1

Introduction

1.1 Background

Rendezvous and docking or berthing (RVD/B) is a key operational technology, which is required for many missions involving more than one spacecraft. RVD/B technology and techniques are key elements in missions such as

- assembly in orbit of larger units;
- re-supply of orbital platforms and stations;
- exchange of crew in orbital stations;
- repair of spacecraft in orbit;
- retrieval, i.e. capture and return to ground, of spacecraft;
- re-joining an orbiting vehicle using a lander in the case of lunar and planetary return missions.

The first rendezvous and docking between two spacecraft took place on 16 March 1966, when Neil Armstrong and Dave Scott manually performed rendezvous in a Gemini vehicle and then docked with an unmanned Agena target vehicle. The first automatic RVD took place on 30 October 1967, when the Soviet vehicles Cosmos 186 and 188 docked. Thereafter, RVD/B operations have regularly been performed by the Russian (Soviet) and US space programmes; e.g. in the following:

- US Apollo (1968–1972) and Skylab programmes (1973–1974);
- Russian (Soviet) Salyut and Mir Space Station programmes (1971–1999) with docking of the manned Soyuz and unmanned Progress spaceships;

- US/Soviet Apollo–Soyuz docking mission (Apollo–Soyuz Test Project, ASTP, 1975);
- US Space Shuttle retrieval and servicing missions (starting in 1984 with the retrieval and repair of the Solar Max satellite);
- US Space Shuttle missions to the Russian space station Mir in the 1990s in preparation for the ISS programme;
- assembly, crew exchange and re-supply of the International Space Station (ISS) (begun in November 1998).

RVD/B technology and techniques have been studied and developed in Western Europe by the European Space Agency since the beginning of the 1980s, first as ‘enabling technology’ and, from the mid-1980s onwards, for the Columbus Man-Tended Free-Flyer (MTFF), which was intended to dock with the American Space Station Freedom, and for the European spaceplane Hermes, which was intended to visit the MTFF (Pairot, Fehse & Getzschmann 1992).

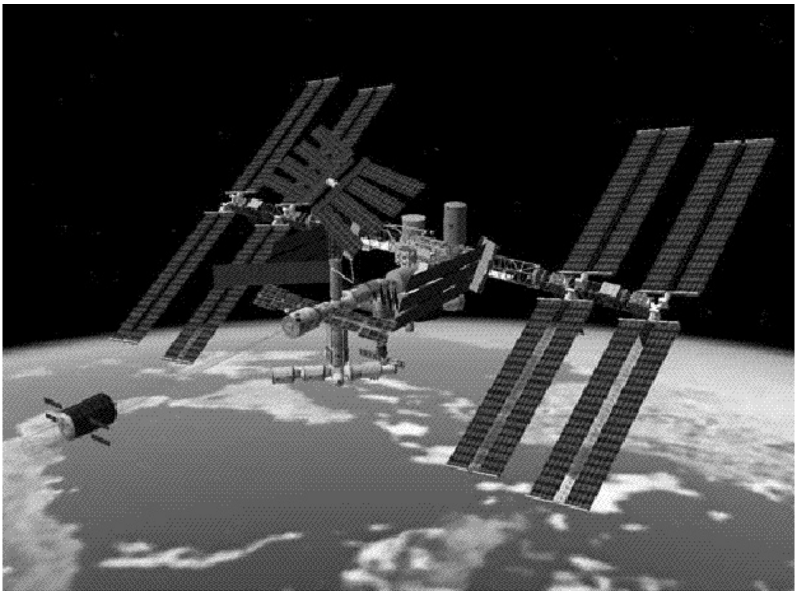

Figure 1.1. Approach of the ATV to the International Space Station (courtesy ESA).

After the cancellation of the MTFF and Hermes projects (as a result of the political changes in Europe) and after the merger of the eastern and western space station programmes into the International Space Station (ISS) Programme (NASA 1998*a*), the Automated Transfer Vehicle (ATV) has become part of the western European contribution (Cornier *et al*. 1999). The ATV will participate in the re-boost and re-supply missions to the ISS. The total fleet of vehicles, which will perform RVD/B operations with the ISS, includes the US Space Shuttle (manned), the Russian Soyuz (manned) and Progress (unmanned) vehicles, the European ATV (unmanned) and the Japanese H-II Transfer Vehicle (HTV, unmanned; (Kawasaki *et al*. 2000)). In addition to these transport vehicles it can be expected that, in future, inspection vehicles will be attached to the ISS. If required, they will fly around the station to inspect problem areas and to identify the nature of problems (Wilde & Sytin 1999). In the far future, such vehicles may also be used for maintenance and repair tasks. RVD/B technology will be required for the departure and re-attachment of such vehicles as well as for their operational tasks.

Although the ISS will probably be the most important application of RVD/B technology and techniques for the first two decades of the twenty-first century, there have been and will be other rendezvous missions, e.g. servicing of spacecraft in orbit (Hubble Space Telescope for example), spacecraft retrieval (EURECA, SPAS for example) and lunar/planetary return missions. Rendezvous and docking operations in geo-synchronous orbit for the servicing of communication satellites have been studied in the past in some depth; however, no such mission has yet been realised.

1.2 The complexity of the rendezvous process

The rendezvous and docking/berthing process consists of a series of orbital manoeuvres and controlled trajectories, which successively bring the active vehicle (chaser) into the vicinity of, and eventually into contact with, the passive vehicle (target). The last part of the approach trajectory has to put the chaser inside the narrow boundaries of position, velocities, and attitude and angular rates required for the mating process.

- In the case of *docking*, the guidance, navigation and control (GNC) system of the chaser controls the vehicle state parameters required for entry into the docking interfaces of the target vehicle and for capture.
- In the case of *berthing*, the GNC system of the chaser delivers the vehicle at nominally zero relative velocities and angular rates to a meeting point, where a manipulator, located either on the target or chaser vehicle, grapples it, transfers it to the final position and inserts it into the interfaces of the relevant target berthing port.

The complexity of the rendezvous approach and mating process and of the systems required for its execution results from the multitude of conditions and constraints which must be fulfilled. These conditions and constraints will be discussed in detail in the relevant chapters. A few examples are given below.

Launch and phasing trajectory strategy

For the chaser to arrive in the close vicinity of the target, it must be brought into the same orbital plane and must eventually have the same orbital height, phase angle and eccentricity parameters as the target. Due to the oblateness of the Earth, the orbital plane drifts with time and the drift rate depends on the orbital height. Therefore, the difference in plane drift of the chaser during phasing at lower altitude must be taken into account when choosing the orbital plane at launch.

After launch of the chaser, changes in the orbital parameters of the target station, e.g. due to attitude and orbit correction manoeuvres and orbital disturbances, have to be taken into account up to the final part of the orbital rendezvous, and the approach trajectories have to be updated accordingly.

Operations in the vicinity of the target station

The target station may impose safety zones, approach-trajectory corridors and hold points along the way to check out vehicle functions and other conditions. At certain points, permission to proceed by either ground or target crew may have to be received by the chaser prior to further approach. Any dynamic state (position and velocities, attitude and angular rates) of the chaser vehicle outside the nominal limits of the approach trajectory could lead to collision with the target, a situation dangerous for crew and vehicle integrity. Therefore, all approach trajectories must fulfil the following two conditions:

(a) Where possible, they should be inherently safe, which means that they should not lead to collision with the target, even in the case of loss of thrust capability or control at any point of the trajectory.

(b) If condition (a) cannot be achieved, a collision avoidance manoeuvre, valid for each point of the trajectory in question, must be available, which will move the vehicle safely out of the critical area.

Onboard system requirements and constraints

The nominal attitude of the chaser vehicle is determined by several factors, e.g. by the operational range of the sensors for attitude and trajectory control, by the range of the antennas for communication with ground and with the target station, and by the need to point solar arrays toward the Sun to obtain the necessary supply of power. Thrusters may also be arranged on the vehicle in such a way that they can produce certain forces with respect to (w.r.t.) a certain trajectory direction only at a certain vehicle attitude.

Synchronisation with Sun illumination conditions and crew work cycle

The rendezvous process has to be synchronised with the occurrence of suitable illumination conditions, i.e. the last part of the approach prior to arrival and the capture process must take place under proper illumination conditions. This is necessary in order to make monitoring of the docking or berthing process possible, either visually or by video cameras. An alternative would be artificial illumination, but this is constrained by the available electrical power. Also, the work/rest cycles of the crew in the target station may have to be taken into account. All these constraints may lead to very limited windows in the timeline where final approach and capture can take place.

Communication link constraints

In missions where at least one of the vehicles is manned, ground and/or target crew must, for safety reasons, monitor the last part of the approach and the docking. Since communication coverage, in particular to ground, is not complete, even when using two relay satellites, synchronisation with the communication windows imposes another constraint on the trajectory design. Furthermore, the data rate which can be transmitted is usually limited to a few kilobytes per second. Video transmission is very costly and, if it is available at all, would for this reason be restricted to the last few metres of approach and contact. In the major part of the approach, human operators can, therefore, monitor only key parameters of the vehicle, and human interaction with the onboard system will be restricted to simple commands, such as stop and go and collision avoidance manoevre initiation.

Effects on system and operations

The onboard system must cope with all these constraints by active control; otherwise the timeline and all events have to be pre-planned or controlled by ground. After launch, however, the nominal interaction with the spacecraft by ground is limited, as mentioned above. For unmanned vehicles this leads to the requirement of high onboard autonomy and, as a result, to highly complex onboard systems. It is not too difficult to meet each single condition and constraint addressed above. The combination of all the requirements, conditions and constraints, however, makes the automatic control of rendezvous and docking/berthing by an onboard system a very complex and challenging task.

In addition to the constraints addressed above, and to the multitude of functions required aboard chaser and target vehicles, monitoring and high level control by their respective control centres on ground, together with the infrastructure for communication and navigation in orbit and on ground, further increase the complexity of the rendezvous process. The most important functions in space and on ground required for automatic rendezvous and docking are shown schematically in figure 1.2.

Verification of proper operation and performance of all these functions alone and together in a system is the most difficult and critical task of the development of a rendezvous system and of the preparation of a rendezvous mission. It is not possible to test the various functions of the complete system in the proper environment, as this environment will only be available during the mission itself. Therefore, verification has to rely to a large extent on simulation. The validation of these simulations is an additional challenge.

Owing to the many players involved in rendezvous missions, both in orbit and on ground, and due to the fact that the sequence of operations will be relatively rapid toward the end of a rendezvous mission, operations tasks for the ground segment are more complex and challenging than for the operation of a single satellite. Proper coordination, allocation of tasks and a hierarchy of control authority have to be established between all players for the nominal mission operations and for all credible contingency cases.

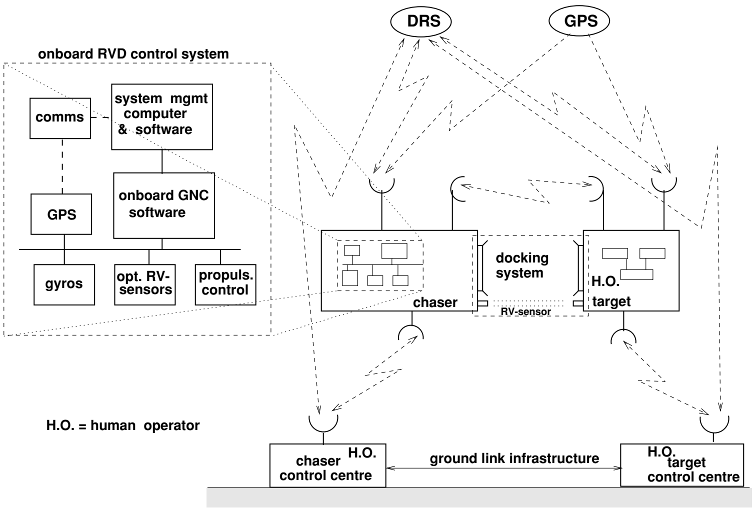

Figure 1.2. Major functions involved in the RVD process.

1.3 Objective and scope

The objective of this book is to provide a compendium for space engineers on all issues related to rendezvous and docking/berthing. The intention is to describe and explain issues in such a way that students and newcomers to the field can acquire a basic understanding of the problems and receive an overview on the major issues governing the approach and mating strategies and the system concepts for RVD/B. In particular, the book will enable spacecraft system engineers to obtain the background information on the RVD/B issues necessary for the conception of missions and vehicles.

The book is structured to provide successive answers to the following questions:

- How does the chaser reach the target spacecraft, and what manoeuvres and trajectory elements are needed to achieve this?
- What onboard functions are needed to perform RVD/B?
- What other functions in space and on ground must be available for the performance of RVD/B operations?
- How can proper functioning of all rendezvous systems and operations be assured before launch?

Chapters 2–5 are dedicated to the approach strategy, i.e. they intend to provide answers to the question: ‘How does the chaser reach the target spacecraft?’ In chapter 2, all phases of a rendezvous mission, including departure, are briefly described. Manoeuvre objectives, end conditions to be achieved and major issues for each phase are discussed. Chapter 3 provides an introduction to orbit dynamics and the trajectory and manoeuvre elements used in the rendezvous approach. The properties of the various manoeuvres concerning trajectory evolution, duration and delta-V (ΔV) requirements are derived and explained. Chapter 4 deals with fault tolerance and trajectory safety requirements. In particular, it addresses the effects of external disturbances, the sensitivity to measurement and thrust errors, the protection possibilities against such errors and the implementation of collision avoidance manoeuvres. Chapter 5 looks at all the other operational issues and constraints which are driving the design of the approach strategy. Issues such as location and attitude of docking ports and berthing boxes, sensor characteristics, monitoring conditions (illumination and ground coverage) and safety zones and corridors around the target vehicle are discussed.

Chapters 6–8 discuss the onboard functions required for RVD/B, including the algorithmic functions and the equipment. In chapter 6 the guidance, navigation and control (GNC) functions of the chaser vehicle are described for automatic systems and with man-in-the-loop. This chapter discusses further the automatic mission and vehicle management (MVM) functions and basic implementation possibilities of failure detection, identification and recovery (FDIR) functions. The MVM function is responsible for the automatic switching of GNC modes and of equipment required to implement the various trajectories and manoeuvres. Chapter 7 looks into the most important sensor design principles used for rendezvous trajectory control, and provides information on their performance requirements and operational range. Chapter 8 describes the docking and berthing concepts, the problems of contact dynamics and capture, the interfaces between GNC and mating systems and the different types of docking and berthing mechanisms.

The tasks of the ground control centres and of the target crew are discussed in chapter 9. This chapter also addresses the control hierarchy for RVD missions, involving manned and unmanned vehicles, and includes a description of typical setups and constraints of a communication infrastructure between space and ground and between the control centres. Requirements and concepts for support tools, used for monitoring and interaction with chaser spacecraft by ground operators and target crew, are addressed.

Chapter 10 intends to provide an answer to the question: ‘How can proper functioning and performance of all systems and operations involved in the rendezvous and mating process be verified and validated prior to launch?’ Verification and validation are the most critical and expensive parts of any development of a RVD capability, which has to be understood not as just the final act of development, but as an integral process of it, starting with the first mission concept and continuing with the development process. In this final chapter the possibilities and limitations of mathematical modelling of spacecraft, onboard systems and environmental features are discussed, various simulators and stimulation facilities for sensors used for verification are described, and the possibilities for validation of models and simulators by means of comparison with other proven models or simulations and comparison with actual flight data are addressed.

2

The phases of a rendezvous mission

The purpose of this chapter is to give the reader a short overview of the different phases of a rendezvous approach and to describe the major issues of these phases. It is hoped that it will be easier, after familiarisation with the basic concept of a rendezvous mission, for the reader to put the information given in the subsequent chapters into their proper context. For this reason, some of the information provided in more detail in the later chapters had to be duplicated in condensed form here.

A rendezvous mission can be divided, as indicated in figure 2.1, into a number of major phases: launch, phasing, far range rendezvous, close range rendezvous and mating. During these phases, the kinematic and dynamic conditions that will eventually allow the connection of the chaser to the target spacecraft are successively established. In the following sections of this chapter an overview of the objectives, the end conditions to be achieved and the trajectory implementation possibilities of each of those phases will be given. This includes a rough order of magnitude of the major performance values which the guidance, navigation and control system of the chaser will have to achieve. For completeness, a short section on departure has been added, which addresses the issues and constraints of separation from and moving out of the vicinity of the target station. The mission phases between mating and departure and after departure are not addressed as they are both, in objective and concept, fully independent of the rendezvous mission.

2.1 Launch and orbit injection

2.1.1 The launch window

Owing to the rotation of the Earth, each point on its surface passes twice per day through any orbit plane. However, as a launch in an easterly direction produces a gain in launch

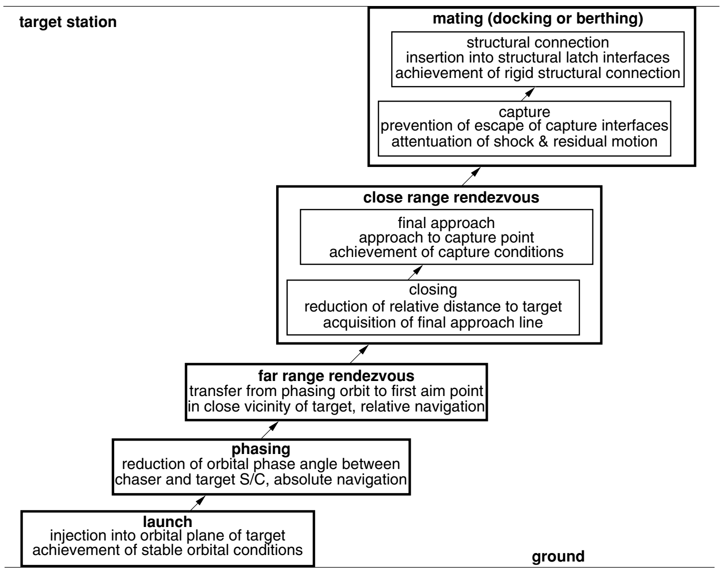

Figure 2.1. Main phases of a rendezvous mission.

velocity due to the tangential velocity component of the rotation of the Earth (≈463 m/s at the equator), and since at most launch sites only a limited sector of launch directions can be used (e.g. toward the sea), there is, practically, only one opportunity per day to launch a spacecraft into a particular orbit plane. With the Earth rotation of 15 deg/h, during every minute the launch site will move ≈0.25 deg w.r.t. the orbital plane (neglecting for the moment other drift effects). Plane differences resulting from a deviation from the nominal launch time can be most efficiently corrected by the launcher shortly after lift-off, when the relative velocities are still relatively low. A correction of the plane error in the final orbit would be much more expensive; e.g. at an orbital height of 400 km it would cost a ΔV of about 32 m/s to correct a 1 minute launch delay, see Eq. (3.20). Therefore, the size of the launch window, i.e. the margin around the time when the launch site passes through the orbital plane, will mainly be determined by the correction capabilities of the launcher.

2.1.2 Definition of orbit plane and other orbit parameters

Some brief definitions of concepts used in orbit mechanics are given here to provide the basis for the description of the rendezvous mission phases. A more detailed treatment is provided in chapter 3.

The direction in inertial space of the plane of an Earth orbit can be defined by two angles (see figures 2.2 and 2.3):

- its 'inclination' angle i, measured w.r.t. the equatorial plane of the Earth;
- the angle Ω w.r.t. a reference plane that is orthogonal to the equatorial one, but fixed in inertial space.

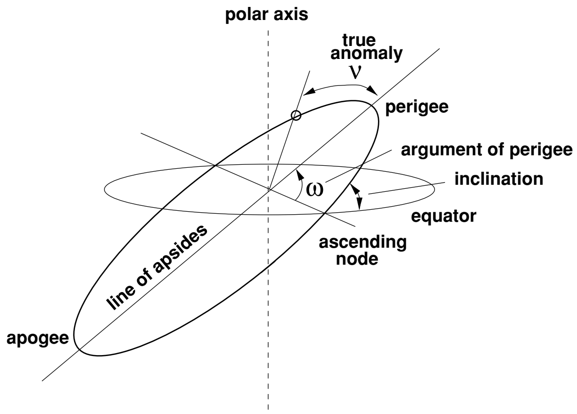

Figure 2.2. Definition of orbit parameters.

As the Earth rotates, one has to find a fixed point in space for the definition of this second reference plane. Convenient fix points for this purpose are the equinoctial points, defined by the intersection of the equatorial plane with the plane of the orbit of the Earth around the Sun (ecliptic).

The crossing points of a satellite's orbit plane with the equatorial plane are called the 'nodes'. The 'ascending' node refers to the point where the satellite is crossing in a northbound direction, and the 'descending node' refers to the southbound crossing point. This second angle, Ω, required for the definition of the orbit plane, is measured between the point of the vernal (spring) equinox and the ascending node (see figure 2.3). This angle is called the 'right ascension of ascending node' (RAAN).

An elliptic orbit is further defined by the size of its major (a) and minor (b) axes and by the location of its apogee and perigee w.r.t. the nodes (ω) or by corresponding expressions. The instantaneous position of a satellite on its orbit is defined by the 'true anomaly', which is the angle (ν) measured from the perigee of the orbit. These parameters are shown in figures 2.2 and 3.6.

2.1.3 Launch operations flexibility

In order to provide for sufficient flexibility of the launch operations, i.e. to provide as much margin as possible for possible interruptions of the countdown, one will attempt always to launch at the beginning of the launch window, whereas the nominal launch time will be in the middle of the launch window. The corresponding plane errors will