1. Introduction

1.1. Space Rendezvous and Docking

Space rendezvous between two spacecraft includes orbital maneuvers that bring both the vehicles into the same orbit in the close vicinity of each other. This requires a precise match of the two spacecraft orbital velocities to allow them to remain at a constant distance. Docking, so far most frequently done between a spacecraft and a space station, is one step further to rendezvous which includes close approach maneuvers to mate both the spacecrafts to form a single connected system.

To achieve space rendezvous and docking the standard technique applied so far is to dock an active vehicle with a passive target. This has been used successfully used in many of the previous missions such as Gemini, Apollo, Soyuz, Mir, International Space Station (ISS) programs to mention a few [3]. The active vehicle is put on a gradual course towards the target with a reduced rate maintained by the reaction control system. Maneuvers are mostly performed in the orbital plane containing both the spacecraft and most of the methods used until recently are performed with a human in the loop supervision. Particularly, the last phase of docking was specially dependent on astronauts for manual control and to protect the mission against possible anomalies.

1.2. Cooperative vs Non-cooperative targets

Before we proceed further to distinguish between different types of non-cooperative targets and their behavior, we need to understand some basic elements of an RVD mission. In general, a RVD or a servicing mission comprises of two spacecrafts.

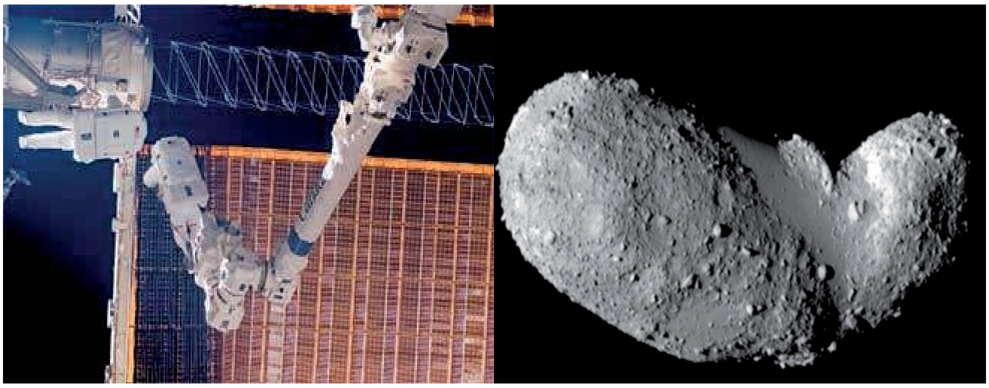
- ***Chaser***: a fully operational spacecraft which performs RVD with another spacecraft,
- ***Target***: the key spacecraft with respect to which the entire RVD is planned and performed.

Precisely, chaser is required to perform rendezvous and docking approaches towards that target satellite. Note that in rendezvous terminology, a chaser is also referred to as a deputy or follower and the target is also called a chief or leader.

Target vehicles in a RVD mission are usually passive and these can be cooperative or non-cooperative. *Cooperative targets greatly facilitate the rendezvous and docking processes by providing their navigation solution states to the chaser and performing cooperative maneuvers for docking/berthing. Non-cooperative targets, on the other hand, cannot give any information concerning their states nor can be autonomously controlled.* These can be objects orbiting around Earth such as spacecrafts which have lost their control authority in one or more degrees of freedom. Other notable non-cooperative targets, not specifically dealing with man-made satellites include deep space objects such as asteroids. With appropriate changes to definition terminology given by *Simon*, the following category of targets can be identified depending upon their navigation performance, control authority and the level of cooperation that they offer to the chaser in the RVD mission [4, 5]:

1. ***Cooperative target***: Target is fully capable to communicate as well as control its states and facilitate for a coordinated and cooperative docking.
2. ***Target controlling its attitude***: This kind of target is able to communicate its states, but has control authority only over its attitude. A fuel depleted satellite which uses reaction wheels for its attitude control falls under this category.
3. ***Target uncontrolled***: This target is able to communicate its states, but has no control authority on its displacements and attitude. Such a target would show a drift, tumble or both w.r.t. the chaser. For e.g., a fuel depleted spacecraft which has no working reaction wheels.
4. ***Target non-cooperative***: This is a target which cannot give any information of its states and has no control authority on its displacements and attitude and therefore cannot be autonomously controlled. Examples include dead satellites, space debris etc.

All the categories from two to four can be called non-cooperative in some sense as none of them are completely cooperative in a RVD mission. Incapability in conveying their states fully and incompleteness in exersizing control authority in all degrees of freedom differ them in their extent of cooperation that they can offer during the RVD process. We shall therefore refer to the term non-cooperative synonymously to apply to all these three categories in general. Also is clear from the above categorization is that the first type of satellites can be easily approached and docked with by a chaser. Category two can also be tackled easily but the most difficult ones are the uncontrolled and non-cooperative satellites of categories three and four. It is in the light of dealing with these targets that this thesis aims to propose some useful guidance and control strategies. Fig. 1.1 shows some examples of non-cooperative targets (courtesy: NASA) such as the satellite STS-116 with an uncontrollable solar panel and the Itokawa asteroid [6].



(a) STS-116 with uncontrolled solar array.

(b) Itokawa asteroid.

Figure 1.1.: Examples of non-cooperative targets: satellite STS-116 with an uncontrollable solar panel (left) and an asteroid (right).

Special focus is laid upon exploring the GNC module in this work. Therefore, we can broadly distinguish between a cooperative and non-cooperative target based upon its GNC subsystem as follows:

- *A cooperative target is axis stabilized where as a non-cooperative target can exhibit random motion such as a tumble or a spin.*
- *A cooperative target has a functional sensor system so that it can convey its states to the chaser. The states of a non-cooperative target are to be estimated using a navigation filter on the chaser.*
- *A cooperative target has a functional actuation system that helps it to control any of its degrees of freedom. Thus it greatly facilitates docking/berthing process in a RVD mission which is not the case with a non-cooperative target.*
- *A cooperative target offers less risk and can be maneuvered away from the chaser in anomalous situations and can perform collision avoidance maneuvers. This is however not the case when dealing with a non-cooperative target where all the Fault Detection Isolation and Recovery (FDIR) and Collision Avoidance Maneuver (CAM) functionalities must be taken care of only by the chaser.*

Fully or partly functional satellites already in orbit are called *current assets* where as those which are in a planning or manufacturing stage and would be placed in orbits at a later date from now comprise *future assets*. Some of these current assets must have lost their control only over their attitude but others, on all of their states including displacements. Depending upon their residual angular momentum, such targets can be either stabilized due to gravity, show a slow drift or tumble motion. In some cases they can also exhibit a slow gradient rotation or a faster spin. *Matsumato* et al., categorizes the current non-cooperative assets in orbits according to their attitude and angular rate errors. This is illustrated by Fig. 1.2 which also describes the current state of these targets in orbit. According to this four stage classification, a satellite whose attitude rate error is less than 0.1 deg/sec is considered to be 3-axis stabilized where as one with an error up to 1 deg/sec still aligns itself along with the gravity gradient vector and can be stabilized. Satellites having an attitude rate error from 1 deg/sec to 18 deg/sec are classified tumbling and those with more than 18 deg/sec rate error are considered spinning [7].

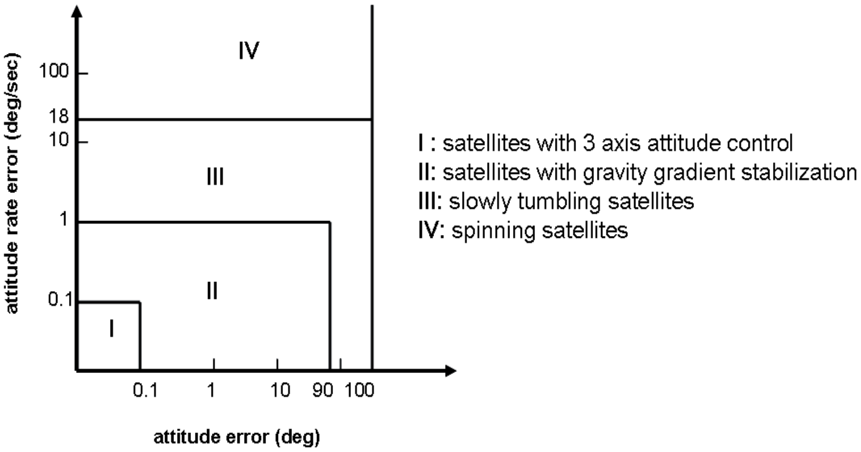


Figure 1.2.: Non-cooperative target categories based on attitude and rate error.

For categories three and four, there are no internally generated forces or torques. Once operational satellite is shut down after its end of mission life time, it is freed of its remaining fuel from its pressurized tanks, drained off its electrical energy and angular momentum is completely desaturated by spinning down wheels. Unless otherwise left over with residual momentum, such a dead satellite still is stable or very slowing rotating. The motion of these satellites is driven only by the natural orbital dynamics coupled with any external disturbance forces or torques that may act upon them. As a result, depending upon their attitude and attitude rate errors, it is expected that these targets either exhibit a slow tumble or a spin. A non-cooperative spinning target usually has its spin axis along one of its axis of principal inertia. For symmetric targets, this can be any of the three body axis whereas for assymetric ones, this axis is either major or minor axis of inertia [8].

1.3. Motivation

Yet, the most important question still remains. Why do we need to deal with this kind of complicated targets? The answer is rather straight forward: leaving aside the commercial angle of the story, it is predominantly more to do with safety issues.

In a recent move to avoid drastically increasing space debris, NASA has clearly stated that any future spacecraft orbiting around Earth should be de-orbited in a span of 25 years after their launch. This emphasizes on the problem of increasing space debris as most of the current assets orbiting around earth were designed without any idea of getting serviced or removed from the orbit. Shut down satellites after their life time simply move in orbit and are a big hindrance to other functional spacecrafts either as a whole or in parts when hit by other objects. Fig. 1.3 shows startling images produced by the European Space Operations Center (ESOC). These images consist of thousands of objects orbiting in different orbits around Earth most of which are only junk. As a rough estimate, ever since the first launch of Sputnik and out of 6000 spacecrafts that were placed in different orbits above Earth until now, the functional spacecrafts at present are only less than a thousand. Whereas a few have already escaped into deep space, most of these no-use spacecrafts simply orbit around the earth only to threaten the existence of other functional ones. It is also suggested that big target removal is more advantageous than focusing more upon the smaller ones. This would lessen the hit zone and impact area and also cuts down the amount of small little debris emerging out of a collision [9].

Figure 1.3.: Trackable objects in LEO (left), from LEO to GEO (right) around Earth comprising mostly of space debris.

Objects from deep space such as asteroids can always guide themselves towards Earth to threaten its safety and the enormous and diverse life it supports. Though the concepts of docking would be meaningless to this interplanetary object, the problem of rendezvous, safe landing etc. would still remain the same. The GNC study made here can also be applied to dealing with these type of targets and develop suitable protective measures if any possible collision with Earth is detected.

All the reasons aforementioned justify the need for the development of safe and efficient strategies to perform autonomous rendezvous and docking both with cooperative and non-cooperative targets. Development of technologies able to deal with these kind of targets is mandatory before the situation goes desperate and dangerous.

1.3.1. OOS with autonomous RVD technology

Perhaps, a more realistic and beneficial way of highlighting a solution to the problem of dealing with any kind of targets in general is to develop OOS technology. OOS adds a commercial dimension to the problem and is yet another important area of intensive research. It aims to ensure greater survivability of a mission by repair of malfunctional satellites, refueling, retrieval and rescue of stranded satellites. It also facilitates assembly of larger units in space and perform clearance operations such as de-orbit of space debris. As the terminology itself indicates that it is a servicing mission, it involves two or more spacecraft in which one or more (in case of satellites flying in formation) may not be fully cooperative. Satellite servicing, particularly with non-cooperative targets, can result in unforeseen complicated scenarios and introduces new challenges not met in the previous docking missions. These missions can give rise to anomalous situations that may arise out of navigation problems, fuel depletion, insufficient safety, hardware issues etc. For e.g., mechanical assistance to restore operation is needed for a troubled satellite with a non-deployed solar array or antennas. Spinning or tumbling spacecrafts posses high risk of collision with rotating appendages like solar panels or antennas. Tumbling motions are to be stabilized in many cases: the deployment after orbit insertion is an example. A thruster failure on the satellite when it attempts to stabilize the tumble can result in an uncontrollable motion. Hence, proximity or close range operations with these target spacecrafts need an increased level of autonomy in task sequencing and their robust execution. This not only ensures greater success of the mission but also faster and safer reaction to random internal or external events such as component failures or obstacles in the desired flight path.

OOS can be realized by RVD/B technology. This technology lays foundation from far range to proximity to terminal or final phase operations normally encountered in OOS. Assuming continued market opportunities and service reliability, extension of lifetime of customer satellites through regular repair and maintenance in orbit is totally justified. Although the costs of servicing remain high during the initial phases due to point-design solutions, as the technology matures and a knowledge base is acquired from experience, serviceability becomes enhanced and the costs begin to deflate. Furthermore, with developed OOS technologies and cooperatively designed future assets, a maximum serviceability to cost ratio can be realized. More significantly, it also suggests for compulsory de-orbiting strategies at the end of mission life time and a need for a systematic structural development of future assets.

1.4. Historical review

This section is intended to brief a survey on the automated RVD technology and associated missions and the extent to which they have been successful. The review is gradually evolved in three subsections with the first one briefing the general docking missions that have been attempted so far. The following subsection outlines a review on OOS and related missions. The last subsection highlights the current research trends and missions under study that are exclusively dedicated to deal with non-cooperative targets.

1.4.1. Brief survey on RVD missions

Most of the missions till date dealt with cooperative targets, the targets which are fully functional. Furthermore, RVD strategies with these targets were usually mission specific. They mostly relied on crew control during proximity operations with humans facilitating the final phase docking process. To envisage OOS, non-cooperative targets, which comprise most of the current assets, are now looked upon with special interest and new automated trends in RVD strategies with these targets are seriously considered and attempted, for e.g., in Orbital Express mission.

Automated Rendezvous and Docking (ARVD) interests surfaced mainly in two areas, the first being the autonomous delivery of cargo to the ISS for resupply and reboost and the second to plan complex manned and unmanned missions to Mars. Studies on executing manned and unmanned missions to Mars greatly influenced the development of this area of research. Significant reduction in size and mass of the Mars surface sample return spacecraft was noticed if the sample collecting lander is separated from the orbiter . However upon return, owing to a long transmission delay with Earth-based ground controllers, an autonomous docking maneuver is to be performed in the Mars orbit between the orbiter and the sample capsule taking off from Mars. To ensure crew safety, an autonomous docking maneuver in the Mars orbit seems unavoidable [4]. ARVD is also a must during failures or in situations of long communication/transmission delays due to which sufficient ground control cannot be executed. NASA's new vision for a long term Space Exploration in the 21st century involving completing ISS assembly, building the Crew Exploration Vehicle (CEV) etc. all require sophisticated RVD techniques to be routinely implemented.

The U.S. astronauts Armstrong and Scott performed the first successful docking maneuver on March 16, 1966 when they docked their Gemini 8 capsule to the Lagena Target vehicle. However, Russian's approach to docking was mostly automated in their approach with standardized operations. Docking of the Soviet experimental unmanned spacecraft Cosmos-186 with Cosmos-188 on October 30, 1967 was the first automated docking maneuver ever performed. Low computational capabilities available in those early days of spaceflight restricted the use of extremely simple guidance strategies and control algorithms for docking. The same automated approach was used in manned missions of the Salyut space station during the early 1970s, and in this case, the crew was mostly involved in monitoring and manual backup functions. Both the cosmonauts and the ground controllers remained available to gain control to counteract anomalies [10].

A modified unmanned Soyuz ship called Progress was developed by Russians in mid 1970s. This vehicle was used to ferry cargo to the space stations and to trash disposal when it disintegrates in the Earth's atmosphere during return. The development of this spaceship was necessitated from a series of malfunctions with the previous automatic docking system and the need for a frequent resupply of the Salyut space station. Progress was modernized after the Salyut era and was then used initially for Mir space station until mid 1990s. After the collapse of Mir station, it was used for ISS and is still the unmanned vehicle to dock with ISS [11].

Figure 1.4.: Appollo-Soyuz docking scenario (courtesy: NASA).

The above discussion was mostly confined to performing a RVD mission with a cooperative target, the ISS for example. Each of these missions showed an improvement in their technological design and demonstrated increased level of autonomy. Future day missions such as European Automated Transfer Vehicle (ATV), Japanese H-II Transfer Vehicle (HTV), advanced servicing missions like Hubble Space Telescope (HST) robotic servicing mission, de-orbit missions, etc. will definitely benefit from the experience acquired from these past missions.

1.4.2. Survey on On-Orbit Servicing

The early experiences with OOS, e.g., servicing of the Skylab space station in 1973, required space suited humans to perform the servicing tasks through Extra-Vehicular Activity (EVA) missions. Important technological advances for OOS are made since the manned OOS of the Skylab. As an example of such advances is the fifth service of the Hubble space telescope by the STS-125 accomplished jointly by robotic systems and astronauts [12]. Nowadays, robotic OOS activity is becoming a favorable option due to emerging set of key technologies for autonomous rendezvous and capture such as development of integrated systems, machine vision, autonomous control etc.

On orbit serviceability of space systems architectures and the concept for space tugs were presented in a greater detail in [13, 5]. As far as the real world implementation is concerned, on-orbit service demonstration has been done by the Roboter Technology Experiment (ROTEX) in 1993, a German experiment flown by NASA. By accomplishing tasks from autonomous scripts, ROTEX became the first autonomous space robotic system to demonstrate several prototype tasks such as assembly and repair functionalities [14].

Autonomous rendezvous had been used for docking more recently on the ETS-VII and Demonstration of Autonomous Rendezvous Technology (DART) missions. However, anomalies troubled both of these last missions. The Engineering Test Satellite flown by Japan Aerospace Exploration Agency (JAXA) was composed of a resident space target (Orihime) and a chaser (Hikoboshi), see Fig. 1.5. It successfully demonstrated cooperative control of the robotic arm and satellite attitude, visual inspection and satellite handling [15, 16]. Developed and launched by National Space Development Agency of Japan (NASDA) in November 1997, it carried out a lot of interesting orbital experiments with a 2 meter long, 6 degrees of freedom (DOF) manipulator arm mounted on the spacecraft. The mission consisted of two subtasks: one to do autonomous RVD and the second to perform robotic experiments. With final stage guidance performed exclusively along V-bar of Hill frame, its main objective was to test robotics technology and demonstrate its utility for un-manned orbital operation and servicing tasks. Multiple anomalies caused safe mode entries over the course of the mission. Guidance and navigation errors caused a programmed maneuver to move the chaser spacecraft 2.5 m away from its target [17].

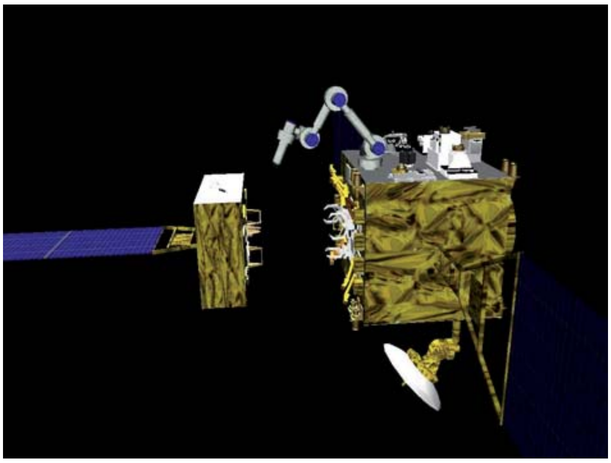


Figure 1.5.: Engineering Test Satellite (ETS-VII).

The DART spacecraft was launched a week after XSS-11 by NASA in April 2005. It came up with an objective to demonstrate in space the hardware and software necessary for ARVD down to a few meters from the target. The vehicle used a linear static gain feedback control law for both attitude and translational control and modulation was done using pulse width technique. Excessive fuel usage than required resulted in anomalies and on-orbit collision. The mission failed in its first approach to the target. This was due to a bias in the velocity measurement from primary Global Positioning System (GPS) receiver by almost 0.6 m/sec. This resulted in the divergence of its navigation filter and caused errors in thruster firing. Ineffective collision avoidance made DART eventually collide with the target. This is a clear indication that ARVD has not matured enough to be a safe technology. It also highlights the need for designing approach trajectories that guarantee collision avoidance for some common failures and simultaneously decrease the likelihood of catastrophic failures [18].

An on-going mission after DART dedicated to ARVD and usage of robotic technology in space is the DARPA Orbital Express Advanced Technology Demonstration experiment. Launched in March 2007, the mission's goal was designed to meet a broad range of U.S. future security and commercial space programs. Feasibility in using robotic, autonomous on-orbit refueling and reconfiguration of satellites were tested in this mission [19, 20].

Orbital Express mission demonstrated critical technologies concerning OOS systems including servicing interfaces, autonomous GNC systems, close proximity operations, ARVD, fluid replacement transfer unit, etc. To verify the system's autonomous fault response capability, multiple docking scenarios with increasing difficulty were attempted. It has demonstrated the ability to approach, rendezvous, autonomous

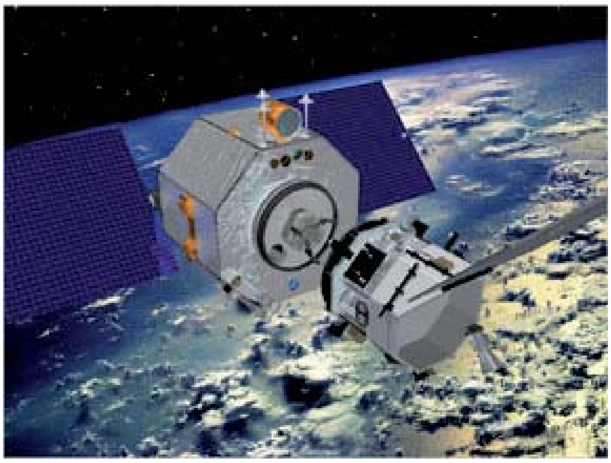


Figure 1.6.: The DARPA Orbital Express mission.

capture of the target satellite and then used robotics for service [20, 21, 22]. This project envelopes key technologies for robotic OOS of future cooperatively designed assets which can still be referred to as non-cooperative targets in the sense that they cannot be maneuvered to facilitate the berthing/docking process. Of particular note is the use of two different patterns on the target spacecraft to estimate its pose: one bigger size pattern was used during far approaches and the other one was exclusively designed to facilitate visual navigation during proximity or close range operations when the chaser is within a range of 5 meters from the target. The SUMO is a DARPA project designed to perform OOS with many types of customer spacecraft without requiring servicing aids [23]. Fig. 1.7 illustrates the SUMO spacecraft grasping the target by using dexterous arms.

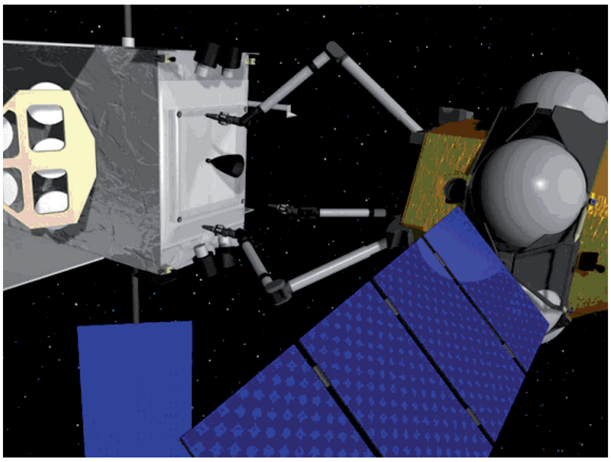


Figure 1.7.: The SUMO servicing spacecraft.

It needs no mention that targets that were handled by Orbit Express or ETS-VII experiments were to some extent cooperative as they were designed with an intention to be serviced. The problem of RVD with current assets which are already in orbit and are extremely non-cooperative still remains to be addressed. These spacecrafts are not equipped with any special aids such as docking ports/fixtures or retro reflectors. No doubt the level of difficulty that the problem poses is definitely higher, but a solution still seems to be plausible with a combined development of integrated technologies on robotics, machine vision, and GNC strategies. Familiar future day OSS missions for current assets comprise de-orbiting of large space debris or rescue and relocation of stranded spacecraft to its nominal orbit.

Table 1.1 provides a historical review of some important RVD and OOS missions attempted so far [24, 25, 26, 27].

Table 1.1.: Historical review of autonomous docking missions.

Mission	**Country**	**Year**	**Status**	**Type**	**Anomalies if any**
Cosmos-186, Cosmos-188	Russia	1967	success	docking	Misaligned capture
ETS-VII	Japan	1998	success	docking	Thruster anomaly, multiple anomalies caused safe mode entries over the course of mission
XSS-10	U.S	2003	success	inspection	Navigation problem, communication interruption
XSS-11	U.S	2005	unknown	inspection	Unknown
DART	U.S	2005	failure	inspection	Navigation problem, excess fuel expenditures due to biased measurements, on-orbit collision
Orbital Express	U.S	2007	on-going	docking	Navigation problem (GPS synchronization)
ATV-I	Europe	2008	success	docking	unknown
HTV-I	Japan	2009	success	docking	unknown