The Lunar Landing Research Vehicle; Prelude to the Arrival at Tranquility Base

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The flight of Apollo 11 was the end of a decade-long race to reach the moon, a race between the US and Soviet Union, but also a race with time, for we as a nation only had the 1960s to reach our objective. Most of us remember that particular day—July 20, 1969—but the further we are from any date the harder it is to recall details. It's easy to forget, for instance, how close together the Apollo flights came to each other as the lunar flight date approached. Apollo 7 circled Earth for almost 11 days testing the systems of the spacecraft in October 1968; Apollo 8 gave us the first glimpse of our entire planet while circling the moon during Christmas of 1968. Apollo 9 lifted off on March 3 of 1969, and Apollo 10 returned to Earth on May 26 of that year. Less than two months later, on 16 July, Apollo 11 lifted off on its mission of landing on the moon. That's five Apollo launches in ten months, three of which went to the moon.

That Apollo 11's Armstrong and Aldrin landed safely—and returned successfully—is the result of a lengthy and dangerous program on Earth, a program that took place not far from here, in fact, at what is today the NASA Dryden Flight Research Center, at Edwards Air Force Base.

Today's story begins on May 25, 1961, when president John F. Kennedy issued his now-famous challenge to put a man on the moon and return him safely again to Earth. With the intervening years it's not easy to keep this challenge in perspective, so let me offer a few neighboring events in 1961. Mickey Mantle became the highest paid baseball player that year, with an annual salary of $75,000; in-flight movies were introduced by TWA; a gallon of gas cost .27 cents; *Wagon Train* was the most popular show on tv; *Runaway* by Del Shannon was a hit on the radio, and both Chico Marx and Gary Cooper died that year. On May 5, less than three weeks before Kennedy's challenge, NASA placed a human into space, Alan Sheppard. That came in response to the Soviets, of course, who sent Yuri Gagarin into orbit on 12 April of 1961. The US had been playing catch-up with the Soviets for nearly five years by then, and Kennedy's challenge was intended to change that, to give the

Americans the lead in space, and to demonstrate to the world that we weren't second fiddle on the global scene.

Kennedy's challenge electrified much of the country but it floored most NASA engineers. Indeed, "no one" at NASA's Langley Research Center "could quite believe it." The leader of the Space Task Group at Langley was simply "aghast," noted historian James R. Hansen.[1] Not that going into space was a new idea to engineers at NASA, or its predecessor, the National Advisory Committee for Aeronautics. NACA engineers had been discussing putting humans into space since the early 1950s. But thinking about orbital flight is not the same thing as planning for an excursion to the moon's surface. Just getting to lunar orbit, never mind how to reach its surface, was a daunting task.

Interestingly, two organizations were thinking about the same thing, unaware of the other's activities in the matter: the astronauts would need something to simulate here on Earth the descent to, and landing on, the moon. These two organizations were the NASA Flight

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[1] James R. Hansen *Spaceflight Revolution: NASA Langley Research Center From Sputnik to Apollo* (Washington, D.C.: NASA SP-4308, 1995), chapter 8, "Enchanted Rendezvous: The Lunar-Orbit Rendezvous Concept," in which there is a fascinating account of the internal competition among NASA engineers and scientists to devise a means of reaching, landing on the moon, and returning to Earth. p. 221-268.

Research Center at Edwards AFB, (today Dryden) and the Bell Aircraft Corp in Niagara Falls, NY,

The task they contemplated is not as easy as it seems.

Chief among the challenges was simulating the moon's gravity, which is 1/6th that of Earth's. How, in the early 1960s, are you going to do this with a wingless aircraft? What method will you use to negate 5/6th of the Earth's gravitational pull in flight or the atmospheric forces at play? How will you compensate for the fuel you burn off while in flight? Need I remind you of the state of computing in 1962, and more importantly, of portable computers? The operative words here are big, heavy and analog. And how will you control and maneuver the vehicle in a lunar simulation?

And what are you going to use to keep your simulator up in the air? The engineers had in mind a vehicle with no wings, could transition in any direction at 15 mph, yet could also hover in place.

The group at the Flight Research Center, or FRC, looked at three possible simulators: helicopters, vertical take off and landing, and short take off and landing vehicles. A little digging revealed that the Naval Ordnance Test Station at China Lake had been conducting simulated unmanned lunar landings since 1959 with a

700-pound flying vehicle powered by unsymmetric dimethyl hydrazine mixed with red fuming nitric acid as fuel. The vehicle was constrained by four cables suspended from the top of a 150-foot tower and was controlled entirely from the ground. All of this was interesting, but not that helpful to the group from the FRC, and they continued their search for options. Bell engineers, meanwhile, were advocating a free-flying machine, although they only had ideas, and no drawings for such a machine.[2]

Both parties ultimately dismissed tethered flight because it could not adequately simulate the motions they felt necessary for the mission. Helicopters were soon discounted as well. While at first glance helicopters appear useful, thrust vector created by the rotor blades would not allow for large attitude excursions needed for lunar simulation. It also created a coupling between lift and attitude control that would be hard to mask.

The FRC and Bell also rejected an off-the-shelf visual simulator because of its inability to offer valid motion cues, meaning visual and especially physical motion cues, which they deemed important to the project. In the end both NASA and Bell independently turned

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[2] *Project 1055, Proposal for the Development of a Soft Landing Vehicle* U.S. Naval Ordnance Test Station, China Lake, California, 5 October, 1961.

to a free-flying simulator. Bell engineers proposed a light frame in which hung a double gimbaled engine to provide vertical lift. Strategically located rocket motors would provide deceleration and translational forces, all of which would simulate controlled flight in the lunar environment.[3]

Bell's proposal was accepted and funded by NASA in 1962, and the company set to work designing and building the machine, dubbed the Lunar Landing Research Vehicle.

The Lunar Landing Research Vehicle, or LLRV, had a General Electric CF-700, the fan jet version of the J-85, mounted inside two gimbaled rings. The dual gimbals enabled the engine to provide true vertical thrust—perpendicular to the Earth's surface—while allowing the cockpit and truss to rotate freely in pitch and roll up to 40 degrees. Eight thrusters were clustered around the gimbal frame where they served as lift rockets, capable of producing 500lbs of thrust each. These were used for lift when flying a lunar landing simulation. For maneuvering, the engineers chose sixteen smaller thrusters, four at each corner of the vehicle. These were fired in pairs, one up and one down at opposite corners of the vehicle. Half

[3] Bell study report, *Feasibility Study for a Lunar Landing Research Vehicle* Bell Aerosystems Report 7161-950001, 8 March 1962.

of the 16 thrusters were adjustable on the ground to vary their thrust between 18-90 lbs. so they could find which setting was best suited for training. The pilot could select one set or the other.

Given the precarious nature of this craft and the risks involved, they also decided to add three emergency recovery-and-escape systems. First, eight emergency thrusters were added to the frame to arrest the vehicle's descent in an emergency, and particularly at touchdown. Fired all at once they generated 3000 lbs of thrust. Second, and meant to be used in conjunction with the emergency rockets, was a mortar-deployed parachute attached to the frame designed to lower the entire vehicle at 33.4 feet per second. The logic here was that the craft, so rare and yet so essential, was worth saving at all costs. Third, the pilot sat on a Weber zero-zero ejection seat. The entire system was designed to save the LLRV in a free fall, with one small caveat: it only worked well above an altitude of 200 feet—which turned out to be the typical altitude for the *start* of a lunar simulation profile. Below 200 feet the mortar parachute could not be deployed in time to save the vehicle. Furthermore, in order for this mortar parachute to do its job the pilot had to remain with the vehicle to activate the lift rockets at touchdown and completely arrest the descent. Because the emergency-lift thrusters were powered by the same propellant all the other thrusters used, a drop in propellant might occur just when that propellant was needed to arrest the descent of the LLRV. Even worse, once the recovery parachute was deployed, the ejection seat could not be fired because the pilot would not be able to clear the vehicle without becoming entangled in the chute.

The arrangement was less-than-ideal, and eventually the emergency lift rockets and vehicle recovery parachute were discarded in favor of just the ejection seat. Management finally accepted that the pilot was more valuable than the machine—and since the pilots of the LLTV, or Training Vehicle, were to be astronauts, this wasn't a stretch.

The craft carried two fuels: JP-4 for the jet and a 90% pure solution of hydrogen peroxide (H_2O_2) for the thrusters, which was pressurized with helium to ensure a constant flow to the thrusters. NASA had used H_2O_2 for two decades by then, most recently in the Reaction Control System's maneuvering thrusters on the X-15 when it was outside the Earth's atmosphere; using it on the LLRV came naturally.

Bell delivered the first LLRV to the FRC in the spring of 1964. The second vehicle followed not long after. Ground tests began once the first vehicle was uncrated and assembled, and in October of that year Joe Walker, the Center's chief pilot, took the LLRV up for its first flight. In its final configuration for the program the CF-700 put out 4200lb of thrust under *ideal* conditions, barely enough for a thrust-to-weight ratio of 1.05/1. The team quickly shifted flights to dawn, taking advantage of the cooler air for greater thrust.

Perhaps more remarkable than anything else about it, the LLRV was a fly-by-wire aircraft—one of the very first—controlled by three electronic, albeit analog computers. There was no mechanical backup control system of any kind, setting the LLRV apart from the few other electronic flight control programs in existence. Artificial force gradients were part of the controls for acceptable sensory characteristics. The fly-by-wire system allowed them to maximize the number of control parameters that could be varied during flight-testing, and the changes could be made on site.

The LLRV's Flight Control Systems had two purposes: vehicle attitude control, and jet engine stabilization. The engine stabilization computer controlled the primary means of lift. In operation the FCS had to manipulate the engine in four different modes. Gimbal-locked was for takeoff and emergencies, centering the jet and locking it there. In lunar simulation the FCS directed the engine to remain perpendicular to the Earth, yet automatically deflect to counter aerodynamic forces. The thrust-to-weight calculator established the vehicle's weight before lunar simulation, something only done in flight. And the auto-throttle controlled the jet's thrust in lunar simulation mode, not only countering 5/6th gravity, but also accounting for both fuel burn-off and thrust propellant expenditure throughout the flight to keep the thrust at a constant in simulation.

The LLRV's attitude-control system itself had three separate components. An attitude-rocket system for generating control moments; a primary and backup electronic systems for controlling operation of the attitude-control rockets, and; a monitoring system containing failure-detection circuitry for monitoring system performance and reconfiguration in case of failure.[4] Engineers separated the redundant electronic systems to boost reliability, housing all three independently in

[4] Calvin R. Jarvis, *Flight-Test Evaluation of an On-Off Rate Command Attitude Control System of a Manned Lunar-Landing Research Vehicle* (Washington, D.C: NASA TN D–3903, April, 1967); Donald R. Bellman and Gene J. Matranga, *Design and Operational Characteristics of a Lunar-Landing Research Vehicle* (Washington, D.C: NASA TN D–3023, 1965).

assemblies at the rear of the vehicle. A series of gyros, some of which could be nulled in flight after erection, provided feedback for the flight computers.

During operations the primary FCS for vehicle attitude control was designed to automatically switch to the backup mode if it detected a failure or anomaly. There were times, however, when the pilot had to manually make the switch since the system did not always detect the failure. The backup FCS was a single-string system with no failure detection: if *it* failed, the pilot had to manually return to the primary system. An anomaly detection monitor compared the primary and backup systems and if a discrepancy of longer than 150 milliseconds occurred, it commanded a switch the backup. And then, only the failed axis transferred to backup. A mobile ground unit monitored operations, receiving telemetered data throughout the flight.

LLRV flights usually lasted no more than about 8 minutes, after which the JP-4 and H_2O_2 were nearly exhausted. And while capable of climbing higher, the flights rarely went above 200-300 feet.

Because the LLRV's jet engine could barely lift the aircraft, the pilots were carefully weighed at the start of the program; one of them had the habit of eating well and had to lose weight in order to participate. Cans of lead shot were added to the vehicle for a lighter pilot and removed for a heavier one so that the vehicle remained balanced. And each sat on a custom cushion so their mass, measured at the Weber factory, was consistently located.

Initially the controls were like those of a helicopter: a center stick, a side stick (cyclic), and rudder pedals. Within three months, however, engineers and mechanics at the FRC had replaced these with two side sticks that better emulated the controls of the emerging lunar module. The left stick still controlled the lift thrusters and the jet engine (when not in lunar simulation) while the right stick now controlled all the maneuvering thrusters, eliminating the rudder pedals.

A typical flight in the LLRV began when the pilot lifted off vertically and climbed to 200’ above ground level. He engaged the program that weighed the entire machine, including pilot. To do this the computer commanded a brief surge in the jet; accelerometers measured the vehicle’s upward motion and the computer summed this measurement with engine thrust, the known weight of the vehicle at start up, as well as other factors, and then calculated the weight of the vehicle at that moment. Once weighed, the lunar simulation program automatically reduced jet thrust to cancel just $5/6^{th}$ of the Earth's gravity. But since both fuel and thruster propellant were being consumed throughout the flight the FCS had to calculated the fuel and thruster consumption at a standard rate to keep the simulation realistic. Just as importantly, accelerometers recognized side forces on the LLRV and fed this information to the FCS, which automatically fired the thrusters or tilted the jet to cancel them out.

In Lunar Simulation Mode all of this was invisible to the pilot, who was busy using both hands to control and maneuver the LLRV toward a landing. Now weighed and in simulation mode it was up to the pilot to keep the LLRV in the air. He flew a machine that felt as close to being in lunar gravity as one could on Earth, as well as in the absence of an atmosphere.

The pilot's left hand commanded the large thrusters located around the gimbals that now emulated the lift rockets on the LM. With his right hand he manipulated the maneuvering thrusters that fired bursts of steam for control. Once at altitude the objective was to initiate a steady descent to a landing further down the flight line, and it was anything but an easy task.

Beginning in 1964, over the next 2½ years three pilots at the Center flew the aircraft: Joe Walker, Don Mallick, and Jack Kluever. The flight research program led to many changes in the vehicle, from how the machine responded to control inputs to an almost fully enclosed cockpit, the better to simulate the LM pilot's. All told, vehicle no. 1 flew 245 missions; vehicle no. 2 flew six times, all at Dryden.

Changes to the LLRV were incorporated into the plans for three LLTV, or Training Vehicles, which Bell was asked to construct and deliver to the Manned Spacecraft Center in Houston, starting in 1966. LLRV no. 1 was modified into LLTV and sent to Houston for astronaut training; although modified likes its sibling, LLRV No. 2 it remained at the FRC where it was cannibalized for parts. Meanwhile two pilots from the MSC, Bud Ream and Joe Algranti, came to the FRC to be qualified in the LLRV since they would lead the astronaut training in Houston. The two pilots found what each of the three FRC pilots had found—as would all the others—no matter how good the instructions were, your first lift-off as PIC was also your first lift-off. There was no second seat.

The plan was for each Apollo crew heading for the moon to spend time flying the LLTVs as their launch approached. That way both astronauts were qualified to fly the LM all the way down. In practice, however, only the LM commander flew the LLTV with any frequency—in Aldrin and Armstrong's case, for example, Aldrin hardly ever flew the LLTV.

By March of 1967 only a handful of flights had taken place at the Manned Spacecraft Center before the loss of Apollo 1 on the launch pad froze flight training until the accident had been solved and a sweeping review of flight safety was complete. On top of this, once flying did resume, the MSC suffered a string of accidents with the LLTVs, the first involving Neil Armstrong, in 1968.

Were the LLRV and later LLTV worthwhile? The comments of the astronauts themselves are perhaps the best measure of this.

Neil Armstrong said that, because of the LLRV and LLTV, when it came to finally landing on the moon: "I felt very comfortable -- I felt at home. I felt like I was flying something I was used to and it was doing the things that it ought to be doing. [The moon] was not the kind of place I wanted to try to make the first landing."[5]

Pete Conrad: "In my case, there were a couple of times I had to get [the LLTV] stopped and I only had 60 seconds to do it, and it's not a question of saying 'reset the simulator; I blew that one.' There is no other way you can get that confidence. Were I to go back to the moon, I personally would want to fly the LLTV again as close to flight time as practical."[6]

The LLRV's legacy is more than simply preparing astronauts for landing on the moon, however. It's most consequential impact was on fly-by-wire technology. The first attempt at controlling a aircraft strictly with a computer was the Canadian CF-105 *Arrow*. But that program was cancelled in 1959, before it ever entered service. The second attempt came in 1972 when both the Air Force and NASA independently modified aircraft with fly-by-wire controls. The AF chose an F-4 Phantom onto which they grafted a digital fly-by-wire system. NASA, on the other hand, took a Chance Vought F-8

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[5] Neil A. Armstrong, "Wingless on Luna" delivered at the Wings Club, New York City, 1988, 1988.

[6] NASA MSC minutes of meeting of Flight Readiness Review Board, Lunar Landing Training Vehicle, Houston, 12 January 1970, cited in Gene J. Matranga, C. Wayne Ottinger, and Calvin R. Jarvis, *Unconventional, Contrary, and Ugly: The Lunar Landing Research Vehicle* with Christian Gelzer, NASA Monograph in Aerospace History #35, SP-2204-4535, (Washington, D.C.: 2006), Appendix D, 172-178,

Crusader and removed *ALL* the mechanical and hydraumechanical links, then placed a digital computer in the gun bay, where it acted as the flight control unit.[7] This was the first truly digital fly-by-wire aircraft ever to fly; the Air Force chose to keep the mechanical system in place on its F-4 as a backup, whereas NASA's F-8 had none. The engineers and program managers' logic was that if they left in a back up no one would be convinced of the system's potential or take seriously what they were trying to demonstrate. Besides, its engineers had considerable experience with an all-fly-by-wire system: the LLRV. Even more groundbreaking was that the LLRV introduced electronically controlled *engines* as well as flight controls, something that Dryden would work with again two decades later.

There is a final and somewhat charming twist to the LLRV/digital fly-by-wire program. Conceived by Dryden engineers in 1970, they relied on the command module computer on Apollo 15 that had then only recently returned to Earth, which they put in the F-8 for its first series of experiments.[8]

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[7] See James E. Tomayko, *Computers Take Flight: A History of NASA's Pioneering Digital Fly-By-Wire Project,* (Washington, D.C.: 2000).
[8] Ibid.