JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 44, No. 4, July–August 2007

Navigating the Road to Autonomous Orbital Rendezvous

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DOI: 10.2514/1.30734

The fundamental techniques and approaches to orbital rendezvous have predominantly been defined by the United States and Russian space programs. Although both programs were initially pursuing the same goal, they chose two very distinct paths. The manual method pursued by the United States has given it the capability to handle a variety of complex rendezvous and docking missions, whereas the Russians' automated approach has come to symbolize efficiency and reliability. What is the reason that these two storied programs chose such different paths? How have these pioneering decisions affected the course of orbital rendezvous? Where is orbital rendezvous heading in the future? This paper provides a comprehensive overview of the programs, missions, and techniques that have set the standards for orbital rendezvous. In particular, it reveals the rationale and events behind the early engineering decisions regarding orbital rendezvous navigation systems, how they have come to influence ensuing programs, and why these traditional methods are beginning to be replaced by new autonomous approaches for current and future missions.

I. Introduction

THOSE who envisioned humans going to the moon and exploring other worlds, those who dreamed of humanity's long-term presence in space, and those who actually made it happen, recognized that orbital rendezvous and docking would play a crucial role in making these imaginations a reality [1]. With the limited lifting capacity of chemically propelled rockets, orbital rendezvous was a natural solution for assembling the necessary resources, stage by stage, for the exciting journey ahead. It is no surprise that once a nation has developed the capability to send a person into orbit, one of the next major objectives of that space program is to develop and demonstrate the technology for orbital rendezvous. It is not unreasonable to speculate that as access to space continues to increase, the necessity of orbital rendezvous will only continue to grow. The motivation will not be fueled by human exploration alone, but will also emanate from demands to capture, service, monitor, and inspect national and commercial assets in space.

Currently the majority of all the spaceflight experience in orbital rendezvous comes from the United States and Russian space programs. From the onset, both programs took two distinct approaches. The United States favored a more manual approach, which allowed greater initial flexibility and eliminated the need for additional redundancy and complexity [2]. The downside to this mode of operation is that each mission becomes unique and requires specialized training and planning, making the process more labor intensive and expensive [3]. The Russians pursued an automated methodology that used the crew in override or monitoring roles. Although the initial development costs were high, the system has become very reliable with standardizations that provide significant cost benefits in repetitive routine operations [4]. The history of these two storied programs reveals the basic challenges associated with orbital rendezvous and their proposed solutions, which have served as standards over the past four or five decades. In fact, many of the fundamental concepts and techniques of orbital rendezvous engineered in the early space age continue today largely unchanged. However the motivation and purpose for orbital rendezvous is beginning to change from those of the past, causing a reevaluation of these traditional methods and exploring the possibility of new innovative ideas, particularly in the area of autonomous orbital rendezvous navigation systems.

Much has been written regarding the technology that has made orbital rendezvous possible [5,6] and how it was actually performed for particular programs [7–10], but little has been mentioned about the motivation behind their selection and how they have affected the course of orbital rendezvous. The objective of this paper is to provide a comprehensive overview of the programs, missions, and techniques that have come to define orbital rendezvous by 1) highlighting the rationale and events that influenced the early rendezvous navigation systems and methodologies, 2) showing how they have matured to influence ensuing programs, and 3) explaining why and how these traditional methods are beginning to be replaced with new autonomous approaches for current and future missions.

II. Birth of Orbital Rendezvous

In some respects, the birth of orbital rendezvous came in the 1960s during the height of the space race between the United States and the Soviet Union. It was during this era that orbital rendezvous transformed from a mere concept to reality. For the first time governments established programs and allocated significant resources for the primary purpose of building equipment, forming procedures, and establishing the necessary technology for orbital rendezvous. Because orbital rendezvous had never been previously accomplished, this creation period generated countless ideas that were eventually molded and refined into the basic standards still in use today. Ironically two distinct approaches emerged from these competitive rivals; manual and automated rendezvous. Although these roads to orbital rendezvous were different, they are complementary and together converge on the road toward autonomous orbital rendezvous. To examine this initial stage of orbital rendezvous, attention will be given to the four programs that symbolize its beginnings; Vostok, Gemini, Soyuz, and Apollo.

A. Vostok

Some may claim that the first orbital rendezvous occurred on 12 August 1962 when the Russian Vostok 4 spacecraft piloted by Pavel Popovich was launched into orbit and came within 6.5 km of Vostok 3, launched the previous day with cosmonaut Andrian Nikolayev at the controls [11]. Neither spacecraft had the necessary maneuvering capability to maintain their relative position, and so they eventually drifted over 850 km apart before the end of the day [12]. Regardless of the official status of this dual mission, it ignited the speculation that orbital rendezvous and docking missions were

Received 1 March 2007; revision received 1 May 2007; accepted for publication 2 May 2007.

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on the horizon [13]. Less than a year later, a similar dual mission, historically known for launching the first woman into space, performed a similar rendezvous feat. On 16 June 1963 Valentina Tereshkova, who was the only cosmonaut launched aboard Vostok 6, came within 5 km of Vostok 5. Once again, the direct ascent trajectory did not allow the two nonmaneuvering vehicles to maintain a close relative distance.

The Vostok program was analogous to the United States Mercury program, whose primary objective was to place an astronaut into Earth orbit, examine man's ability to survive and function in the weightlessness of space, and return him safely back to Earth. The Soviets' initial experience with manned spaceflight reveals valuable insight about their tendency to gravitate toward automated systems. The fame of this program came when Yuri Gagarin orbited once about the Earth in Vostok 1, becoming the first man in space on 12 April 1961. (Alan Shephard made his famous Freedom 7 flight on 15 May 1961, a month after Yuri Gagarin's flight. Shephard was scheduled to make his launch a few months earlier in March, but due to some minor problems with the booster, NASA delayed his flight until early May to allow time for more unmanned testing. If this delay never occurred, the title of "first man in space" could have belonged to Alan Shephard [14].) Shortly after Gagarin's flight, eighteen Vostok-type spacecraft were ordered, half of which were for piloted missions and the others reserved for military reconnaissance missions. The military's influence in the space program pushed to maximize the use of automatic devices, with manual override to be used only in emergencies, such that a minimal redesign was required between manned and reconnaissance missions [11]. In addition, the Vostok program lacked specific objectives and as it evolved, the military's presence became more apparent. At times, the piloted space program was not only reduced to a nonpriority, but it was viewed as a hindrance to the reconnaissance effort [12]. This perspective carried over into subsequent programs and continued to prevail as an underlying ideology for the Russian space program.

B. Gemini

The National Aeronautics and Space Administration's Gemini program served as a bridge between the path-breaking but limited Earth-orbital missions of Project Mercury and the unprecedented lunar missions of Apollo. With President John F. Kennedy's historical speech that committed the United States to landing a man on the moon and returning him safely to Earth, Gemini's central purpose was defined. Gemini was charged to demonstrate several key objectives including long duration space flight, astronaut activity outside the confines of a spacecraft, and precision landing. However Gemini was first and foremost a project to develop and prove equipment and techniques for orbital rendezvous and docking [15]. The goal was manned orbital rendezvous, not automated orbital rendezvous. From the onset of the program, manned space flight was the top priority and automated features were included only when time and budget constraints allowed. If a decision between manual or autonomous control was debatable, the scale tipped in favor of manual operation. Autonomy became a nicety, not a necessity. This trend and view of spaceflight shaped the techniques and methods of orbital rendezvous implemented by the U.S. space program for the years that followed and continues to exist today.

By the summer of 1965 Gemini's rendezvous test flights began with Gordon Cooper and Charles Conrad piloting Gemini V in a phantom rendezvous operation which became the first-ever astronaut-controlled maneuver in space. Later that year the first-ever orbital rendezvous between two spacecraft occurred. On 4 December 1965, Frank Borman and James Lovell were launched into orbit aboard Gemini VII for a long duration space flight mission. Eleven days into their flight, on the 15 December, Walter Schirra and Thomas Stafford pulled their Gemini VI spacecraft to within 40 m of Gemini VII for the first-ever orbital rendezvous. Over the next three orbits the two spacecraft stayed within ranges of 30 cm to 90 m. The first docking between two spacecraft finally occurred several months later on 16 March 1966 when Neil Armstrong and Dave Scott docked Gemini VIII with an Agena target vehicle. This great success did not last long when a stuck thruster valve [16] caused the two vehicles to inadvertently roll. Unable to stop this undesirable motion, Armstrong undocked Gemini, throwing them into a violent spin. Switching to the reentry control thrusters, they were able to stabilize the spacecraft, but forced to cut the mission short. The astronauts' effective display of detecting and resolving mission critical problems in real time seemed to reinforce NASA's position of using manual control over autonomous systems. The Gemini program ended with four successful missions including the accolades of the first dual rendezvous, the first rendezvous with a passive target using optical navigation, and various tethered operations.

The baseline mission for Gemini's orbital rendezvous flights used an Atlas rocket to launch an unmanned Agena vehicle into a 298 km circular orbit to serve as the target vehicle. Once in orbit, Agena was stabilized using attitude and maneuvering control systems. It could be operated either by radio commands from the Gemini spacecraft or a uhf command link from the ground. Agena's docking adapter was equipped with flashing acquisition lights, submerged floodlights, and phosphorescent markings to enhance visibility and it also contained a radar transponder that received signals from the chaser's transmitter and amplified the return to improve observability [17]. Following Agena's successful orbit insertion, the Gemini spacecraft was carried to orbit on a Titan launch vehicle and acted as the chaser. After the initial ascent phase, the Gemini spacecraft was eventually inserted into a coelliptic orbit 28 km below the Agena vehicle [18] as

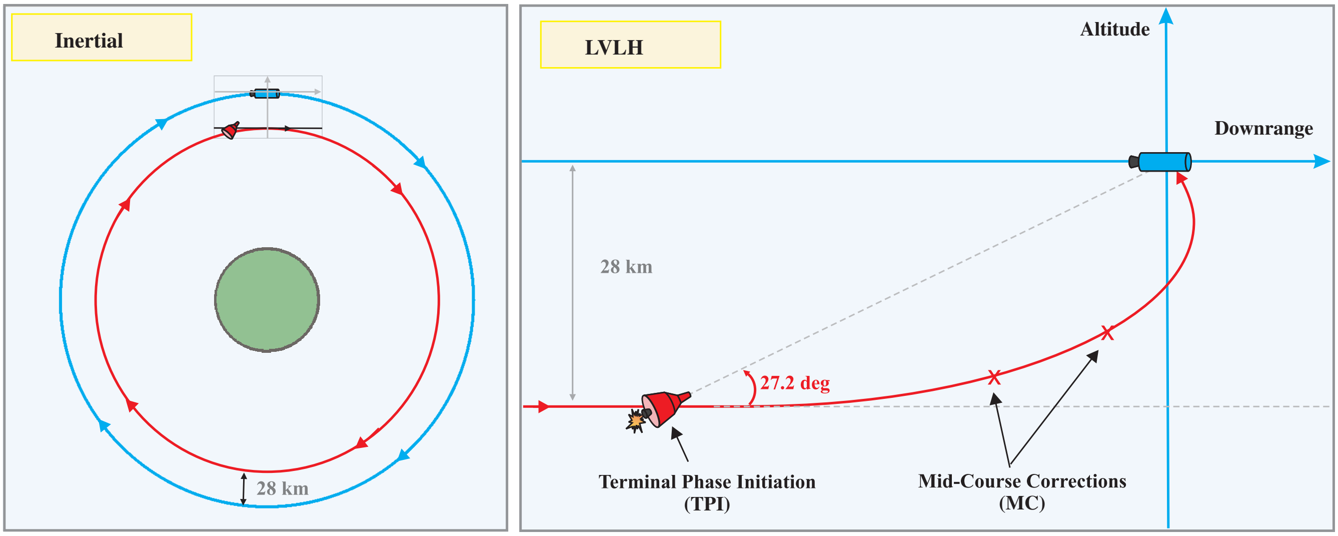

Fig. 1 Gemini coelliptic approach.

shown in Fig. 1. (The chaser is on a coelliptic approach when its relative trajectory maintains a constant altitude either above or below the target vehicle. This relative motion occurs when both the target and chaser vehicles are in the same orbital plane with the same argument of perigee but their orbits have a slight offset in their semimajor axis as depicted in Fig. 1.) This nominal height differential between the two spacecraft was based on a tradeoff between a desire to be close enough to allow visual acquisition of the target but distanced enough to minimize the sensitivity to orbit insertion errors. When Gemini was about 60 km (33 n miles) downrange, the relative elevation angle to the target reached the discrete value of 27.2 deg which cued the astronauts to execute an impulsive maneuver known as the terminal-phase initiation (TPI) burn. This maneuver transitioned the Gemini spacecraft from the coelliptic approach trajectory to an intercept trajectory with the Agena target vehicle. If needed, two midcourse correction maneuvers were executed to correct for trajectory dispersions [19]. The maneuver resulting from this strategically designed orbit pointed along the line-of-sight to the Agena spacecraft. If for any reason the radar or onboard computer system malfunctioned, the astronauts could measure the elevation angle with a sextant and perform the maneuver manually. (During the Gemini XII mission, the last flight of the Gemini program, the rendezvous radar system malfunctioned producing intermittent signals that the onboard computer refused to accept. Buzz Aldrin, whose doctoral work at MIT focused on this very problem [20], used a manual sighting sextant to measure the relative elevation angle to the Agena target vehicle. Based on these observations and various rendezvous charts, Jim Lovell was able to pilot the Gemini spacecraft to rendezvous and dock with Agena [21].) During the final braking phase, the target could be clearly detected against the stellar background with small line-of-site rates to the target. These and other desirable pilot-oriented features were prime factors for the selection of the coelliptic rendezvous flight plan.

Gemini was equipped with an interferometric-type rendezvous radar system that provided range and angle data at distances varying from 450 km down to 150 m. The onboard computer received this data and displayed it to the astronauts. When the Gemini vehicle was close enough to Agena, the astronauts manually controlled the spacecraft using the pilot displays and optical markings on Agena for navigation aides. At a relative separation between 15–60 m, the rendezvous radar could no longer generate accurate range data. At this point, visual observations to the docking features provided the only relative navigation information [4]. Besides relying heavily upon the *eyeball ranging system* as some astronauts referred to it [22], the relative orientation between Gemini and Agena was entirely determined by the astronaut's eyesight. Of course Agena was commanded and controlled to some nominal orientation suitable for docking, but the Gemini spacecraft did not contain the instrumentation to independently detect the relative attitude between the two spacecraft.

C. Soyuz

By the spring of 1967, almost two years had passed since a piloted Soviet flight. There was clearly immense political pressure to get manned flights off the ground as the world witnessed one successful Gemini mission after another. The long delay only led to exaggerated expectations of the Soyuz program that it would deliver a spectacular mission involving complicated manned operations in orbit [23]. In some respects, many of the expectations were met despite some significant setbacks. This program accomplished the first rendezvous and docking between two robotic spaceships, the first docking of two piloted vehicles, and the first transfer of crew members to another ship [11]. Like the Gemini program, the Soyuz program established the fundamental orbital rendezvous capabilities and techniques for the Russian space program. Unlike Gemini, however, the Soyuz vehicle was designed primarily for automated orbital rendezvous with piloted capabilities generally reserved for contingency operations. It was a far more complex spacecraft than Gemini. Its autonomous operation led to a longer development process and initial problems that may have cost Russia the race to the moon, but it eventually produced a reliable efficient system used for decades that followed.

The Soyuz program had the following basic profile for each mission. The active Soyuz vehicle or the chaser was launched first followed by a direct orbit insertion of the passive or target Soyuz spacecraft the ensuing day. Each was equipped with the Igla (Needle) rendezvous navigation system that provided relative position and attitude information for the chaser Soyuz to rendezvous and dock with the target Soyuz[‡] [24]. As shown in the top diagram of Fig. 2, there were five different types of RF antennas between the two vehicles labeled A, B, C, D, and E. The two type-A antennas mounted on the passive target vehicle were fixed omnidirection antennas that broadcast continuous wave signals to alert the chaser Soyuz of its general location. The set of type-B antennas located on both vehicles were rotating reception antennas used to determine relative orientation. These search reception antennas would pick up incoming signals from the other vehicle and generate error signals that were used to orient each spacecraft so that they were properly pointing at one another. Antenna C was a transmit/recieve narrow-beam gimbaled dish antenna on the chaser Soyuz that tracked the relative angular motion of the target vehicle. Antenna D was a fixed dish antenna mounted on the target spacecraft to transmit ranging data back to the chaser vehicle. Antenna E was another fixed antenna on the chaser used in close proximity operations to eliminate nonlinear anomalies that were amplified at close ranges.

At the point of orbit insertion, the target Soyuz was remarkably brought within kilometers of the chaser Soyuz [11] and both vehicles began the mutual search and acquisition phase as shown in the bottom of Fig. 2. First the target spacecraft transmitted signals using its two omnidirection antennas (A) to alert the chaser vehicle of its current location. Meanwhile the chaser spacecraft slowly rotated to make it possible for one of its receive antennas (B) to acquire the beacon signal. The difference in signal strength received by the two antennas (B) generated an error signal that helped the chaser determine in which hemisphere the target was located. With this knowledge, the chaser spacecraft pointed itself toward the target and maintained this relative attitude. The chaser spacecraft then began transmitting an interrogation signal through its narrow-beam antenna (C) toward the target. The target craft picked up the interrogation with one of its rotating reception antennas (B). Depending on the signal strength received by each antenna (B), the target could determine the direction of the chaser spacecraft and properly orient its narrow-beam antenna. With both spacecraft mutually aligned, the Igla system began bringing the two vehicles together. The target spacecraft switched off the omnibeacon (A) but continued to receive the interrogation signals from the chaser vehicle by its rotating antennas (B) and retransmitted them through its fixed narrow-beam antenna (D). The chaser's gimballed antenna (C) picked up this rebroadcast signal and the chaser's onboard computer used these observations to determine range, range rate, and the rotation of the line-of-sight vector. At close distances, antenna E on the chaser Soyuz would transmit the interrogation signal to antenna B on the target to help determine the roll reference. Using a control law that kept the line-of-sight rotation to zero and the range rate to some desired function of range, the chaser vehicle slowly closed the relative distance until docking was achieved. (For the Soyuz 4/5 rendezvous mission, the Soyuz 4 approached the Soyuz 5 craft at a rate of 25 cm/s until hard dock [25].)

The heralded Soyuz 1 launch ended in a deadly catastrophe, which derailed the Russian manned space program. On 23 April 1967, cosmonaut Vladimir Komarov piloted the Soyuz 1 spacecraft into orbit with plans to rendezvous and dock with the Soyuz 2 vehicle containing three crew members. It would be the first docking and

[‡]See "A Brief Description of the Radar Approach Equipment of the Soyuz-Type Spacecraft (Kratkoye Opisaniye Radioapparatury Sblizheniya Kosmicheskikh Korabley Tipa Soyuz), NASA technical translation edition, November 1970, http://history.nasa.gov/astp/APSYZ-descharac3.PDF, starting at p. 27 [retrieved January 2007]; also see Grahn, S., "The IGLA Radio System for Rendezvous and Docking," http://www.svengrahn.pp.se/histind/RvDRadar/IGLA.htm [retrieved January 2007].

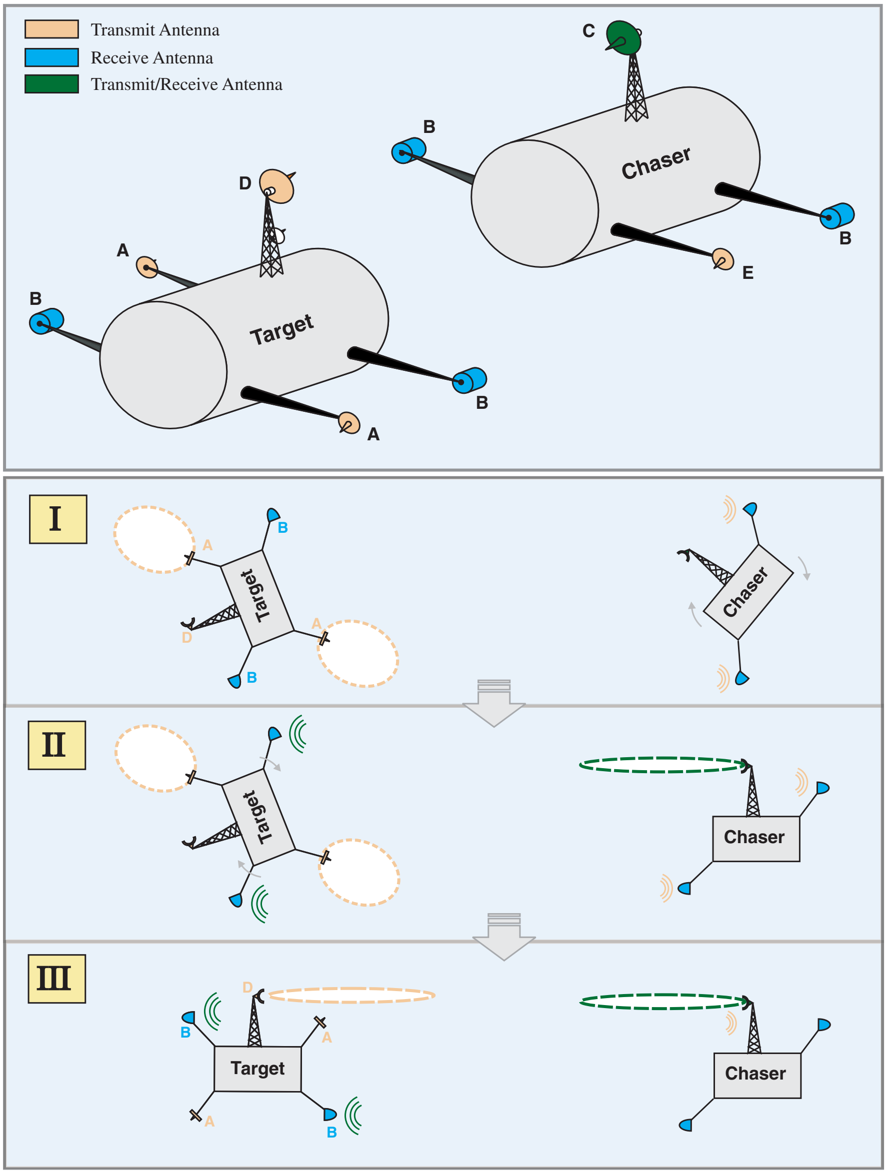

Fig. 2 The Soyuz Igla (Needle) rendezvous radar system.

crew transfer between two piloted spaceships. For years Komarov and other commanders debated with engineers over the operation mode for docking as to whether the Igla system should perform the entire procedure. The cosmonauts were reluctant to let automation do the whole thing and suggested that the Igla system could autonomously bring the active vehicle within 200–300 m of the passive vehicle, after which the cosmonaut could manually dock the two spacecraft. Just a few days before the launch of Soyuz 1, this semi-automatic approach won approval. Unfortunately none of these plans materialized when the Soyuz 1 spacecraft began having problems with the solar panel deployment, the backup antenna system, and the attitude control sensor [23]. The launch of Soyuz 2 was immediately canceled and Soyuz 1 was ordered to return home. Upon reentry, the parachutes did not open causing the vehicle to crash and killing Komarov.

Although manned operations came to a temporary halt, automated missions continued to move forward. Under the cover name of Kosmos 186 (chaser) and Kosmos 188 (target) two unmanned Soyuz prototypes were launched in October 1967 and performed the first-ever rendezvous and docking between two robotic spaceships. After Kosmos 188 direct ascent brought it within 24 km of Kosmos 186, the Igla rendezvous radar system automatically guided the two vehicles together within 62 min of the launch of Kosmos 188 [26]. A similar successful unmanned rendezvous and docking mission was performed six months later with Kosmos 212 (chaser) and Kosmos 213 (target). This impressive display of automation bolstered their position of using automation and cast a questioning shadow upon Soviet piloted flights.

By October 1968, six months following the successful mission of Kosmos 212/213, manned missions were back in the rotation. On 27 October, a day after the unmanned launch of Soyuz 2, Georgi Beregovoi was placed into orbit aboard Soyuz 3. The Igla system automatically brought the Soyuz 3 vehicle to within 200 m of the Soyuz 2 target when Beregovoi took over the controls. Because of piloting errors, he exhausted too much fuel and was unable to dock the spacecraft [26]. The perception of manual control was once again tainted. What finally cemented Russia's commitment to automated space flight came a few months later in December 1968 when Apollo 8 circled the moon. Unable to keep pace with Apollo, the Russian space program shifted gears. It now claimed that manned lunar flights were never in their plans but that the key to exploring other planets was automation beginning with the development of orbital space stations. From this point on, automation and space station building became the rallying creed of the Russian space agency. The high expectations of the Soyuz program eventually materialized in January 1969 with the Soyuz 4/5 orbital rendezvous, docking and crew transfer mission that the Russians strategically proclaimed as the world's first "experimental orbital station" [25].

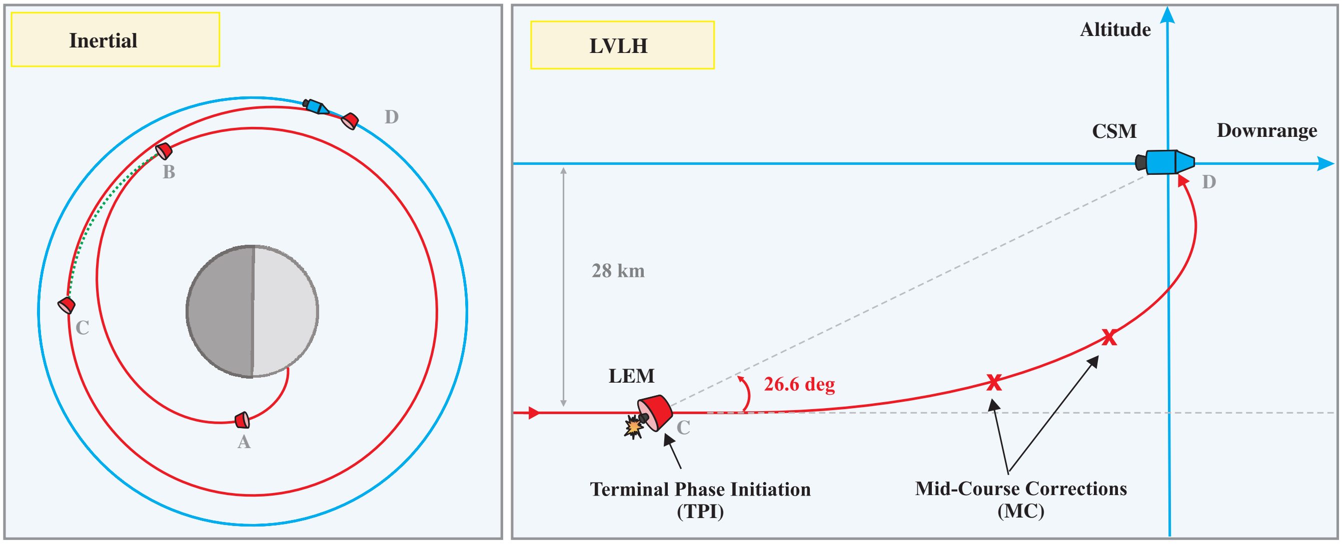

Fig. 3 Apollo orbital rendezvous scenario.

The program finally concluded in October 1969 with an impressive rendezvous mission involving three Soyuz vehicles, but these final missions failed to receive much attention with NASA already sending routine trips to the moon.

D. Apollo

The Apollo lunar program was the original motivation and inspiration for the U.S. Space program to develop the capabilities for orbital rendezvous. It was well understood that to go to the moon and return the astronauts safely back to Earth, orbital rendezvous would be required and the time had finally come for its implementation. Although these moon missions were unprecedented and would eventually take 24 astronauts to lunar orbit and land 12 of them on the surface, the orbital rendezvous and docking techniques had been tried and proven. For Apollo, the critical orbital rendezvous phase occurred in lunar orbit with the ascent stage of the lunar excursion module (LEM) chasing the target command/service (CSM) to rendezvous and dock before the return trip back to Earth. Similar to the Gemini program, the LEM was equipped with a digital guidance computer, an inertial measurement unit (IMU), optical equipment, and rendezvous radar [27,28]. The rendezvous radar provided the range, range rate, and bearing to the CSM and operated at ranges from 740 km to 24 m [4]. During the entire rendezvous process, astronauts played an important role from monitoring the launch to actually docking the LEM to the CSM.

Approximately 70 s after the CSM passed over the LEM's landing site in its 110 km circular orbit, the LEM ascent stage was launched from the lunar surface as shown in Fig. 3. At an altitude of 18 km it was inserted into a transfer orbit (point A) that would bring it 28 km below the CSM (point B) into a coelliptic phasing orbit. About 2.5 h after liftoff the TPI burn occurred (point C). (For the Apollo 11 lunar mission the height differential was actually 26 km instead of the nominal 28 km. This lower relative altitude decreased the catchup rate and required an extra 6.5 min to get the proper angular geometry for the terminal-phase burn.) At this critical point the look angle to the CSM as measured from the LEM's local horizontal (i.e., elevation angle), reached 26.6 deg. Regardless of the actual height differential between the two vehicles, this angle corresponded with a required thrust in the direction toward the CSM which provided a convenient visual reference in emergency backup situations. Nominally the magnitude of this burn was about 7.6 m/s and would cause the LEM to intercept the CSM approximately 45 min later following a 130 deg central-angle travel. This central travel angle (i.e., the angle between point C, the center of the moon, and D) of 130 deg was chosen from Gemini experience as the optimum value to produce desirable line-of-sight rates during the final approach. The entire rendezvous sequence was completed approximately 3.5 h after liftoff with the docking of the two spacecraft [9].

After the historic Apollo lunar missions, the United States followed the Russian course of pursuing the capability of developing orbital space stations for long space duration missions. The first of these, Skylab, was built and visited using the Apollo spacecraft. The same Apollo vehicle was also used to rendezvous and dock with the Russian Soyuz vehicle for the first-ever linkup between spacecraft from different nations. Although these missions played an important role in gaining experience with orbital rendezvous, they essentially implemented the same orbital rendezvous technology and techniques described previously for the Apollo lunar missions. The close of the Apollo era signaled the beginning of a new phase of orbital rendezvous.

III. Orbital Rendezvous Refined

Following the initial space race to the moon, humans had developed the ability to have frequent access to space and maintain a long-term presence there. The focus of the two competing space programs shifted from creating orbital rendezvous technology to implementing these newly acquired capabilities. The innovative applications ranged from the construction and routine use of space stations to retrieving and servicing a variety of space assets. Although orbital rendezvous played a pivotal role and advancements continued, the major emphasis was on the application, not the enhancement of orbital rendezvous. As expected, both the United States and Russian space programs used their respective manual and automated rendezvous approaches with limited modifications to the two original systems. The emerging vehicles from this era capable of performing rendezvous operations included the U.S. space shuttle and the Russian manned and unmanned vehicles, Soyuz and Progress.

A. Space Shuttle

In just over two decades from June 1983 to August 2005, the space shuttle performed 57 missions that had as one of its objectives at least one rendezvous or close proximity operation. The vast experience of the shuttle with respect to rendezvous and docking is meticulously documented with descriptions of the first rendezvous demonstration flights, satellite servicing missions, deployment and retrieval of scientific payloads, missions retrieving and returning satellites back to Earth, flights to the Russian space station Mir, and the assembly, crew exchange, and resupply missions to the International Space Station (ISS) [10]. Even though the shuttle was expected to perform a greater variety of complex rendezvous missions than Gemini or Apollo, the rendezvous navigation system used for these missions still had a striking similarity to its predecessors. It has guidance digital computers, IMUs, optical equipment, and rendezvous radar. The range of operation of the rendezvous radar system depends on the target vehicle's status. If it has active sensing capabilities (i.e., contains a transponder), the rendezvous radar system can operate at ranges from 555 km to 30 m. If the target has passive sensing where the radar is simply reflected off the target vehicle, the rendezvous radar has a range of 22 km to 30 m [4]. There are also three additional tools available on the space shuttle to help the astronauts navigate during the rendezvous and docking phase. Mounted in the orbiter's payload bay is a laser ranging device that provides range, range rate, and bearing to the target for display to the crew at distances varying from 1.5 km to 1.5 m. There is also a centerline camera attached to the center of the orbiter's docking mechanism. When the shuttle is within 90 m of the target, it generates images that serve as a visual aid to the crew for docking. Also available to the crew is a hand-held laser ranging device which can measure range and range rate during approach to complement the other navigation equipment.

The aggressive requirements for the shuttle necessitated the orbiter to have the capability to rendezvous, retrieve, deploy, and service multiple targets that had different sizes, possessed varying degrees of navigational aids (transponders or lights), and in many cases were not designed (or functioning) to support these operations [29]. In addition, when the shuttle wasn't visiting one of the different space stations it was typically larger than its rendezvous target, which often contained sensitive payloads. With Apollo and Gemini plume impingement issues were not significant, but for the shuttle serious considerations regarding contamination and induced dynamics on the target had to be faced. As a consequence, the approach trajectory was redesigned. Instead of the direct approach as performed previously, the shuttle would transition to a station-keeping point and then perform one of a variety of possible final approach trajectories.

A typical rendezvous scenario for the shuttle to the International Space Station is as follows [30]. The ground controllers compute the necessary phasing maneuvers to get the space shuttle within 74 km of the target, as shown in Fig. 4 (point A). From this moment on, either the shuttle's guidance, navigation, and control (GNC) system automatically calculates and executes the remaining maneuvers or the flight crew manually guides the spacecraft. Initially the onboard GNC system has control and automatically executes the first maneuver that transfers the crew to a specified point about 15 km behind the target (point B) in preparation for the terminal-phase initiation maneuver. Once the shuttle executes this initiation burn to place itself near the target, it enters a trajectory that will pass underneath the target (point C) and place it in front of the target (point D). Shortly before the shuttle passes underneath the target, the astronauts assume control over the vehicle. Using hand controls and displays, the crew members will manually guide the shuttle until it is securely docked.

There are two common final approach modes used by the shuttle: the v-bar or r-bar approaches. (In the local vertical local horizontal reference frame, the v bar generally points along the target's velocity vector and is commonly known as the downrange or local horizontal axis, whereas the r bar refers to the relative altitude or local vertical axis and points radially upward.) If the r-bar approach is selected, an impulsive maneuver in the negative downrange direction is performed when the shuttle crosses the r bar (point C) reducing the forward velocity. Because of orbital mechanics, the shuttle will naturally follow a course which crosses the r bar again. At this point another impulsive maneuver directed up and in the negative downrange direction causes the shuttle to slowly hop its way up to the target. For a v-bar approach the shuttle transfers to a point downrange from the target (point D). The final approach begins with a change of velocity toward the target. To remain on the v bar, an upward Δv is required causing the shuttle to slowly hop toward the target. It will gradually move toward the target at a controlled rate proportional to the relative range distance [$v = (\text{range}/1000)$ m/s] until the vehicles have docked.

B. Soyuz/Progress

The man-rated Soyuz vehicle and the cargo carrying Progress vehicle are Russia's work horses for space station activity. Initially these vehicles were equipped with the Igla rendezvous and docking system but in the mid-1980s the Soviet space program replaced the Igla system with the new Kurs (Course) system. During the transition to the new system, the Mir space station actually incorporated both; the Kurs system from one docking port and the Igla system from another. Currently the Kurs system supports the rendezvous and docking efforts at the International Space Station. It provides all of the necessary relative navigation information from target acquisition to docking which includes range, range-rate, line-of-sight angles, and relative attitude measurements. Some of the noticeable changes between the Igla and Kurs systems are that Kurs uses a different set of antennas, allows for acquisition and maneuvering at much greater

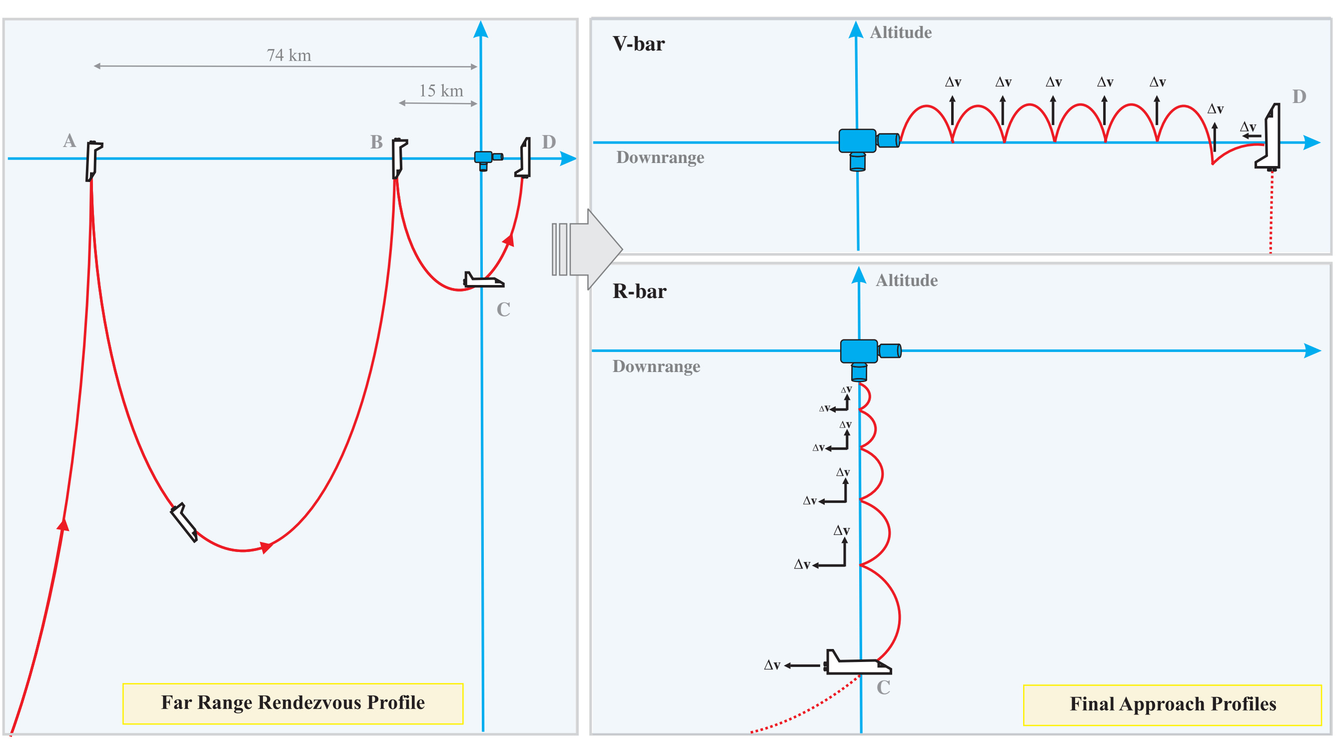

Fig. 4 Shuttle orbital rendezvous scenarios.

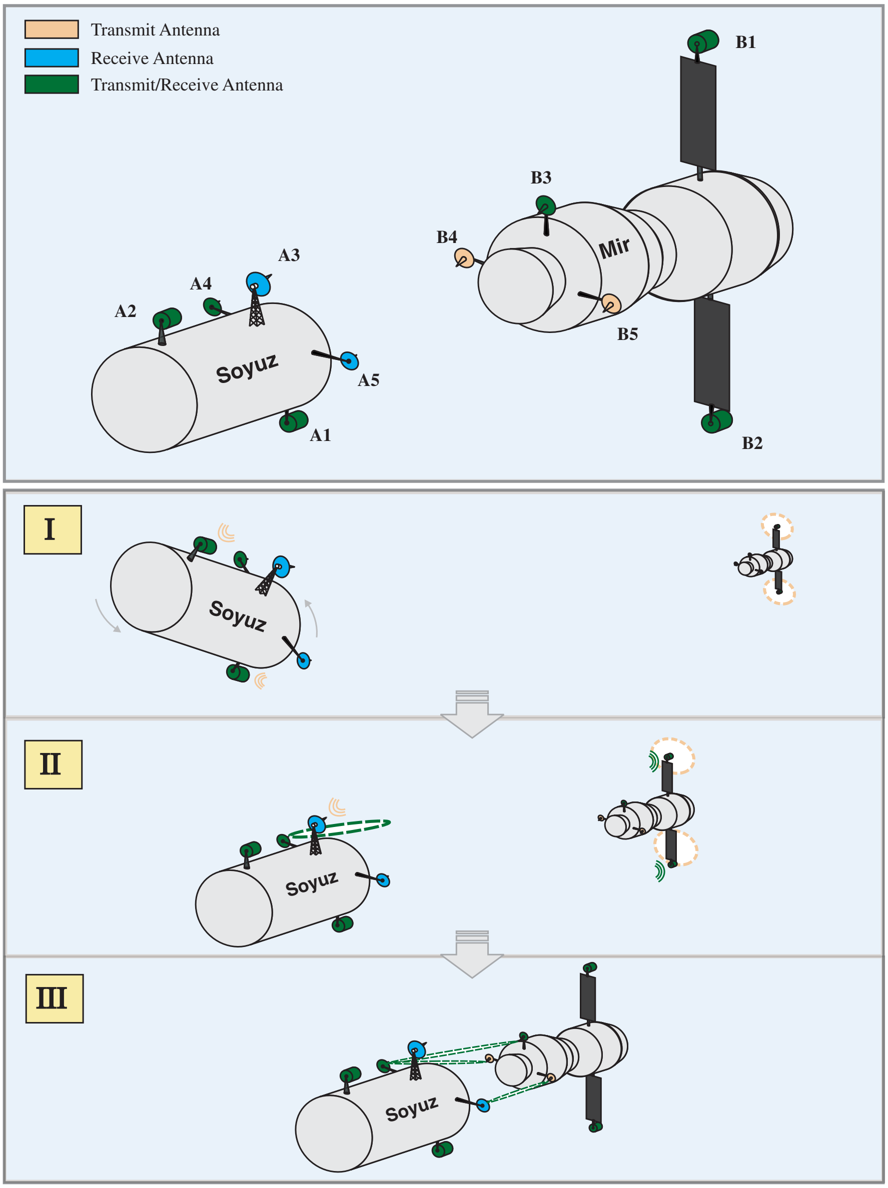

Fig. 5 The Soyuz Kurs (Course) rendezvous radar system.

distances (hundreds of kilometers instead of tens of kilometers), and allows for rendezvous with nonmaneuvering targets (space stations).

Similar to the Igla system, Kurs uses a variety of antennas on both the active Soyuz/Progress vehicles and the targeted space station as illustrated in Fig. 5. There are four types of antennas on the active Soyuz vehicle. The first type is an omnidirectional transmit and receive antenna; one on the front docking port (A1) and a second on the backside of the vehicle (A2). These antennas are used during the acquisition phase to determine the general direction of the target vehicle. Once acquisition is established, they begin transmitting and receiving signals that determine the relative range and range rate. The next type of antenna is the wide angle gimbaled antenna (A3) and is used to help point the approaching Soyuz spacecraft toward the space station. The third antenna type (A4) is a fixed electronic scanning antenna (similar to antenna C on the Igla system). The last antenna (A5) is a fixed narrow-beam reception antenna which is used in the close proximity phase to measure the bearing angles to the target and determine relative attitude. In addition to the antennas on the Soyuz vehicle, there are also four types of antennas mounted on the target vehicle (i.e., Mir space station). There are two omnidirectional transmit and receive antennas (B1 and B2) mounted on the ends of the solar panels that are initially used to broadcast a beacon signal to alert the Soyuz/Progress vehicle of its location. The remaining three antennas are primarily used during the proximity phase. The fixed antenna with a 30 deg cone (B3) is used to determine range and range rate when antennas B1 and B2 are turned off during the proximity phase. The fixed antenna with a 20 deg cone (B4) is used over the final 30 m to improve the range measurement quality. The last antenna (B5) is a motor driven conical scanning antenna that rotates at 700 rpm. The chaser spacecraft can determine the relative attitude of the two spacecraft by measuring the amplitude and phase shift of the carrier signal of B5 as received on antenna A5 [31].

The typical phasing and rendezvous sequence for the Soyuz/Progress vehicle is illustrated in Fig. 6. Following the launch and the initial orbit insertion (M0), two maneuvers (M1 and M2) are executed to transfer the Soyuz/Progress vehicle to its correct phasing altitude. A trajectory correction maneuver (M3) is eventually made to offset any trajectory dispersions following the initial velocity changes. Up to this point, all the maneuvers are controlled from the ground. When the time comes to transfer up to the target, an intercept maneuver (M4) is executed by the onboard control system. Shortly after this Δv when the Soyuz spacecraft is approximately 200 km from the target, it enters the operational range of the Kurs rendezvous system. The Kurs system begins its search and acquisition phase. The passive target transmits a homing signal on its omnidirectional antennas (B1 and B2) while the two antennas on the front docking port (A1) and backside (A2) of the Soyuz or Progress vehicle are enabled to detect these alerting signals and ultimately determine

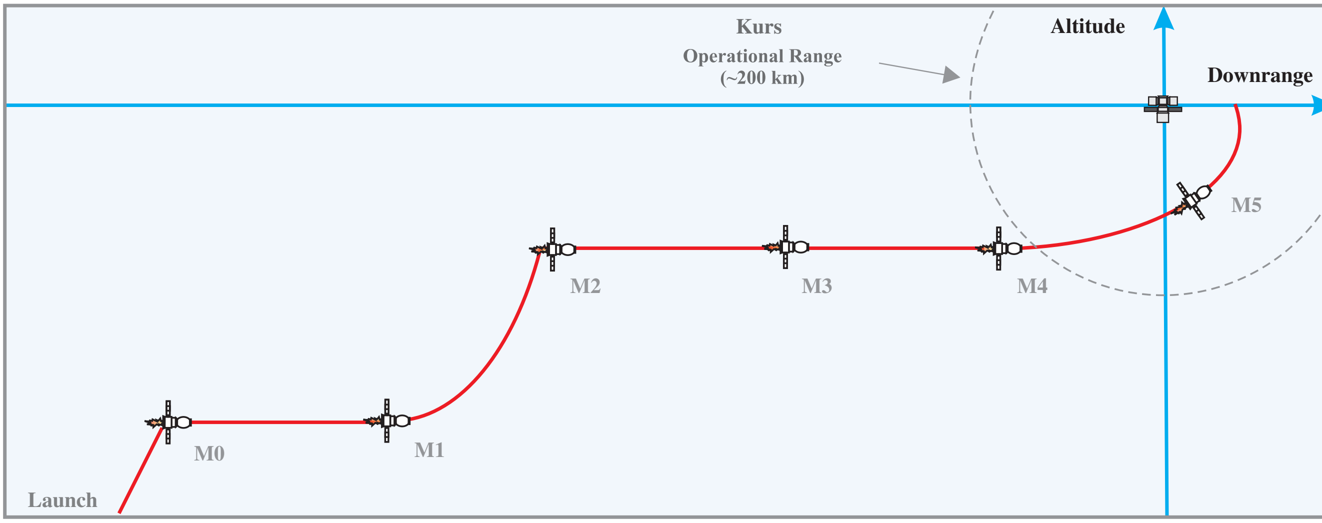

Fig. 6 Phasing and rendezvous sequence for Soyuz/Progress vehicles.

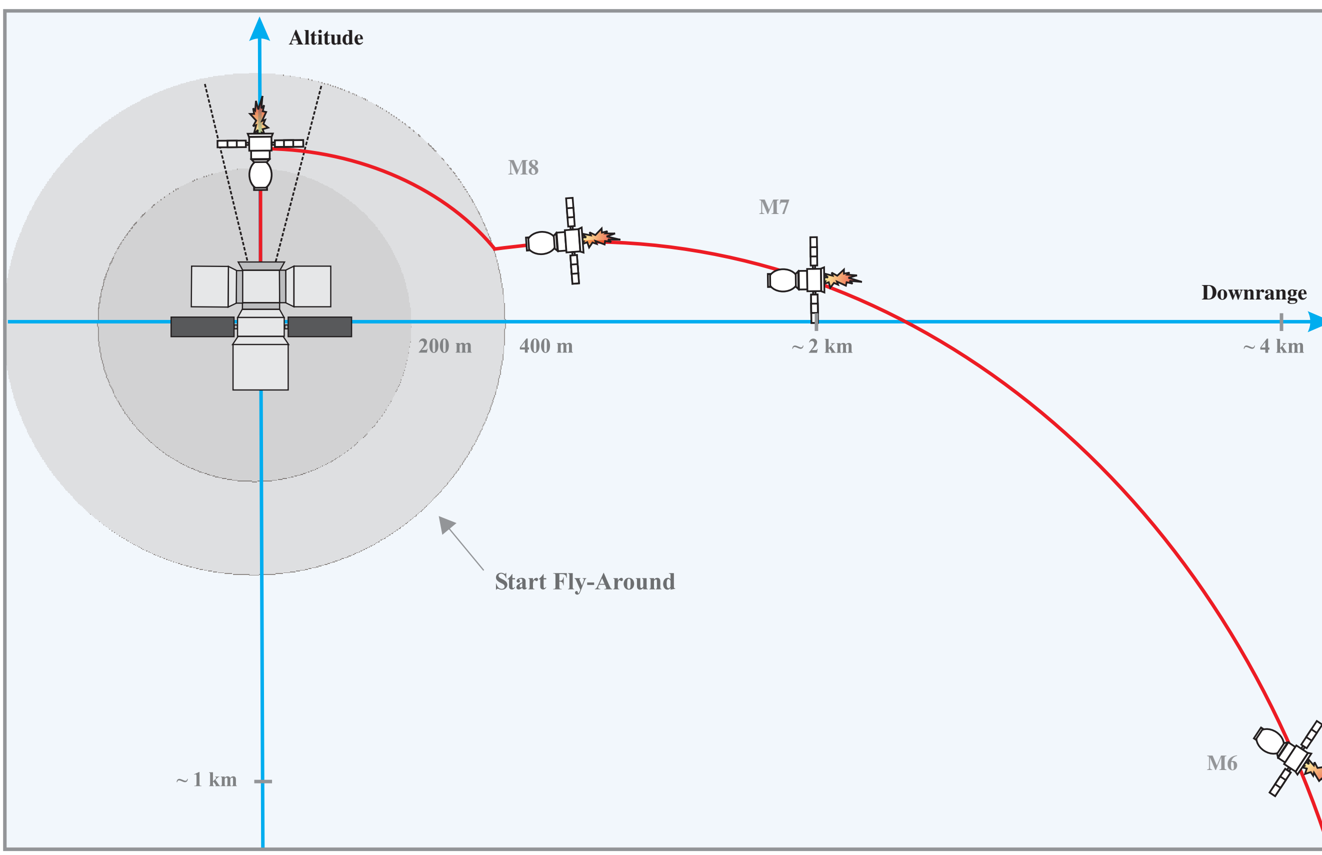

Fig. 7 Final approach sequence for Soyuz/Progress vehicles.

which hemisphere the target is located in (see Fig. 5). If needed, an attitude maneuver is initiated to ensure the spacecraft is properly pointed in the direction of the target. Once the Kurs system knows which hemisphere the target is in and the Soyuz is oriented appropriately, the scanning antenna (A3) is activated to determine more precisely the pointing direction to the target. Eventually the distance and orientation of the Soyuz spacecraft with respect to the target is sufficient to allow the main tracking antenna (A4) to interrogate the target to obtain range and range-rate information. With this additional information, the Kurs system updates the estimated position of both vehicles and executes a correction maneuver (M5).

To ensure a smooth braking velocity profile when approaching the target vehicle, three impulsive maneuvers are implemented (M6–M8) as shown in Fig. 7. The first one (M6) occurs when the Soyuz is about 1 km below the target's orbit. Following the last maneuver (M8), it is likely that the current approach trajectory is not aligned with the target's docking port. To position itself along the target's docking axis for the final approach, the Soyuz performs a fly-around at a relative distance between 200–400 m. Regardless of whether docking axis is pointed along the v bar, r bar, or some inertially fixed axis, the Soyuz begins transferring to intersect this final approach line. During the fly-around, the scanning antenna on the Soyuz (A4) tracks the target antenna B3 to obtain range, range-rate, and line of sight (LOS) angle information while antenna A5 tracks B5 to deduce the relative attitude. (For a general discussion regarding the principles of determining range, range-rate, LOS, and relative attitude from RF-sensor measurements, see [32], Sec. 7.2.) For Soyuz, relative attitude is determined by measuring the tone modulation and rotating pattern from antennas located on the target space station.) After the fly-around, the spacecraft will hold a constant relative position about 200 m from the target while waiting for the go-ahead signal from the ground. Once approval is given, it begins the final approach following a straight line closed-loop controlled trajectory with an initial closing rate of 1 m/s. When the relative distance drops below 30 m, antenna A4 on the Soyuz begins receiving signals from antenna B4 (in addition to signals from B3) to continue estimating range. By the time contact is made, the relative velocity is generally reduced to 0.1–0.3 m/s [33,34].

The Kurs navigation system is the current standard of automatic rendezvous systems and has a rich tradition of success. However there are several drawbacks primarily in the form of mass, power, and design. The total mass for the Kurs equipment on the Soyuz or Progress vehicle is about 85 kg while consuming 270 W of power. On the target side, the total mass is around 80 kg with a power consumption of 250 W [31]. In addition, it still uses vacuum tube technology with a questionable lifetime. Although this system works for its current application and may continue for years to come, this current design will not satisfy many new demands and needs for current and future autonomous orbital rendezvous missions.

IV. Push for Autonomy

The great accomplishments and technical developments that have been achieved with regard to orbital rendezvous are slowly being overshadowed by their limitations to meet new demands. Presently to perform such close proximity operations generally requires significant cooperation between both vehicles, cumbersome navigation instrumentation, or a man-in-the-loop to ensure successful maneuvering of both spacecraft. Future concepts no longer limit the chaser vehicle to a large spacecraft piloted by astronauts or guided by bulky automated systems relying on sophisticated collaboration schemes; but they now include smaller spacecraft operating in conditions where human involvement is undesirable or impractical and the cooperation between vehicles does not exist. The idea of performing rendezvous maneuvers autonomously without necessitating complex communication schemes between spacecraft while incorporating light weight, low power, compact navigation sensors has become a sought-after ideal for a variety of missions. This autonomous capability allows for the possibility of robotic rendezvous and docking missions as required for sample return missions [35], a reduction in the work load on human missions, or the servicing and retrieval of a variety of target objects that may be functioning or malfunctioning [36], alien or familiar, passive or active, cooperative or uncooperative. As a consequence of this new demand, conventional navigation systems are being put aside and new innovative approaches are being considered and implemented. In particular, the manual and automated methods are slowly converging to the road of autonomous orbital rendezvous [37,38] as evidenced in the recent and coming orbital rendezvous missions that include: Engineering Test Satellite VII (ETS-VII), Experimental Satellite System-11 (XSS-11), Demonstration of Autonomous Rendezvous Technology (DART), and Orbital Express.

A. ETS-VII

In anticipation of developing the H-II Transfer Vehicle (HTV) for logistic support for the ISS, the National Space Development Agency of Japan (NASDA) created the ETS-VII flight experiment to develop the necessary autonomous rendezvous and docking technology for future missions. On 7 July 1998 the day of Tanabata the Japanese Stellar Festival, ETS-VII successfully performed the first autonomous rendezvous and docking procedure between uninhabited spacecraft [39,40]. The two satellites, Hikoboshi (2,500 kg) and Orihime (400 kg) named after the hero and heroine of Tanabata, were launched together by NASDA's H-II rocket on 28 November 1997 and injected into their 550 km mission orbit. The chaser satellite, Hikoboshi, was equipped with global positioning system (GPS) receivers, rendezvous laser radar (RVR) for relative range and bearing angles data, and a camera-type proximity sensor (PXS) to measure relative position and attitude. The target satellite, Orihime, was a cooperative target and had passive RVR reflectors and a PXS marker to help the chaser navigate. It also was equipped with a GPS receiver and transmitted this data to the chaser using a direct communication link between the two vehicles. Depending on the relative distance separating both spacecraft, there were three possible navigation methods that could be used. For ranges between 10 km to 500 m, the GPS measurements were used for relative navigation. During the final approach phase (2–500 m), the three dimensional relative position vector generated by the RVR sensor was used. Once the vehicles were within 2 m of one another the PXS sensor was used for the final docking phase.

For the first actual flight experiment, the ground support crews sent a separation command to the chaser to release the target satellite, which it did by pushing out Orihime at a speed of 1.8 cm/s. Immediately the chaser Hikoboshi vehicle began to control the relative position and attitude automatically and separated to the 2 m station-keeping point where it held this position for 15 min using the PXS navigation system. Then the docking command was sent from the ground and Hikoboshi began approaching the target at 1 cm/s and docked with the target. Over three weeks later after some unexpected delays, the second flight experiment was performed. The chaser separated from the target and departed along the v bar to a distance of 525 m. Because of anomalies with the thrusters the approach was delayed and modifications made that eventually allowed the chaser to redock. By the third flight experiment they were finally able to test and verify their autonomous flight management software along with the capability for remote pilot rendezvous.

B. XSS-11

Commissioned by the U.S. Air Force Research Laboratory and under the direction of the Lockheed Martin Space Systems Company, the XSS-11 demonstration mission had the mandate to develop and verify on-orbit guidance, navigation, and control capabilities to safely and autonomously rendezvous a microsatellite (the microsatellite class vehicle $0.76 \times 0.63 \times 0.56$ m, dry/wet weight of 105/145 kg) with multiple space objects [41]. All the target objects would be derelict or have no means of assisting the chaser XSS-11 vehicle during the rendezvous and close proximity operations. The XSS-11 spacecraft contained a LN-200 IMU for angular rate and acceleration sensing, a coarse sun sensor assembly for sun acquisition, a visible camera system for star detection and target imaging, and a scanning light detection and ranging (LIDAR) instrument to determine relative range and angle measurements to the target. Although provisions were made to allow ground controllers to interact with the vehicle, XSS-11's onboard planner could autonomously guide the spacecraft by selecting from a variety of operational modes. The spacecraft was not simply operating automatically, but had the unique capacity to also respond to various situations autonomously.

A typical rendezvous scenario, as shown in Fig. 8, starts with XSS-11 in some initial phasing orbit waiting to transfer to the target vehicle's orbit (point A). Once the proper alignment occurs, the transfer burn (point B) will carry XSS-11 to a coasting coelliptic orbit (point C) where it will remain for about 48 h until it performs a height adjustment maneuver (point D) to set up the terminal approach phase (point E). It remains on this coelliptic trajectory until the LIDAR system acquires the target object (point F), which then initiates the close proximity phase by either transferring to the v bar or initiating a survey orbit.

XSS-11 was launched on 11 April 2005 from Vandenberg Air Force Base on a Minotaur expendable launch vehicle. Initial testing and operational procedures were performed using the Minotaur 4th stage ($1 \times 1 \times 2.3$ m) as the target object. The mission duration is slated to be 12–18 months and by the fall of 2005 it had performed

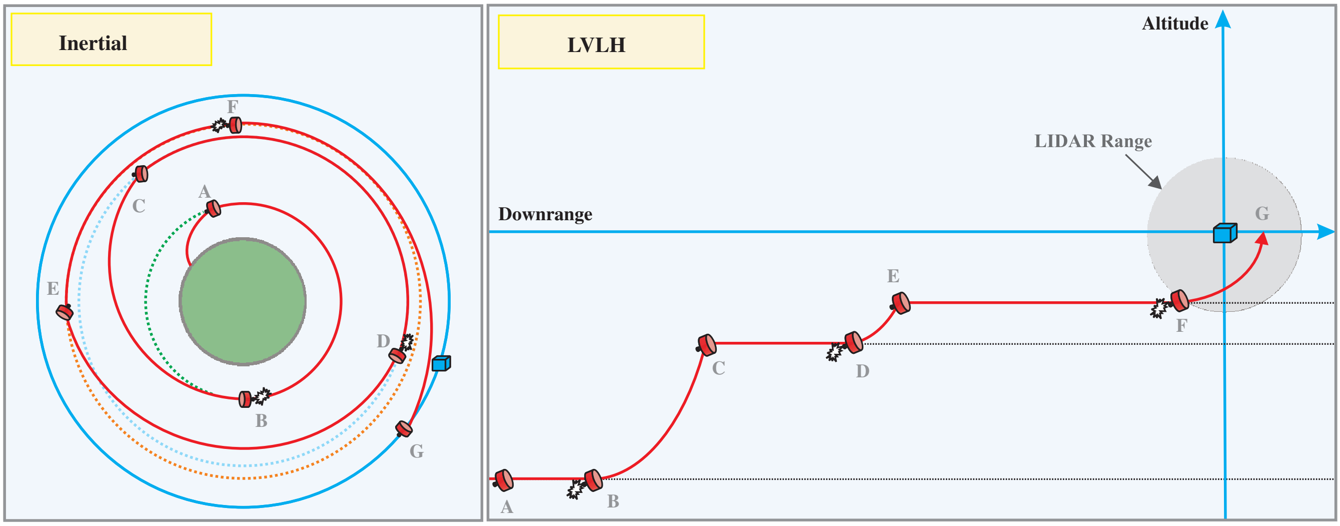

Fig. 8 XSS-11 orbital rendezvous scenario.

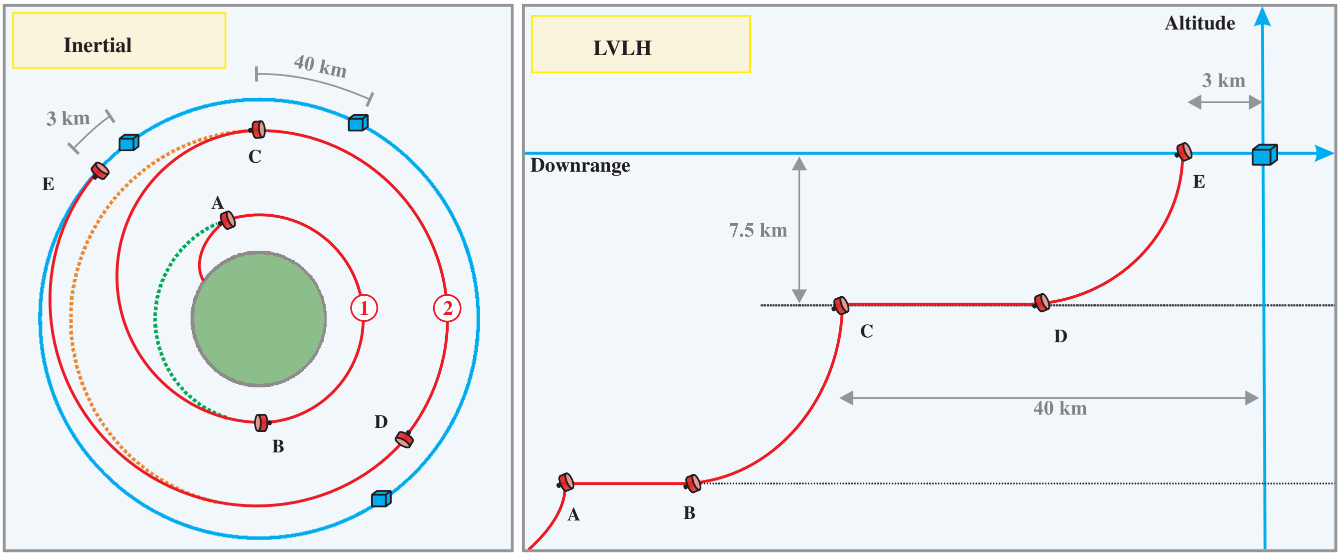

Fig. 9 DART orbital rendezvous operations.

over 20 rendezvous maneuvers with the Minotaur 4th stage, several days of circumnavigation operations, and hours of active, closed-loop station keeping at various ranges and vantage points. Current plans suggest that XSS-11 will conduct rendezvous and proximity maneuvers with several U.S.-owned dead or inactive target objects near its current orbit.

C. DART

In an attempt to establish an autonomous rendezvous capability for the United States, NASA developed the DART test flight[§] [42,43]. The DART mission would last only 24 h and in that time it would automatically perform flight operations from orbital insertion to close proximity operations. According to the mission scenario, it would come within 5 m of the target vehicle, the Multiple Paths Beyond-Line-of-Sight Communications (MUBLCOM) satellite that was positioned in a 500 km polar orbit. All the maneuver sequences would be preplanned and controlled onboard without any human intervention from ground controllers to be consistent with the objective that DART be a demonstration of autonomous rendezvous.

[§]See NASA's "Demonstration of Autonomous Rendezvous Technology Press Kit," http://www.nasa.gov/mission_pages/dart/media/index.html, April 2005 [retrieved January 2007].

As planned, DART would be launched aboard a Pegasus XL launch vehicle and inserted into an initial parking orbit as shown in Fig. 9 (point A of orbit 1). DART would remain in this orbit until the proper phasing existed to transfer to the second phasing orbit (from point B to C) which would place the DART chaser vehicle in a coelliptic orbit 7.5 km below the target communications satellite and 40 km behind it. Once the relative geometry between the two vehicles was appropriate (at point D), another transfer maneuver would be performed that would bring the DART spacecraft 3 km behind the target vehicle (point E). After a period of station keeping, DART would then perform a hop maneuver to position itself within 1 km of MUBLCOM and begin performing a variety of approach and circumnavigating maneuvers.

DART, a 6 ft long 800 lb spacecraft, was equipped with two GPS receivers for primary navigation data and the advanced video guidance sensor (AVGS) for relative position and orientation information. The experimental communications target satellite, MUBLCOM, also had GPS and was specially outfitted with retroreflectors designed for the AVGS sensor. During the mission, MUBLCOM would stabilize its orientation in all three axes and broadcast its GPS position information to DART who would use this information to compute the relative range when the two vehicles had large separation distances. Once the two rendezvousing vehicles were within 200–500 m, DART would begin transitioning its navigation data source from GPS to AVGS which was capable of providing bearing data (azimuth and elevation angles) to the target at these distances. When the relative range between DART and MUBLCOM was within 200 m, AVGS could then measure azimuth, elevation, range, and relative attitude.

On 15 April 2005, just four days after the launch of XSS-11, DART was successfully launched into orbit. For the first 8 h from launch to early orbit to the initial rendezvous phases, DART performed as planned with only a few noticeable anomalies with the navigation system. However when DART began its transfer out of the second staging orbit to begin proximity operations (point D in Fig. 9), it began using excessive amounts of fuel. As DART approached MUBLCOM, it missed an important trigger point that would have initiated the final transition to full AVGS operation. Consequently the AVGS sensor never supplied DART's navigation system with accurate range to MUBLCOM. About 11 h into the mission it detected that its propellant supply was depleted. It immediately began a series of maneuvers for departure and retirement not realizing it had collided with MUBLCOM almost 4 min earlier. According to the summary of the accident report, navigation errors due to a 0.6 m/s offset in DART's GPS receiver caused unnecessary thruster firings and depleted the fuel supply. It is suggested that these biased measurements would not have doomed the flight had the preprogrammed gain matrix in the navigation filter been properly tuned.¶

D. Orbital Express

The Orbital Express mission lifted off on 8 March 2007 from Cape Canaveral Air Force Station in Florida with an aggressive agenda to demonstrate the potential to approach, rendezvous, and capture another spacecraft autonomously and then service the vehicle using robotics** [44]. Unlike any preceding mission, it will attempt to perform a series of capture and separation scenarios over a wide range of conditions including approaches from several meters to many kilometers followed by electrical coupling, fluid transfer, and the exchange of critical components such as batteries and computers using an onboard robotic arm. The Orbital Express Demonstration System (OEDS) is a cooperative agreement between the Defense Advanced Research Projects Agency (DARPA) and NASA who selected the Boeing Company to carry out the mission goal of validating the technical feasibility of robotic, autonomous on-orbit refueling and reconfiguration of satellites.

The demonstration system includes a prototype servicing satellite, the autonomous space transfer and robotic orbiter (ASTRO), that will serve as the chaser vehicle and a surrogate next-generation serviceable satellite, NEXTSat, that will act as the target. ASTRO is equipped with the Autonomous Rendezvous and Capture Sensor System (ARCSS) that consists of three imaging sensors; a narrow field of view acquisition and track sensor, a mid- to short-range wide field of view visible track sensor, and an infrared sensor for continual observations during day and nighttime operations. In addition to these imaging sensors, ARCSS has a precision laser range finder used for mid-range tracking. For ranges within several hundred kilometers, ARCSS can generate range and bearing data initially using the narrow field of view visible sensor. As the separation distance is reduced, the infrared sensor and laser range finder can provide the same relative navigation information. As the image of NEXTSat becomes more prominent, the attitude of the target satellite in addition to the range and LOS angles is computed using Boeing's Vision-based Software of Track, Attitude, and Ranging (Vis-STAR). This unique imaging software package can process either the visible or infrared camera images providing complete coverage regardless of lighting, range, or background conditions. The ASTRO chaser satellite will also have the advanced video guidance sensor (AVGS), used previously for the DART program.

¶See NASA's "Overview of the DART Mishap Investigation Results: For Public Release," http://www.nasa.gov/mission_pages/dart/main/index.html, May 2006 [retrieved January 2007].

**See Dornheim, M. A., "Orbital Express to Test Full Autonomy for On-Orbit Service," *Aviation Week*, http://www.aviationweek.com/aw/generic/story_generic.jsp?channel=awst&id=news/aw060506p1.xml, 4 June 2006 [retrieved January 2007].

V. Conclusions

The road to autonomous orbital rendezvous is the convergence of two ideologies initiated during the first days of space flight. Although the United States and Russian space programs sought the same objective, they seemed to diverge in their approach practically from the onset. Following the national mandate to place a man on the moon and return him safely to Earth, the United States gravitated toward a manual methodology to orbital rendezvous that reduced development time and increased the capability to handle unanticipated anomalies. The close ties of the Russian military to their fledgling space program directed their focus toward an automated mind-set that minimized redesign efforts between manned and reconnaissance missions. These initial trends of manual and automated rendezvous were cemented only as time passed with the intense political competition so evident during the Vostok, Gemini, Soyuz, and Apollo programs.

For decades, both approaches have been tried and proven in a variety of applications carried out by the U.S. space shuttle program and the Russian Soyuz and Progress vehicles in connection with the Soviet space station program. As claimed, their advertised strengths have been supported, but their known weaknesses have also become evident. Manual orbital rendezvous has become mission unique even for routine missions. Specialized training and planning is required, making the process labor intensive and expensive. Automated orbital rendezvous has high development costs and often requires rigorous cooperation between both vehicles. This approach can lead to reliable techniques with standardizations that provide significant cost benefits in repetitive routine operations, but it can also be a rather inflexible system in responding to off-nominal events.

For future rendezvous missions where ground or crew intervention is impractical or undesirable and the cooperation between spacecraft is impaired or nonexistent, there is currently no feasible solution based on the traditional methods of the past, particularly when small light weight chaser spacecraft are involved. In an attempt to meet these new and increasing demands, the standard orbital rendezvous techniques are being reevaluated and refined with more autonomous solutions. This push for autonomy in orbital rendezvous is evident in the missions of ETS-VII, XSS-11, DART, and Orbital Express, and will continue to expand with future space exploration endeavors.

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