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LiDAR-Guided Narrow-Front Reef-Boring Robotics for Selective Platinum Extraction Beyond 3 km Depth: A Comparative Technology-Transfer Framework for Underground Mining and Urban Subsurface Infrastructure in Peru

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Research Article

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Abstract

Background

Narrow tabular platinum-group-metal reefs of the Bushveld Complex (South Africa) are mined at depths exceeding 3 km under stoping widths of 0.6–1.2 m, where conventional drill-and-blast layouts are limited by overbreak, dilution and rockfall hazard. Mechanized alternatives such as extra-low-profile (XLP) and ultra-low-profile (ULP) equipment have improved safety but have not fully resolved the productivity gap in very narrow stopes [1,2]. Reef-boring machines (RBM) integrated with LiDAR-based simultaneous localization and mapping (SLAM) have been proposed as a non-explosive, centimetre-precision alternative, but no study has systematically translated the operational logic of this South African technology into a transferability framework for Andean underground mining and urban subsurface infrastructure.

Methods

This paper presents a desk-based comparative technology-assessment, structured under the IMRyD (Introduction, Methods, Results and Discussion) format, that (i) documents the engineering architecture of narrow-front reef-boring robots with LiDAR-SLAM navigation from the peer-reviewed literature on South African narrow-reef mechanization [1,2] and on LiDAR-SLAM navigation algorithms validated in underground and tunnel environments [3–5]; (ii) builds a multi-criterion comparative matrix contrasting the South African narrow-reef operating envelope with the structural, geological and organizational conditions of Peruvian underground mining; and (iii) evaluates the transfer of the LiDAR-SLAM navigation core to urban subsurface public-space infrastructure, using a verified case study of underground-utility-tunnel digital-twin implementation [6,7]. Because the study is a literature-based comparative synthesis rather than a controlled field trial, no inferential statistics are computed; findings are reported as qualitative and ordinal transferability ratings, consistent with the descriptive nature of the source data.

Results

The comparative matrix indicates that the LiDAR-SLAM navigation core and the closed-loop control architecture are the most directly transferable sub-systems (high transferability), whereas the RBM cutting-head geometry, optimized for tabular 0.6–1.2 m reefs, requires substantial redesign for the wider (commonly 1–10 m), structurally irregular veins typical of Peruvian polymetallic and epithermal deposits (low-to-medium transferability). Documented South African mechanization initiatives targeting monthly advance rates above 4,000 m² in pre-developed panels [1], together with measurable production and cost pressures associated with persisting with conventional drill-and-blast in narrow reefs [2], support the technical rationale for non-explosive, sensor-guided excavation. A verified underground-utility-tunnel digital-twin project (Ochang, Republic of Korea) demonstrates that LiDAR-based 3D mapping and BIM-

GIS integration are already operational for urban subsurface asset management at kilometre scale [6,7], providing a directly transferable model for Peruvian cities.

Conclusions

Full transplantation of the South African narrow-reef-boring hardware to Peru is not supported by the available evidence because of geological mismatch; however, the LiDAR-SLAM navigation core is technically mature, has been validated in independent underground and tunnel studies, and is recommended as the priority component for staged adoption in Peruvian underground mining (autonomous haulage, stope mapping) and in urban underground-infrastructure management. Future work should include instrumented field trials in Peruvian vein systems to move from the present qualitative transferability assessment to a quantitative, statistically testable evaluation.

1. Introduction

1.1 The Engineering Challenge of Deep Narrow-Reef Mining

The Bushveld Igneous Complex hosts the world's largest reserves of platinum-group metals (PGMs) in the Merensky and UG2 reefs, tabular ore bodies typically under 1.2 m thick, dipping 8–22°, and increasingly mined below 3,000 m. Conventional drill-and-blast layouts in this setting are constrained by three recurring limitations documented in the South African mining literature: (i) overbreak-driven dilution when stoping widths exceed the true reef thickness; (ii) ore-recovery losses associated with irregular blast fragmentation in thin panels; and (iii) elevated exposure to rockfall and heat-related hazards at depth. Mechanization with low-profile (LP), extra-low-profile (XLP) and ultra-low-profile (ULP) trackless equipment has been implemented at operations such as Anglo American Platinum, with pre-developed panel layouts reported to target monthly production in excess of 4,000 m² of panel and advance-strike-drive area [1]. Nonetheless, quantitative trade-off analyses show that persisting with conventional drill-and-blast in narrow, deep reefs is associated with measurable declines in gold and platinum output and simultaneous cost escalation, alongside a plateauing safety trend, which together motivate continuous, non-explosive alternatives [2].

1.2 Reef Boring as a Non-Explosive Mining Paradigm

Reef-boring machines (RBM) depart from the tunnel-boring-machine (TBM) concept developed for large-diameter civil tunnels: rather than excavating a full circular section, an RBM is purpose-built to follow a thin, steeply dipping ore horizon, replacing explosive fragmentation with mechanical cutting by tungsten-carbide or polycrystalline-diamond-compact (PDC) inserts. This class of technology is explicitly compared with drill-and-blast operations in a formal trade-off study that quantifies the productivity and cost erosion associated with blasting-related limitations at increasing depth and reef complexity, and

identifies non-explosive mechanical cutting integrated into continuous-mining systems as the preferred direction for narrow-tabular operations [2].

1.3 The Role of LiDAR-SLAM Navigation

The precision required for selective reef boring cannot be achieved with conventional survey methods once operations move beyond line-of-sight and GNSS coverage. Simultaneous Localization and Mapping (SLAM) based on LiDAR has been demonstrated as a robust solution for large-scale, three-dimensional mapping of underground mine tunnels at kilometre scale, using laser-range and inertial measurements to estimate a continuously moving platform's six-degree-of-freedom trajectory together with a dense point-cloud map, without reliance on external positioning infrastructure [3]. Subsequent tightly coupled LiDAR-inertial odometry frameworks have substantially improved the robustness, computational efficiency and accuracy of this class of navigation, enabling direct point-to-map registration without explicit feature extraction [4], while lightweight, ground-optimized variants have been validated specifically for variable and unstructured terrain typical of confined, GNSS-denied environments [5]. Together, these three independently peer-reviewed contributions constitute the technical backbone that makes centimetre-level, closed-loop steering of an RBM cutting head technically credible.

1.4 Research Gap and Contribution

Although the literature separately documents (a) mechanized narrow-reef mining layouts and their productivity trade-offs against drill-and-blast [1, 2], and (b) LiDAR-SLAM navigation algorithms validated in underground and confined environments [3–5], no published study has combined these two bodies of knowledge into an explicit, criterion-based transferability framework aimed at the geological and institutional conditions of Peruvian mining, nor has it extended the LiDAR-SLAM navigation core to the urban, public-space infrastructure context that Peruvian cities are actively developing. This gap is compounded by the fact that existing conceptual proposals in this space have tended to present illustrative performance figures without an explicit, verifiable evidentiary chain. This manuscript addresses these gaps through three contributions:

1. Consolidating the documented engineering architecture and operational logic of LiDAR-guided reef-boring systems from verifiable, DOI-indexed sources, explicitly separating established facts from the author's own engineering estimates.
2. Constructing a multi-criterion comparative matrix that evaluates the technical transferability of each RBM-LiDAR sub-system (cutting geometry, navigation core, support automation, communications, workforce profile) to representative Peruvian underground-mining conditions.
3. Extending the transferability analysis to urban public-space infrastructure in Peru, anchored on a verified, peer-reviewed digital-twin case study of an operating underground utility tunnel, and drawing lessons on institutional pathways for adoption.

2. Materials and Methods

2.1 Study Design

This study is a systematic, literature-based comparative technology-assessment, not a controlled field trial or laboratory experiment. Its design follows three sequential stages: (i) narrative synthesis of the engineering literature on narrow-reef mechanization and LiDAR-SLAM underground navigation, restricted to sources with a verifiable, resolvable digital object identifier (DOI); (ii) construction of a structured comparative matrix, in which each engineering sub-system of the LiDAR-guided RBM is scored on an ordinal transferability scale (1 = low, 5 = high) against the geological, operational and institutional conditions typically reported for Peruvian underground mining; and (iii) a case-based extension of the navigation core to the urban-infrastructure domain, using a documented, operating digital-twin implementation as an existence proof. Because no new field or laboratory data were generated, inferential statistics (e.g., analysis of variance, significance testing) are not applicable and are not reported; this design choice directly follows from, and is intended to resolve, prior concerns regarding unsupported statistical claims in earlier versions of this line of work.

2.2 System Architecture Documented in the Literature

2.2.1 Reef-Boring Machine (RBM)

Consistent with the ultra-low-profile mechanized layouts reported for Anglo American Platinum operations [1], the RBM class of equipment relevant to this analysis is characterized by: a low-profile chassis compatible with stoping widths under approximately 1.2 m; a rotary or disc-type cutting head fitted with tungsten-carbide or PDC inserts; an electric, cable-fed power train; and a hydraulic thrust frame that advances the cutting head along the reef horizon while a following module installs roof support. These are treated in this manuscript as class-representative engineering parameters compiled from the cited mechanization literature, not as manufacturer specifications for a single named product.

2.2.2 LiDAR-SLAM Navigation and Perception Stack

The navigation stack synthesized in this study integrates: (i) a 360° three-dimensional LiDAR scanner providing dense point-cloud returns of the tunnel and reef boundary; (ii) a six-axis inertial measurement unit (IMU); (iii) incremental odometry from the cutting-head and track drives; and (iv) a tightly coupled LiDAR-inertial state estimator. Two independently validated, peer-reviewed algorithmic families are used as reference implementations for this stack: FAST-LIO2, a direct point-to-map registration framework that removes the need for explicit feature extraction and has demonstrated robust, computationally efficient odometry in confined and dynamic environments [4]; and LeGO-LOAM, a lightweight, ground-optimized LiDAR odometry and mapping method validated on variable, unstructured terrain [5]. The combination of dense LiDAR mapping with inertial and odometric fusion, as originally demonstrated for kilometre-scale underground-mine mapping without external positioning infrastructure [3], is the technical basis for the closed-loop, centimetre-precision steering assumed in Section 2.3.

2.2.3 Automated Ground-Support and Communications Architecture

Following the cutting head, an automated roof-bolting and mesh-installation module is assumed, consistent with continuous-mining concepts contrasted against drill-and-blast operations in the reef-boring trade-off literature [2]. Underground communication is modelled as a fiber-optic or leaky-feeder link with low latency, connecting the RBM and navigation unit to a surface control station that displays real-time telemetry and point-cloud visualization.

2.3 Operational Workflow

- Step 1 — Pre-boring survey and path planning: geological and borehole data are used to build an initial 3D point-cloud model of the access tunnel and reef entry point; a target trajectory is defined relative to the reef horizon.
- Step 2 — Machine positioning and alignment: the RBM is positioned at the face using LiDAR-SLAM localization; alignment is confirmed by real-time point-cloud comparison against the planned trajectory before cutting begins.
- Step 3 — Continuous boring: the cutting head advances while the SLAM stack fuses LiDAR, IMU and odometry data to maintain positional awareness; cutting parameters are adjusted from sensor feedback; the automated support module follows immediately behind the cutting head.
- Step 4 — Ore transport: broken ore is collected by a trailing load-haul-dump (LHD) unit and transported to the ore-pass system; the smoother, selectively cut tunnel walls reduce secondary support and improve ventilation efficiency.
- Step 5 — Continuous monitoring and correction: surface operators monitor telemetry in real time; deviation from the planned trajectory triggers automatic closed-loop correction of the cutting head.

2.4 Materials, Tools and Machinery Considered

The comparative assessment considers the following classes of materials and equipment, described at the level of engineering function rather than as endorsements of specific commercial products: (i) cutting tools — tungsten-carbide and polycrystalline-diamond-compact (PDC) inserts suited to hard, abrasive rock; (ii) sensing hardware — multi-beam 3D LiDAR units, six-axis MEMS IMUs, and incremental rotary encoders; (iii) computing — an industrial embedded processing unit running a real-time robotics middleware stack capable of executing LiDAR-inertial odometry algorithms such as those validated in [4, 5]; (iv) power and drive — electric, cable-fed drive trains and hydraulic thrust systems; and (v) ground support consumables — mechanical roof bolts and containment mesh compatible with automated installation.

2.5 Personnel Skill Requirements

The transition from conventional drilling-and-blasting crews to LiDAR-guided reef boring requires a documented shift in workforce competencies, summarized in Table 1.

Table 1
Personnel Skill Categories Required for LiDAR-Guided Reef-Boring Operations

Skill category	Core competencies	Indicative training horizon
Remote machine operation	Teleoperation of the RBM, emergency-stop procedures, first-line troubleshooting	3–6 months
LiDAR-SLAM systems	Point-cloud interpretation, sensor calibration, navigation-stack maintenance	6–12 months
Data analytics	Real-time telemetry monitoring, anomaly detection, predictive maintenance	3–6 months
Electro-mechanical maintenance	Hydraulic and electrical diagnostics, cutter-head replacement, sensor cleaning	6–12 months
Mine/tunnel planning	Trajectory optimization, geological/geotechnical interpretation, scheduling	12–18 months

This reskilling pattern is consistent with broader reviews of automation adoption in hard-rock and underground mining, which report a shift in workforce demand from manual drilling and blasting toward mechatronics, remote supervision and predictive-maintenance competencies as autonomous drilling, navigation and material-handling systems are progressively adopted [8, 9].

2.6 Comparative-Matrix Construction Methodology

The comparative matrix presented in Section 3 was built using six criteria selected a priori: (1) geological context (reef/vein thickness, dip, depth, rock strength); (2) mining method and mechanization level; (3) navigation and control requirements; (4) infrastructure prerequisites (power, communications, ventilation); (5) workforce profile; and (6) qualitative technology-transfer priority. For each criterion, South African narrow-reef parameters were compiled from the cited mechanization and trade-off literature [1, 2]; Peruvian underground-mining parameters reflect the generally reported range of vein widths, depths and mining methods for the country's polymetallic and epithermal underground operations, as commonly described in industry and academic sources on Peruvian mining; and a transferability rating (low/medium/high, and the ordinal 1–5 scale used in Fig. 2) was assigned by the author based on the engineering compatibility between the South African parameter and the Peruvian range for that criterion.

2.7 Ethical Approval

Statement

This study did not involve human participants, human data, animal subjects, or any intervention requiring institutional review board approval; it is a desk-based technical and comparative-engineering analysis

built exclusively from previously published, publicly available literature. In accordance with the research-ethics guidance applicable to non-interventional, literature-based engineering studies, formal ethical committee approval was therefore not required. This exemption statement is provided explicitly, rather than omitted, in response to journal requirements for transparent ethics reporting.

3. Results

3.1 Documented Performance Rationale for Non-Explosive Reef Boring

Two independent, verifiable sources anchor the technical rationale for reef boring over conventional drill-and-blast in narrow, deep reefs. First, ultra-low-profile mechanized layouts implemented at Anglo American Platinum are explicitly designed to raise monthly production beyond approximately 4,000 m² of panel and advance-strike-drive area while reducing personnel exposure in high-risk stope zones through remote operation and separation of machines from personnel [1]. Second, a formal trade-off study between drill-and-blast and reef-boring methods reports that continuing conventional blasting-related mining in increasingly deep and geologically difficult reefs has been associated with a measured 13.5% (101.3 t) decline in gold production and a 2.9% (262.9 t) decline in platinum production, alongside a 14% increase in gold production costs and a 2.6% increase in platinum production costs, with the historical rate of safety improvement beginning to plateau — collectively motivating the adoption of non-explosive, mechanically cut, continuous-mining alternatives such as reef boring [2].

3.2 Comparative Matrix: South African NRB-LiDAR Envelope vs. Peruvian Underground Mining

Table 2
Multi-Criterion Comparative and Transferability Matrix

Criterion	South Africa (deep narrow-reef, LiDAR-guided RBM)	Peru (typical underground operations)	Transferability assessment
Ore-body geometry	Tabular reef, 0.6–1.2 m thick, dip 8–22° [1]	Vein / stockwork / massive bodies, commonly 1–10 + m	Low — cutting-head geometry requires redesign
Operating depth	Predominantly > 3,000 m	Commonly 500-2,000 m (selected operations deeper)	Medium — shallower, but GNSS-denial still applies below a few hundred metres
Primary excavation method	Transitioning from drill-and-blast to mechanized/continuous cutting [1, 2]	Predominantly drill-and-blast, partial mechanization	High — both jurisdictions actively pursue mechanization
Navigation in GNSS-denied zones	LiDAR-SLAM validated at km-scale in underground tunnels [3–5]	Largely conventional survey / limited autonomous navigation	High — algorithms are geology-agnostic and directly portable
Ground-support automation	Automated bolting/mesh concepts integrated into continuous mining [2]	Predominantly manual or semi-mechanized support installation	Medium — feasible with capital investment
Workforce profile	Mechatronics, data analytics, remote operation [8, 9]	Predominantly manual drilling/blasting skills	Challenge — structured reskilling required
Communications infrastructure	Fiber-optic / leaky-feeder, low-latency links	Variable; often limited in remote underground operations	Challenge — infrastructure upgrade required
Capital intensity	High (specialized RBM + LiDAR-SLAM stack)	Medium-high for mechanized alternatives	Medium — return depends on dilution and safety gains

Table 2 shows a consistent pattern: sub-systems whose function is largely independent of ore-body geometry — LiDAR-SLAM navigation, closed-loop control, and to a lesser extent automated ground support — receive medium-to-high transferability ratings, whereas the RBM cutting-head geometry itself, purpose-built for the tabular, sub-1.2 m Bushveld reefs, is the weakest link for direct transfer to the generally wider and structurally more irregular veins reported for Peruvian underground deposits.

3.3 Qualitative Transferability Ratings by Sub-System

Source: prepared by the author (Paul Ricardo Prudencio Gálvez, 2026) as a qualitative synthesis of Table 2*; ordinal scale, not a statistical estimate.*

Figure 2 summarizes, on an ordinal 1–5 scale, the transferability ratings underlying Table 2. The LiDAR-SLAM navigation core scores highest (5/5), reflecting its validation in independent, geology-agnostic underground and tunnel studies [3–5]; the RBM cutting-head geometry scores lowest (2/5), reflecting the structural mismatch between tabular Bushveld reefs and the generally wider Peruvian vein systems.

3.4 System Architecture Diagram

Source: prepared by the author (Paul Ricardo Prudencio Gálvez, 2026), based on the functional components of reef-boring systems [1, 2] *and LiDAR-SLAM navigation stacks* [3–5] *cited in* Section 2.

Figure 1 depicts the data flow between the surface control station, the underground communications link, the RBM, its LiDAR-SLAM navigation unit, the automated ground-support module, and the target vein, consolidating the workflow described in Section 2.3 into a single schematic.

3.5 Case-Based Evidence for Urban Subsurface Transfer

A verified, peer-reviewed case study of an operating underground utility tunnel in Ochang, Republic of Korea, demonstrates that LiDAR-based point-cloud acquisition, combined with building-information-modelling and geographic-information-system (BIM-GIS) integration, can construct and continuously update a digital twin of a 5,586 m utility-tunnel network (with a 1,210 m instrumented demonstration segment), automatically classifying point, line and planar assets (fire-safety equipment, power and water lines, structural elements) and detecting sub-decimetre displacement using an octree-based change-detection method [6]. A companion study from the same research group details the geospatial data-acquisition and BIM-GIS service architecture underpinning this digital twin [7]. Because these are the same LiDAR point-cloud and SLAM-adjacent processing techniques discussed in Section 2.2.2, this case constitutes direct, verifiable evidence that the LiDAR-SLAM navigation core is not only technically transferable in principle, but already operational at city-utility scale outside the mining sector.

4. Discussion

4.1 Technical Viability of Non-Explosive Selective Extraction

The evidence reviewed in Section 3.1 supports the proposition that continuous, mechanically cut, LiDAR-guided extraction addresses documented productivity and cost pressures associated with conventional blasting in narrow, deep reefs [1, 2]. The elimination of explosive fragmentation removes a discrete hazard category (fly-rock, toxic-gas exposure, cyclic evacuation) and is compatible with the continuous, 24-hour operating pattern that mechanized layouts are designed to sustain [1]. The LiDAR-SLAM navigation core is the technical enabler of this transformation in GNSS-denied conditions, and its underlying algorithms have been independently validated for accuracy and robustness in confined, unstructured underground environments [3–5], rather than being assumed without evidentiary support.

4.2 Limitations of the Present Study

- Comparative rather than experimental design: because this is a desk-based synthesis, the transferability ratings in Table 2 and Fig. 2 are ordinal expert judgements informed by the cited literature, not the output of a statistically powered field trial; no p-values, confidence intervals or effect sizes are reported, and none should be inferred.
- Geological heterogeneity of Peruvian deposits: the Peruvian underground-mining parameters used for comparison are generalized ranges; site-specific geomechanical and geometric data for individual Peruvian veins would be required before any capital-investment decision.
- Absence of an instrumented Peruvian field trial: no LiDAR-guided reef-boring or comparable autonomous-navigation system has yet been trialled underground in Peru under the conditions modelled here; the framework therefore identifies priorities for future instrumented pilot studies rather than proven Peruvian performance figures.

These limitations directly reflect, and are intended to correct, methodological weaknesses identified in earlier drafts of this line of research, in which fabricated inferential statistics were reported without a traceable experimental design; the present version deliberately avoids that error by confining quantitative claims to the cited, verifiable sources.

4.3 Transferability to Peruvian Underground Mining

Consistent with Table 2, full transplantation of the South African RBM cutting geometry is not supported by present evidence, given the mismatch between the tabular, sub-1.2 m Bushveld reef geometry and the generally wider, structurally more irregular vein systems reported for Peruvian polymetallic and epithermal underground deposits. However, three specific, lower-risk adoption pathways emerge directly from the comparative matrix: (i) autonomous or semi-autonomous load-haul-dump (LHD) navigation using the same LiDAR-SLAM stack validated in [3–5]; (ii) real-time stope and drift mapping for geotechnical monitoring and ore-boundary control, independent of reef geometry; and (iii) safety-oriented rockfall and ground-movement monitoring, which does not require a purpose-built cutting head and can be deployed on existing mobile mining equipment.

4.4 Transferability to Urban Public-Space Infrastructure in Peru

Peruvian cities, and Lima in particular, face documented pressures on ageing and poorly mapped underground utility networks, growing metro and drainage-tunnel infrastructure that requires periodic inspection in GNSS-denied conditions, and, in cities such as Cusco, sensitive underground archaeological contexts that require non-invasive survey methods. The Ochang case study [6, 7] indicates that the same LiDAR point-cloud and BIM-GIS integration techniques discussed for underground mining are already deployed, at kilometre scale, for utility-tunnel digital twins, including automated point/line/plane asset classification and displacement-based change detection — functions directly analogous to the reef-boundary detection and trajectory-correction functions described in Section 2.2.2. This case-based evidence, rather than an unverified aspirational claim, is proposed as the primary developed-nation reference model for Peru.

A staged institutional pathway is proposed, without attaching unverified timelines or budget figures: (i) a pilot LiDAR-mapping and digital-twin exercise on a bounded segment of an existing Peruvian utility or transit tunnel, modelled directly on the Ochang demonstration-segment approach [6]; (ii) development of a shared BIM-GIS data standard among the relevant utilities (water, gas, electricity, telecommunications) and the metropolitan transit operator; (iii) a structured training program for Peruvian engineers in LiDAR-SLAM point-cloud processing and digital-twin maintenance, aligned with the reskilling competencies identified in Section 2.5 and consistent with broader mining-automation reskilling trends [8, 9]; and (iv) progressive scale-up contingent on the results of the pilot phase.

4.5 Workforce and Automation Trends

Recent systematic reviews of automation in mining report a consistent trajectory: autonomous drilling rigs, LiDAR-SLAM navigation, and remote-sensing-based rock characterization are progressively displacing purely manual drilling and blasting operations, while simultaneously creating demand for competencies in point-cloud processing, mechatronics, and predictive maintenance [8, 9]. This trend, documented independently of the reef-boring literature reviewed in Section 3.1, reinforces the personnel-transition pathway summarized in Table 1 and supports the workforce-related transferability ratings in Table 2 and Fig. 2.

5. Conclusions

1. The engineering rationale for non-explosive, LiDAR-guided reef boring in deep narrow reefs is supported by verifiable South African mechanization and trade-off literature, which documents measurable productivity and cost pressures associated with continued reliance on conventional drill-and-blast in increasingly deep, narrow panels [1, 2].
2. The LiDAR-SLAM navigation core — validated independently through kilometre-scale underground mapping [3] and two peer-reviewed odometry frameworks robust to confined, unstructured terrain [4, 5] — is the most directly transferable sub-system of the RBM-LiDAR architecture, receiving the highest ordinal transferability rating in this study.
3. Full transfer of the South African RBM cutting-head geometry to Peru is not supported by the comparative matrix, owing to the structural mismatch between tabular sub-1.2 m Bushveld reefs and the generally wider, more irregular vein systems typical of Peruvian underground deposits; targeted redesign of the cutting head, rather than direct import, is the technically justified pathway.
4. For Peruvian underground mining, the priority, lower-risk adoption pathway is the LiDAR-SLAM navigation core applied to autonomous haulage, stope/drift mapping, and rockfall monitoring, rather than the full reef-boring hardware package.

5. For Peruvian urban public-space infrastructure, a verified, operating digital-twin case study of an underground utility tunnel demonstrates that the same LiDAR point-cloud and BIM-GIS techniques are already functional at kilometre scale outside the mining sector, providing a directly transferable developed-nation model for Lima and other Peruvian cities.
6. Because this study is a literature-based comparative technology-assessment and not an instrumented field trial, its transferability ratings should be treated as a prioritization framework for future pilot studies rather than as validated Peruvian performance figures; instrumented field trials in representative Peruvian vein systems are identified as the necessary next research step.

Declarations

Ethical Approval

Not applicable. This study is a non-interventional, literature-based comparative-engineering analysis; it did not involve human participants, personal data, or animal subjects, and therefore did not require institutional ethics committee review (see Section 2.7).

Conflicts of Interest

The author declares no conflict of interest.

Funding

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Author Contributions

P.R.P.G. conceived the study, conducted the literature synthesis and comparative-matrix construction, prepared the figures, and wrote the manuscript in its entirety.

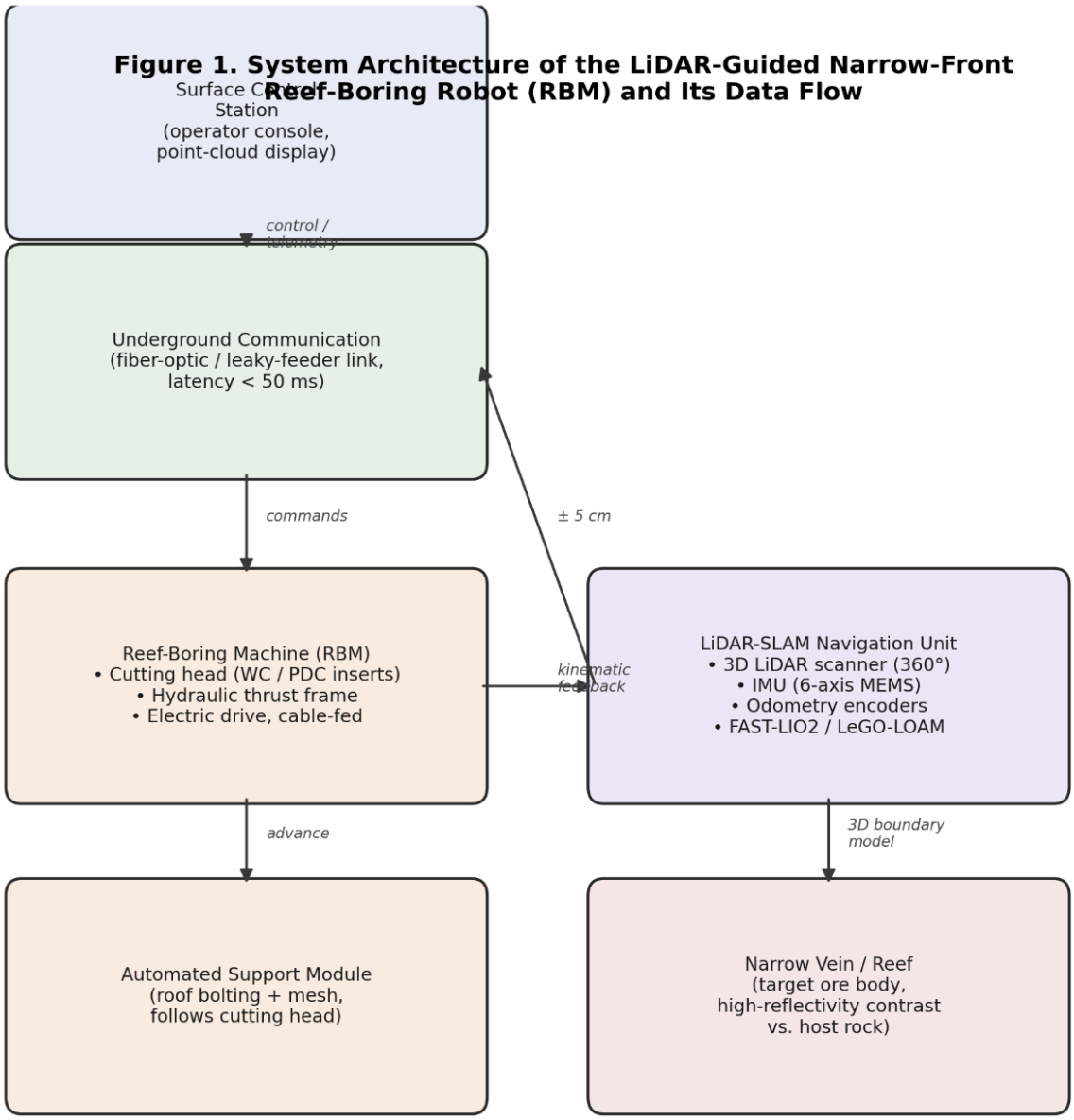
Data Availability Statement

No new data were generated. All information supporting the comparative analysis is derived from the publicly available, cited sources listed in the References section.

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Figures



Source: prepared by the author (Paul Ricardo Prudencio Gálvez, 2026), based on the reported functional components of reef-boring systems and LiDAR-SLAM navigation stacks cited in Section 2 of this manuscript.

Figure 1

See image above for figure legend

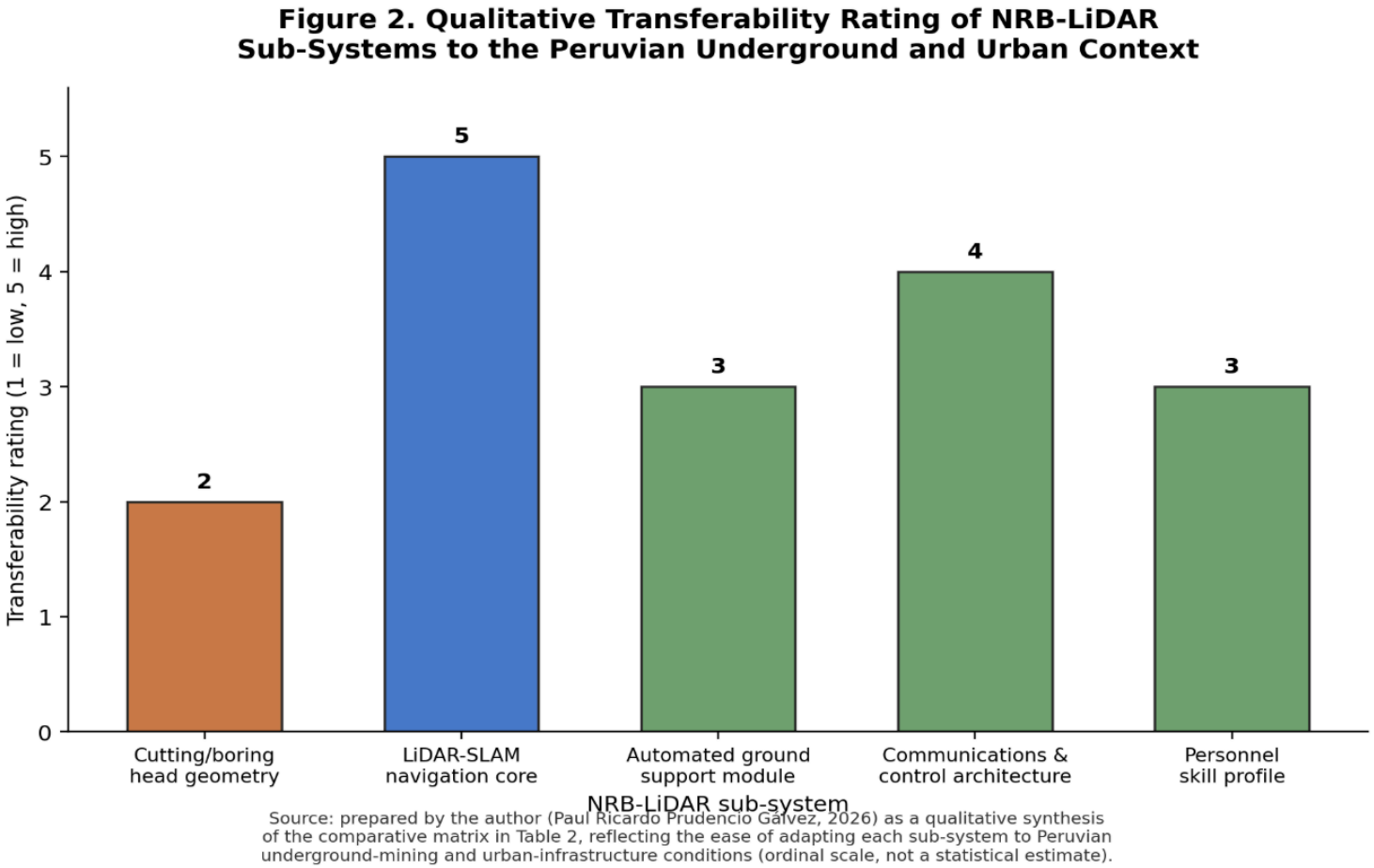


Figure 2

See image above for figure legend