Beyond depth: Decoupling the astronaut from coring in crewed lunar drilling

Ke Wang,[1,2,*] Shaokun Wang,[1] Dong Guo,[1] Lu Zhang,[1] Xihe Yu,[1] Lin Guo,[1] Haifeng Zhao,[2] and Yong Wei[2,*]
[1]Technology and Engineering Center for Space Utilization, Chinese Academy of Sciences, Beijing 100094, China
[2]School of Space Exploration, University of Chinese Academy of Sciences, Beijing 101408, China
*Correspondence: wangke@csu.ac.cn (K.W.); weiy@mail.iggcas.ac.cn (Y.W.)
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Fifty years of lunar drilling—three crewed campaigns and a succession of robotic missions from Luna 24 to Chang'e-6—has converged on a consistent pattern: no coring architecture has yet preserved the uppermost stratigraphic interval intact while reaching multi-meter depth safely. The Apollo record, through the lens of engineering failure-mode insights, shows that coupling the astronaut's body into the drill's load path was the common root of its extraction, stratigraphic, and thermal disturbances. The robotic record shows the mirror image: crew risk was eliminated, but reliable penetration stalled near one meter and, even in the deepest success of Luna 24, the top 50–60 cm of the core returned empty. As China prepares for a crewed lunar landing before 2030, we contend that the design question is not "astronaut or robot" but how completely a system decouples human presence and mechanical actuation from the geological record it seeks to preserve. We propose a functional-decoupling paradigm—load-path, operational, and stratigraphic decoupling—supported by early-stage prototype hardware now under development, and call for an explicit sample-integrity budget to stand alongside mass and power budgets in future mission design.

A FIFTY-YEAR PATTERN IN LUNAR CORING OUTCOMES

The lunar regolith is a layered archive of solar-wind implantation and impact gardening, and its scientific value survives only if vertical order survives extraction.[1] Judged against this criterion, the historical record of lunar coring is remarkably consistent, and no architecture tried so far has fully met it.

Consider the three deep cores that remain the benchmark for depth. Apollo 15 recovered a continuous core of 242 cm from a penetration of 236 ± 1 cm,[2] but extraction from the hole was so difficult that segments 15001–15003 could not be separated on the lunar surface and returned to Earth as a single fused length[3]—the astronaut functioned not merely as the drill's operator but as a structural component of the drill, with the crew reporting that they lifted the stuck drill string by hooking their forearms beneath it "under the crook of our elbow" and bracing it with their shoulders until it broke free.[4] Apollo 16 recovered 224 cm, yet the uppermost section (60007) arrived only half full, with partial voids in two further sections—a disturbance attributed either to material loss during sampling or to migration within the sealed tube after capping.[2,5] The vulnerability of this uppermost interval was, in fact, anticipated in real time: as Duke drove the first stem in in under five seconds ("That one went in like gangbusters!"), Houston immediately radioed a warning to slow the penetration rate, and the mission record itself notes that "a slower drilling rate will yield a more compact core that will better preserve layering in the soil"[6] —an early, real-time acknowledgment of the stratigraphic vulnerability discussed here. Apollo 17 drove a 3 m drill string to a verified sample depth of ~292 cm,[7] but the mission record itself notes that drilling and extraction were "very difficult and must have caused significant heating" of the returned segments;[7] real-time biomedical telemetry during this drilling confirms the physiological cost, with Cernan's heart rate sustained at 120 bpm and peaking at 140–150 bpm.[8] Three missions, three distinct disturbance signatures—extraction, stratigraphic, thermal—yet one shared mechanical cause: downforce, posture control, and reaction torque were all routed through the astronaut's musculoskeletal system.

The robotic record occupies the opposite corner of the design space, and its pattern is equally consistent. Luna 24 (1976) remains the deepest robotic core: 2.25 m of penetration along an inclined trajectory, corresponding to a vertical depth of approximately 2.0 m—essentially matching, not exceeding, the Apollo 16 record when the vertical component is considered.[9] Moreover, only 160 cm of core (170 g) was returned, and upon opening in the laboratory the uppermost 50–60 cm of the flexible liner was found empty.[10] Nearly half a century later, Chang'e-5 and Chang'e-6 both encountered more complex-than-expected subsurface conditions and terminated near one meter, short of their multi-meter design targets.

Two independent lines of evidence—the half-empty top of the crewed Apollo 16 core and the empty top of the robotic Luna 24 liner—thus point to the same conclusion: loss or disturbance of the uppermost, most fragile stratigraphic interval is a recurring failure mode that crosses the human/robot divide. This indicates that the failure mode arises from coupled coring architectures rather than from whether the operator is human or robotic.

THE DEPTH–FIDELITY–SAFETY TRIANGLE

These observations can be organized into a simple but consequential framework (Figure 1). Every lunar coring system to date has optimized, at most, two vertices of a triangle whose corners are coring depth, crew safety, and stratigraphic fidelity. Apollo bought depth at the price of safety margins and fidelity;[4,6,7] robotic missions bought safety at the price of depth and, as Luna 24 shows, did not thereby secure fidelity. [9,10] The triangle is not a law of nature—it is a signature of insufficient mechanical isolation between three functions that current architectures conflate: generating cutting forces, holding the sample, and interfacing with the operator.

This reframing matters because the question facing mission planners is routinely posed as a choice—send astronauts for depth and judgment, or send robots for safety and repeatability. The historical dataset does not support this dichotomy. The relevant engineering variable is the degree of decoupling among the three functions, and it can in principle be raised in either a crewed or a robotic system. This reading is supported by the record's most instructive success: Luna 24's flexible core tube, mechanically isolated from the cutting auger, achieved the deepest robotic penetration ever—and its one conspicuous failure, the empty upper liner, occurred at the interface where isolation was weakest.[10]

FUNCTIONAL DECOUPLING AS A DESIGN PARADIGM

We therefore propose that future crewed coring systems be designed around three explicit decoupling principles, each traceable to a documented failure mode (Figure 1).

Load-path decoupling

Reaction torque and downforce should be transmitted into the regolith through a deployable anchor-footrest structure rather than through the astronaut's body. This directly addresses the Apollo 15 extraction problem: an astronaut in a pressurized suit is an unreliable structural anchor, with limited posture control, constrained hand strength, and a metabolic budget that drilling loads consume rapidly—a cost documented directly in Apollo 17's telemetry, where sustained drilling drove heart rate to 120 bpm with peaks of 140–150 bpm.[8] Decoupling the load path converts the astronaut from a load-bearing element into a supervisor—preserving human judgment, which remains the strongest argument for crewed operations, while removing the astronaut's body from the mechanical load path.

Operational decoupling

Sample retrieval should be modular: astronauts should recover short, indi-

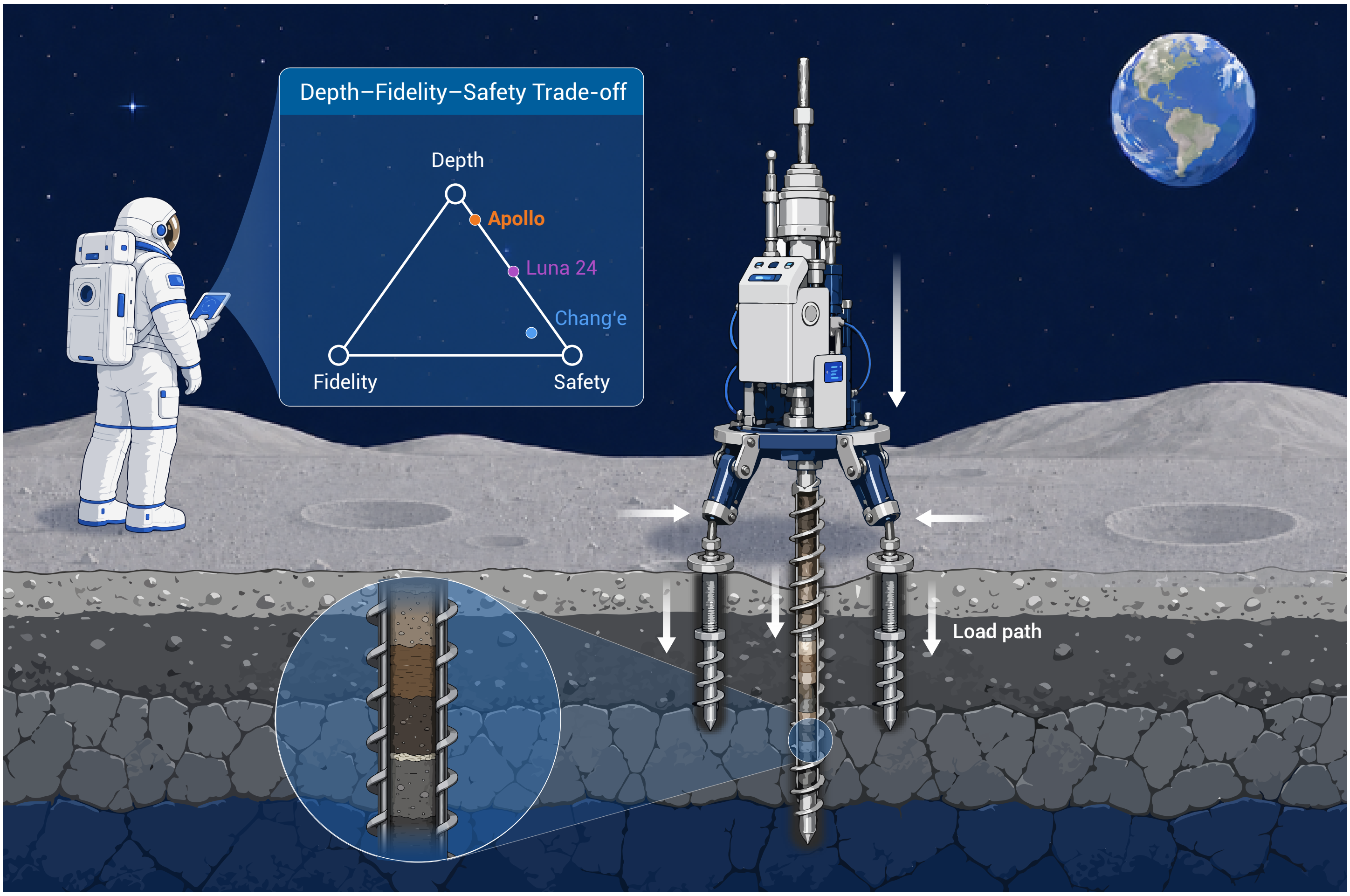

Figure 1. Functional decoupling framework for crewed lunar coring The inset summarizes the depth–fidelity–safety trade-off observed in historical lunar coring missions: Apollo achieved meter-scale crewed drilling but coupled the astronaut into the drill load path and disturbed sample fidelity; Luna 24 achieved the deepest robotic penetration but returned an empty upper liner interval; Chang'e-5/6 eliminated crew risk but reached only near-meter drilling depths. The main schematic illustrates a functionally decoupled crewed coring architecture targeting a full-scale drilling depth of 3 m, in which drilling loads are routed through an anchor-footrest structure into the regolith rather than through the astronaut. The system uses a double-tube, single-motion coring design advancing in 400 mm increments, with a protected inner core tube preserving stratigraphy within a rotating outer drill pipe. The enlarged subsurface view highlights the protected core path and the separation between cutting, load-bearing, and sample-retention functions.

vidually sealed core segments rather than extracting and handling a rigid multi-meter stem. Apollo 15's fused segments illustrate what happens when segmentation is deferred to the lunar surface under suit constraints;[3,4] this approach has not been attempted in any robotic mission and need not be repeated in future crewed missions. Modularity also localizes any single handling error to one segment rather than propagating it along the entire stratigraphic column.

Stratigraphic decoupling

The cutting mechanism should be torsionally and mechanically isolated from the core-holding structure, with particular protection for the uppermost interval that both Apollo 16 and Luna 24 independently identify as the most vulnerable.[5,6,10] This extends the flexible-tube heritage of Luna 24 and the drill-surface separation and double-tube coring lineage of the Chang'e program into the crewed-EVA context, where suit-limited dexterity makes passive mechanical protection more valuable than procedural safeguards, implemented here as a double-tube, single-motion design advancing in 400 mm increments.

It bears emphasis that these principles are not speculative imports from other fields; each is the inverse of a failure documented in primary mission records, and each has at least partial flight heritage in the robotic lineage. What has never been attempted is their systematic integration in a system designed for astronaut supervision.

FROM PARADIGM TO HARDWARE

A design paradigm gains credibility only through demonstration in hardware. Hardware development toward a functionally decoupled crewed coring system, targeting a full-scale depth of 3 m, is now underway: an early-stage laboratory prototype—comprising a motorized rotary drive head and a linear-feed guide rail mounted above a lunar-regolith simulant bed—is being used to validate drilling actuation and control functions under a formal project test protocol. The anchor-footrest, modular retrieval, and torsional-isolation subsystems remain to be integrated and validated in subsequent phases; we report this work not as a completed solution but as evidence that the paradigm is entering engineering practice rather than remaining a conceptual proposal.

The critical next step is not a specific mechanism but a specific metric. We propose that future missions adopt a sample-integrity budget: an explicit, quantitative allocation of allowable disturbance across each stage of the sampling chain—drilling, capture, extraction, sealing, transfer, and Earth return—spanning compositional, stratigraphic, pressure, and thermal fidelity. Mass and power budgets have disciplined spacecraft engineering for six decades precisely because they force early, traceable trade-offs; stratigraphic fidelity deserves the same discipline. Under such a budget, the Apollo 16 and Luna 24 upper-interval losses would not have been post-hoc laboratory surprises but pre-launch design constraints.[5,10]

OUTLOOK

Three developments would accelerate this transition. First, retrospective quantification: the Apollo and Luna archives, including the still-frozen Apollo 17 segments,[7] could be re-examined specifically to calibrate disturbance metrics, turning historical cores into a validation dataset for the sample-integrity budget. Second, integrated testing: decoupled architectures should be validated end-to-end in regolith simulants under suited-operator constraints, not as isolated subsystems—because the historical failures all occurred at interfaces. Third, cross-program convergence: the robotic decoupling heritage of Chang'e and the human-factors knowledge of crewed programs currently reside in separate engineering cultures; a crewed lunar drill is precisely where they must merge.

As crewed lunar hardware matures from laboratory prototype toward flight system, the guiding benchmark should shift accordingly. In 1972, mission success was measured by how deep an astronaut could drill. Before 2030, success should instead be measured by how completely a system can decouple the human presence that enables deep drilling from the fragile geological record that drilling is intended to preserve.

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AUTHOR CONTRIBUTIONS

Ke Wang and Yong Wei conceived the study and developed the central argument. Ke Wang and Yong Wei drafted the manuscript. Shaokun Wang, Dong Guo, Lu Zhang, Xihe Yu, Lin Guo, and Haifeng Zhao contributed to the engineering analysis, prototype development, literature review, and interpretation of lunar coring records. All authors discussed the results, reviewed and edited the manuscript, and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.