configure one as a Master and other member satellites as slaves. Master satellite only will have complex hardware/processor. It will only be used to frequently communicate with the ground station. All the uplinked commands reach the Master only. Then as demanded by the formation for the particular mode of operation, Master will issue the commands to the member satellites. Slave designated satellites will send their house keeping data to the nearby Master satellite only. Master will collect this house keeping data/telemetry of all the satellites, combines with the payload data and transmit to the ground stations. This approach reduces the transmitting power requirements of the slave satellites and makes their design very simple with simple hardware. Master slave approach is more suitable in the design of autonomous formations flying requirements of deep space missions.
7 Conclusion

Through this paper we have tried to give an overview of the need aspect of the spacecraft formation flying concept both in the Deep space and near earth orbits. Some of complexities/challenges involved in the realization are introduced in brief. Some of the new technological ideas which can be used in the realization of spacecraft formation flying and latest works being done in this domain are mentioned. Because of the involved complexities major research works being carried in this field and may take much more time to mature. MMS (Magnetospheric Multiscale mission) was launched in March, 2015 and functioning. Few more complex technology demonstration experiments are near completion and may be launched in near future.

References

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