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Innovative Design Considerations for Adaptive Spacecraft

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***Abstract*—**Space technologies have changed the way we live in the present day society and manage many aspects of our daily affairs through Remote sensing, Navigation & Communications. Further, defense and military usage of spacecraft has increased tremendously along with civilian purposes. The number of satellites deployed in space in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and the Geostationary Orbit (GEO) has gone up. The dependency on remote sensing and operational capabilities are most invariably to be exploited more and more in future. Every country is acquiring spacecraft in one way or other for their daily needs, and spacecraft numbers are likely to increase significantly and create spacecraft traffic problems. The aim of this research paper is to propose innovative design concepts for adaptive spacecraft. The main idea here is to improve existing design methods of spacecraft design and development to further improve upon design considerations for futuristic adaptive spacecraft with inbuilt features for automatic adaptability and self-protection. In other words, the innovative design considerations proposed here are to have future spacecraft with self-organizing capabilities for orbital control and protection from anti-satellite weapons (ASAT). Here, an attempt is made to propose design and develop futuristic spacecraft for 2030 and beyond due to tremendous advancements in VVLSI, miniaturization, and nano antenna array technologies, including nano technologies are expected.

***Keywords*—**Satellites, low earth orbit, medium earth orbit, geostationary earth orbit, self-organizing control system, anti-satellite weapons, orbital control, radar warning receiver, missile warning receiver, laser warning receiver, attitude and orbit control systems, command and data handling.

I. Introduction

SPACE is becoming unmistakably more multilateral in character for the day-to-day requirements of modern man; the number of satellites in space is likely to double in the next 10 years. Continued growth in the number of spacecraft will amplify the risks of ambiguities and potential accidents and generate further requirements for effective cooperation in space surveillance. Most of the satellites do not need orbital correction when they are in their designed orbit. Satellites need orbital correction to perform their intended task only due to external forces acting on them [1]. In practice, orbital control is a routine issue to bring back the satellite to its original position at least once in a month.

In the days of the space revolution, defense satellites were utilized basically for military communications, reconnaissance, early warning of missile launch detection, weather forecast and arms data collection. Though the satellites perform old functions, in this age they are used for force multiplication functions during war. Navigation and targeting has become a crucial function in modern day warfare including damage assessment after war [2]. This also needs orbital control to forcibly move the satellite away from its original position to safe guard it from Anti-satellite weapons (ASAT).

Dependence on space for the daily needs of modern man is ever increasing; there is a need to design self organizing satellites for automatic orbital control for its maintenance in the original orbit as well as to move the satellite away from its original path for self protection.

II. Historical Background and Necessity

The number of satellites deployed by the whole world in various orbits such as Low earth orbit, Medium earth orbit and Geostationary orbit at present in 2012 and projections for 2015, 2020, 2030,2040 and 2050 [3], [4], are as shown in Table I. The methodology for developing the forecast has remained consistent throughout the history of space technology. The Forecast Team, through Federal Aviation Administration, and Allied Security Trust, requests projections of satellites to be launched over the next 10 years from global satellite operators, satellite manufacturers, and launch service providers [5]-[7]. In addition to this, other factors that were considered and studied in developing the forecast include that it is expected satellite technology may change drastically, which may also further increase the number of satellites, currently to further higher numbers.

- Publicly-announced satellite and launch contracts,
- Projected planned and replenishment missions,
- Growth in demand from new and existing services and applications,
- Availability of financing and insurance,
- Potential consolidation among operators, and
- New launch vehicle capabilities.

So far over 5,000 to 6,000 satellites have been launched into space, and more than 1,000 are still functioning as of today. These space platforms provide vital information in near real time, which is useful for national security, economic functions and human comforts; hence, the owners of these satellites are highly worried about their safety from interference by enemy countries and Anti-satellite weapons.

Modern society is heavily dependent on space platforms, since they provide real-time services for mobile communications, global positioning services, faster economic activity, crop assessment, forest coverage assessment, land usage, cyclone warning, disaster management, and such

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important remote sensing functions. For these reasons, owners are highly keen to protect them from damage and destruction. The loss of an important space platform could escalate into dangerous situations between countries, in addition to the creation of space debris. This explosion in the number of satellites will create increasing numbers of conflicts between the vehicles and their Earth-bound owners. Assuming advancements in miniaturization, better lift capability, significant technology breakthroughs, or huge commercial demand, the rush to space could be overwhelming. Without a system for fused organization and deconfliction of space vehicles, conflicts caused by crowding will reach critical mass. In sum, space will likely become a very busy place in near the future.

TABLE I
FORECAST OF SATELLITES FOR 2050

Year	LEO	MEO	GEO	Total
2012	5,554	957	791	7,302
2015	5,887	1,043	839	7,769
2020	6,442	1,093	919	8,454
2030	7,552	1,143	1,079	9774
2040	9,817	1,485	1,402	12,704
2050	12,762	1,930	1,822	16,514

Electromagnetic energy in the form of electromagnetic pulse, laser with different intensities can be used as ASAT from ground-based platforms. They can cause temporary and permanent damage including destruction of the space platform depending on their intensity level. Hence, there is a strong necessity for technological help to overcome these problems and design new satellites with self-organizing capabilities for self-orbital control including for self-protection. Telemetry tracking, and controlling of satellites is most likely to become complex in future situations, and the best way is to have a technical solution. That is, to design future satellites with a self-organizing system for atomization of orbital control and monitoring. In other words, design future satellites as self-organizing systems for orbital control to maintain its original path and to move away from it to avoid anti-satellite programs including ASAT.

III. Methodology

In this research paper, the methodology for the design of adaptive spacecraft for self-maneuverability and self-protection capabilities is brought out in two steps, as given below. The aim is to propose an improved methodology to innovatively design spacecraft for self-adaptive capabilities in real-time. The two steps involved are:

1) Design of an adaptive spacecraft system for self-maneuverability; and,
2) Design of an adaptive spacecraft system for self-protection.

A. Design of Adaptive Spacecraft System for Self-Maneuverability

In order for satellites or spacecraft to accomplish their mission, their orientation and position in space often require extremely precise management, performed by onboard control systems. Spacecraft health monitoring is required for all space missions to accomplish their predetermined tasks. The general scope of spacecraft trajectory is set by the launcher that hauls it skyward, selected by orbital dynamics experts long in advance of the spacecraft being built, after which smaller thrusters maneuvers, it into its operational orbit. After that the onboard closed-loop control is in charge of health monitoring of the spacecrafts pointing direction, known as its attitude, as it proceeds along its predetermined orbital path.

The practical problem is that spacecraft have their predetermined attitude perturbed for various reasons, which are listed as:

1) Gravitational forces from Earth;
2) Higher layers of atmosphere create air-drag;
3) Interference between the magnetic fields of the Earth and satellite;
4) Vibrations within the satellite due to propellants carried by itself; and,
5) Radiation from the sun [8].

Generally, in the present day situation, the perturbing effects of such external and internal torques are monitored under a health monitoring system on a regular basis from spacecraft ground control stations. The health parameters are downloaded regularly, monitored by expert spacecraft controllers and then to be counteracted by firing the thrusters to maintain the spacecraft in its pre-designated path, known as orbital control measures. The thrusters are fired very precisely on a selective basis for the required amount of time. The health monitoring system corrective measures from the ground are based on downloaded inputs from onboard sensors to identify the satellite's current attitude, such as gyroscopes, star trackers, Sun sensors or magnetometers and actuators including thrusters, reaction wheels or magnetic torques, to trigger the desired corrective rotations around the satellites center of mass.

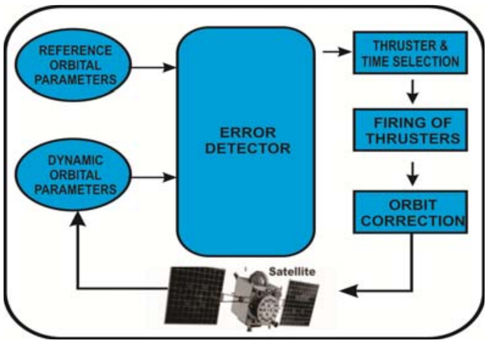

Fig. 1 Block Diagram of a Self-Organized Spacecraft System for Self-Orbital Control

The proposed onboard closed-loop control system designers should use the latest technological advancements in miniaturization, modular concepts to design the closed-loop control system. This system should be able to continuously respond to external disturbances in a proper manner. The closed-loop control system must include controlling software algorithms along with suitable actuators and sensor technologies. This closed-loop control system also ensure the solar arrays face the sun for power, data handling and pointing of the spacecraft towards Earth for its designated task including maintaining the spacecraft clock and onboard systems of health monitoring status.

The closed-loop control system focuses on the modeling of dynamic systems and the design of closed-loop controllers that cause these systems to behave in the manner desired. Maintenance of the spacecraft's relative position in space requires a closed-loop control system. In this, a group of sensors need to continuously monitor the orbital positional parameters and give inputs to an onboard computer system through actuators to control the error and keep the spacecraft in its designated path. This computer system automatically compensates the errors in real-time arising due to external disturbances and maintains the spacecraft as per the owner's operational specifications as well as design. This would include satellite attitude and orbit control, antennas or optical terminal fine pointing, and more generally guidance, navigation and control for space vehicles that have to accomplish specialized functions.

Design considerations, as shown in Fig. 1, must change which is proposed here in this research paper to prepare for space operations in the near future and beyond. Virtually all aspects of spacecraft orbital control system design need to be addressed, including interfaces, closed-loop control system, spacecraft housekeeping, navigation, telemetry, tracking and control, mission payload management, space controllers monitoring and control system along with ground segment. From the block diagram, the dynamic parameters are continuously monitored for its deviations. The deviations are preset limits such as 5 to 6 kilometers from the original path. Once the deviation limits are being approached, they are compared with reference parameters and the error detector generates error voltage. This error voltage is fed to a suitable thruster motor–spin wheel mechanism for selection of the respective thruster motor and required time duration. This firing of the thruster motor-spin wheel mechanism will bring back the spacecraft to its original position. This closed-loop control system will automatically operate for self-organizing the spacecraft for self-controlling it to maintain the spacecraft in its intended position. These proposed design considerations will help in more effective self-control by the spacecraft with in itself. Interfaces specifications are required to be reworked and suitably redesigned. Redefining and redesigning is highly applicable to onboard hardware interfaces such as physical, electrical, thermal, but even more critically on the data interfaces for payload to communications systems, inputs and outputs for spacecraft housekeeping, navigation, closed-loop control systems and ground station hardware.

B. Design of Adaptive Spacecraft System for Self Protection

In present day defense scenarios, where intercontinental missiles and ASAT play an extended role to achieve dominance in space, there is need for surveillance, monitor and defend these space assets. Every nation across the world is trying to acquire space-based platforms for its services. The United States has most advanced capabilities in space-based platforms as well as destruction resources from the ground [9]. China and Russia also have quite enhanced capabilities to destroy satellites from ground-based weapons. India is also keen to develop its own capabilities to destroy satellites from ground-based weapons [10]. China has conducted testing of an anti-satellite weapon on January 11, 2007, by destroying its own weather satellite successfully [11]. China has used its SC–19 missile to destroy the FY-1C weather satellite with a kinetic kill warhead [12]. Russia is believed to have been continuously developing ASAT, including laser beam ASAT [13]-[18]. China continues to test ASAT in space [19]. India is known to have been developing an Exoatmospheric Kill Vehicle (EKV) that can be integrated with the missile to engage satellites [20].

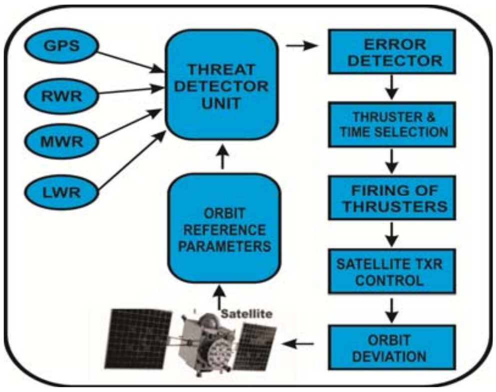

Fig. 2 Block Diagram of a Self-Organized Spacecraft system for Self-Protection

An important consideration here is the development of Radar Warning Receivers for threat detection of spacecraft. With the Electromagnetic spectrum being extremely volatile, the radar warning receiver is a helpful device for the location of incoming direction and other details of threatening radar waves so that suitable defensive actions can be initiated for self-protection by any satellite. The radar warning receiver block receives the radio frequency input and gives the pulse width, pulse repetition rate and frequency of attack [21]-[24]. The data acquisition subsystem needs to be carefully designed with suitable filters, amplifiers, and the data acquisition on board to work for spacecraft altitudes.

Providing timely warning against missiles is a challenge. The missile warning receivers must therefore provide reliable and timely warning to allow appropriate counter measure responses by the spacecraft. Near 100% probability of warning and very fast reaction times to counter missile launches are therefore essential. The missile warning receiver must also have sufficiently low false alarm rates, even when illuminated by multiple sources (which may include threats) from different directions [25]. Spacecraft usually have limited space and mass capacity for additional equipment. The missile warning receiver will generally have smaller pulse widths compared to radar warning receivers though similarities exist.

Laser warning receivers yield accurate ranges and give precision guidance to missiles towards a target, especially towards fast moving platforms [26]. Spacecraft can also be detected and tracked by laser radar sensors. Hence, the spacecraft is required to be equipped with laser warning receivers, in addition to radar warning and missile warning receivers.

Additionally, to avoid heat/infra-red seeking missiles, suitable design can also be considered to switch off onboard and transmission systems for short durations.

The proposed closed-loop control systems as in Figs. 1 and 2 should also not cause adverse space drag which demands minimal physical size and number of units. The power requirements for the closed-loop control systems proposed in this paper are an additional load to the existing onboard electrical system capacity. The design of interfaces and integration aspects should be such that, it has to coexist with the other onboard spacecraft electronic systems in an amicable manner. The design and development should be in such that duplication units to be avoided and suitable interfacing circuits since space is a limited source on board the spacecraft. This platform is required to be equipped with radar, missile and laser warning receivers, clear sensing of threats to have clarity and in an unambiguous manner. Further the performance and availability of the systems in required to be maintained throughout the life cycle of spacecraft. Installation and integration of these systems have to be suitably matched with the other housekeeping systems of the spacecraft.

IV. Analysis and Discussions

In the year 2020, an ever-increasing number of satellites will be orbiting the globe. Access to space is assumed to be much more affordable and responsive. Satellites will be smaller and last much longer than the satellites of today, while some might be deliberately designed for short life and early replacement to take advantage of continually emerging technology. Satellite missions will be more varied, but the underlying spacecraft capabilities will enable a more routine approach to space operations. Human involvement with each satellite will be greatly reduced. As observed from Figs. 1 and 2, the proposed system can increase the scope of commonality among closed-loop control systems for both hardware and software integration and has the potential to greatly reduce the proposed onboard equipment.

A focus on interfacing and integration of these systems allows an increased degree of commonality among space systems, both in hardware and software, and has the potential to greatly reduce ground station equipment in space segment, ground segment including training and operations costs.

The advantages of threat warning receivers include:

- Can potentially achieve longer detection ranges at altitude where there is no ground clutter.
- Can potentially detect the kinetic heat of missiles after motor burnout at altitude, compared to low-level aviation targets due to high infrared background clutter.
- Provides good area of operation information for pointing and good decision-making regarding positional change and maneuvering.
- The threat detection system proposed in this paper is ideal for low earth orbit satellites, since they fall well within the ranges of long range missiles.
- The self-organizing system idea itself, if achieved, will be a great boon for space technology.

The disadvantages of threat warning receivers include:

- Spacecraft operation which precludes all-weather operation, even a few tens of micrometers of water in the atmosphere between the threat and the sensor, is sufficient to effectively blind both the missile warning receiver and laser warning receiver sensors.
- Must compete with massive amounts of natural (sun) and man-made infrared clutter.
- False alarm rate and/or probability of warning can therefore be a problem against surface-to-space missiles due to high infrared background clutter originating from the Earth.
- Needs vast computing power to alleviate a false alarm problem which in turn drives up the cost.
- To assist in the suppression of background clutter and lower the false alarm rate, design of suitable equipment on board the spacecraft may solve some problems, while it creates others, as it complicates the system further due to the optical, sensitivity and extremely high pixel rate requirements which impact negatively on cost, weight, size and reliability.
- Cannot provide accurate range information.
- Traditionally missile and laser warning detectors have very narrow instantaneous fields of view to achieve good enough signal to target ratio. Large detector arrays are therefore required to provide 360° azimuth coverage which is difficult to design on any space platform.

V. Conclusions

Space is becoming unmistakably more multilateral in character. The number of satellites in geostationary Earth orbit (high altitude) is likely to double in the next 10 years and usage applications are ever increasing. Continued growth in the number of spacecraft will amplify the risks of ambiguities and potential accidents and generate further requirements for effective self-organizing capabilities in respect of orbital control and self-protection. The self-organizing system proposed in this paper is most ideally suitable for low orbit earth satellites, since their number is ever increasing due to their vast usage by modern society. This can be seen from Table I, where low earth orbit satellite numbers increase over the years to justify the proposed technological solution for self-organizing orbital control for maintenance in its original position and also for deviation as required for self-protection.

The key theme of each of these changes is increased satellite autonomy, to include onboard navigation and housekeeping functions, which implies the need to think about an entirely new way of self-tracking and controlling space systems. In other words, each spacecraft has to have a self-organizing control system for monitoring and for orbital control and protection capabilities. Many of the improvements proposed in this paper, when viewed in isolation, have the potential, on their own, for cost saving and increasing operational effectiveness through self-organizing capabilities. When combined, these proposals constitute a novel approach to space operations and a pivotal and dynamic space role for the space industry.

In this paper, the primary elements of a new spacecraft with self-organizing capabilities for orbital control have been successfully elucidated as a self-control concept. First, the paper has come out with an idea of self-correction of orbital changes automatically. Second, it has suggested self-monitoring of space threats and to take corrective measures through the closed-loop control system for orbital changes for automatic protection from ASAT. Thus, the design changes needed to eliminate stove piped systems based on satellite ground station control in favor of systems that can be unique yet conform to interface standards for self-organizing capabilities. Third, the paper successfully describes how spacecraft system design must change to support this philosophy, as well as the implications these design changes will have for space operations.

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