Six Degrees of Freedom: The Valuable Failures of the Lunar Landing Research and Training Vehicles

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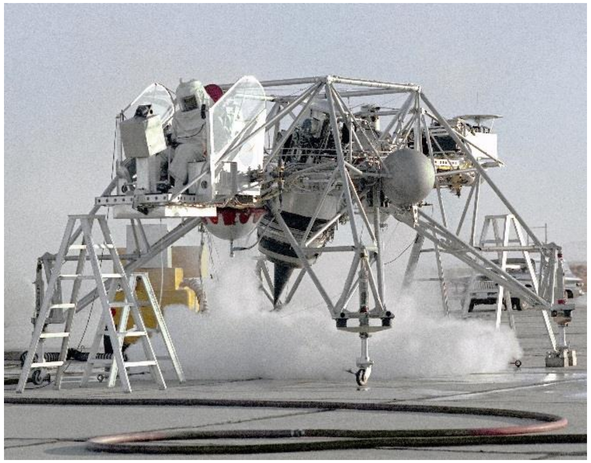
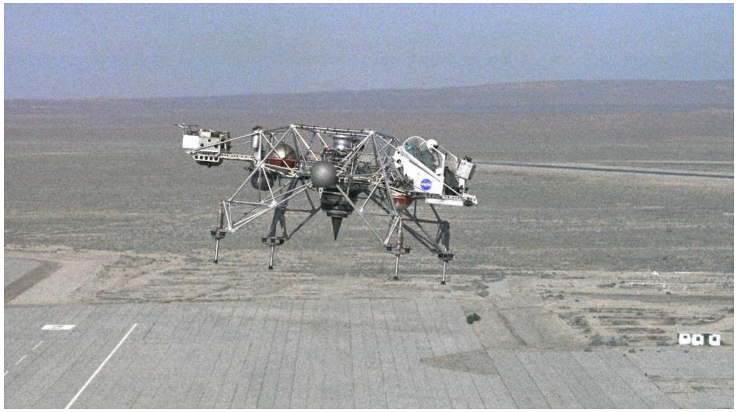
Background

- May 21, 1961: NASA's Apollo team committed to unravelling the program's numerous design challenges of landing humans on the Moon. Grumman Aircraft Corporation was able to design and build the four-legged Apollo lunar module (LM) that could land in the airless, reduced gravity lunar environment using a complex rocket propulsion system that controlled pitch, yaw, roll, descent, and ascent.
- However, the LM's limited fuel supply precluded multiple landing attempts during missions and no electronic simulator would fully develop the skills for flying such an unusual configuration. Although an autopilot would be available as a backup, true lunar surface conditions were almost unknown and could not be left to automation.
- To solve the problem of LM flight training, NASA employed a three-phased approach: an electronic simulator, a tethered flight test unit, and a free flight test unit.
- In 1963, Bell Aerosystems was chosen to create the free flight Lunar Landing Research Vehicle (LLRV).



Bell Aerosystems testing the LLRV design. Note the open pilot platform. Source: NASA

The Lunar Landing Research Vehicles



The LLRV in flight at MSC. Source: NASA

- In 1964, Bell Aerosystems built, tested, and delivered LLRV No. 1 and LLRV No. 2, both of which could take off and land on their own power, reach an altitude of 4,000 feet, hover, move horizontally, and remain inflight for 14 seconds. They were initially designed to give pilots a platform to study and analyze piloting techniques needed to fly and land Grumman's LM.
- The LLRVs were piloted from an open platform. In order to simulate a lunar landing profile, they utilized a centrally gimballed 4,200-pound thrust General Electric CF-700-2V turbofan jet engine. The engine was locked and supported the full weight of the vehicle during ascent. At altitude, the pilot transitioned to a Lunar Sim Mode where the gimballed engine would support five-sixths of the vehicle's weight and keep the engine vertical-to-the-ground.
- Two lift rockets handled the LLRV's descent rate and lateral movement. Eight pairs of smaller thrusters were linked to the pilot station through an electronic fly-by-wire control system to control pitch, yaw, and roll. Helium tanks pressurized hydrogen peroxide propellant for all lift and attitude rockets. Telemetry was transmitted to a ground station and was collected for post-flight study.
- If the main engine failed, six 500-pound rockets could take over the lift function and stabilize the craft for several seconds. Each vehicle was also equipped with a newly perfected "zero-zero" ejection seat.

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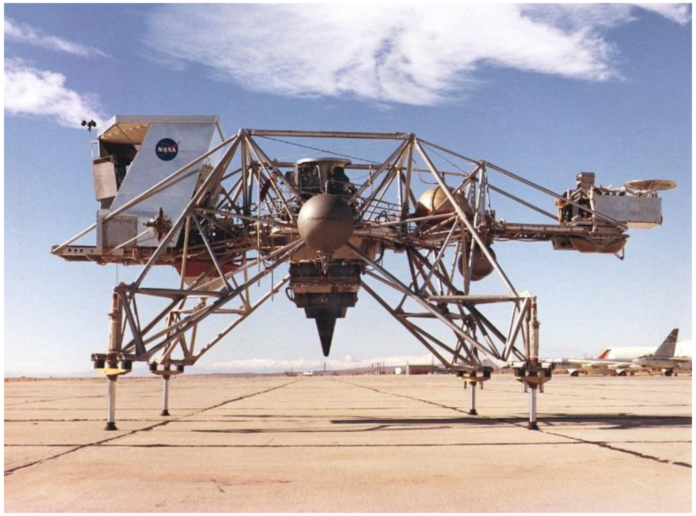
Transition to Lunar Landing Training Vehicles

- By 1966, test data from the LLRV flight program demonstrated that a free-flight vehicle could safely simulate lunar descent conditions and could be used as a training vehicle. Bell delivered three improved Lunar Landing Training Vehicles (LLTVs) for use as dedicated training platforms that more closely matched the LM configuration. The LLTVs were designated LLTV B1, B2, and B3.
- LLRV No. 1 and LLRV No. 2 were shipped to the Manned Spacecraft Center (MSC) in Houston, TX They were upgraded to be used as full-fledged training vehicles and redesignated LLRV A1 and A2. By 1968, the three LLTVs joined the two modified LLRVs to make up the five-vehicle training fleet.



Bell Aerosystems' LLTV with enclosed cockpit was truer to Grumman's LM design. Pilots coped with reduced visibility in the same manner as they would during lunar descent. Source: NASA.

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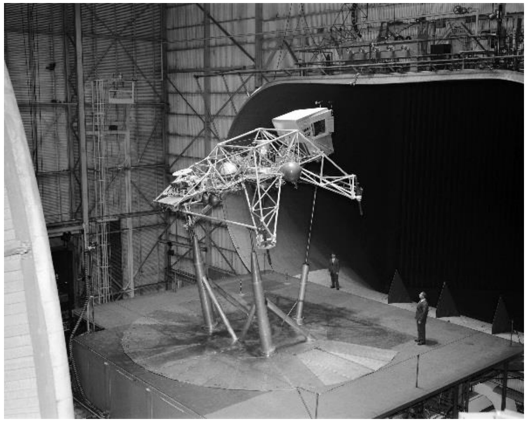
May 6, 1968 LLRV A1 Crash

- Pilot Neil Armstrong successfully ejected during a training flight after losing control of LLRV A1. An LLRV Accident Review Board was established to determine the cause of the accident and find corrective actions, including any implications of the accident on the LLTV and Apollo LM. The Review Board worked with the MSC Accident Investigation Board, which had been established by the MSC director.
- The boards concluded that the proximate cause of the accident was a loss of attitude control stemming from a loss of helium pressure to the propellant system. The helium had vented through the hydrogen peroxide propellant tanks and out the lift rockets and small thrusters. It was determined that although the LLRV could have been landed safely, it would have required immediate response from Armstrong at the first moment of the warning during the heavy workload period that developed during the flight. This was compounded by gusty wind conditions and a failed sensing system's inadequate warning to the ground crew and pilot of the low propellant supply.
- **Recommendations included**
  - Improved monitoring equipment to both ground and flight personnel
  - Improved communications among operating personnel
  - More rigorous operating criteria, training procedures, and project discipline
  - Addition of fire and rescue equipment on the ground and added manpower for the control team
- The corrective actions were also applied with equal force to the LLTV. The mishap triggered a comprehensive study of the LM, but no significant problems or special actions result in LM corrections because of system design differences.

Pilot Neil Armstrong parachutes back to the ground as the wreckage of LLRV A1 burns on the airfield at MSC. Source: NASA

December 8, 1968 LLTV B1 Crash

- Seven months later, LLTV B1 was lost in a crash during a training flight. Pilot Joseph Algranti had ascended and begun a landing run. Shortly after the engine gimbal was unlocked, the LLTV began to oscillate about all three axes. Algranti attempted to relock the engine; however, the LLTV continued to oscillate to the point where the engine and lift rockets could not recover the craft. Algranti safely ejected before the vehicle crashed.
- An LLTV B1 Accident Investigation Board was immediately appointed to investigate the crash. They determined that the primary cause of the accident was that the LLTV entered a region of flight where “aerodynamic movements overpowered the control system in such a way that attitude control was lost.” The source of the issue was not identified in time during the flight to add a second control system, which could have restored control capability.
- The Board also noted the aerodynamic limitations of the LLTV were not completely known by anyone, the existing wind conditions were insufficiently accounted for in flight planning, and the configuration of displays in both the LLTV and the ground support van inadequately defined the existing flight conditions.
- **Recommendations included**
  - Wind tunnel tests to measure aerodynamic characteristics in order to set operating limits
  - Automating portions of the attitude control system when the LLTV hit a hard stop
  - Improving cockpit field of view, references, and displays



LLTV B3 at MSC undergoing post-mishap wind tunnel testing after the 1968 LLTV B1 crash. Source: NASA

January 29, 1971 LLTV B2 Crash

- Almost 9 months after the launch of Apollo 13, LLTV B2 was destroyed during a routine check flight. Pilot Stuart “Stu” M. Present ejected safely before the LLTV crashed on a runway and burned. The NASA Investigation Board formed to investigate the cause of the incident concluded that an electrical system malfunction was the principal cause of the failure. The flight control system lost primary power and the emergency generator and switching malfunctions prevented the battery from supplying emergency power.
- General Electric had replaced the original generator with an upgraded battery-powered emergency bus model intended to improve reliability; however, the upgrade prevented the switchover circuitry from engaging the bus. Post-mishap analysis showed that the exhaust from the ejection-seat rocket had caused the turbofan engine to flame out, causing the DC generator to spin down, removing the magnetic field, and enabling the emergency bus to activate with battery power. The attitude rockets began firing as the LLTV crashed. The obscure failure mode had not been identified in Bell’s formal Failure Mode and Effects Analysis.
- **Recommendations included**
  - Modification of the electrical system to ensure that the backup power was available to the flight control systems before flight operations were resumed

Pilot Stuart “Stu” Present ejected safely from LLTV B2 before it crashed. Source: NASA

Aftermath

- Only two vehicles out of the five remained intact by the program's end. The experience gained from hundreds of successful flights and three failures led the pilots to respect the vehicles' command of an unforgiving flight regime. Apollo astronauts repeatedly praised and credited the experience and confidence gained from their LLTV training.

The Apollo 11 LM Eagle piloted by astronaut Neil Armstrong in lunar orbit. Source: NASA

- Although the Apollo LM was equipped with a fully functional automatic landing system, all Apollo mission commanders opted to land the LM manually. As Apollo 1 astronauts Armstrong and Edwin "Buzz" Aldrin descended towards the lunar surface in the LM Eagle, Armstrong saw they were nearing a rocky area. He set a precedent for the program by disregarding the LM's automatic landing system and switching to manual control during the last moments of descent, landing the LM on a safer, more suitable spot. While it is impossible to speculate as to whether the automatic landing system would have operated successfully had it been utilized, it is clear that the LLRV testing at FRC and the astronausts' LLTV training contributed to successfully placing humans on the moon.
- The final LLTV flight was on November 13, 1972 for pre-launch training for the final Apollo mission to the moon, Apollo 17.

Relevance to NASA

- The program finished as an excellent example of how individuals can increase a measure of success of a spaceflight project through close cooperation and a complete understanding of differing engineering disciplines.
- Throughout the Apollo missions, astronauts worked closely with engineers to make optimal changes during the testing and operation phases. Many changes hinged on ease of use for the operator.
- The theme of human operators' confidence and creativity persists in the debate between human operation and automation. From the LM Eagle to the Mars Science Laboratory Curiosity lander's "seven minutes of terror," technology has evolved from a tool used by operators to a highly independent agent that can eliminate mundane systems from a workload or eliminate the operator and automate the entire system. However, total reliance on technology to eliminate the operator can present problems. Lander failures like that of the Mars Polar Lander can be attributed to automation factors that have been highly subtle and difficult to anticipate or detect.
- The Apollo decision to expose test pilots and astronauts to the risks necessary to master experimental vehicles seems easy to applaud in retrospect. However, had subject matter experts lacked the right mix of knowledge and experience, they could have suffered failure of imagination and recommended conventional training. Had program managers suffered failure of nerve, they could have accepted safer, low-fidelity training alternatives than persisting despite three crashes.
- Today's challenge to land humans on Mars faces even tougher mission and environmental hurdles. No Cold War politics drive competition or demand teamwork this time. The benefits of mission success deserve study equal to the well-publicized risks; otherwise how can technical brilliance and courageous leadership combine to find the level of needful risk to allow mission success?