A Structured Survey of Client-Based and Client-Assisted Localization for Underground Environments

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Abstract

Positioning in underground environments poses a fundamental challenge due to the absence of GNSS signals and often limited communication infrastructure. This survey investigates positioning systems in mines, tunnels, and other subterranean settings that involve the client device in a significant way — either by performing the localization directly on the device (fully client-based) or by recording sensor data locally for server-side processing (client-assisted). Based on a structured analysis of over 30 selected systems, we classify and compare approaches by signal technology, algorithmic method, infrastructure requirements, and system topology. The results show a dominance of RF-based solutions, but also highlight promising alternatives like magnetic methods. While fully client-autonomous systems are still rare, recent advances in onboard processing, sensor fusion and SLAM demonstrate the increasing potential of client-side localization in safety-critical and infrastructure-poor underground scenarios.

Keywords

Underground localization, indoor localization, self-positioning, client-side positioning, infrastructure-free, geomagnetic positioning, dead reckoning, geomagnetic localization, survey, tunnel environments.

1. Introduction

Positioning in underground environments such as mines, tunnel systems, or caves poses considerable challenges to current research. Unlike above-ground or urban settings, no external signals such as GPS are available underground. Additional constraints such as darkness, moisture, narrow geometries, and highly variable material structures further limit conventional indoor localization approaches. This becomes particularly critical in emergency situations: power outages, damaged infrastructure, or lack of communication technology may render traditional systems completely inoperative—precisely when reliable positioning is needed most.

Compared to conventional indoor environments, underground localization scenarios differ not only due to the absence of GNSS signals but also in terms of technical boundary conditions: Tunnel geometries—particularly for radio-based systems—are prone to multipath propagation and signal reflections. Lighting conditions and line-of-sight paths for radio-frequency systems are severely limited or subject to significant attenuation. Moreover, infrastructure failure can quickly escalate into an emergency situation, which is why special attention must be given to this aspect.

In well-equipped mines, advanced infrastructure-dependent localization systems are already in use to reliably track personnel and machinery. However, these systems typically rely on complex installations such as wireless networks, RFID tagging, or so-called leaky-feeder cables—solutions that require continuous maintenance and substantial investment. Such systems are unavailable for visitor mines, temporary operations, scientific expeditions in cave systems, or unauthorized entries. Even in well-equipped mines, infrastructure cannot be assumed to remain functional in real emergency scenarios.

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Accordingly, the development of systems that determine and display positions on the user side (client-side) is of high importance. The degree of operational independence—possibly even without communication links or network coverage—must be critically examined. Such infrastructure-resilient solutions are essential not only for safe return from uncharted or damaged areas, but also for explorative scenarios with minimal equipment.

This survey provides a systematic overview of current approaches to underground localization, focusing on systems that operate on the client side. The aim is to classify existing methods, identify key challenges, and highlight research gaps. Particular attention is given to the question of whether, and to what extent, localization can be achieved without external infrastructure, and which technologies enable reliable positioning under extreme conditions.

2. Application scenarios & Requirements

Unlike typical indoor environments, underground settings are characterized by extreme attenuation and lack of fallback infrastructure. Traditional infrastructures such as GNSS, WLAN, or mobile networks are generally unavailable in mines, tunnels, or cave systems—or become non-functional in emergency scenarios. In short: there is “no longer any help from above” [1]. At the same time, the demand for reliable positioning information is high—both in routine operations and in critical emergencies.

Typical application scenarios include:

(a) Routine operation in industrial settings (e.g., navigation of personnel, machine guidance, documentation of tunneling progress),

(b) Emergency operation in the event of power failure or structural collapse, such as for self-rescue or locating missing persons,

(c) Exploratory use in research, e.g., in unmapped mines or caves where no technical infrastructure exists, can be provided, or is allowed (e.g., visitor mines, cave expeditions, or unauthorized entries).

In routine operation, underground positioning systems are typically designed to transmit the position of workers and machines to a central control unit. Seguel et al. refer to such systems as “Remote Positioning” when the position is determined externally to the client, and as “Indirect Remote Positioning” when the client determines its position but transmits it to a central system [2, p. 9]. A variety of commercial solutions exist for this use case, predominantly based on radio-frequency technologies. A key example are *leaky feeder systems*, also referred to as “radiating cables” [3, p. 1], [4, p. 15]. These systems use special cables with periodic openings (“leaks”) to emit signals at regular intervals along a tunnel (first core) and simultaneously receive signals (second core).

Originally designed for communication, these systems are now also being explored for positioning purposes using spectral analysis of dedicated chirp signals [5, 4]. Algorithms such as *Time of Flight* are also employed. Both methods rely on external infrastructure and specialized end devices [6, 4]. As long as the infrastructure remains intact, these systems are robust and widely used in the mining industry.

In a review study, Yarkan et al. point out the advantages of coverage, but also highlight the need for line-of-sight (*LOS*), power supply, and the susceptibility to single cable cuts as major disadvantages [7, p. 136]. If the cables remain intact, *leaky feeder systems* can provide cost-effective communication even in emergencies [“£10/100 m” 8, p. 226]. Bedford et al. report a “useable signal strength [...] to a range of 800 m” [8, p. 224].

The application contexts of “emergency operation” and “exploration” in particular lead to a number of specific requirements for localization systems. The main focus is on resilience to infrastructure failure, robustness to environmental conditions (e.g., darkness, moisture, dust, unstable geometries), and intuitive usability—even under stress, systems must be operable by non-expert users [9]. This results in a clear demand for localization systems that operate on the client side and are capable of delivering reliable position information despite adverse conditions.

3. Research on Client-side Underground Localization

In routine underground operations, it is essential to know the location of personnel at all times in order to initiate targeted rescue measures in the event of an emergency. Workers are trained in how to act. In non-productive settings—such as visitor mines or cave exploration by laypersons—client-side localization is often the only way to inform the user of their position. Seguel et al. refer to this approach as "Self Positioning", but describe the clients as "dumb node[s]" [2, p. 9]. This terminology suggests that the clients do not perform the position estimation themselves but merely receive externally computed results. In such underground applications, mines can be retrofitted after their productive phase with localization technologies. With the increasing substitution of formerly specialized technology by standardized "off-the-shelf" solutions, positioning functionality is becoming available to clients without further technical effort. WiFi access points with RSSI-based distance estimation [10, 11], as well as ZigBee, Bluetooth [12, 13], and 5G [14, 15] are increasingly used. These technologies enable both centralized and client-side communication and localization.

The notion of *Self Positioning*—understood as actual position estimation performed by the client—stands in contrast to the dumb-node paradigm. In exploration scenarios, no external option for position estimation or communication is typically available. Systems should therefore also be evaluated in terms of the degree to which the client is capable of autonomously determining its own position. Table 1 lists works that implement signal acquisition and evaluation on the client side.

Summary of Trends and Gaps The literature shows a clear dominance of RF-based approaches, yet true infrastructure-free client-side systems remain rare. While many systems achieve sub-meter accuracy in controlled environments, real-world evaluations—especially under emergency constraints—are scarce. Magnetic methods offer promising alternatives, particularly when combined with inertial fusion, but their deployment is currently limited to prototypes.

3.1. System classification by signal source

An analysis of the identified signal technologies reveals a clear dominance of radio-frequency (RF)-based systems. A total of 15 of the examined systems utilize RF communication. Another focus is on optical systems, either in the form of visible light communication (VLC) or through sensor technologies such as cameras. These optical methods often achieve very high accuracy in the sub-meter range, but rely on line-of-sight conditions and stable lighting environments.

Magnetic field–based localization is represented by a total of five systems. Two of these systems generate and evaluate artificial magnetic fields: Lin et al. and Abrudan et al. use wireless underground sensor networks (WUSNs) to create time-modulated magnetic fields, which are then used by clients to estimate their position [36, p. 1454], [25, p. 4389].

Of the three systems that rely on the Earth's magnetic field [43, 42, 44], one is used to reconstruct the trajectory of a drill during a boring operation [42]: In this case, the position of the drill head is estimated via dead reckoning and refined using geomagnetic fingerprinting ["dead reckoning is used at first" 42, p. 1379].

Haverinen and Kemppainen recorded magnetic vectors using a sensor array mounted on a board containing 60 sensors distributed over an area of $0.5 \times 0.5\,\mathrm{m}$ [44]. The authors employed Monte Carlo Localization (MCL) using the measurements from these 60 sensors. Particle filter–based methods often require a prior reference map or rely on server-side computation, as is the case in the work of Haverinen and Kemppainen [44].

Among the surveyed systems, filtering techniques include Kalman filters (e.g., for inertial fusion), Particle filters (e.g., for geomagnetic localization), and SLAM-based graph optimization.

In summary, RF-based systems continue to play a dominant role in underground positioning. While optical methods are being explored, their real-world deployment remains limited. Alternative signal sources such as magnetism, light, or acoustics are currently used primarily in specialized niche applications.

Table 1

Comparative overview of underground self-localization systems based on primarily client-side or client-assisted signal processing and positioning ("client-side" topology means: both, signal acquisition and processing on client)

Year	Reference	Signal Technology	Technology	System Topology	Infrastructure Setup	Algorithm	Accuracy Class	Implementation
2025	[16] Štroner et al.	Optical (LiDAR)	LiDAR SLAM	client-side	strategic placement: external "geodetic network" by "total station"	Feature-based SLAM, pose graph optimization (GTSAM), ICP and Surfel Matching	Sub-Meter	120 m Real Mine Tunnel
2025	[17] Meng et al.	Magnetic + Inertial	Baseline-RFMDR	client-side	Strategic placement ("A pair of tags be placed at a specific distance"	Fusion of MEMS IMU and reference-based Tags, Extended Kalman Filter (EKF)	Sub-meter	Real world 90 m long tunnel
2019	[18] Dehghan et al.	RF (VLC)	Visible Light	client-side	Use of existing infrastructure	RSSI and trilateration	Sub-meter	Computer simulation
2018	[19] Tahir et al.	RF	ZigBee	client-side	Strategic sender placement	RSSI	Meter	Computer simulation
2018	[20] Banda et al.	RF	Wireless Sensor Network	client-side	Strategic sender placement	RSSI	Meter	Computer simulation
2018	[21] Li and Zhan	Optical	Laser	client-side	Strategic sender placement	Sensor fusion (Laser/UWB/IMU), symmetric path smoothing	Sub-meter	Real-world scenario
2017	[22] Iturralde et al.	RF (VLC)	Visible Light	client-side	Use of existing infrastructure	RSSI and trilateration	Sub-meter	Computer simulation
2017	[23] Xu et al.	Optical	Camera	client-side	Strategic sender placement	Cell of Origin	Sub-meter	Real-world scenario
2016	[24] Song and Qian	RF	Zigbee RSSI	client-side	Strategic placement	Sequence-Based Localization (SBL)	Meter	Real-world scenario
2016	[25] Abrudan et al.	Magnetic	Magnetic Field	client-side	Strategic placement	RSSI	Sub-meter	Real-world scenario
2015	[26] Qin et al.	RF	UWB	client-side	Strategic placement	Time of Flight (TOF)	Sub-meter	Real-world scenario
2015	[9] Hammer et al.	Acoustic	Audible Sound	client-side	Strategic placement	Hyperbolic Frequency Modulated Chirps with Angle of Arrival (AoA) Cross correlation	Sub-meter	Real-world scenario
2014	[27] Fan et al.	RF	ZigBee	client-side	Strategic placement	Time of Flight (TOF)	Meter	Real-world scenario
2012	[28] Lavigne and Marshall	RF hybrid	Hybrid INS / scanning laser / RFID	client-side	Strategic placement	Dead reckoning and Cell of Origin		Real-world scenario
2012	[29] Reid et al.	INS, RF	Vehicle-Motion-aided INS + Doppler Radar	client-side	Infrastructure-free	Dead reckoning	Sub-meter	Real on-Device test on surface test field
2016	[30] Krommenacker et al.	RF (VLC)	Visible Light	client-side	Use of existing infrastructure	Cell of Origin	Meter	Computer simulation
2024	[31] Li et al.	Optical	Camera + Odometry	client-side	Infrastructure-free (requires light) + onboard cams + prior knowledge about "berths"	Dead reckoning and image-based methods (clothoid trajectories, visual features, WH-KNN matching	Sub-meter	Test field (real-world underground parking scenarios)
2022	[32] Ren and Wang	Optical	LiDAR 3D	client-side	Infrastructure-free (requires light)	Point cloud odometry + Unscented Kalman Filter	Sub-meter	Real-world scenario
2022	[33] Wang et al.	Optical	LiDAR 3D	client-side	Infrastructure-free (server DB is synchronized to clients)	SLAM with scan-to-scan matching, loop closure, odometry fusion		Operational on real tunnel datasets (DARPA SubT)
2023	[34] Adhikari	RF	RF multipath	client-side	Strategic placement	RLS multilateration, enhanced with ANN-based error reduction	Sub-meter	Simulation with MATLAB
2018	[35] Minhas et al.	RF	Low Power WPAN	client-side with return channel	Strategic placement	RSSI-based distance estimation	Meter	Real-world scenario
2017	[36] Lin et al.	Magnetic	Magnetic Field	client-side with return channel	Strategic placement	RSSI-based distance estimation	Sub-meter	Computer simulation
2016	[37] Wu and Zhang	RF (VLC)	Visible Light	client-side with return channel	Use of existing infrastructure	Cell of Origin		Real-world scenario
2014	[38] Lin et al.	RF	WLAN	client-side with return channel	Use of existing infrastructure	Fingerprinting	Meter	Real-world scenario
2013	[39] Cypriani et al.	RF	WLAN	client-side with return channel	Use of existing infrastructure	Fingerprinting	Decameter	Real-world scenario
2012	[40] Qin et al.	RF	ZigBee	client-side with return channel	Strategic placement	Time of Flight (TOF)	Meter	Real-world scenario
2020	[41] Pang et al.	RF (VLC)	Visible Light + Inertial Navigation	client sensing, server processing	Strategic placement	Combination of frequency tracking, base station assignment (similar to RSSI), and step counting (dead reckoning)	Meter	Real devices in laboratory scenario (indoor corridor as tunnel model)
2018	[42] Park and Myung	INS + geomag.	Geomagnetic + dead reckoning	client sensing, server processing	Principally infrastructure-free, but server required, no live calculation	Fingerprinting	Sub-meter	Test field
2014	[43] Makkonen et al.	geomag.	geomag. Anomalies	client sensing, server processing	Ref. phase with dedicated infrastructure, Pos. phase infrastr.-free	Not specified (third-party API)	Meter	Test field
2011	[44] Haverinen and Kemppainen	INS, magn.	Dead reckoning + geomagnetic	client sensing, server processing	Principally infrastructure-free, but no mobile live calculation	Particle filter, covariance matching to reference map	Meter	Real-world scenario
2019	[45] Yinjing et al.	RF	WiFi RSSI	client sensing, server processing	Strategic placement	Feature Vector Matching Algorithm (FVMA)	Meter	Simulation with MATLAB
2017	[46] Song et al.	RF	UWB with symmetric SDS-TWR method	client sensing, server processing	Strategic placement	TOA measurement (direct) + Fingerprinting (indirect) + Particle filter (optimization)	Sub-Meter in NLOS	Real scenario (lab corridors, straight and curved tunnels)
2020	[47] Larionov et al.	RF + Inertial	WiFi (RSSI + ToF)	client-side sensing, server-side proc.	Strategically placed access points	Particle filter (FastSLAM), PDR, and AP correction via UKF	Meter	Simulation
2025	[48] Li and Li	RF (UWB)	TDOA + CBORF	client-side signal sending, serverside sensing and calculation	Strategic placement ("reference label-guided")	Time Difference of Arrival (TDOA), Offset correction: "reference coordinates to compensate [...] offset and dispersion errors."	Centimeter	Simulation

3.2. System classification according to topology and infrastructure

The systems considered in this survey can be categorized based on their topology into three types:

- fully client-side systems,
- systems with a return channel,
- and approaches with server-side computation based on client-side data acquisition.

A special case in which the client merely transmits a signal while reception and computation are fully handled on the server side was included as last item in table 1 for completeness, but strictly speaking, it does not qualify as client-side data acquisition or processing.

3.2.1. Client-Side Systems

In the first category—fully *client-side systems*—all positioning computations are carried out locally on the device, without any return channel or external servers. These systems are characterized by high autonomy and are particularly suitable for emergency scenarios and exploration settings without network connectivity. Examples include systems that rely solely on optical sensing or inertial navigation. Ren and Wang describe a system based on 3D LiDAR and odometry, which operates entirely onboard a remotely controlled vehicle in a tunnel environment [32]. Similarly, the LiDAR-based solution by Reid et al. follows this topology and was evaluated in a small-scale test setting on a paved surface [29]. It should be noted that while both systems function autonomously, the required computing hardware necessitates integration into larger vehicles.

An intermediate form between pure client-side and server-based approaches is represented by the system of Li and Zhan. They use a laser scanner for onboard localization of mining vehicles in a real-world scenario, while higher-level functions such as path planning, progress monitoring, and data fusion are handled by a central server [21].

Client-side systems typically rely on *infrastructure-free* principles or *strategically placed* sensors [40, "distance between nodes"], [20]. Their accuracy varies, but often reaches the sub-meter range—particularly when visual or inertial sensor fusion techniques are applied. Compared to *client-side with return channel* or *client-side data acquisition with server-side computation*, these systems are more frequently tested in real-world underground scenarios.

3.2.2. Client-Side with Return Channel

Another category includes systems with a *return channel*, in which the end device collects data locally, but the actual position estimation is carried out by a central instance. Wu and Zhang implemented a system based on visible light, in which the mobile device communicates with a central unit using Manchester-modulated headlamp signals [37]. In [41], VLC signals are combined with inertial step counting, and a reverse communication path to the base station is integrated. This inverts the traditional principle: headlamps transmit a code, which is received by ceiling-mounted sensors. Lin et al. use a magnetic system enhanced by return-channel communication to improve positioning accuracy [36].

Infrastructure in this class is typically characterized by *strategic placement* or *reuse of existing infrastructure*. The resulting accuracies often fall below one meter, especially when UWB or hybrid methods are employed.

3.2.3. Client-Side Data Acquisition with Server-Side Computation

In the third category, data is acquired locally, while the actual position computation is carried out on a server. Cypriani et al. refer to the central unit as an "aggregation server" [39, p. 3]. These systems are therefore not suitable for offline use and are typically intended for production-related applications. Lin et al. present a WiFi fingerprinting system, in which positioning for "moving Android smart phones" is handled by a dedicated server module ("database server") [38, p. 4]. The system was deployed in a large-scale tunnel setting of a dam project and achieved positional accuracies of around 3–5 meters.

Yinjing et al. developed a method based on feature vectors and matching against a previously recorded tunnel database. Signal characteristics are captured on the mobile device, but the actual matching is performed on a server [45]. The UWB-based system by Song et al. also follows this architecture and uses a particle filter to enhance server-side estimation accuracy [46]. However, the test setup was limited in scale ["nine reference points" 46, p. 7]. The underlying infrastructure in this category is typically *strategically placed.*

3.2.4. Conclusion on System Topology

The variety of analyzed systems demonstrates that there is no one-size-fits-all solution for underground applications. Systems with fully client-side computation offer the greatest potential for autonomous operation in infrastructure-poor or emergency-driven scenarios. In contrast, return-channel and server-centric architectures provide high accuracy and feature-rich functionality for production use but rely on intact communication links.

Conclusion and Outlook

The review of existing systems for client-side underground localization reveals a wide range of technical approaches, whose suitability depends heavily on the specific application context. While infrastructure-based solutions still dominate in productive mining operations, autonomous client-side systems are particularly relevant for exploratory scenarios, temporary deployments, and emergencies. Their ability to operate independently of central infrastructure or communication makes them an essential component of future localization strategies.

The systems analyzed can be grouped into three main categories: fully client-side systems, systems with a return channel, and systems with server-side computation. Notably, there is a growing number of solutions that enable localization directly on the client device. These systems increasingly rely on modern sensor technology (e.g., LiDAR, cameras, inertial units, magnetic sensors) and algorithmic methods such as particle filters, SLAM, or deep learning. The rising computational power of mobile devices is gradually shifting previously server-side computations to the clients themselves, increasing their autonomy—especially in the context of computationally intensive methods such as fingerprinting, particle filtering, and neural networks.

Nevertheless, significant research gaps remain. Many of the systems described in the literature are prototypes, simulations, or were evaluated only under idealized conditions. As a result, their applicability to real, complex underground environments is not always guaranteed. In particular, systems that operate entirely without infrastructure remain rare—despite their especially high value in emergency scenarios.

Future research should increasingly focus on robust localization methods that function without infrastructure and remain operational even under harsh conditions. In addition, systematic evaluation under realistic field conditions is needed to ensure the practical viability of proposed approaches. The combination of standardized sensor technology, efficient signal processing, and adaptive, learning-based algorithms offers promising perspectives for the development of resilient underground navigation systems.

Author Contributions, CRediT Statement

In accordance with the CRediT (Contributor Roles Taxonomy) taxonomy, the first author was solely responsible for the conceptualization, methodology, investigation, formal analysis, data curation, visualization, and writing of the original draft and revisions of the manuscript. Authors 2 and 3 acted in supervisory and administrative roles, providing institutional support and funding acquisition. They were not involved in the conceptual development, writing, or editing of the manuscript.

Author Contributions and Declaration on Generative AI

In line with the CEUR-WS Taxonomy for the Use of Generative AI in Scientific Writing[1], the author(s) used GPT-4 during the preparation of this work for piecewise translation of text segments (T1.1) and for grammar and spelling correction (R1.1). These uses were limited to language-level assistance; all intellectual contributions remain the sole responsibility of the human authors.

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