CHALLENGES AND TECHNOLOGIES IN NAVIGATION FOR RENDEZVOUS AND DOCKING

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Abstract

Rendezvous and docking (RVD) is a key operational technology which finds application in a variety of space missions involving on orbit assembly, re-supply, exchange of crew, repair and re-fuelling of spacecraft in orbit, spacecraft retrieval, re-joining an orbiting vehicle with a Lander in the case of lunar and planetary return missions, etc. The RVD process involves a series of orbital maneuvers and controlled trajectories of two orbiting vehicles, which successively bring the chaser vehicle into the vicinity of, and eventually into contact with the target vehicle. The absolute and relative navigation state vectors required during the initial launch phase and the far rendezvous phase can be derived by combining information from INS system, ground segments and by the fusion of raw GPS data from both chaser and target. The final approach and docking phase (within 300 meters) where the chaser has to navigate through narrow boundaries of position, velocity, attitude and angular rates is highly complex and challenging. The accuracy requirement at this point is in centimeter level in range, few tenths of degrees in Line Of Sight (LOS) and relative attitude. This requires a dedicated, reliable, high precision relative navigation and attitude reference system. This paper gives an overview of the navigation technologies employed presently and the challenges involved to meet the accuracies. RVD sensor architecture of a Videometer system comprising of laser sources, laser retro reflector clusters, detectors and processing algorithms is proposed. The optimal target pattern, the various elements like detectors, the algorithms required for image processing, state estimation filters and the related issues are addressed in this paper.

Keywords: Videometer, Rendezvous, Docking, Relative GPS, Laser retro reflectors, Chaser, Target

1. Introduction

The RVD missions require that two orbiting spacecrafts start at a remote distance, come together in a common orbit, come closer by rendezvous, dock and control the new combined spacecraft in both orbit and attitude. In this process, the final approach and docking phase is far more complex compared to the initial launch and orbit phase. In the earlier days, the approach operations as well as the on-orbit servicing operations were all carried out manually. The manual approach is costly and exposes astronauts to danger, while the scripted approach is tedious and error-prone. Unmanned, tele-operated, ground-controlled missions are infeasible due to communication delays, intermittence and limited bandwidth between ground and servicer.

Autonomous Rendezvous and Docking ensures that all operations are carried out in space without human intervention. But automated rendezvous mission towards a manned facility raises severe performance and safety constraints on the approaching vehicle. The mission should be operational after any first failure and safe conditions should be reached after a second failure. The navigation system of Autonomous Rendezvous and Docking missions should be designed to fulfill the stringent requirements of accuracy. They involve several functions to provide state vector estimations and health reports according to the flight phase along with attitude and drift estimation functions to provide the vehicle's absolute attitude and angular rate during the whole flight. All these navigation functions provide high level of performance, robustness and autonomy required for Autonomous Rendezvous and docking.

Rendezvous and docking missions can be divided into various major phases corresponding to the type of activities, the complexity involved, the relative distance between the two vehicles and the navigation architecture followed. Different systems and technologies are used in each phase for navigation and control of both chaser and target vehicle. While it is possible for both chaser and target spacecrafts to maneuver, the standard technique for rendezvous and docking is to maneuver the active chaser vehicle with the passive target vehicle being reasonably stable.

2. Phases of Docking

2.1 Launch and orbit phase

The RVD mission starts from the injection of the chaser to the initial orbit by the launch vehicle. The launch vehicle injects the chaser into a stable lower orbit in the target orbital plane. At this point, the chaser will be behind the target depending upon the phase angle between the two vehicles. From there, the chaser slowly drifts towards the target to reduce the phase angle and by orbit correction maneuvres reach an orbit very close to it.

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2.2 Far range rendezvous phase (homing)

This phase starts from a range of 30-50km. The main objective of the far range rendezvous phase (homing phase) is to achieve the position, velocity and angular rate conditions which are necessary for the initiation of the close range rendezvous operations. Major tasks of this phase are establishing link to the target, acquisition of target orbit, reduction of approach velocity and the synchronization of mission timeline. Typically the far range rendezvous starts at a range of few tens of kilometers and ends at a range of few kilometers from the target. For docking, typically an ‘Approach Ellipsoid’ of dimension 2km x 1km x 1km (major half-axis of 2km along the target orbit direction and minor ones of 1km) is defined [Wigbert Fehse]. The far range rendezvous phase ends at a point located outside the ellipsoid. Thereafter the close range rendezvous phase starts.

2.3 Close range rendezvous phase

The close range rendezvous phase (closing phase) aims at the reduction of the range to the target and achieve conditions required for the final approach. At the end of this phase, the chaser will be ready to start the final approach on the proper approach axis within the safety constraints of the approach corridor in terms of position, velocity, attitude and angular rates. For observability and safety reasons, a cone-shaped approach corridor will usually be defined within which the approach trajectory has to remain. The cone originates from the mating point at the target vehicle (i.e. from the docking port or from the berthing box) and has a half cone angle of 10 to 15deg (fig 1). Such a corridor allows ground operators and/or target crew to assess the accuracy of the approach trajectory via video cameras or other sensor information. If corridor boundaries are violated, collision avoidance maneuver commands will be issued.

2.4 Final approach phase

The objective of final approach phase is to achieve docking or berthing capture conditions. This phase ends with the delivery of chaser docking interfaces into the reception range of the target docking mechanism or of the capture tool of the manipulator in the case of berthing. In the case of passive capture latches (impact docking), there must be a certain axial contact velocity, as energy is needed to operate the capture latches. In the case of active capture latches (soft docking), the capture latches are motorized and triggered by sensors. This type of docking mechanism will work also with very low contact velocities. For berthing, the capture interface for the manipulator mounted on the chaser must remain for certain duration within a volume, which can be reached by the manipulator within that time.

2.5 Mating phase

The mating/docking phase starts when the GNC system of the chaser has delivered the capture interfaces of the chaser into the reception range of those of the target vehicle. This must be achieved within the constraints of the interface conditions, concerning approach velocity, lateral alignment, angular alignment, lateral and angular rates for docking; position and attitude accuracy, residual linear and angular rates for berthing. The mating system then achieves capture, attenuates the residual relative motion between the vehicles, brings the interfaces of the structural latches into their operational range, achieves rigid structural connection and establishes the necessary interfaces. The most important mating function is capture, as it is the natural end of the rendezvous process. The subsequent structural and utility connection tasks are for the success of the mission.

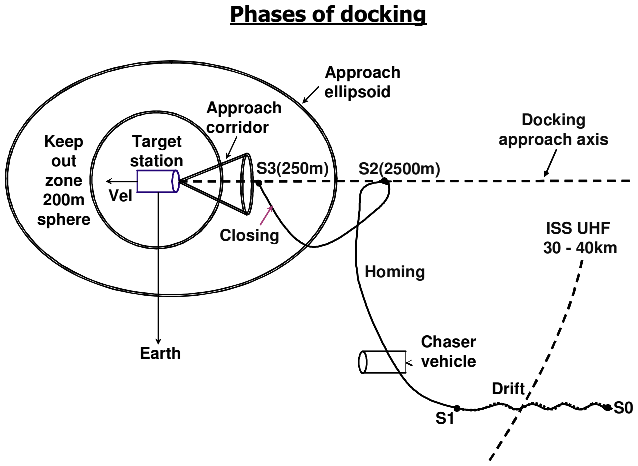

Figure 1: Phases of docking

The basic difference concerning capture between docking and berthing is that in docking, the body of the approaching vehicle is actively controlled to guide its capture interfaces into the corresponding interfaces on the target vehicle [Daero lee and Henry Pernicka]. In berthing, the manipulator arm plays the active role guiding its grapple mechanism to capture the passive grapple fixture on the other vehicle.

3. Design Drivers and Navigation Architecture

In RVD missions, the navigation systems residing in the chaser need to be active from the time of injection of the spacecraft into an orbit by the launcher to the point of docking with the target, and also from departure to re-entry. The accuracy of maneuvers and minimization of fuel consumption are permanent design drivers. This is possible only if the navigation state vectors are autonomously and continuously available with very high reliability throughout the mission duration [D.Pinard, S Reynaud and P.Delaux]. The chaser should not only know its own orbit but should have the knowledge of target orbit also. Depending upon the various docking phases, the orbit information can be derived from different sources like INS, GPS, ground segments, RVD sensors, etc. Table 1 gives a glimpse of the navigation methods and accuracy requirements in each phase.

Table 1: Accuracy requirement during each phase

Phase	Navigation methods	Accuracy requirement
Launch / Orbit	Absolute nav using INS, GPS	-
Far range rendezvous	Relative GPS, INS	100m in position 0.5m/s velocity
Close range rendezvous	Relative GPS	10m in position 0.05m/s in velocity
Final approach phase	Laser Radar, Optical rendezvous sensors	1deg in attitude 1cm/s in velocity 0.1deg/s in angular rates

During the **initial launch and orbit phase**, the two vehicles will be well apart by hundreds of kilometers and so they can't communicate with each other. The general requirement for two spacecrafts to communicate each other is that they should be in Line Of Sight (LOS) with each other; otherwise relative navigation won't be possible. The chaser then has to rely on absolute navigation only. Here the movements are in part based on utilizing the combined information from both INS and GPS system to determine the chaser state vectors and using stored information of the target location together with TDRSS (Tracking and Data Relay Satellite System) information and the information communicated from ground segments.

For the **far rendezvous phase**, typically within a relative range of 30 to 40km, Relative GPS (RGPS) navigation system is the natural candidate. This is because at this point, radio link can be established between the chaser and the target thereby making it possible for the two vehicles to communicate their state vectors with each other. The relative measurements of position and velocity can be derived by the fusion of raw GPS data from both the chaser and target. The required measurement accuracy of the relative navigation sensor at the beginning of the far range rendezvous phase is of the order of 100 m for position and 0.5m/s for velocity [J L Gonnaud, L Lagarde, S E Strandmoe and A ballereau].

For the start of the **close range rendezvous** operations, the required positioning accuracy is typically of the order of a few tens of meters and the measurement accuracy is of the order of 10m for position and 0.05m/s for velocity. The RGPS system can provide the required accuracy and reliability needed in both far range and close range rendezvous operations. Due to multi-path effect and shadowing, RGPS cannot be used in the final approach phase starting from a range of about 200 to 300 meters.

The **final approach phase** requires a fully dedicated optical rendezvous sensor based relative navigation system to meet the safety requirements in the approach corridor. Rule of thumb for the navigation measurement accuracy is approximately 1% of range (i.e. within few meters). It is compatible with the final control accuracies for docking, which is few cm in lateral position, about 1deg for attitude and of the order of 1cm/s for axial and lateral rates and 0.1deg/s for angular rates. For berthing, the absolute position and attitude accuracies are less critical, i.e. About 5 times higher values than those for docking may be acceptable. In contrast, the accuracy in measuring linear and angular rates must be approximately 5 times lower than those acceptable for docking.

The choice of the type of optical sensor for berthing is relatively easy. As measurement of relative attitude is not necessary, the laser range finder type of sensor is the best choice. For range and LOS angle measurement, only one reflector is required, and the sensor can cover the entire short range from the order of a kilometer down to the berthing box. For docking missions, based on the characteristics and performance required in the different ranges from a few hundred meters down to contact, a combination of laser range finders and camera type sensors would provide optimal performance. The laser range finder type of sensors provide range and LOS information in the entire range, whereas the camera sensors provide all navigation parameters, including relative attitude with increasing accuracy within the last 30m to docking.

4. Present docking schemes

4.1. Russian Soyuz/Progress docking system

The KURS system is a rendezvous navigation system used for the automated rendezvous and docking of Russian-built Soyuz and Progress vehicles with ISS (used initially for docking with MIR) [James R Wertz and Robert Bell]. It is an example of the combination of various RF-sensor principles into 1 navigation system. It can provide all the required navigation measurements during entire approach from a few hundreds of kilometers down to contact. The KURS system includes two omni-directional antennas to identify the hemisphere of the target direction, a large angle scanning antenna to identify the target direction within the identified hemisphere. An RF beacon signal sent by ISS is received by an antenna in the vehicle. The antenna is mechanically spun about an axis and the received signal from the beacon will be constant if the beacon signal originates on the docking axis. The received signal will be amplitude modulated at approximately 4% for every degree the beacon signal is off-axis. The vehicle can thus be controlled to keep the beacon (and thus the ISS) on axis via a control loop that controls the vehicle to move in a direction to minimize the amount of amplitude modulation in the signal. An additional complement of similar equipment provides similar measurements from the ISS perspective. Additionally, there is a set of antennas and electronics that separately perform round trip range and range rate measurements.

4.2. US docking system

In the US Space Shuttle docking missions, the initial maneuvers upto about 75km are controlled from ground. The subsequent maneuvers coming in the far rendezvous phase are controlled autonomously by the onboard GNC system based on star tracker and rendezvous radar measurements. The navigation filter processes inputs of star tracker, rendezvous radar, IMU, thrust commands and the inputs of initial conditions by ground to propagate the state vector of the vehicle. The manually controlled phase commences during the final approach. The sensors available for relative navigation during this phase are Shuttle Rendezvous RADAR, Hand Held LIDAR (HHL), Shuttle payload bay mounted Laser Ranging device called Trajectory Control Sensor (TCS) and camera system (2 cameras – one mounted at front and the other at aft end of payload bay) pointed at static visual target aids.

The Shuttle rendezvous radar is a Ku band radar used to provide relative LOS range, range rate and bearing information between the Shuttle and the target vehicle. TCS is the most accurate of the laser systems. It automatically acquires and tracks the target vehicle-mounted laser reflector, and provides the crew with continuous range, range rate, bearing and bearing rate information at 1Hz. The second laser system is a Hand Held LIDAR (HHL). The crew manually aims the unit out the overhead cabin window at a point on the station and the HHL provides a single range and range rate mark when the trigger is depressed. The range rate measurement accuracy is a function of the duration that the trigger is depressed. HHL does not need to be pointed at a laser reflector in order for measurements to be taken.

4.2.1. Next generation AR&D missions: Lunar, Mars

The US AR&D missions use rendezvous/docking sensor that allows automated proximity operations and docking. A first generation rendezvous/docking sensor, the Video Guidance Sensor (VGS), was developed and qualified in two shuttle missions where a satellite was captured from 250m. The VGS technology uses retro reflectors and laser range finder for gathering the navigation information. The VGS sensor proved the concept of video-based sensor and provided a baseline for the development of a new generation of video based sensor - Advanced Video Guidance System (AVGS). The AVGS system greatly increased the performance and additional capability for longer-range operation. It was successfully tested in a Demonstration Automatic Rendezvous Technology (DART) flight experiment with AVGS as the primary proximity operations sensor. It is selected for Aries – Orion - Altair mission and for Lunar rendezvous missions.

4.3. Japanese Engineering Test Satellite (ETS-VII) docking system

By ETS-VII, Japan demonstrated their capability of achieving autonomous rendezvous and docking. Two ETS-VII satellites launched aboard an H-II rocket docked in orbit at an altitude of 550km. The system included a combination of GPS receiver, laser radar (with a pulsed laser), and a proximity sensor. The GPS receiver assisted with position locating from a range of 10km to 600m, the laser radar was used from 600m to 2m, and the proximity sensor was used inside 2m. The proximity sensor included approximately 100 LED's and a CCD camera.

4.4. Japanese H-II Transfer Vehicle (HTV) docking system

HTV is a Japanese unmanned space vehicle for ISS re-supply and waste cargo disposal. After separation from the H-IIB rocket, HTV will approach the ISS using its own onboard system and ground control system. By Absolute GPS (AGPS) navigation, it will reach 23km near to ISS and from 23km to 500m, RGPS will be used [Koji Yamanaka, Dai Asoh and Kotaro Kiritani]. HTV will perform the final approach to ISS after confirmation by Mission Control Centre, HTV Control Centre and also by the onboard ISS crew while holding at pre-defined hold points. During the final phase (i.e. within 500m range), optical laser range finder type rendezvous sensor is used. HTV will acquire laser reflector targets on the surface of the ISS using laser sensors and precisely measure the relative distance to ISS. Using this precisely measured navigation information, HTV will approach to approximately 10m below the ISS and keep its position and zero relative velocity. After confirmation, the ISS crew will capture HTV using the Space Station Remote Manipulator System (SSRMS).

4.5. European ATV - ISS docking system

The Automated Transfer Vehicle (ATV) use fully automatic Videometer based rendezvous sensor for the final rendezvous maneuvers. ATV is first brought to a circular orbit below the station. Then it goes through a drift phase to make its orbital rate coincide with that of ISS. Homing transfer is then initiated to bring ATV to a point on ISS orbit, 2.5km behind it [J.M.Pairot, M.Frezet and J.Tailhades]. To proceed further, chaser has to get clearance from ISS and ground control. Closing transfer is then executed to bring ATV to a point 250m behind the docking port. Final translation along the docking axis is then performed until contact is made between ATV and the docking mechanisms of ISS. AGPS navigation technology is used by ATV to reach up to 30km [Hugo

Zunker and Hans-Georg backhaus]. The homing and closing maneuvers require higher accuracy navigation and so RGPS navigation is used from 30km to 500m. A scanning laser range finder type optical rendezvous sensor (RVS) is switched on below 500m to acquire the image of the retro reflectors placed in the vicinity of the ISS docking port. Below 20m, camera type optical sensors are also used.

Table 2: Comparison of docking schemes

Space agency	Sensor type
Russian Soyuz	RF sensors, scanning antenna
ETS - VII	GPS, laser radar, proximity
HTV H-II	RGPS, optical laser range finder
US shuttle	Star tracker, radar, IMU
ATV	Videometer, RGPS

5. RVD sensor architecture based on Videometer technology

The operating principle of the Videometer is based on laser diodes located on the illuminator head illuminating rendezvous targets placed on the target vehicle. The target is composed of several laser retro reflectors which forms a specific recognizable pattern [Piotr Jasiobedzki, Stephen Se, Tong pan, Manickam Umasuthan and Micheal Greenspan]. Except for the illumination system and the rendezvous targets, Videometer basically operates as a star sensor. Star tracker is able to recognize different constellations in the sky and uses this information to calculate its own orientation in space. Similarly the Videometer analyses the image formed by unique light patterns reflected by the target reflectors to provide 3 axes position and velocity information. The Videometer thus implements pattern recognition and objects tracking algorithms with extended performance in order to estimate range, line of sight and relative attitude information. At short distance, the accuracy on range is a few centimeters while that on LOS and relative attitude is in the range of some tenth of degrees. Below 30m, the relative attitude angles can be obtained with greater accuracy.

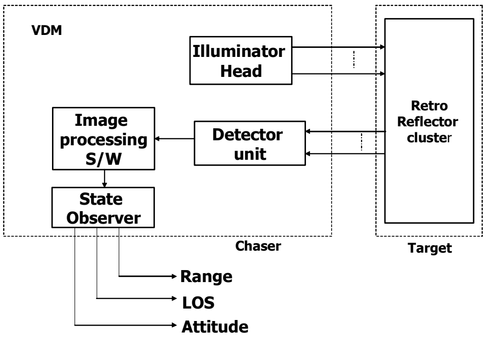

Figure 2: Videometer Navigation system

The Videometer based navigation system consists of an active and passive part. The active part of the system with the illuminator sensor head, scanning mirrors/lens assembly, electronic & processing unit is mounted on the chaser vehicle. The illumination system is made of two kinds of laser diodes – 4 long range and 2 short range (one nominal and one redundant) differing in the size of their illumination cone. A lens set is used for each diode to match the beam divergence to the required shape. Each group of laser diodes can be selectively powered by the Videometer software and synchronized with the detector integration sequence. The passive part mounted on the target vehicle is composed of two sets of different pattern. One is formed by an outer target consisting of 3 clusters of 7 laser retro reflectors (LRR) forming a 1.5m sided triangle. It is dedicated for long distance guidance. The other one is the inner target used for short distance guidance. It is composed of 4 LRR's (in square shape) and one forward LRR at a height of 8.5cm forming a pyramidal shape.

The Videometer detects the range and LOS of each retro reflector within its scan window i.e. field of view (FOV). The beams coming from the illuminator head pass through the moving lens/mirror assembly. If the beam hits a retro reflector, then the reflected beam goes back to the receiver. The values of range and LOS of the detected retro reflector are determined by calculation of time of flight of the light beam and by measuring the actual angles of the mirror/lens. The combination of measurements of three or more retro reflectors gives range and LOS of the target pattern (position) and the relative attitude between chaser and target as outputs.

Based on the defined sensor and the target pattern co-ordinate system, mathematical relations between the measurements and outputs are made. The state variables of the chaser are estimated after fixing the target co-ordinate system. The state vector contains the position of the chaser, its quaternion (Euler angles), the translatory velocities and the rotatory velocities. Thus 12 state variables of the chaser are formed from the reflected target pattern. These state variables can be used to determine the relative position & attitude between the chaser and target.

The Videometer head of the chaser sequentially scans the different retro reflectors mounted at the target side. This sequence of measurements made by the moving chaser is processed by a multi-model discrete-time state observer. The state observer models a reduced discrete-time state equation system of the chaser using the measurements to the different retro reflectors. So for each retro reflector a partial model depending on its position in the target pattern exists.

The number of models used depends on the number of retro reflectors. Because of the sequential measurement of the single retro reflectors from the moving chaser, a precise determination of the attitude can only be performed, if all the state variables of the position and attitude with the belonging velocities of the rigid chaser are estimated. All retro measurements together with the belonging partial models contribute to update the common database of the 12 state variables. With the knowledge of the complete state vector, state feedback control of the chaser movement can be done.

The results of the retro measurements are fused to the relative position and attitude between the chaser and the target. Information fusion reduces the uncertainty of the state vector as each retro reflector measurement gives a specific contribution to determine the state variables. As the sequential scanning process progress, the observer converges and its estimation accuracy increases. On the basis of the estimated state variables and the developed model, the range and LOS values for the actual retro reflector are predicted and compared with the measurements. The state variables are updated using the differences between calculated and measured data and the partial model-specific observer feedback matrix.

The dynamic behavior of the observer, its stability, its convergence and its accuracy depend mainly on the set of observer feedback matrices and the initial conditions of the state vector. The obtainable accuracy in the attitude measurement also depends on the observer feedback matrix, initial conditions of the state vector and on the distance between chaser and target, the size of the target pattern, the number of retro measurements for averaging, the observer feedback matrix and the initial conditions of the state vector. For normal rendezvous and docking scenarios, the state observer is linear. An adaptive observer considers variation in optical mapping depending upon the variation in distance between the Videometer and target.

6. Qualification process

Test facility for Videometer qualification with proper test environments should be developed to demonstrate the performance accuracy. Tests need to be carried out over both long range and short range. The facility should have three-axis dynamic control of attitude and position of the docking heads, simulation of sun in the field of view. The navigation chain should undergo numerous validation and qualification steps. Functional validation and performance of algorithm should be first assessed in simulation. Software unit tests need to be performed on all elementary functions before integration. This must be followed by the evaluation of real time behavior of the flight software.

In order to validate the Videometer software, to test the algorithm robustness and to check Videometer operations in harsh conditions, the Videometer must be fed with simulated digital images which replicate the effects of space environment. These images generated by image simulation software must include the effects of stray light, proton hits, sun in the field of view and CCD degradation after radiation. By using a moving target, it is possible to simulate the attitude drift of the space station. Monte Carlo simulations also need to be carried out to validate the integrated GNC performance. Specific tests are to be devised to evaluate the robustness of GNC performance under hardware failures and also to verify the transition between the flight phases.

7. Conclusion

Rendezvous docking is a major technology required for all advanced missions and major space faring nations have capability for it. Navigation system for rendezvous docking is a very complex technology which requires long term development effort. Automatic rendezvous and docking system architecture using Videometer navigation system based on ranging systems, reflectors, detectors, software for image processing and state observers is the state of art technology and has been successfully used by space agencies. The Videometer navigation chain provides the high level of performance, robustness and autonomy required by modern spacecrafts involved in present human programs and also for future space exploration missions.

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