United We Orbit [Docking in Space]

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When two giant vehicles meet in space, collision becomes collaboration.

How a space docking feels can depend on which side of the interface you're facing – whether you're the docker or the dockee. But when the 100-ton spaceship Atlantis made its "controlled collision" with the 100-ton space station Mir in June 1995, neither crew had any doubt of what had just happened.

Just before contact, with the two spacecraft perfectly aligned, the Atlantis crew had pushed a button to fire thrusters that rammed them forcefully against the Russian docking mechanism. For the shuttle astronauts, it was the noise of the thrusters more than anything that signaled their arrival at Mir.

"You could hear the booming of the forward jets," recalls STS-71 co-pilot Charlie Precourt. The contact itself is "absolutely imperceptible," says Kevin Chilton, who commanded the third Shuttle-Mir docking mission nine months later. You know something's happening from "all those cannons going off all around you," but there's no bumping or jostling inside the Shuttle cabin.

On the Russian side it was a different story. The impact felt "like a big hug," commander Vladimir Dezhurov recalled. "A real man's hug." The Mir began quivering, then calmed down. When the station finally stopped shaking, says Dezhurov, "we understood the docking had occurred."

Over on Atlantis, shock absorbers on the docking mechanism dampened the mechanical impact. "It bounced like a baby carriage," Precourt recalled, but the back-and-forth motion was too subtle to be sensed directly. "The only way we could tell there was any rebound at all was to look in the camera."

The first orbital hook-up of American and Russian spacecraft in two decades had come off without a hitch.

Docking has been part of the spaceflight repertoire for more than 30 years, and as usual NASA has made a complex and challenging operation look boring and routine. In practice it is anything but. Robert "Hoot" Gibson, who commanded Atlantis during the first Shuttle-Mir mission, calls space docking "a cross between air-to-air refueling and a carrier landing." When the two spacecraft are still at a distance, it seems easy. "But the closer you get, the tighter you control, and the smaller the allowable errors can be," he says. With the wrong combination of equipment problems and human error, things can go spectacularly wrong, and that's reason enough to regard each space docking with apprehension, suspense, and respect.

When Neil Armstrong flew the world's first orbital docking on Gemini VIII in 1966, his joy was soon overshadowed by a life-threatening out-of-control tumble that led to an emergency splashdown in the Pacific (the fault lay in a stuck thruster on the Gemini, not the docking technique). Docking problems frustrated Russia's first space station mission in 1971 and nearly aborted NASA's first Skylab mission two years later. When the Russians added the Kvant science module to the Mir station in 1987, an errant trash bag got stuck in the docking interface, preventing an airtight seal until spacewalking cosmonauts removed it. Other failures and close calls convinced both American and Russian space engineers that there would never be anything routine about space docking.

Bumping two weightless behemoths together in orbit without damaging or breaking anything turns out to be a tricky physics problem. Vehicles docking on Earth have at least some of their motion already constrained at the time of contact. Freight cars move along rails, ships float on water, even aircraft have aerodynamic stability. But in space, position and orientation can vary in all three dimensions, and can change at different rates. All these variables – Precourt calls orbital docking an "eight-degrees-of-freedom problem" – have to be controlled simultaneously to make sure the final contact happens within the mechanical limits of the docking hardware. On Earth we also are surrounded by natural damping forces – friction, air and water resistance, the restraining forces of rails or cables. In space, all that energy has to be absorbed and damped out within the vehicles themselves.

Given the inherent problems imposed by the laws of physics, it's no surprise that American and Russian engineers came up with essentially the same design for docking mechanisms in the mid-1960s. Both countries built systems that worked like this:

The active vehicle – the moving one – extended a long, stinger-like probe with capture latches at its tip. On the target vehicle was a cone-shaped receptacle. When the tip of the probe entered the wide end of the cone, it was naturally guided to the back, where another latch mechanism was waiting. The engagement of these two latches was called "soft docking." The docking probe then retracted, drawing the two vehicles together so that facing rings could be latched together for a "hard dock." From each side, the docking mechanisms – the conical "drogue" and the spindly probe – would then be removed, and a pressurized transfer tunnel opened up so the crews could float from one vehicle to another.

This was the basic design used for NASA's Apollo lunar missions and for the Skylab space station. It also became standard for Soviet vehicles and, with one exception, has served all Soyuz, Progress, and science module dockings with Russian space stations to this day.

The inescapably "male" and "female" nature of the probe/drogue system has led to countless earthy jests by astronauts and cosmonauts over the years. The major drawback is equally obvious: Only mechanisms of different types can successfully mate. For short space flights this wasn't really a problem, since each vehicle could easily be outfitted with mission-specific hardware. But engineers knew that at some point in the future, spacecraft would need to be able to dock with any other vehicle in orbit.

The "androgynous" docking mechanism sprang from this anticipated requirement. When Nixonian detente thawed relations between Moscow and Washington in 1971-2, the resulting plan for the symbolic Apollo-Soyuz orbital docking gave space engineers the opportunity to build and test an androgynous docking mechanism. The new design had an immediate political advantage: Neither the Russian nor the American spacecraft would look dominant. Arguably for the wrong reasons, space engineers were allowed to do the right thing.

Based on preliminary sketches by NASA's virtuoso spaceship inventor Caldwell Johnson (a self-made engineer who had co-designed the Mercury capsule in the 1950s), and on a symmetric ring-to-ring system designed at about the same time in Moscow, American and Russian engineers (led by docking expert Vladimir Syromyatnikov) together came up with a new design. Each vehicle would have a docking ring with three open "petals" extending out from the ring. The petals were for alignment only: They fit slot-and-groove-style between the petals of the other vehicle's ring, so that the facing rings could only fit together in the desired way. During docking, the ring on the active vehicle (complete symmetry was sacrificed), would extend outward on shock absorbers, and would be rammed (slowly!) into the passive vehicle's ring. The petals would then interleave like clasped fingers, and latches on the active vehicle's petals would catch latches on the target docking ring. Finally, after the motion from initial contact damped out, the extended ring retracted to pull the two vehicles closer together. At that point the heavy latches around both rings would engage to achieve a hard docking.

The new system worked fine three times on the one mission it flew (Apollo-Soyuz), and its advantages over probe/drogue immediately became clear. For one thing, the damping mechanism allowed it to handle much more massive vehicles. True, it demanded more accurate alignment from the pilots, but that wasn't seen as a problem.

By the time the Russians were designing the Mir space complex in the mid-1980s, they needed exactly this kind of system for the Buran space shuttle to mate with the station. The shuttles were too massive for the limited probe/drogue design, and the Russians would now be using different docking combinations – Soyuz to Mir, Soyuz to Buran, and Buran to Mir. The androgynous system was the only one that could satisfy all these requirements.

The Russians called their design "APAS," for "androgynous peripheral aggregate of docking" ("docking" in Russian is stykovka). They improved the Apollo-Soyuz design in several significant ways. First and most visibly, the guide petals were turned inward rather than outward, which allowed a much larger internal tunnel. Structural latches were placed outside the pressurized tunnel, and there was more space for electrical and hydraulic connections. The result was a complicated system of struts, jackscrews, dampers, and actuators perfectly designed for the Buran/Mir dockings. But the Russian shuttle was scrapped before the system got the chance to prove itself.

Meanwhile, American space designers had been developing their own docking mechanisms for the shuttle and the Freedom space station. The only principle guiding this complicated, clumsy system seemed to be that it deliberately not look like the Apollo-Soyuz design. By the early 1990s, however, the political winds had changed, and it was no longer seen as unacceptable for NASA to acknowledge Russian space expertise. After a brief review, the Russian system designed for Buran/Mir was adopted for Shuttle/Mir and the space station, with Rockwell and RSC Energia doing the modification work.

When Gibson and Precourt were tapped to fly the first docking mission, they knew they were in for a challenge. No space shuttle docking hardware had ever worked properly on its first attempt in orbit. The highly public embarrassments of failed first docking attempts to the Solar Maximum satellite in 1984 and to the Intelsat satellite in 1993 (both of which involved spacewalking astronauts, not vehicles) as well as several less publicized but equally galling frustrations with other space hardware, reminded everyone how easily things could go wrong.

Even after all the hardware had been analyzed and tested piece by piece, experienced experts knew they weren't finished. At the insistence of veteran space docker astronaut John Young, NASA added a special program for "end-to-end testing" at the Kennedy Space Center. The docking assembly was installed in the shuttle's payload bay with all the flight hardware in place. Test engineers rigged up a mockup of the passive mechanism on Mir, and lowered it by crane at docking speed. They verified in the cockpit that the instrument panel performed as advertised through the whole sequence.

One value of these tests was to raise the crew's comfort level with the post-contact damping process, the time between initial capture and hard docking when the two giant vehicles would be only loosely joined together. During this time, the Mir's attitude control system is switched off so as not to introduce motions that could bend the docking mechanism. But even in this "free drift" mode, the Russians had worried that random twisting of the two large masses might never settle down. Noted Precourt: "We might never see ring alignment, and this would prevent us from drawing the ring back in."

Based on the ground tests, the crew came up with a solution. "We interrupted the auto[matic] sequence at the first point we saw ring align," Precourt explains, "stayed there about a minute, waited until motion stopped, and then we retracted." With the rings on Mir and the Shuttle perfectly parallel, the hard dock could proceed.

Even though their hardware was different, the Shuttle-Mir dockers knew they had much to learn from the previous generation of astronauts. Gibson spent a lot of time on the phone with Tom Stafford, who had piloted the US side of the Apollo-Soyuz docking 20 years earlier. "I didn't really get a lot of useful advice on the actual docking," says Gibson, "because the rates and the procedures are different. Most of the advice I got from Tom Stafford had to do with political aspects, public relations, protocols." In other words, how to be a space diplomat when all the world is watching to see how two former competitors handle their new partnership.

Precourt spent time chatting with six-time spaceflight veteran John Young, now a special assistant to the Johnson Space Center director. Precourt was especially interested in the difference between simulation and reality. "In a simulator, a lot of the sensations aren't there, but in flight you are subject to a lot of distractions," he says. Young told him to trust the simulators, which was good advice – the crews who've docked with Mir say the simulators are extremely faithful to the true experience. If anything, says Precourt, the real flight "was a lot smoother than most of the sims, in terms of everything working."

Before their mission the STS-71 astronauts "flew" over 200 approaches in a variety of simulators. Docking with Mir requires a very slow closing speed – barely more than an inch per second during the final approach. It also demands great precision. The angular alignment of the docking rings has to be within two degrees in each axis, and the targets have to be within 3 inches of lateral displacement from each other. The astronauts have various tools to help them measure the alignment. A metal "stand-off cross" extends on a rod above and parallel to a black painted cross on the Mir target. If the crosses appear to line up perfectly, the pilot knows he's on track. Shuttle astronauts also can look through a television camera with grid markings to check the alignment.

One concern had been the disorienting view caused by the camera's being at a distance from the pilot's eyeballs. "You're not looking at the real world, "explains Precourt. "It's not like landing an airplane with a view straight out the front windshield." It's more, he says, like trying to close your eyes, hold your fingers out, and touch your finger tips. But even though it took some getting used to during training, it turned out not to be a problem.

Gibson and Precourt, and every docking crew after them, learned in the simulators to hit the marks every time, even when jets and instruments and computers failed. On the actual STS-71 docking, the angular errors were measured in tenths of degrees, too small almost to be noticed. The arrival time was nearly perfectly, too: In an allowable window of two minutes, they were only two seconds off.

Experience has shown that on-time arrival doesn't matter all that much. "I always argued against getting hung up on the docking time as if it were critical," says Kevin Chilton. "I wanted to dock a minute later, or a minute early, just to show it's not important." He ended up docking "pretty much on time" anyway.

In fact, so far every docking has been a model of precision. "When you think about it," says Precourt, "it's pretty amazing that you'd have two vehicles flying in space that are subject to bending and moving, yet the relative position of the docking ports can be precisely known when we arrive."

With at least five more Shuttle/Mir missions scheduled, and with international Space Station dockings to begin in 1998, orbital docking is finally becoming, if not routine, then at least no cause for great anxiety. Engineers working on the Space Station have come up with a few modifications to the Shuttle/Mir design, but not many. They plan to fine-tune the orbiter's damping mechanism to further reduce the energy transferred to the Station at contact. The Station also will have a few of the old-style probe/drogue ports, since a variety of Russian, U.S., European, and Japanese vehicles will have to dock with it.

Dockings have now taken place with four different configurations of the Shuttle and Mir (approaching the Russian station, with all its protruding solar arrays, modules, and vehicles, is "like docking with a porcupine," says STS-79 commander Bill Readdy). The STS-74 crew brought up a new docking module to attach to Mir last year, which provides greater flexibility and places the docking interface at a distance from the main station. This addition, and the station's greater mass, may account for the fact that Mir crews are now feeling less of a jolt than did Dezhurov and his companions. Readdy says Shannon Lucid and her cosmonaut crewmates hardly felt a thing when Atlantis pulled up to the docking port last September.

The STS-74 astronauts even came up with a sound track to accompany all the slow, graceful maneuvers in space. A Strauss waltz had already been appropriated by Stanley Kubrick, and besides, it evoked Vienna, not Moscow. So Ken Cameron and his Atlantis crew went with Tchaikovsky's "Swan Lake" for their final approach and docking.

Precourt is now back in Houston training to command another Mir rendezvous mission, and will be the first astronaut to make a second such docking. On his first trip to Mir he spent time with his cosmonaut hosts inside the attached Soyuz spacecraft, and has been through the complete cosmonaut training program for Soyuz dockings to Mir. As it stands, he has the inside track to become the world's leading space docker.

Still, he keeps worrying about what could go wrong, what might be done ahead of time to reduce the risk, and what he might have to do should there be an unforeseen problem in orbit. His biggest fears are shuttle failures that could cause a sudden increase in closing speed during final approach. He's also thought out another failure scenario.

"I've told folks that I really think we're going to see a bounce-off," he says. "At some point there's going to be a mechanism that doesn't work for us right. The Russians have had it happen to them." He pauses thoughtfully. "I hope we're adequately prepared to deal with that."

It's Not as Easy As It Looks

The space docking simulator at NASA's Johnson Space Center in Houston so accurately mimics motion in space, boasted its operators, that some visitors actually get motion sick. Over the previous few months, I was told, two of them actually had to use the airsick bags hung by the back door.

When I tried it myself, my vestibular system wasn't the only one of my senses that was fooled. The combination of realistic views out the cockpit windows, plus the television scenes, plus the high-fidelity data displays, plus the sound of maneuvering rockets firing, convinced me that I really was in control of a 100-ton spaceship heading straight for an equal-sized target. My thumping heart, high-pitched voice, and sweating palms must have been convinced, too.

Practice docking runs usually start about 200 feet out, with the shuttle directly below the space station's docking port. The shuttle moves "top first" toward the station, rising slowly like an aircraft on a carrier elevator. The pilot (me) stands at the aft flight deck, behind the Shuttle's two pilot seats. I can watch what's happening through a pair of overhead windows, or on two TV monitors displaying the views from half a dozen cameras. I guide the spaceship by gently tweaking two hand controllers, one for translating in any of six directions, and the other (less often used) for rotating. From time to time I punch a button to adjust the digital autopilot that maintains certain constant conditions, like holding the shuttle's orientation steady. I also have a set of laptop computers showing my predicted motion over the next ten minutes.

Certain rules of thumb apply to any orbital rendezvous. During the last 1000 feet of climbing up the "R-bar" (the station's radius vector toward Earth's center), the approach speed should gradually drop as the distance to the target gets smaller. At 200 feet, I'm down to two-tenths of a foot per second, a genuine "space crawl." At first glance out the overhead windows, the station looks like it's just hanging there. But the lack of motion is deceptive, because very soon things begin happening with startling speed.

At this point, you'd better have your alignment right. If the shuttle's docking ring doesn't contact the station's ring within tight margins of speed and accuracy, the latches may not capture properly. Worse yet, the docking equipment could be damaged, ruining the mission. In a truly nightmare scenario, the shuttle collides with the station, damaging or destroying both vehicles and putting lives at risk.

The flying skills that ward off these unpleasant outcomes are honed in simulators like this one. A top-notch space pilot doesn't over-correct, thrashing back and forth on the flight path. Instead, he keeps a running catalog of soon-to-be-needed changes in all axes of motion, and knows which of them will be accomplished gratis by impending maneuvers in other axes.

This occurs because the jets on the shuttle aren't pointed strictly in one axis. Using the sideways jets, for example, also imparts a slight roll to the whole vehicle. The result is that some apparent motion is genuine and some is counterfeit. A good pilot learns to tell the difference.

The sound of thruster firings is one of the simulator's "user options," and can be toggled on or off. Leaving it on is called "dragon's breath mode" by the operators, who went to great pains to duplicate the muffled howitzer sound of the 900-pound shuttle jets.

"I went to a shooting range and recorded shotgun blasts," one of the engineers told me. "Then we digitized the sound and stretched it out a bit. Crewmen say it's close." At some point he wants to get close to a real howitzer, so he can record it and raise the simulator's fidelity another notch.

By the time the station is within 30 feet and the final alignment adjustments have been entered into the autopilot, I no longer have the time or inclination for casual conversation with my hosts. With a sky full of very real looking space station hardware above me, and with instruments delivering highly convincing reports of imminent contact, my concentration, like that of the man to be hanged in the morning, has become wonderfully concentrated.

Pulse, pulse. Small jet firings push the aiming crosshairs on the television screen toward the right, closer to the target painted on the station. Pause, agonize. Do I need a plus-X-axis burn now, or will the vertical trend reverse in time? Is my approach rate right? Mentally juggling all these parameters of motion, I have to decide every instant which are okay, which can wait, and which have to be changed right now. Dangerously close to cerebral overload, I surf the breaking wave of final approach as the station's docking structure comes in sight out the aft window, only a few feet from contact.

The time for computer displays and digital read-outs is past, and only the sight of the looming station fills my senses. I make one final crosswise pulse to center the crosshairs. Just as the petals overlap on their way to contact, I hit the button to fire jets that shove the mechanisms hard enough together to guarantee latching.

The jets boom as the docking rings lock. There is no further motion or sound.