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REVIEW

Research on the Application of Industrial Robot Technology in Large-Scale Geodetic Data Acquisition

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ABSTRACT

Large-scale geodetic data acquisition is fundamental to infrastructure lifecycle management, construction quality control, urban digital twins, and hazard monitoring, yet conventional surveying workflows remain labor-intensive and difficult to scale in complex or hazardous environments. The industrial robot technology is proving to be an enabling technology in providing repeatable, high-throughput, and safety-conscious geodetic acquisition through its ability to offer controllable motion, stable sensor deployment, and autonomy coupled with perception stacks. The review itself is a synthesis of the recent studies on robot-based geodetic acquisition from the platform workflow application perspective. We summarize in the priority industrial robot platforms which have potential applications in geodesy, distinction being made between those based on autonomous mobile robots, mobile manipulators, fixed-base manipulators, cooperative multi-robot arrangements, and the design considerations underlying their construction: geometric stability, payload loading, and tightly constrained safety of operation. We then consider sensing configurations, principles of calibration and synchronization, as well as acquisition strategies that regulate the completeness of data and measurement consistency. The foundations of core processing are examined in light of georeferencing, registration, Simultaneous Localization and Mapping (SLAM)-based localization, and uncertainty propagation, which are essential to achieve survey-grade outputs. The evidence of application is discussed in the framework of infrastructure monitoring, construction, industrial facilities, urban/corridor mapping, mining, and indoor/underground settings, showing areas of obvious robotics advantage in repeatability and risk mitigation, as well as conditions of limitation because of the Global Navigation Satellite System (GNSS) denial, drift, calibration sensitivity, and inconsistent evaluation practices. Lastly,

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we determine research priorities such as benchmark datasets and metrics, accuracy-motivated autonomy, strong multi-sensor fusion with uncertainty results, and a closer association with Building Information Modeling (BIM)/digital twin pipelines.

Keywords: Industrial Robots; Geodetic Data Acquisition; Mobile Mapping; SLAM; Sensor Fusion

1. Introduction

The vast amount of geodetic data obtained through mass data acquisition forms the basis of much of the modern engineering and earth-observation efforts (including transportation and utility corridors, compact urban form, industrial facilities, underground infrastructure, and open-pit mines) [1]. Good geodetic information, often in the form of true geo-referenced point clouds, image-based models, control networks, time series of deformations, and as-built/as-is geometrical products, has found its role in infrastructure lifecycle management, construction budgetary quality assurance, safety evaluation, updating digital twins, and disaster reaction [2,3]. With the maturity of digital engineering paradigms, such changes as creating a baseline representation of the built and natural environment are being replaced by continual, repeatable, and audit-provable measurements: not just a one-time mapping, but also one allowing frequent re-surveys to detect any changes, monitor deformations, track progress, and verify compliance. This development is summarized in **Figure 1** and provides the rationale for considering industrial robots as a new level of execution in geodetic acquisition.

Although there is a fast development of sensing and computing, traditional geodetic acquisition procedures continue to exhibit challenges in their application at scale [4]. Classical surveying techniques (e.g., total stations and control based on GNSS) are highly accurate and low in labour intensity; however, they are highly operator-reliant, and restricted by line of sight and the accessibility of the site. The geometry of terrestrial laser scanning (TLS) is dense, but it is important to plan stations carefully, repeat setups, and register terrestrial laser scans, which are time-consuming, especially in complicated scenes with occlusions. The systems of mobile mapping carried out on vehicles are more productive in road corridors but may be limited by the traffic flow, safety regulations, vehicle access, and the necessity of stable performance of GNSS/Inertial Navigation System (INS). Unmanned Aerial Vehicle (UAV) photogrammetry and UAV Light Detection and Ranging (LiDAR) are cost-effective in covering large outdoor facilities, but are restricted by airspace regulations, weather, vegetation, or structure occlusions, and in small areas (e.g., tunnels, under bridges, indoor facilities). In each of these modalities, it is often found that the cost and logistical burden of field operations, safety, risks in hazardous or difficult-to-reach areas, issues arising when seeking consistent measurement geometry, and problems in achieving repeatability over time when the desired result is monitoring are often found to be a common set of bottlenecks.

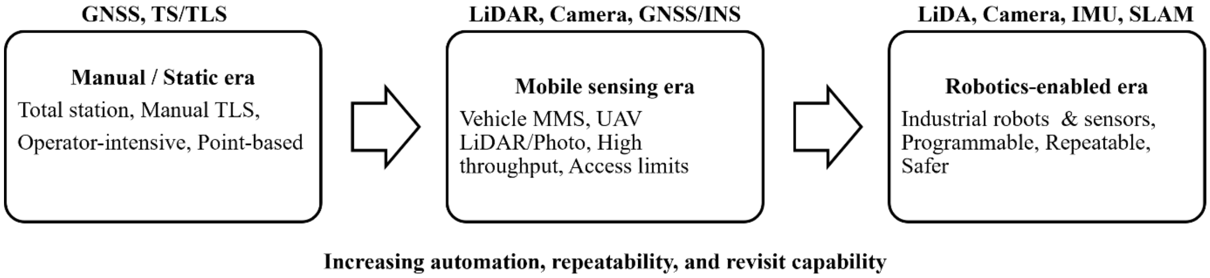

Figure 1. Evolution of large-scale geodetic data acquisition toward robot-enabled surveying, illustrating the transition from operator-intensive static methods to high-throughput mobile sensing and finally to programmable, repeatable robot-assisted acquisition.

Here, the industrial robot technology is proving to be an interesting enabler of the next-generation geodetic acquisition [5,6]. The industrial robots in the broad sense of this phrase (including fixed-base robotic arms, automated guided vehicles (Vs), autonomous mobile robots (AMRs), mobile manipulators, and hybrid robotic systems) provide a unique set of features that directly help to solve the major sore points of surveying. First, the industrial robots offer motion that is very controllable and repeatable. Robotic platforms can follow very precise paths and look at areas in a very methodical fashion; unlike manually transported sensors or vehicle routes, which are subject to traffic and human driving patterns, robotic platforms can cover them in a very methodical way and revisit these areas in a consistent geometry to monitor. Second, robots offer consistent sensor placement and kinematics, which can be calibrated and controlled incidence angles that could help to enhance data quality and eliminate systematic error. Third, robots can work in places that are hazardous to human operators, such as constrained areas, unstable slopes, polluted areas, operating industrial sites, and still keep sensors close to the structure of interest. Lastly, the robotics stack (localization, navigation, planning, and control) is intrinsically integrated with recent perception and mapping algorithms, and end-to-end automation: Between the mission description and the data acquisition, quality evaluation, and product creation is possible.

The reason behind the geodetic application of industrial robots is not to substitute well-established principles of survey, but rather to reinvent the implementation layer of data collection [7]. In geodesy, sensor specifications are only one of the controls of the quality of measurements, along with the geometry of the acquisitions, calibration fidelity, and environmental conditions, and the rigor of georeferencing and adjusting. It is possible to conceptualize industrial robots as programmable sensor-bearing measurement instruments, which provide repeatable geometry of acquisition and include high-throughput operation. This point of view is especially applicable in large-scale applications where the same location has to be surveyed over an extended period of time (e.g., weekly construction progress, periodic bridge inspections, long-term slope monitoring, as-built updates of industrial plants). Productivity improvements in these situations are not only due to the ability of data capture to occur more quickly, but also because of less time required to set up, less reliance on operator experience to ensure the same level of consistency in station location, and better standardization of the workflows across projects and teams.

Meanwhile, the use of industrial robots in geodetic acquisition on a large scale raises its own technical and methodological issues. In geodetic environments, a lot of geodetic settings are GNSS-denied or GNSS-degraded (e.g., underground, inside canyons in urban areas), and so precise and drift-controlled localization is a central issue. Simultaneous localization and mapping (SLAM) are frequently used in robotic mapping, but it may achieve impressive relative consistency, but is susceptible to drift, sensitive to scene dynamics, or may not work in adverse geometrical/texture environments. In the case of survey-level products, the workflow needs to have traceable georeferencing, quantified uncertainty, and be geodetically compatible, and in addition to creating a visually plausible map. Similarly, the time synchronization of multi-sensor systems on robots, boresight/lever-arm calibration, and modeling of motion distortions are also problematic, and are only compounded by the fact that robots in continuous motion and with multiple sensing modalities (LiDAR, cameras, Inertial Measurement Units—IMUs, GNSS/Real-Time Kinematic—RTK, Ultra-Wideband—UWB, radar, etc.) also demand careful time synchronization. Realistically, the effectiveness of robotic geodetic acquisition relies on the integrated development of platform layout, sensor design, calibration procedures, mission planning techniques, and processing algorithms that observe geodetic standards of accuracy [4,8].

The other essential force is the growing significance of geodetic data as a source of operational input to digital twins and automated decisions [9,10]. A digital twin can be as trustworthy as its update pipeline: if the acquisition cost is too high or erratic, the twin is outdated; the uncertainty cannot be measured, and engineering choices can be made with false geometry. Industrial robots may assist the transition to an always-on or frequently-changed data measurement model where the acquisition of data is standardized, repeatable, and auditable. Nonetheless, this change also introduces new demands of data management on scale metadata standards of calibration and paths, tracking of processing processes, BIM/GIS integration, and management of privacy and sensitive location information, in particular, in urban or industrial contexts.

With these changes, a scientific study of industrial robot-based technology in large-scale geodetic data collection is long overdue. The available literature spans many communities—geomatics, robotics, remote sensing, construction automation, and industrial inspection—with various terminology, assessment criteria, and views of what constitutes accuracy and ground truth. Robotics. Often, performance is measured in terms of trajectory error or mapping consistency; in geodesy, the focus is on absolute accuracy, control networks, adjustment, and uncertainty propagation [11]. A reconciliation of these points of view is required to gauge the actual maturity of robot-enabled surveying, and also to understand what still needs to be resolved before the widespread implementation of these systems in surveying, which is survey-grade.

To this end, the platform sensor workflow application perspective will be used in this review and aims at the end-to-end pipeline needed to produce geodetic products in large-scale industrial robotic systems. This article defines and discusses the technology of industrial robots as robotic platforms and the autonomy stack that is needed to support them, which may include geodetic sensors and planned acquisition missions (such as fixed-base arms to provide controlled scanning, Autonomous Mobile Robot (AMR)/Automated Guided Vehicle (AGV) to provide site-scale mapping, and mobile manipulators to provide reach and perspective control) [12,13]. Large-scale geodetic acquisition Large-scale deployments, on top of small laboratory scenes, such as corridors and networks (roads, rail, and pipelines), large facilities and plants, complex indoor/underground spaces, and outdoor locations, such as mines and urban areas, are where coverage, repeatability, and operational constraints become of central concern. Under this area, the paper highlights (i) the effect of robot motion and autonomy on the geometry of acquisition and calibration stability, (ii) the role of localization and registration in georeferencing and error control, and (iii) the evaluation of performance in ways relevant both to robotics and geodesy.

This review has threefold contributions. First, it suggests a systematic taxonomy, which also correlates the types of robotic platforms with sensor suites, calibration and acquisition policies, and the geodetic deliverables. This taxonomy assists in the organization of a quickly expanding and non-homogeneous literature and the explanation of which combinations might be used in specific settings and accuracy objectives. Second, it summarizes the methodological principles of robotic geodetic acquisition, namely, georeferencing, SLAM and sensor fusion, registration and adjustment, and uncertainty modeling, and points out at which modern solutions perform or fail to comply with the expectation of a survey grade. Third, it outlines essential gaps in research and future development goals, such as benchmark datasets and metrics, resilient GNSS-denied georeferencing with uncertainty products, autonomy policies that relate to accuracy goals (e.g., adaptive viewpoint planning), multi-robot coordination to cover the city, and more extensive integration with BIM/digital twins' pipelines to provide an up-to-date view of the city.

The rest of this paper is divided into five parts. Section 2 is the review of industrial robot platforms to be used in geodetic acquisition and explains the requirements of design and the level of autonomy to be used in the large-scale deployment (Method). Section 3 gives a summary of sensing modalities, calibration principles, and acquisition workflows with special focus on the correlation between motion control and data quality (Method and Theory). Section 4 discusses processing and algorithmic underpinnings—georeferencing, registration, SLAM, and fusion and uncertainty propagation—that prove necessary to generate traceable geodetic products (Theory and Criteria). Section 5 is an overview of key application areas and the ability to compare performance across various applications, showing where industrial robots have apparent benefits over more traditional approaches and where the situation remains constrained (Context and Criteria). Section 6 summarizes the work and future research aims on the standardized, scalable, and survey-grade robotic geodetic acquisition.

The review is based on the research on robotic systems used in large-scale geodetic data collection in the geomatics, robotics, remote sensing, and construction automation departments. The literature was located by searching in the largest academic databases, such as Web of Science, Scopus, IEEE Xplore, and Google Scholar. Some keywords were used, such as robots surveying, mobile surveying, industrial robots, robotic SLAM, geodetic data, LiDAR surveying, and autonomous inspection. The search was based mostly on the publications dating 2010–2024, the range when robotic mapping platforms and multi-sensor SLAM systems became developed enough to be used practically. Peer-reviewed journal articles and conference papers that talked about large-scale or field-deployable systems were given priority. Research papers were incorporated in a manner that they talked of robotic platforms, sensing configurations, calibration techniques, or processing techniques pertinent to survey-grade mapping and geodetic deliverables. The resulting literature with dozens of papers in various fields was reviewed and synthesized according to a conceptual framework in a structured form presented in Section 2.

2. Industrial Robot Platforms for Large-Scale Geodetic Data Acquisition

The robot platforms of robotics have gained more relevance in geodetic data collection due to the ability to introduce controlled and repeatable sensor motions and also provide high-throughput control in large and intricate environments [14]. Robotic platforms provide the platform on which the acquisition process is integrated in a programmable kinematic system, unlike traditional surveying systems, which are heavily reliant on hand selection of the station and hand execution of the implementation. This property is especially useful in large-scale projects where the information has to be gathered under conditions of the lack of access, danger, tight timeframes, or repetitive surveys in case of deformation control and change origination. But the range of mechanical forms and the degrees of autonomy of industrial robot platforms is broad, and their application in geodetic work should be determined by the interaction between platform kinematics, stability, payload capacity, and navigation performance with sensor properties and geodetic performance needs. This part presents a platform-based taxonomy and explains the design and operational issues that control the performance of robot-enabled geodetic acquisition. To demonstrate the variety of robotic shapes in the modern system applied to the surveying work, **Figure 2** shows a platform taxonomy.

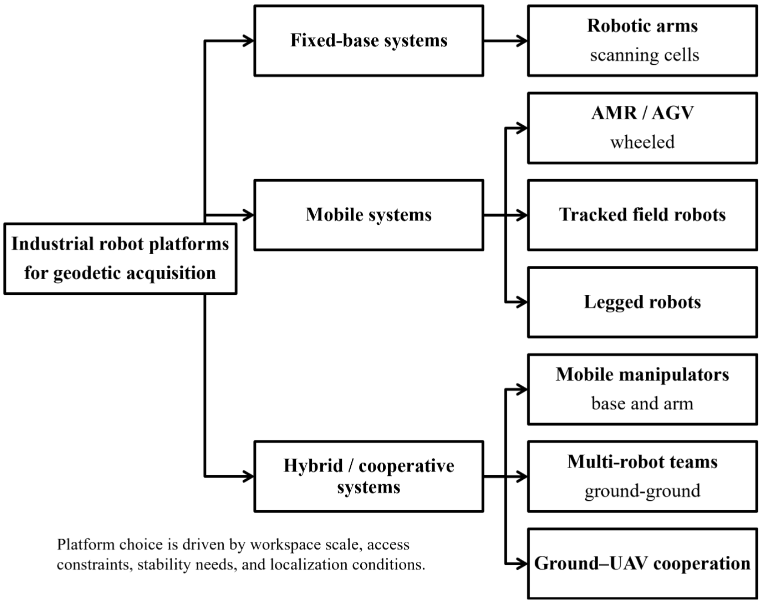

Figure 2. Taxonomy of industrial robot platforms for geodetic data acquisition, categorizing fixed-base systems, mobile systems, hybrid mobile manipulators, and cooperative multi-robot configurations.

In order to organize the elaboration of a multidisciplinary literature base, the Theory Context Criteria Method (TCCM) analytical framework is adopted in this review. In this context, Theory means the key concepts of geodetic acquisition of robotic geodetic, which include georeferencing, localization through SLAM, sensor fusion, and uncertainty modelling. Context describes the operating environments and the application areas where robotic surveying is applied, which include infrastructure surveying, industrial, construction site, and hazardous areas. Criteria refer to the dimensions of evaluation of performance, which are absolute accuracy, repeatability, robustness, operational efficiency, and quantification of uncertainty. Lastly, Method explains the technological deployments supporting these abilities, such as robotic platforms, sensor suites, calibration processes, and data acquisition processes.

2.1. Platform Taxonomy and Functional Roles

Robot platform industrial robots used in geodetic acquisition may be arranged in fixed-base systems, mobile systems, and hybrid systems, which mix mobility with articulation. The most developed and accurate type is the fixed-base industrial robotic arms, which usually have good repeatability and controllable end-effector paths in a restricted workspace. In geodetic applications, such systems are mostly applicable in scanning or imaging high precision of the localized structure, e.g., critical parts in industrial plants, structural joints, prefabricated components, or laboratory calibration conditions. Their controlled movement allows them to select the viewpoint in a systematic way and uniform incidence angles, which can minimize the levels of occlusion and enhance the uniformity of point clouds or gridwork of image networks. Fixed-base arms are, however, coverage-constrained in nature and thus are best used when integrated into a greater measurement cell, or when the target area can be shifted in relation to the robot [1].

Mobile systems, often AGVs or AMRs, are able to increase the size of the spatial scale of robotic surveying by moving sensors along corridors, industrial plants, warehouses, tunnels, or outdoor areas with installed corridors [15,16]. They are useful and efficient in terms of coverage and productivity, but not as precise as a sub-millimetric repeatability of an industrial arm. In large-scale mapping, a mobile platform is an effective implementation of an execution of a multi-sensor payload, suitable for sustained acquisition designs as mobile mapping, and capable of operating in areas inaccessible to traditional vehicles. Their locomotion creates vibration, wheel slip, as well as variable motion dynamics, which makes the quality of the end geodetic products more closely linked to localization and motion compensation techniques than in fixed-base configurations. Consequently, mobile platforms may frequently be considered not just based on the mechanical reliability but also based on the capability to maintain constant localization in GNSS-denied or GNSS-degraded conditions.

Mobile manipulators consist of a mobile base and an articulated arm, which offer coverage, as well as viewpoint control. This mixed kinematic configuration is particularly beneficial to geodetic acquisition in obstructed, cluttered conditions where the line-of-sight is often obscured and where the sensor has to be mounted at a certain offset or orientation to the target surface. In one example, the mobile base may move to the region of interest in an industrial plant or heavy structural environment, whereas the arm may change the sensor pose to minimize the extent of occlusion, stay at good incidence angles, or access a small space. Mobile manipulators can also allow the robot to separate navigation requirements and sensing geometry, so when the safe or feasible locomotion path is different than the path that gives the best measuring geometry. These systems are more complicated, and the burden of their calibration is increased since the base and arm kinematics have to be considered in the sensor pose estimation pipeline [17,18].

Field-oriented robotic platforms have been considered to be used in geodetic acquisition in unstructured or unsafe geometries that include rugged tracked robots, and more recently, legged systems [19,20]. Access and safety are the major benefits in such settings as opposed to speed. Robots on legs can overcome steps, rubble, or rough terrain, which would otherwise be implemented by wheels, and their ability to do so may increase the reach of the geodetic acquisition process to previously high-risk manual surveying. Simultaneously, legged locomotion imposes more complicated motions and higher rates, which may impair sensor stability and make motion distortion correction of LiDAR and image capture difficult. The geodetic value of these platforms, therefore, requires effective stabilization, synchronization, and robust state estimation and mission planning that ensures a balance between traversability and quality of measurements.

Hybrid and cooperative robotic systems are another extension whereby two or more platforms will work jointly, such as a ground robot scanning a site closely and an UAV providing an overview, or a group of ground robots breaking down a site into areas that can be covered quickly [21]. These systems are driven by scale: the larger the survey ranges, the less viable one-robot missions can be since their batteries might be insufficient, they may run into occlusions, or the field operating time. Cooperative systems also provide redundancy and have the ability to enhance robustness by providing cross-platform loop closures and constrained mutual localization. But they require more coordination, time synchrony, and consistency of calibration between platforms, and they present additional data fusion and network adaptation requirements to provide a consistent survey-grade global frame. **Table 1** gives a comparative summary of these platform classes and their nomenclature surveying functions.

Table 1. Comparative characteristics of industrial robot platform types for large-scale geodetic data acquisition, including mobility, stability, coverage, typical environments, and representative use cases.

Platform Type	Typical Mobility	Workspace Scale	Geometric Stability	Coverage Capability	Typical Environments	Main Advantages	Main Limitations	Representative Use Cases
Fixed-base robotic arm	None	Local (meters)	Very high	Very limited	Factories, labs, plants	High repeatability; controlled viewpoints; excellent calibration	Requires relocation; poor scalability	Precision scanning of components; calibration tasks
AMR/AGV (wheeled mobile robot)	Wheeled	Site/corridor scale	Moderate	High	Warehouses, tunnels, campuses, plants	Large-area coverage; automation; safety	Vibration; wheel slip; GNSS dependence	Corridor mapping; indoor mapping; asset inventory
Mobile manipulator	Wheeled + arm	Site scale with local reach	Moderate–high	High	Industrial plants, construction sites	Combines mobility and viewpoint control	Complex calibration; higher cost	As-built surveys; complex geometry capture
Tracked field robot	Tracked	Site/terrain scale	Moderate	High in rough terrain	Mines, slopes, disaster sites	Access to hazardous areas	Dust/vibration; energy consumption	Slope mapping; stockpile measurement
Legged robot	Legged	Local–site scale	Variable	Moderate	Rubble, debris, stairs	Extreme terrain access	Motion instability; complex control	Post-disaster mapping; confined spaces
Cooperative multi-robot system	Mixed	Large-area scale	Variable	Very high	Cities, large plants, mines	Redundancy; faster coverage	Coordination complexity; data fusion burden	City-scale mapping; large facility surveys

2.2. Design Requirements for Geodetic-Grade Robotic Platforms

The geodetic acquisition requirements of the field robotics should be balanced with the expectations of surveying by means of the design of robot platforms. Geometric stability is among the key conditions, as any minor differences in sensor mounting or platform deformation may cause systematic distortions, which spread to point clouds, image networks, and computed measurements [22,23]. In the case of fixed-base systems, stability is controlled mainly by the robot structure and mounting base; in the case of the mobile system, it is controlled by the chassis stiffness, suspension design, and vibration isolation, as well as the mechanical connection between the sensor and the vehicle. Large-scale surveys also experience significant thermal effects, especially when using the survey outside or in a factory with temperature gradients. The expansion over temperature can cause changes in lever arms and boresight directions, and the accumulated biases in a series of missions across seasons or across the day can cause significant problems unless the system has some method of compensating or occasionally recalibrating the system.

Another important critical design dimension is payload and mounting geometry. LiDAR scanners, cameras, IMUs, GNSS receivers, as well as auxiliary sensors, are frequently considered geodetic payloads, but have to be positioned in such a way that they can meet line of sight requirements, and so as to cause as little mutual interference as possible [24]. The mechanical layout should be able to maintain well-characterized extrinsic calibration and have clear sensor fields of view. Practically, the location of mounting has an impact on the patterns of occlusion, the distribution of incidence, and is prone to specific self-shadowing by the body. In the case of LiDAR, especially, the mounting height and the mounting orientation affect the ground returns, the coverage of the facade, and the undercut or overhead structure. In the case of imaging systems, the photogrammetric conditioning and reconstruction quality are dependent on the stability of baseline geometry and camera pose. These reflections demonstrate that platform design in robotic geodetic acquisition cannot be discussed outside of the context of the measurement design, since it is the platform that defines what acquisition geometries are possible.

Operational durability and environmental protection are usually key determinants when deploying in large scale [25]. Some of the survey areas could be dust, water spray, chemical exposures, electromagnetic interference, and mechanical dangers. Although industrial robots are normally durable within the confined factory environment, their use in the field demands consideration of ingress protection, cables, connector resilience, and extended working duration. In the case of mobile systems, the choice of wheels or tracks, traction control, and the possibility of moving over a slope or threshold define whether the robot can follow a planned survey path. The optical sensing can be degraded by the conditions of lighting and airborne particulates under the ground or in a closed area, necessitating electrostatic provision on the platform, which can be either internal illumination, sensor cleaning solutions, or multimodal optical sensing.

The issue of safety influences the hardware and software selection, especially when robots are used in an environment where there are workers, traffic, and running machinery. The industrial settings are tough in terms of collision prevention, emergency shutdown, and quality obstacle recognition. These are not strictly speaking regulatory requirements; they are also factors that affect the acquisition strategy that can be achieved. An illustration is the case of a robot that has to keep large safety margins, and thus cannot install sensors near a structure as desired. Similarly, a robot that is deployed in an urban environment is required to consider dynamic barriers and capture of privacy-sensitive data, which may impact the location and time of the surveys. Thus, the platform will have to promote not only accurate movement but also secure communication with dynamic and multifaceted environments [26].

2.3. Autonomy Levels and Deployment Modes

Various levels of autonomy Robotic geodetic acquisition is a continuum between teleoperated and autonomous surveying that is at mission levels [27]. Teleoperation is also used in initial deployments and where the autonomy may be unreliable due to the hazardous nature, as human judgment is capable of addressing the unforeseen challenges as well as the difficult site-specific conditions. Under these conditions, the robot is used as a remote sensor carrier and the quality of the survey is largely based on the knowledge of the operator and interface design. With the maturity of systems, supervised autonomy is more feasible, in which the robot adheres to a laid-out path of routes and undertakes acquisition behavior as a human oversees the condition of the systems and dictates actions during times of need. A supervised autonomy will allow cutting down labor, yet the human factor in making safety-sensitive decisions and quality control will be preserved.

Mission-level autonomy is targeted to make the objectives of the surveying more specific, so that the robot is able to plan routes, choose points of view, and change the formal density, depending on the quality of localization and the complexity of the scene [28]. This kind of autonomy is hard to achieve in geodetic settings since the robot needs to think about the quality of measurement, but not the navigability. Indicatively, a collision-free navigation path can be geodetically incomplete because of occlusions, bad incidence angles, or inadequate overlap to allow registration. In turn, the issue of robotic surveying autonomy should include information-theoretic or geometry-conceptual planning, which has a direct connection, i.e., directly connects movement choices with the projected mapping quality and discrepancy. This is a criterion that enables geodetic autonomy to stand out among most robotics tasks, where one merely has to drive to a place or circumvent obstacles.

In practice, robotic platforms differ further according to modes of deployment [29]. One-time mapping missions are focused on coverage and speed, aiming to achieve adequate density and overlap that can be used to reconstruct the environment with enough reliability. Repeat surveying missions, e.g., deformation monitoring or construction progress tracking, put more emphasis on repeatability and controlled acquisition geometry, in that any variation of the real world may be credited to varying conditions, instead of measurement errors. Repetition With repetition missions, sensor history, and the Bryan of sensor trajectories together with sensor point of view, registration ambiguity can be decreased and change detection sensitivity enhanced. This is a benefit of robotic platforms, which is important; however, it requires the maintenance of localization and consistency between calibrations over time.

Thus, permanent deployments frequently need upkeep schedules, continuously scheduled calibration examinations, and information-driven quality control able to identify drift or institutional prejudice prior to it undermining the outcomes of the monitoring.

Operationally, scalability relies on the ability of a robotic system to be implemented with little localization of the site. Industrial robots are usually good at working in structured environments of known layout, whereas large-scale geodetic acquisition is often found in semi-structured environments or changing ones. The solution in this case is the need to have platforms capable of managing partial prior information and able to tolerate change, like temporary obstructions, yet deliver survey-quality results. One of the trends that is becoming more significant in the field as the field develops is the convergence of industrial reliability and field-robot autonomy, allowing robots that can be used in a wide range of environments and yet provide the traceability and accuracy needed by geodetic tasks [30].

To conclude, industrial robot platforms introduce a strong range of possibilities to the large-scale acquisition of geodetic data, and their efficiency depends on platform form, platform mechanical stability, payload integration, safety considerations, and level of autonomy [31]. The second part is a continuation of the first part, as it considers the sensing configurations, calibration procedures, and acquisition processes that translate the robotic move to geodetically significant data products.

3. Sensors, Calibration, and Data Acquisition Workflows

A volume of geodetically significant acquisition systems in industrial robots can only be achieved by having both a sensing set and calibration physics, and an acquisition process that maintains metric integrity at scale. Surveys using robots more often include continuous motion, changing viewpoints, and mixed sensors with varying rates of sampling than more traditional terrestrial systems [32]. These properties can enhance productivity and do a better job of coverage, yet they incorporate additional failure modes, such as time misalignment, motion distortion, extrinsic drift, and uneven georeferencing. Section 3, hence, looks at a real-world sensing stack in place on an industrial robot in platform, calibration, and synchronization processes necessary to generate survey-level results, and purchase approaches and pipelines accomplishing the conversion of rough results into dependable and dimensioned geodetic data. **Figure 3** focuses on the end-to-end pipeline and its feedback to improve completeness and quality controls.

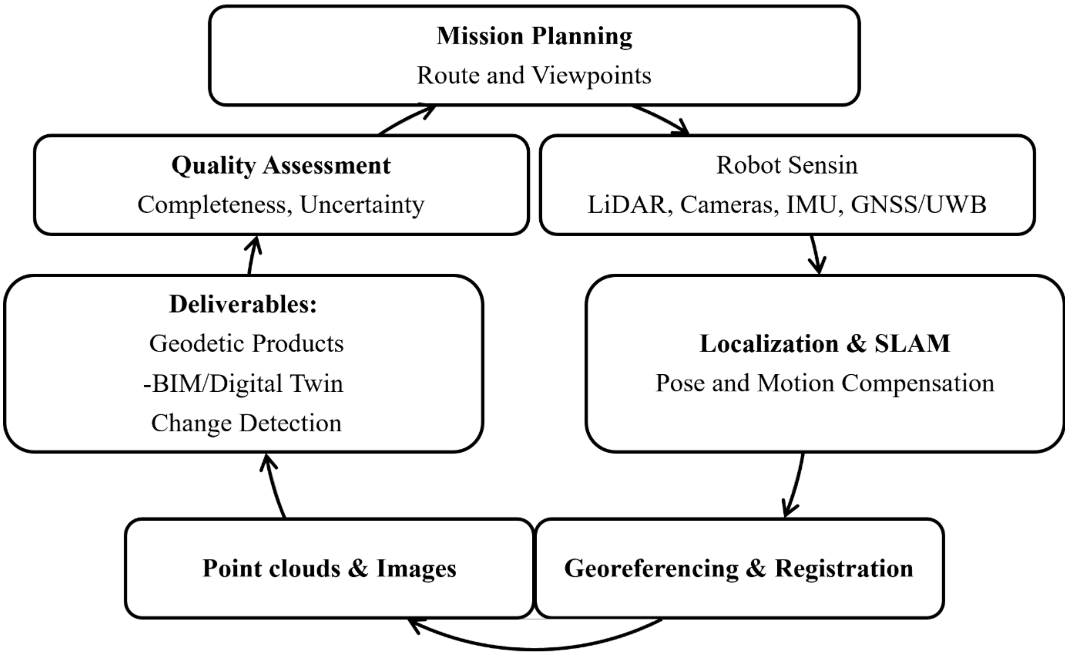

Figure 3. End-to-end workflow of robot-based geodetic acquisition, from mission planning and multi-sensor data capture to localization/SLAM, georeferencing, quality control, and deliverables such as point clouds, BIM/digital twin updates, and change detection.

3.1. Sensor Suites for Robot-Enabled Geodetic Acquisition

Geodetic acquisition with robots usually depends on multi-sensor packages, which integrate geometry sensors, visual sensors, and motion estimation of a navigation grade [33]. LiDAR is the most widespread core sensor of large-scale geometry, since it measures range directly, and is able to produce dense 3D point clouds, which are relatively insensitive to changes in illumination. LiDAR can be a terrestrial laser scanner in quasi-static stop-and-go mode, a spinning multiple-beam sensor, or a solid-state unit, depending on the application and platform. The configurations vary the trade space of point density versus field-of-view completeness, motion sensitivity versus field-of-view completeness, and the field-of-view completeness versus operational speed.

Vision sensors are used to supplement LiDAR with the texture, semantic, and photogrammetric constraints, which may be used to enhance the registration or allow high-fidelity reconstruction in conditions where LiDAR is ineffective. Red, Green, Blue (RGB) cameras are most commonly used for documentation and visual features extraction in SLAM and mapping, and stereo cameras and depth cameras under observation are provided by Red, Green, Blue and Depth (RGB-D) cameras with short and mid-range depth observability. In a field or inspection setup, thermal imaging and multispectral imaging can be combined in assessing material condition, whereas the metric contributions are normally indirect, with some exceptions of being combined with geometric sensors and precise calibration [34,35].

Robot surveying would highly require navigation and motion sensing, as the measurement time and pose cannot be separated when determining the movement of the platform [18,36]. IMUs offer angular velocity and acceleration at high rates, which allows motion compensation and tightly coupled estimation. Relative motion constraints of ground platforms can be given by wheel odometry or ground-contact leg signals, but they are sensitive to contact uncertainty, deformable ground, and slip. In operational conditions, GNSS (usually RTK or Precise Point Positioning—PPP) provides absolute positioning, but in GNSS-denied areas, other infrastructure can be employed to fix the map to an external frame like UWB, beacons, or fiducial markers. As a matter of fact, the strongest systems are not based on one modality; rather, they combine complementary sensors such that in the case of failure in any channel, others can compensate for this failure. **Table 2** gives a summary of the most prevalent sensor elements and the limitations that the sensor elements place on survey quality outputs.

Table 2. Sensors commonly integrated on industrial robotic platforms for geodetic acquisition and their primary roles, strengths, and limitations with respect to survey-grade mapping.

Sensor	Primary Function	Typical Accuracy Level	Strengths	Weaknesses	Typical Robotic Use
Terrestrial LiDAR	3D geometry acquisition	mm–cm	Dense, accurate point clouds; robust in low light	Sensitive to motion distortion; heavy data	Mapping, deformation monitoring
RGB camera	Visual documentation, photogrammetry	cm–dm (Structure from Motion—SfM/Multi-View Stereo—MVS)	Low cost; rich texture	Lighting dependent; scale ambiguity	3D reconstruction, change detection
RGB-D camera	Short-range depth	cm	Fast depth capture; lightweight	Limited range; noise outdoors	Indoor mapping, obstacle perception
IMU	Motion estimation	sub-degree /sub-cm drift	High-rate motion data	Drift over time	Motion compensation, SLAM
GNSS/RTK	Absolute positioning	cm	Global reference frame	Poor indoors/urban canyons	Outdoor georeferencing
UWB/Beacons	Indoor positioning	cm–dm	Works in GNSS-denied spaces	Requires infrastructure	Indoor control networks
Wheel odometry	Relative motion	dm	Simple, reliable	Wheel slip errors	AMR navigation
Radar/Ground Penetrating Radar (GPR) (niche)	Subsurface detection	dm–m	Penetrates ground	Low spatial resolution	Utility mapping

3.2. Calibration Principles and System Geometry

Calibration is the key science enabling a robotized sensing system to deliver survey-level results [37,38]. In the case of multi-sensor robotic platforms, calibration should deal with intrinsic sensor parameters, extrinsic relationships between sensors and the robot body, time synchronization, and stability of the calibration parameters across the mission, as well as repeat deployments. In a static land surveying process, the error can be brought down to a manageable level due to repetitive configurations and due to the appropriate setting up of the stations; in robot-based acquisition, the errors tend to be very small in nature, but they are recurrent, due to minor but consistent mis-modeling of sensor geometry and timing.

Intrinsic calibration involves calculating camera intrinsics and distortion parameters, as well as LiDAR beam calibration parameters, where necessary, supplied by the manufacturer. In geodetic use, extrinsic calibration: determining the rigid-body transforms between LiDAR, cameras, IMU, GNSS antenna, and robot reference frame is more difficult. These transforms characterize leverage lengths and boresights, and they are the one that has a direct impact on the projection of measurements into a world frame. Extrinsic errors may manifest in mobile systems as systematic errors in point cloud strips, mapping biases related to the trajectory, or as apparent deformation of multiple surveys. In the mobile manipulators, further kinematic calibration can be necessary since sensor pose computation is based on the forward kinematics of the arm, in which any offset of the joint or error in link parameters can be transferred into the map [39].

Time synchrony is also very important. LiDAR scan and camera frame timestamps are never synchronized and can be affected by variable delay, and IMUs tend to have high-rate streams with distinct clocks [40]. Without modeling of time offsets, the motion distortion may not be recoverable with the best accuracy, and the resultant point clouds or image networks may have warping that cannot be eliminated using rigid registration. Robotic acquisition Survey-grade is thus advantageous because it supports hardware synchronization, where practical, disciplined timing, and also the explicit estimation or test of time offsets in calibration. In massive implementations, calibration cannot be a once-laboratory test; field verification methods are required to realize modifications proving vibration, handling, or thermal cycles. Short checks in the calibration of the workflow are often implemented into practice at the start and end of missions and at the close of long-duration mapping.

3.3. Motion Distortion, Pose Interpolation, and Measurement Integrity

In contrast to non-portable scans on land, robot-based acquisition is often characterized by a constant motion, and hence the measurements should be interpreted in the context of the pose of the robot when the sensations are obtained [41]. The first issue that is of concern to spinning LiDAR and rolling-shutter cameras is motion distortion since both scan or frames are obtained within a finite period of time. Assuming that the robot is rotating or translating during that period, the points are gathered at other poses, and the point cloud is a time-smeared view of the scene. The solution to this effect is high-rate pose estimation, which is usually offered by IMU integration that is facilitated by LiDAR or visual updates, and pose interpolation to match each reading with the correct time.

The significance of distortion correction, as far as the geodetic applications are concerned, is not a mere aesthetic issue. Distortion may bias geometrical fitting, impair repeatability between epochs, and lower the interpretability of the change-detecting outcomes. Distortion artifacts can also cause false correspondences in scan matching and loop closure, in repetitive geometry, which can be repetitive, as in the case of corridor mapping and tunnel surveys. As a result, sound workflow involving robots combines distortion measures early in the pipeline and considers it as a condition of successful registration and accommodation [42].

3.4. Acquisition Strategies: Viewpoint Planning, Coverage, and Repeatability

Coverage completeness, overlap, which is sufficient to have registration and required measurement geometry to achieve accuracy, are the governing factors in large-scale geodetic acquisition [43,44]. Industrial robots create the possibility of designing acquisition strategies consciously on the basis of these requirements. Fixed-Base arm operations. Viewpoint planning is used to minimize the effect of occlusions and to satisfy preferred values of incidence angle, such as by running a pre-defined scan of a component or structure. Trajectory design, used in the mobile deployment, has to be a balance between coverage and navigation. Nonstop scanning can optimize productivity, yet in high-precision situations, where the vibration and distortion need to be reduced, stop-and-go acquisition can be used.

Rotund segmentation is core to fortunes registration. Big environments are usually filled with occlusions, repeatable structures, and dynamic obstructions, and therefore, the effective overlap between successive measurements is often significantly less than the nominal sensor field-of-view would suggest. This can be resolved by robots through the implementation of structured routes that purposely form loop closures, as well as revisiting important places to enhance global congruency. This is especially significant in GNSS denied areas where loop closures offer the major drift control mechanism. In repeated surveys, repeated surveys may also be aided by robots that are able to replay reference trajectories to provide more reliable inter-epoch alignment and enhance the sensitivity of change detection. Stable trajectories when replayed are, however, useful provided that the localization is constant, calibration does not change between deployments, therefore, the property of repeatability is a system-level attribute that relies on both robotics and geodetic control.

Another emerging new direction is adaptive acquisition, where robots change their sensing behavior depending on real-time signals of map quality [45]. Indicatively, in case completeness tests show that coverage behind occlusions is absent, the robot can choose new viewpoints; the uncertainty estimates increase as a result of low localization observability, and the robot can attempt a loop closure or a region with better geometry. Geodetically, this is a planning that is expressly accuracy-based as opposed to navigation-based planning. This type of strategy can prove especially appealing in large-scale environments since it minimizes the potential of finding holes when it is already too late to be available on the site, thus lowering the cost of having to redo the work.

3.5. Data Pipelines: Real-Time Quality Assurance (QA), Post-Processing, and Data Management at Scale

Robot geodetic acquisition is often run in two phases: real-time monitoring to ensure that the operation is running, and post-processing to refine the survey to a survey level [46]. Live capacity is useful in checking the well-being of the sensors, coverage, and initial quality of registration, particularly at the complicated sites with a limited access window. Quick-look maps can be generated on board, simple gross failures, like sensor failures or sync errors, can be identified, and on-site decisions as to the need to get further data can be made. The capabilities of mobile platforms are usually limited by computational constraints, and the real-time processing cannot be very sophisticated; moreover, the results of high quality normally need to be refined offline with full-resolution information and more extensive adjustment.

Also often done after processing, rigorous calibration is applied, motion compensation, scan and image registration, loop closure validation, and georeferencing to external control. In the case of geodetic deliverables, uncertainty-aware estimation and independent check validation should be a part of the processing chain. The pipeline should also solve data management issues that emerge in scale, such as massive quantities of point clouds and imagery, metadata that captures the calibration state and trajectories, and traceability of processing steps required to be auditable. Efficient storage formats, tiling plans, and uniform coordinate reference handling can be convenient requirements when robotic acquisition is intended to be employed in recurring monitoring or larger programs of digital twins [47,48].

The final product of a deployment in most deployment situations is not a raw point cloud but some engineering representation (such as BIM-compatible geometry, extracted features, or change metrics). Consequently, the design of the workflow of the acquisition must be made backwards of the deliverables, whereby sensing setting and path planning must guarantee the required resolution, coverage, and diversity in viewpoint to downstream modeling. The approach based on a delivery that is geometrical completeness is especially significant in industrial facilities and construction projects, where geometric completeness needs to be adequate to obtain reliable object extraction, and data needs to be congruent with preexisting design models and asset management platforms [49].

3.6. Practical Workflow Integration and Quality Control (QC)

One of the most striking aspects of survey-grade robotic acquisition is that it requires disciplined quality control procedures, which find out problems early and do not allow their silent ruin of the results [50]. Practical QC is based on the field stage and office stage. QC in the field encompasses sensor status tests, calibration checks, control observation tests, where necessary, and completeness checks. Residual analysis, overlapping pass consistency checks, control or independent measurements, and uncertainty documentation are all part of QC in the office. Since robotic acquisition eliminates the personal contact with the execution of measurements, the QC becomes even more critical as a control tool that helps to preserve confidence in the generated geodetic datasets.

On the whole, sensors and workflows in robot-enabled geodesy should be perceived as a system, but not as a bunch of parts. Optimal performance is achieved with sensor combinations that maximize sensor selection, calibration, synchronization, trajectory planning, and QA, where all the aforementioned factors are designed jointly with the accuracy, repeatability, and completeness required by the large-scale geodetic studies [51,52]. This combined view also explains why robotic mapping cannot be assessed based on algorithmic performance but needs to be assessed as an end-to-end measurement process. Based on these sensing and workflow building blocks, Section 4 examined the conversion of robotic measurements into traceable geodetic products through georeferencing, SLAM, and uncertainty-sensitive adjustment, and Section 5 outlined how these functions translate into domain-specific benefits and constraints in the real world.

4. Geodetic Processing and Algorithmic Foundations

Large-scale geodetic acquisition that uses robots is ultimately successful or becomes unsuccessful in the processing chain that transforms the raw sensor measurements into georeferenced and survey-ready products [53]. Repeatable geometry of acquisition in industrial robots can allow efficient field operations, and such datasets can contain continuous motion, heterogeneous sensors, and complicated environments, which demand novel workflows. There are two requirements in this environment that geodetic processing has to reconcile, which can be independently discussed in the literature. Mapping consistency, which is emphasized in robotics, is the first requirement, in which the objective is to generate a consistent representation of the environment and an internally consistent trajectory. Traceable georeferencing with quantified uncertainty is the second requirement, which is emphasized in geodesy, whereby products must be connectable to a constant reference frame and error models acceptable to engineering decisions. This section is a review of the algorithmic basis on which robot-based geodetic acquisition is supported, which is georeferencing and registration, SLAM and localization, uncertainty modeling, and automated interpretation to connect mapping to actionable geodetic deliverables. Since the survey-grade results require both local consistency and control of external datum, **Figure 4** gives a unifying estimation perspective that relates the SLAM-type optimization with geodetic adjustment.

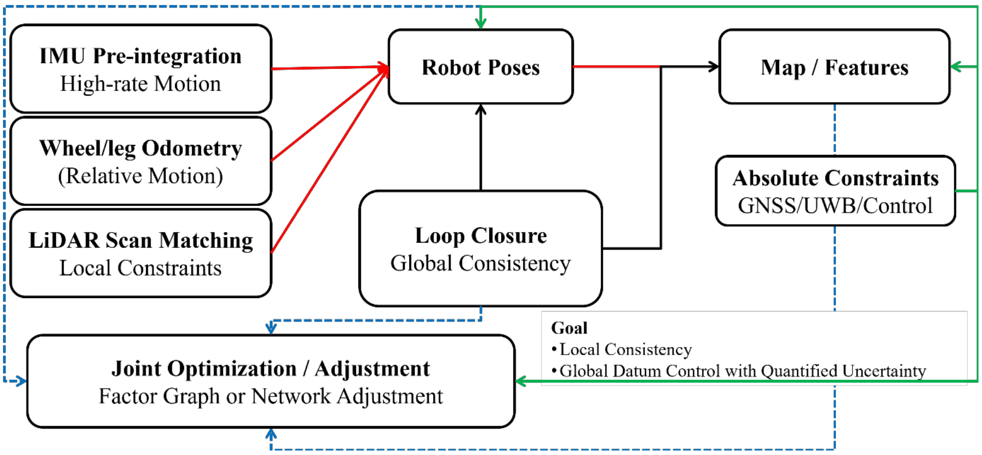

Figure 4. Coupled estimation framework for robotic geodesy, illustrating how odometry, IMU integration, scan matching, loop closure, and absolute constraints (GNSS/UWB/control) can be fused in a factor-graph or adjustment-based formulation to achieve local consistency and global datum control.

4.1. Georeferencing and Registration in Robotic Geodetic Workflows

The process of giving measurements a reference frame that is external to the map being measured is known as georeferencing, and is the distinguishing step that becomes an external reference frame between a local and a geodetic product [54]. Georeferencing for large-scale robotic acquisition, combinations of both absolute sensors, such as GNSS/RTK or PPP, inertial navigation, and external constraints, e.g., control points, targets, or known structural features, are often used. When the GNSS is provided and is competent, the overriding issue is not so much positioning as lever-arms offsets, boresight angles, and timing are modeled appropriately to make sure that absolute positioning propagates correctly to sensor readings. In the event of unavailability or poor quality of GNSS, georeferencing should be carried out by other processes (traverses, which are limited by control networks, scan-to-control alignment, or hybrid adjustment models that combine local mapping with sparse absolute constraints).

Registration is a process of aligning observations that overlap with each other in a single model [55]. In robotic mapping, scan matching or feature-based matching is often used in registration, usually as part of a factor-graph. In geodetic applications, registration should not be just capable of providing a visually acceptable alignment, but it should be required to reduce systematic error and maintain ratio, orientation, as well as datum compatibility. This distinction is significant in the context of environments with a large degree of geometric ambiguity, i.e., long corridors, repetitive industrial buildings, tunnels, and canyons of cities. In these situations, local registration can tend towards plausible but wrong alignment, particularly at the level of minimal overlap, or when the environment is not particularly distinctive. Strong registration then demands purposeful acquisition strategies such that there are adequate geometric constraints, and processing strategies, which take into account priors or survey constraints to avoid drift and misalignment.

The motion distortion is a critical practical concern in mass-scale acquisition, especially for spinning LiDAR and rolling-shutter cameras. The sensor poses change with time, where measurements are made over a limited time as the robot goes through time. To correct motion distortion, the correct time synchronization of the updates and pose estimation at a high rate is necessary and only made possible through IMU integration of the updates with wheel odometry or visual/LiDAR information. Poor motion compensation may cause systematic distortion of point clouds or image geometry, which is carried over to registration and adjustment errors. As such, powerful georeferencing and registration rely on a strong sensing and estimation chain and not a weakly staged process [54,56].

4.2. SLAM and Localization for Large-Scale Surveying

Localization and mapping in parallel have emerged as the new paradigm of GNSS-denied robotic mapping, yet survey-grade geodetic acquisition provides further limitations on the way the SLAM results are utilized and verified [57]. One goal of standard SLAM techniques is to provide an internally consistent trajectory and a map, usually optimized with a graph-based algorithm and loop closure. This is necessary in large-scale surveying due to loop closures, since this is the main way of correcting drifts, especially in long missions. Nevertheless, the loop closure detection might prove inaccurate in those scenes that feature repetitive geometry, pronounced changes in the scene, or objects in motion. Counterfeited loop closures can be disastrous and give solutions based on the globe that can still look locally sensible. Thus, survey-based SLAM needs to significantly improve outlier rejection, the acceptance test needs to be more conservative, and the check-out procedure needs to be able to identify and isolate erroneous constraints.

The environment and operational considerations are the major determinants when deciding between LiDAR-SLAM, visual SLAM, and multi-sensor fusion [58]. LiDAR-SLAM frequently works well in dark environments and offers strong geometrical restrictions, but cannot work well in feature-sparse conditions, like long tunnels or open spaces with minimal structure. Visual SLAM is capable of offering rich features and frequency, but it is also affected by lighting, motion blur, and the texture sparseness and scale observability without added sensors, unless in stereo configurations. Fusion of multi-sensors combining IMU, wheel odometry, LiDAR, and cameras is usually the most robust approach, as it is more observable and has redundancy. The fusion architecture is important for large-scale geodetic results. Loosely coupled fusion can provide adequate navigation for robotics tasks, but can result in unstable error propagation and poorer georeferencing. More appropriate when the goal is to make the products of traceable geodetic are tightly coupled approaches in which one works with raw measurement models to be explicitly modeled and constrained.

The survey environment is dynamic in many large-scale deployment environments. Construction sites are developed, industrial premises are covered with moving machines and people, and the street area is covered with traffic and people. Non-stationary observations over the scene add dynamic effects to scenes that can deteriorate SLAM and registration, especially when the dynamic points have not been filtered before scan matching or when moving objects are dominant in the image. Strong large-scale surveying also enjoys the flexibility of dynamic-object representation, be it by semantic filtering, temporal consistency test, or probabilistic data association, which down-weights inconsistent measurements. This brings in a new relationship between perception and geodetic estimation: the accuracy of the final coordinate products is determined more and more by the capability to isolate stable geometry and the changing elements in real time or post-processing [59].

4.3. Error Modeling and Uncertainty Propagation

One of the issues of geodetic products that has been described is that it is expected to be able to quantify accuracy and uncertainty. In standard surveying, the doubt is usually communicated with statistics of network adjustment, instrument specification, and residual investigation. Uncertainty in robotic mapping. Uncertainty is often modeled as covariance in a state estimation, and fails to be pessimistic when model assumptions are compromised, or when correlations are not completely modeled. To enable geodetic acquisition with robots, the traditions of uncertainty modeling must be reconciled to offer uncertainty meaningfully at the product level, e.g., confidence of point positions, derived dimensions, clearances, or deformation time-series [60].

Uncertainty can be divided into various causes that are sensor noise, calibration error, timing errors, motion artifact, environmental interference, and algorithm bias [61]. In multi-sensor systems, the extrinsic calibration errors are also of special consequence since they add systematic biases, which are hard to eliminate through averaging. Equally, non-Gaussian and time-varying GNSS error can be seen in multipath conditions, and a visual feature measure can have outliers because of a specular surface or a repeated texture. Strong estimation thus stipulates a clear modeling of outliers and heavy-tailed noise in addition to diagnostic mechanisms that expose the occurrence when the system is in a regime where it does not comply with its assumptions.

The natural integrative framework of incorporating the geodetic constraints into robotic estimation is given by network adjustment and graph optimization [62]. Control points, known targets, and previous structural constraints can be added to factor graphs with odometry and scan-matching factors, providing an integrated solution and allowing both the situation of local consistency and the global control of the datum. The real-life problem is to make the solution gained optimized as well as proven. The importance of residual analysis, consistency checks, independent control observations, as well as cross-validation to withheld constraints is critical towards confidence building. In cases of repeated monitoring, uncertainty propagation also needs to be time-dependent and expresses the stability of the reference frame between epochs, as well as distinguishing between true deformation and systematic variability in references caused by acquisition drift due to a drifting calibrant, or references caused by a changing geometry of the acquisition.

The generation of deliverables that are ready to be used in a survey may need to convert the estimated map into something that is easily consumed by the engineering processes, including registered point clouds in an official coordinate system, parametric representations to be included in a BIM, or extracted geometric primitives with tolerance annotations. Uncertainty characteristics can be changed during each step of the transformation. As an illustration, the addition of planes or cylinders to the noisy point clouds can decrease random error but increase systematic bias in case the underlying point cloud has been distorted by motion distortion. Thus, strong robotic geodesy enjoys end-to-end reasoning of uncertainty, in which uncertainty is propagated through raw measurements to the results of determination of pose estimation and registration to the ultimate derived features and metrics [46].

Practically, uncertainty is dealt with by various robotic mapping systems in dissimilar ways. As an example, mobile mapping systems based on LiDAR often use tightly integrated LiDAR RIMU state estimation systems whereby pose and map parameters are co-optimized in a factor-graph formulation. This method enables sensor noise, uncertainties of motion, and constraints of loop-closure to be propagated to covariance estimates of map features and the trajectory. When further geodetic requirements are added (e.g., ground control points or GNSS measurements), the optimization can be formulated to mirror a network adjustment, and absolute accuracy along with uncertainty can be considered in a similar way.

On the other hand, there are robotic SLAM designs that aim to provide finer internal consistency of the map without explicitly modeling absolute reference uncertainty. With a resultant point cloud that is aesthetically consistent, but may have uncharacterized drift against the external reference frame, this can happen. This demerit is especially problematic in the survey-grade applications in which the order of millimeter-centimeter levels of positional precision is stipulated, e.g., deformation monitoring or construction verification.

An increasing amount of literature consequently unites geodetic control measurements, residual-diagnostic measurements, and independent validation measurements in SLAM-based mapping pipelines. The practices enable the propagation of uncertainty in the form of raw measurements through registration and correction to final products like point coordinates, extracted geometric features, or deformation estimates to enhance the traceability and reliability of robotic geodetic data [63].

4.4. Automation of Interpretation and the Mapping-to-Geodesy Bridge

Massive geodetic acquisition is directed not merely to generate dense geometry, but also to serve the purpose of making decisions, e.g., compliance checking, clearance evaluation, progressing measurement, and anomaly detection [43,64]. This change will render automated interpretation a crucial part of the pipeline. In robot-based processes, interpretation usually commences with the extraction of robust geometric structure over raw point clouds and images (such as planes, edges, and cylindrical or prismatic structures which occur frequently in the built environment). These primitives represent an interface between raw sensor data and engineer-friendly engineering models. An example is that planar segmentation assists in extracting floors and walls during indoor mapping, and cylinder extraction assists in extracting pipelines and conduits in an industrial facility.

Machine learning has facilitated the semantic processing of geospatial data by promoting point clouds and image classification and segmentation in an automated manner [65]. In the case of geodetic applications, it is not just the labeling but also making semantic outputs conform to the requirements of metric accuracy. A segmented pipe can only be of use when its fitted centerline and diameter are sufficiently accurate to pass design checks, and a reportedly found crack or spall can only be of use when its location can be reliably measured in the global frame and can be revisited later. This brings a correlation between perception assurance and geodetic uncertainty: automated interpretation has to ideally provide not only labels but also confidence measures and geometry quality indicators that point at sensing conditions as well as localization accuracy.

The detection of change and monitoring of deformation are especially critical roles in which the robots can offer repeated and standardized acquisition [66]. Mathematically, to perform change detection, it is necessary to have strong interpatch alignment, transient object filtering, and statistical thresholds that consider noise in measurements, as well as registration uncertainty. In large size (large point clouds), naive differencing of point clouds may give a large number of false hits because of slight misalignment, point density variations, or incidence angle variations. Good techniques thus use the ideas of uncertainty-conscious comparison, multi-scale analysis, and, in others, feature-level tracking wherein fixed entities in space are used as anchors to time in an effort to track the temporal variations in space. When utilized effectively, the approaches facilitate the automated reporting of significant alterations, including settlement patterns, tunnel convergence, slope movement, or construction advancement, in contrast to BIM.

Lastly, robots are being used more and more in real-time or near-real-time quality inspection [67]. Instead of amassing data and finding the gaps once the site has been left, robots are capable of conducting completeness tests on board, comparing the overlap and registration confidence, and initiating other viewpoints in the case of an uncertain environment. This feature lies at the heart of the realization of scalable and repeatable surveying since it minimizes rework and ensures that the end dataset has coverage and accuracy requirements. Geodetically, real-time QA is also an opportunity to impose standards of measurement in the course of acquisition, such as adequate control measurements, good loop closures, or stable calibration checks during the entire mission.

In brief, it is possible to state that processing principles of robot-assisted geodetic acquisition combine georeferencing, registration, a localization system based on SLAM, and uncertainty modeling into a consistent pipeline producing outputs that are geodetic survey-ready. Such an augmenting importance of automated interpretation also makes the pipeline go beyond mapping to engineering decision support, but increases the desire for rigorous validation and sensitivity to uncertainty. It is based on these algorithmic foundations that the following section examines areas of application and compares and contrasts the performance of robotic and conventional geodetic acquisition methods.

5. Applications and Comparative Performance Synthesis

Many large-scale geodetic acquisition situations are being considered with the use of industrial robot technology due to the need to enhance productivity, enhance repeatability, and minimize human exposure to dangerous or staffing-intensive operational conditions [68]. Real usefulness of robotics is seldom defined by only one aspect like sensor accuracy; it is a product of the interplay between platform capability, mission design, localization robustness, and the needs of the geodetic deliverable in the downstream. This section examines key areas of application and integrates areas of comparison of performance, how and why industrial robots may outperform traditional acquisition strategies in certain areas and be constrained and cost-ineffective in others.

5.1. Infrastructure Surveying and Structural Monitoring

Geodetic acquisition involving robots has one of the most direct use scenarios in transportation and civil infrastructure, since these elements must be inspected and monitored periodically with significant safety and access restrictions in place [69]. Complex geometry and occlusions are common in bridges, tunnels, retaining structures, rail corridors, and highway sections, and they might be situated in operational environments where there is a significant operational burden in terms of traffic control, working at height, or narrow-space access. Robotic platforms can overcome these limitations by accommodating repeatable sensor paths and by allowing acquisition of too short and/or dangerous time windows that a manual scan cannot achieve. Mobile robots can be used in tunnel surveillance, where they can navigate through long tracks and take LiDAR and video, to furnish repetitive surveys, which can be used to perform convergence analysis and detect changes. In bridge inspection and clearance assessment, robots can travel beneath decks or along access lanes and keep a fixed stand-off distance and viewing geometry that enhances the usefulness of the differences in point clouds in different epochs.

In performance aspects, repeatability is usually considered as important as absolute accuracy in infrastructure monitoring. Robots are able to follow very similar paths, which reduces the ambiguity between the epochs in terms of registration and enhances the accuracy of deformation inference. The extent to which this benefit occurs, however, is dependent on how stable localization is and also on the quality of georeferencing constraints. SLAM drift and loop closure quality are the two dominant factors in GNSS-denied tunnels or under bridge decks, and survey-grade monitoring usually needs control points or the periodic absolute constraints to avoid the minor datum changes being interpreted as a structural deformation. Practically, workflows that combine robotic acquisition with geodetic control techniques are the most successful because robotics is used to normalize and speed up data collection, maintaining the survey principles of data integrity and uncertainty measurement [70].

5.2. Construction and Engineering Geodesy

Robotic geodetic acquisition is specifically appealing to construction environments, where it is required to measure often, to track progress, to verify a layout, and to perform quality control, but these are operationally dynamic and are often hazardous [69]. Traditional workflows tend to be based on infrequent total station surveys and infrequent TLS campaigns, which are time-consuming and sensitive to access to the site and workforce. Mobile robots and mobile manipulators have the potential of offering a more continuous paradigm of acquisition, in the sense that they can move around the site gathering dense geometry and imagery that can be compared against design intent. This can be used to support applications like volumetric estimation of earthworks, checking of as-built structural elements, and inspection of installation tolerances of prefabricated components.

One of the main comparative advantages of robotics in construction is that it can be standardized and become less dependent on the skills of the operator [71,72]. Placement Station A station operator may include different placements, overlap planning, and registration choices, which can affect completeness and repeatability in manual TLS campaigns. The same workflow can be coded by a robot to repeatable acquisitions and real-time quality controls to make sure that coverage and overlap are of a particular standard. Additionally, connection to BIM will provide a natural feedback loop where the mission of the robot can be specified in terms of design geometry, and scanning of important features can be specified, as well as deviations can be reported automatically. Construction sites are, however, also one of the most complex environments where autonomy can be represented because of the frequent changes of layouts, moving equipment, and temporary occlusions. This dynamic character may compromise SLAM, and make repeated surveys difficult, which implies that good performance in many cases needs an autonomous quality under supervision, well-crafted tracks, and explicit forms of determining consistent reference structures to align across time.

5.3. Industrial Plants and Facilities for Digital Twin Updating

Industrial plants, refineries, power plants, and large facilities attach a lot of importance to as-is geometric representation, as spatial conflicts, as well as safety clearances and maintenance planning, rely on sound geometry. These conditions are always thick, crowded, and full of things repeated, like pipes, support, and cable trays, making it harder to acquire and process. These settings are especially suitable for the use of industrial robots, considering that the industrial part of this setting also presupposes the control of access, high safety standards, and the necessity of a repeatable and audit-quality measurement. Mobile manipulators can be useful in cases when the sensor positions have to be varied to view around occlusions or to observe twists. Fixed-base arms may also be used as high-precision scan stations for specialized parts or be used as calibration and check stations [73].

Robotic acquisition can reduce downtimes in comparison to manual TLS by conducting scanning activity at off-hours to limit the impact on the operations of the plant. This contributes to the incremental updating of the digital twin since the repeatability of robotic trajectories can focus acquisition only on the areas that have changed. However, sensor capability is not always the main performance hindrance in plants; rather, it is the complexity of data processing, such as registration in repetitive geometry and consistent identification of structured components to integrate into Computer-Aided Design (CAD)/BIM. Within this setting, the key to success is to combine a strong estimation with domain-specific interpretation, like cylinder fitting of pipes and rule-based or learning based identification of equipment. In any place where this coupling is attained, robotics will be able to transform plant documentation into less discontinuous and costly campaigns to more continuous geometric maintenance [74].

5.4. Urban Mapping and Corridor-Scale Asset Inventory

A common approach to mapping the urban environment and linear corridors with vehicles (roads, railways, utilities, and so on) and, more and more, with UAVs is to use mobile mapping systems (vehicles) and, more recently, UAV-based sensing [75,76]. The platform of industrial robots is used when the use of full-size vehicles is constrained by access restrictions, safety factors, or when mapping has to be carried out in pedestrian zones, small roads or corridors, indoor-outdoor access, or areas with low GNSS characteristics. AMRs are small and can be used on sidewalks, campuses, or mixed indoor-outside logistics areas with LiDAR and cameras, which provide the ability to inventory assets and map in 3D at scale, ranging from indoor facility mapping to outdoor streetscape mapping.

Robots may have benefits, comparatively, in slow-speed operation at a fine level of sensing, and in controlled routes that enhance coverage around obstructions like street furniture, vegetation, or parked cars [77]. They can also enhance safety by minimizing the number of human operators who will be required to work close to the traffic. Nonetheless, in large extents of corridors where vehicles are capable of operating, traditional vehicle-mounted systems are usually more cost-effective because they are faster as well as have a larger carrying capacity. Therefore, robot platforms are more likely to be the most interesting in last-meter or access-limited urban mapping and not necessarily a direct substitute for highway-scale mobile mapping. Privacy and governance are also other limiting factors, as close-range urban data capture is frequently sensitive in terms of visual information. The viability of the operation thus relies on proper data governance, anonymization streams, and adherence to local laws.

5.5. Mining, Geological Surveying, and Hazardous Environments

One of the areas where robotics can be the most evident safety-related advantage is mining, unreliable slopes, and dangerous geology [68]. Open-pit mine, waste dump, and unstable surface surveying may subject the workers to risk of rockfalls, equipment accidents, and adverse accessibility. Robotics platforms can minimize exposures by providing the ability to obtain terrain geometry, slope surfaces, and volumetry remotely. Autonomous mapping in underground mining is problematic due to GNSS denial, but tunnels are structured in a way that LiDAR localization can be supported in the event of loop closure possibilities and adequate geometrical variation.

Within such applications, metric accuracy is not always considered a crucial performance measure, but so are operational continuity and reduction of risk. Robots are able to provide the medical staff with more frequent surveys and can enhance situational awareness, as well as be able to detect dangerous deformation patterns earlier. However, harsh conditions mean that the platform must withstand harsh conditions such as dust management, vibration, and dependable navigation on rough terrain. Geodetically speaking, surface irregularities of the terrain and dust or moving equipment may cause poor point cloud quality and registration. Consequently, the most efficient methods are those that are robust in sensing and filtering with mission planning, which focuses on the stable viewpoints and revisits. Under such circumstances, robotic acquisition may be used as a supplement or a partial substitute to human-conducted surveys, especially in places that could be too risky or impractical to carry out using conventional techniques [78].

5.6. Indoor and Underground Mapping in GNSS-Denied Spaces

The most active fields of robotic mapping research include indoor and underground spaces, such as tunnels, metro systems, basements, interior areas of industries, and large warehouses, due to their inherent supporting nature to mobile robots and the constrained nature of conventional GNSS-based surveying [79]. These environments usually require precise geometry to manage the facilities, verify the clearances, retrofit the facilities, and develop a digital twin. It is possible to have robots follow the same lines and go through the same room repeatedly, which allows for collecting point clouds in a comprehensive manner with less labor.

Compared to the TLS and handheld mobile mapping, robots are the most direct competitors of manual systems. Manual TLS is very precise but slow and operationally heavy, particularly when dealing with long corridors or facilities with several levels. The handheld systems are more productive but vulnerable to variability and inconsistent paths by the operator. The middle ground can be a robot, which allows continuous acquisition and more stable motion patterns, and repulsion of routes in a systematic manner to observe. Localization drift has been identified as the main limiting factor, especially in long, topologically simple corridors where there is a low frequency of loop closures and there is a weak constraint of geometry. Survey-grade results in these situations are usually obtained only when control targets are deployed deliberately, or a combination of other positioning systems like UWB or beacons is used. As such, indoor and underground robotic geodesy is likely to be successful when workflow design explicitly integrates robotic autonomy with geodetic control strategies as opposed to the use of SLAM only [80].

5.7. Performance Dimensions and Reporting Practices

The inconsistent reporting measures and varying definitions of accuracy complicate the process of acquisition comparison across studies conducted with the use of robots. To have an evaluation of the Science Citation Index (SCI)-standard, the performance should be characterized in a variety of dimensions that represent both geodetic and operational goals. The absolute accuracy is required with reference to an external reference frame and verified by an independent control when the deliverables have to be integrated into national coordinate systems or engineering design models. Relative accuracy and internal consistency are important in robotics, especially in local measurements and in change detection; however, they are not adequate by themselves where datum integrity is important. The quality of point clouds, completeness, and point cloud quality, such as density distribution, diversity in the incidence angle, and the treatment of occlusion, impacts the reliability of the extracted features and fitted models to engineering applications [81].

Efficiency should be expressed in terms of overall mission time and manhours, and not just sensor capture time, as the overall goal of robotics is to save on setup and rework [82,83]. The level of robustness is supposed to be evaluated under different environmental conditions, such as lighting, weather, dust, dynamic obstacles, and GNSS availability. In a monitoring context, repeatability should be explicitly considered, and the capacity to recreate acquisition geometry and attain consistent inter-epoch accuracy may be considered more useful than a single campaign peak accuracy. Lastly, the cost and operability indicators, such as training needs, maintenance, safety compliance overhead, and integration work with the existing BIM/GIS pipelines, are usually the factors that dictate the use of a robotic approach after pilot applications. **Table 3** presents the practical strengths and weaknesses of robotic and conventional modalities of acquisition based on these dimensions of evaluation.

Table 3. Comparative performance synthesis of robot-based geodetic acquisition versus conventional approaches, summarized across accuracy, repeatability, efficiency, robustness, GNSS dependence, and operational cost drivers.

Evaluation Dimension	Manual TLS /Total Station	Vehicle-Based Mobile Mapping	UAV Mapping	Industrial Robot-Based Mapping
Absolute accuracy	Very high	High outdoors	Moderate–high	High (with control)
Repeatability (multi-epoch)	Moderate (operator-dependent)	Moderate	Low–moderate	High (programmable paths)
Coverage efficiency	Low	Very high (roads)	Very high (open areas)	High in constrained spaces
Indoor/underground capability	Good	Poor	Very poor	Very good
Hazardous environment access	Poor	Poor	Moderate	Very good
Setup complexity	High	Moderate	Moderate	Moderate–high
Labor requirement	High	Moderate	Moderate	Low–moderate
Dependence on GNSS	Moderate	High	High	Low–moderate
Cost efficiency (large scale)	Low	High	High (open areas)	High (constrained areas)

5.8. Comparison with Conventional Methods and When Robots Are Justified

Robot-platform industrial robots are definitely beneficial in situations where the accessibility of the location is limited, the dangers of safety are significant, and frequent surveys are to be performed [84]. Under such conditions, the potential of the robot to follow standardized paths, work at a distance, and minimize exposure of human beings can offer critical value in operation. Another case where robots are appealing is when there is a need to control measurement geometry to a small degree, e.g., in crowded industrial settings where a small shift in viewpoint can have a significant impact on the patterns of occlusion and registration consistency. Robots, on the other hand, are less attractive where the environment is easily available, the survey is a single occurrence, and there are proven ways through which high productivity is achieved. Mobile mapping requires vehicles is more efficient when dealing with long roadways with excellent GNSS connectivity, and UAVs are efficient where there are no airspace or weather limitations. When accuracy in limited regions is of great concern and time and effort are not as restricted, manual TLS can still be a good baseline.

The most convincing case of robotics comes when the researcher shows not only similar accuracy with the traditional processes but also a field time savings, greater repeatability, and a reduction in the rework due to real-time quality control. Practically, it may be necessary to combine workflows such that data capture is sped up by robotics, and geodetic control and validation processes maintain datum integrity. It is thus leaning towards the field of integrated systems instead of the purely robotic or purely traditional, where the robot becomes a standardized acquisition agent that forms part of survey-grade reference and quality paradigms.

In short, industrial robot technology has been most effective in enhancing the safety, repeatability, and operational efficiency of large-scale geodetic acquisition, especially in constricted, dynamic, or hazardous environments, or where geodetic acquisition has to be frequently repeated [74,85]. It is, however, context-dependent and based on strong georeferencing, uncertainty-sensitive processing, and effective integration with engineering deliverables. These reflections precondition the final section, which summarizes general findings and outlines the directions of research that are required to transfer robotic geodetic acquisition out of the realm of demonstrations to the realm of standardized and scalable practice. **Table 4** summarizes representative studies across different robotic platforms and application domains.

Table 4. Representative studies on robotic platforms for large-scale geodetic data acquisition.

Platform Type	Application Domain	Sensors Used	Contribution	References
Fixed-base robotic arm	Industrial inspection/ component scanning	Terrestrial LiDAR, RGB camera	High repeatability and controlled scanning geometry for precision measurements	Bogue [86]
AMR/AGV mobile robot	Indoor facility mapping	LiDAR, IMU, wheel odometry	Autonomous corridor-scale mapping and inventory documentation	Fasiolo et al. [87]
Mobile manipulator	Construction and as-built documentation	LiDAR, RGB camera, IMU	Combined mobility and viewpoint control for complex structural geometry capture	Borrmann et al. [88]
Tracked field robot	Mining and slope monitoring	LiDAR, GNSS/RTK, IMU	Mapping of hazardous or rough terrain environments	Shan et al. [89]
Multi-robot mapping system	Large industrial facilities or urban mapping	LiDAR, cameras, GNSS, IMU	Cooperative mapping to improve coverage efficiency and redundancy	Jiao et al. [90]

6. Conclusion

The technology of industrial robots is also changing the nature of large-scale geodetic data acquisition, by converting surveying into a manual-dominated, operator-sensitive process into a programmable, repeatable, and arguably autonomous process that may be programmed. Throughout the reviewed literature of this paper, one motif emerges: robots add value not just by transporting sensors, but through enforced geometry of acquisition, allowing standardized operation, and through expansion of measurement range into hazardous, access-restricted, or dynamically operational environments. Coupled with modern LiDAR and imaging, industrial robots have the potential to facilitate more frequent data collection rates and revisits, which is vital in services like infrastructure monitoring, quality assurance of construction, documentation of industrial plants, and indoor mapping or underground mapping. These benefits are in line with the increased need for continuously re-validated spatial data and auditable digital engineering processes, specifically for BIM-enabled asset management and digital twin maintenance.

Meanwhile, the review presents the observation that robot-enabled geodetic acquisition is gained between platforms and applications to varying degrees. The fixed-base robotic arms are characterized by high precision of the repeatable scan and control over the localized high-precision tasks, whereas the workspace is limited, which restricts the large-area coverage unless supported with repositioning plans. Mobile manipulators and mobile robots solve the coverage issue and have potential, especially in corridors and facilities and GNSS-denied areas, but result in a shift in the main sources of errors towards localization drift, calibration stability, time synchronization, and motion distortion. Under such systems, geodetic performance is closely pegged on SLAM and multi-sensor combination strength and level of adsorption of absolute limitations, including control points, targets, or sound GNSS/INS cuts. This supports one of the main inferences of the review: results of a survey of the grade that can be achieved by robots alone are seldom realized. Instead, they need to be explicitly integrated with geodetic control principles, be explicitly aware of uncertainty, and verification procedures that provide integrity and traceability of data.

The second significant conclusion is that the comparative performance should be measured with the help of metrics reflecting geodesy and operational deployment. There is excellent relative consistency and visually coherent mapping on many studies, but fewer studies have been rigorously validated for absolute accuracy or have uncertainty quantified in a manner that allows engineering decisions to be made. To be adopted on a large scale, in the real world, reporting practices need to approach standardized methods and protocols of evaluation that reflect absolute and relative accuracy, cross-epoch repeatability, completeness and occlusion laws, high robustness to environmental variation, and end-to-end efficiency in terms of labor and rework. In the absence of these standardizations, it is still challenging to compare outcomes between different sites and systems and to find when robotic acquisition is actually better than established methods, including vehicle-based mobile mapping, UAV sensing, or manual TLS and total station processes.

In the future, there are a number of research directions that should establish whether industrial robots are a part of large-scale geodetic practice. The former one is itself strong georeferencing in both GNSS-denied and GNSS-degraded scenarios, the stronger coupling of multi-sensing fusion to explicit geodetic requirements, and the tighter drift control across intervals of stable loop closures, external beacons, or opportunistic localization to visible structural elements. The second is calibration-centric system design, where the extrinsic stability, synchronization integrity, and field-verifiable calibration routines are considered to be the primary requirements that are not engineering-level details. The third is directly accuracy-oriented autonomy that formulates tailored strategies of planning and control and is to optimize both navigational feasibility and anticipated quality of measurement available, overlap, and reduction of doubt by applying adaptive viewpoint choice and measuring completeness in real time. The fourth one is a scalable multi-robot collaboration that has the potential to overcome the site-scale coverage constraints and offer fresh possibilities of redundancy and cross-validation, assuming coordination and network change are managed in a consistent reference frame. Lastly, it needs to be further integrated with BIM and digital twin ecosystems such that the data obtained through the use of robots is not only efficiently stored but also converted into structured and decision-ready deliverables that can have a traceable provenance and a quantifiable degree of confidence.

Finally, industrial robots provide a plausible solution to large-scale geodetic data acquisition, which is more scalable, repeatable, and safer, especially in areas where standard procedures are operationally or safety-limited and where the same tasks may need repeated execution. Nonetheless, the move towards the feasible idea of demonstrations to bridge the methodological discipline between robots and geodesy lies in ending the ordeal of integrating autonomous sensing with survey-grade rigor, uncertainty quantification, and the standard analysis. This integration will allow the geodetic acquisition with robots to transition into an enabling technology into a standard engineering practice that offers sustained spatial intelligence to current infrastructure and digital engineering systems.

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Conflicts of Interest

The authors declare no conflict of interest.

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