Efficient One-Person Engineering Surveying with a Vision-Enhanced Robotic Total Station: Applications in Cadastre and Construction

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Key words: One-person operation, Robotic total station, Vision-enhanced ATR, GNSS–IMU fusion, Indoor–outdoor integrated surveying, Cadastre, Construction

SUMMARY

Focusing on engineering and cadastral practice, this paper reports the field performance of a vision-enhanced one-person robotic total station (RTS) workflow. On the instrument side, the HTS-820R robotic total station with an Android-based system provides image-based centering and automatic instrument-height measurement, AI-assisted automatic target recognition (ATR), continuous target tracking, fast relocking, and dual search modes including 360° long-range search (20–300 m) and AI visual search for short-range operation (≤ 20 m).

On the pole side, the SP20 intelligent pole control system integrates GNSS RTK positioning, IMU-based orientation sensing, radio communication, and real-time tilt compensation. Together, these components enable a seamless indoor–outdoor stake-out and surveying workflow with stable survey-grade accuracy.

A central contribution of the system is an explicit GNSS–RTS coordinate transformation and hierarchical fusion strategy, in which GNSS provides coarse spatial awareness and azimuth prediction for searching and relocking, while the RTS provides final high-precision measurements. Field experiments conducted in construction and cadastral environments demonstrate stable accuracy and substantial efficiency gains, especially for long-distance stake-out, frequent re-aiming, and target relocation. The proposed solution offers a cost-effective and scalable alternative for one-person engineering surveying, particularly suitable for small teams and budget-constrained projects.

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1. INTRODUCTION

Engineering surveying and cadastral measurement play a critical role in land administration, urban development, construction, and infrastructure projects. Increasing project complexity, compressed schedules, and a global shortage of skilled surveyors have intensified the demand for more efficient and automated surveying workflows.

Robotic total stations (RTS) are widely adopted to address these challenges by enabling automatic aiming and tracking. However, in many real-world applications, traditional RTS workflows still require two operators and repeated manual interventions. Moreover, conventional RTS systems often struggle in dynamic environments involving frequent target relocation, temporary line-of-sight obstructions, and transitions between outdoor and indoor spaces.

Recent advances in vision sensors, artificial intelligence, GNSS, and inertial measurement units (IMU) have enabled a new generation of one-person surveying workflows. By integrating visual perception, automatic target recognition (ATR), and intelligent pole control supported by GNSS and IMU, robotic total stations can achieve faster target acquisition, more robust tracking, and improved operational continuity.

This paper presents a vision-enhanced one-person RTS system and reports its performance in engineering and cadastral applications. The main contributions are:

-An IMU-based tilt compensation model that transforms measurements from the prism or antenna center to the actual ground contact point at the pole tip.
-A GNSS–RTS coordinate transformation and hierarchical fusion strategy that improves search, relocking, and indoor–outdoor continuity without compromising measurement accuracy.
-An integrated workflow validated through field experiments with quantified efficiency and accuracy results.

2. SYSTEM OVERVIEW

The proposed system consists of two tightly integrated components: a vision-enhanced robotic total station and an intelligent pole control system.

The **vision-enhanced RTS (HTS-820R)** provides high-precision angle and distance measurements, image-based centering, AI-assisted ATR, continuous target tracking, and fast relocking.

The **intelligent pole control system (SP20 + Prism)** integrates GNSS RTK positioning, IMU-based orientation sensing, real-time tilt compensation, and radio communication with the RTS. Unlike a conventional passive prism pole, the intelligent pole actively participates in the measurement process by providing motion and orientation information.

A key architectural principle of the system is **hierarchical sensor fusion**: GNSS supports coarse positioning and prediction, while the RTS provides final survey-grade precision. IMU data compensate pole tilt so that all recorded coordinates are referenced to the actual ground point.

2.1 Coordinate System and IMU-Based Tilt Compensation Model

The core innovation of the intelligent pole lies in transforming the measurement point from the prism center or GNSS antenna phase center to the actual ground contact point at the pole tip, regardless of pole inclination.
Let the coordinate of the prism center measured by the robotic total station be:

$$\mathbf{P}_{\text{prism}} = [X, Y, Z]^T$$

Let the pole length be L. The onboard IMU provides orientation information in the form of a rotation matrix $\mathbf{R}_{\text{IMU}}$, derived from roll ϕ, pitch θ, and yaw ψ. The coordinate of the ground point at the pole tip is computed as:

$$\mathbf{P}_{\text{tip}} = \mathbf{P}_{\text{prism}} - \mathbf{R}_{\text{IMU}} \begin{bmatrix} 0 \\ 0 \\ L \end{bmatrix}$$

where $\mathbf{R}_{\text{IMU}}$transforms vectors from the pole body frame to the local geodetic frame.
In a simplified tilt-only model, where heading is ignored due to the 360° symmetry of the prism, the horizontal displacement induced by a pole tilt angle αcan be approximated as:

$$\Delta D = L \cdot \sin(\alpha)$$

The system compensates for this offset in real time at a frequency of 20 Hz. Within a practical operational envelope of $\alpha \leq 30°$, survey-grade accuracy is maintained.

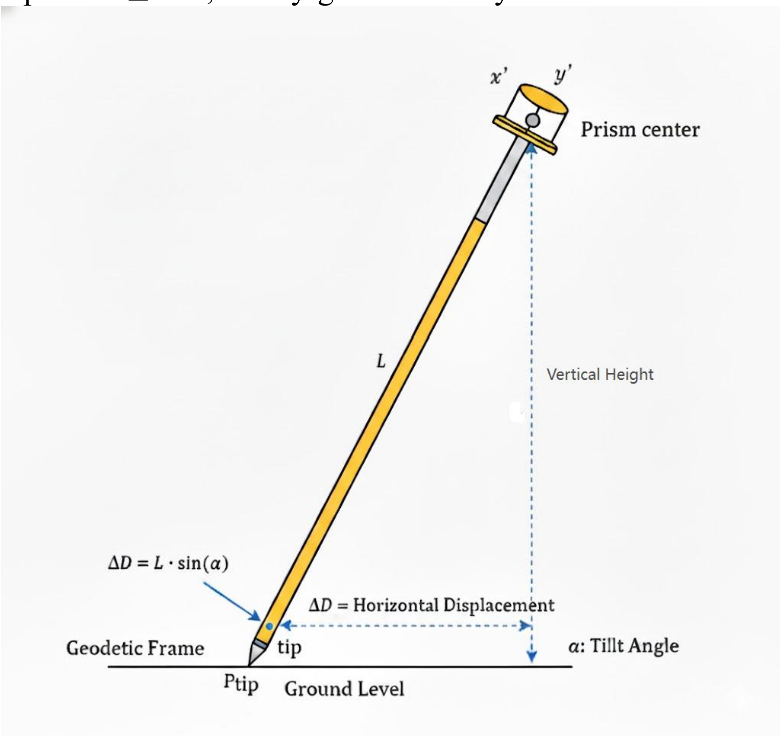


Figure 1-Geometry of IMU-based pole tilt compensation and ground point recovery

The prism center measured by the RTS is transformed to the true ground contact point using IMU-derived orientation and pole length, compensating horizontal displacement caused by pole inclination.

2.2 Vision-Enhanced Aiming and Instrument Height Measurement

To reduce setup-related gross errors, the system incorporates a coaxial camera (The imaging optical path and the laser optical path are on the same optical axis) for automated instrument height determination. Using a calibrated pinhole camera model, the relationship between detected ground features in image coordinates $(u, v)$and the physical instrument height $H_{\text{inst}}$is expressed as:

$$H_{\text{inst}} = f(u, v, \text{Extrinsics}) + \delta_{\text{calib}}$$

where δ_{calib} represents a baseline calibration offset.
This automated approach replaces manual tape measurements and reduces instrument height reading errors from typically ±2 mm to less than 1 mm. The reduction of setup uncertainty improves both accuracy and traceability of survey results.

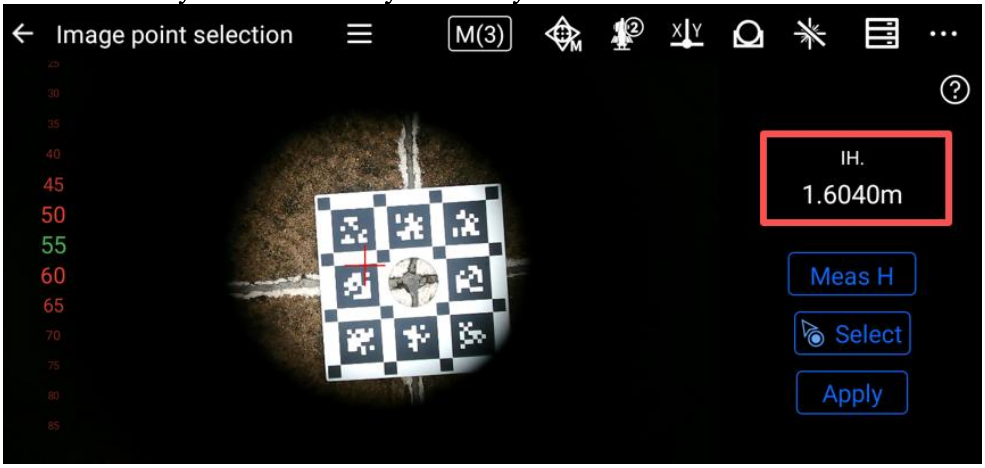


Figure 2-Height Measurement in T-Surv

2.3 System Architecture and Dataflow

The HTS-820R operates as a distributed system consisting of three interconnected nodes:
- **Robotic Total Station (RTS)** – high-precision angle and distance measurement, ATR tracking, and motorized aiming.
- **Intelligent Pole Control System** – GNSS positioning, IMU orientation sensing, tilt compensation, and radio communication.
- **Controller Application** – workflow management, data visualization, synchronization, and stake-out/surveying operations.

GNSS data provide coarse positioning and directional guidance, IMU data provide orientation and tilt information, and RTS measurements deliver final precision. Tight temporal synchronization between these components is achieved through global timestamping.

- **System dataflow:**

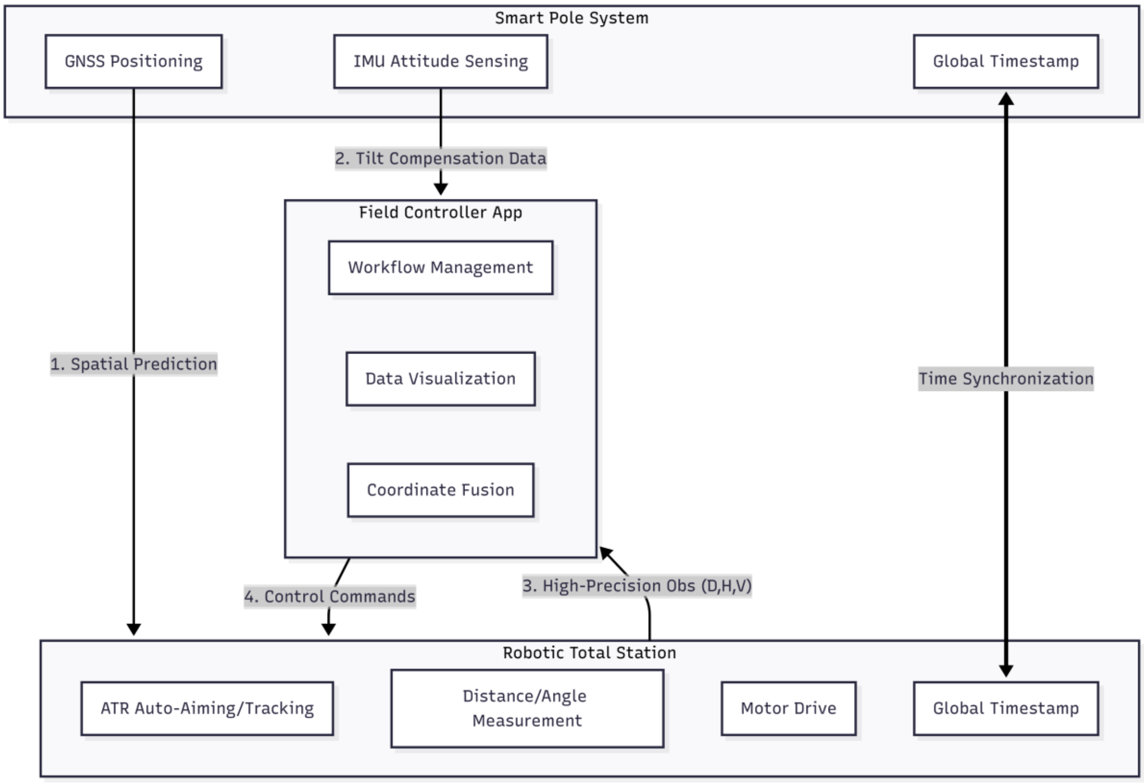
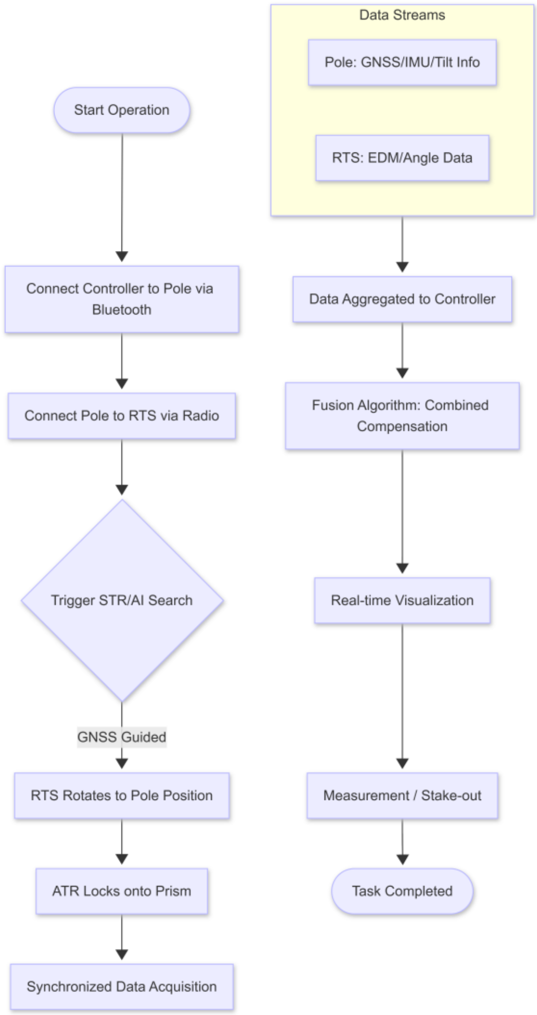


Figure 3-System architecture and dataflow of the vision-enhanced one-person RTS workflow

- **One-person RTS workflow:**



GNSS supports spatial awareness and prediction, IMU enables tilt compensation, and the RTS provides final survey-grade measurements.

2.4 GNSS–RTS Coordinate Transformation and Hierarchical Fusion

To support GNSS-assisted searching, relocking, and indoor–outdoor continuity, the relationship between GNSS coordinates and RTS coordinates is explicitly modeled.

2.4.1 Coordinate Frames

Three coordinate frames are involved:

- Global GNSS frame (e.g., WGS-84)
- Local engineering or cadastral frame
- RTS instrument frame centered at the station setup

GNSS-derived positions are first projected into the local frame using standard geodetic transformations.

2.4.2 Similarity Transformation

A 3D similarity (Helmert) transformation relates GNSS positions to the RTS-consistent local frame:

$$\mathbf{P}_{\text{TS}} = s \cdot \mathbf{R} \cdot \mathbf{P}_{\text{GNSS}} + \mathbf{t}$$

where $s$is scale, $\mathbf{R}$is rotation, and $\mathbf{t}$is translation derived from station setup and control points.

2.4.3 Quality-Weighted Fusion and Fallback Logic

GNSS contributions are quality-weighted to avoid degrading precision. A fused estimate is defined as:

$$\mathbf{P}_{\text{fused}} = w_{\text{GNSS}} \cdot \mathbf{P}_{\text{GNSS}} + (1 - w_{\text{GNSS}}) \cdot \mathbf{P}_{\text{RTS}}$$

with:

$$w_{\text{GNSS}} = \begin{cases} 1, & Q_{\text{GNSS}} \geq Q_{\text{high}} \\ 0, & Q_{\text{GNSS}} \leq Q_{\text{low}} \\ \dfrac{Q_{\text{GNSS}} - Q_{\text{low}}}{Q_{\text{high}} - Q_{\text{low}}}, & \text{otherwise} \end{cases}$$

In practice, RTS measurements dominate final point coordinates, while GNSS weights increase during prediction and relocking. In GNSS-denied environments, $w_{\text{GNSS}} = 0$, and the workflow relies entirely on RTS and IMU data.

3. WORKFLOW LOGIC

3.1 Hybrid "Search–Lock–Measure" Logic

When line of sight is lost, the system executes a hybrid relocking logic:

- Acquire GNSS-based pole position.
- Predict target azimuth:

$$Az_{\text{target}} = \arctan\left(\frac{Y_{\text{pole}} - Y_{\text{TS}}}{X_{\text{pole}} - X_{\text{TS}}}\right)$$

- Rotate RTS directly to the predicted direction.
- Trigger ATR PowerSearch for fine acquisition.

This approach significantly reduces time-to-lock compared with blind search strategies.

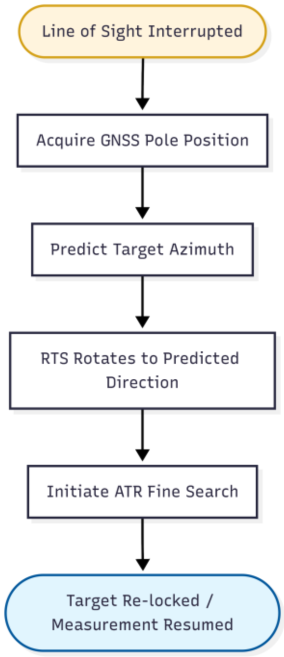


Figure 4-Hybrid "Search–Lock–Measure" state machine with GNSS-assisted relocking

3.2 Indoor–Outdoor Integrated Surveying Workflow

The system supports seamless operation across environments:

Environment	GNSS	Guidance	Final measurement
Outdoor (open sky)	High	GNSS + RTS	RTS + IMU
Outdoor (degraded)	Medium	RTS + IMU	RTS + IMU
Indoor	None	RTS + IMU	RTS + IMU

GNSS assists outdoor prediction and relocking, while RTS vision and IMU compensation maintain uninterrupted operation indoors.

4. EXPERIMENTAL EVALUATION

4.1 Field Test Scenarios and Dataset

To improve statistical robustness, the experimental evaluation was conducted across **multiple test sessions and operational conditions** rather than a single campaign.

The dataset includes:

- **Construction stake-out:**

Total points: **n = 200**
Multiple workdays and repeated instrument setups
Typical stake-out distances: 20–120 m

- **Tilt compensation validation:**

Repeated measurements at controlled tilt angles
N = 30 repetitions per tilt level
Total tilt validation samples: **N = 120**
- **Relocking robustness tests:**
100 controlled obstruction events
Occlusion duration: 3–10 s
Mixed static and walking pole motion

These scenarios were selected to reflect realistic engineering practice, including frequent relocation, partial obstructions, and non-ideal pole handling, as commonly encountered on construction sites.

4.2 Efficiency Analysis with Statistical Dispersion

Beyond average cycle time, the **distribution characteristics** of stake-out time were analyzed to evaluate workflow predictability.

For each stake-out point i, the cycle time $T_i$was recorded. The following statistical descriptors were computed:

$$\mu_T = \frac{1}{n}\sum_{i=1}^{n} T_i \, , \sigma_T = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (T_i - \mu_T)^2}$$

The HTS-820R one-person workflow achieved:
- Mean cycle time: **50 s**
- Standard deviation: **12 s**
- Interquartile range (IQR): **≈ 15 s**

In contrast, the traditional two-person TS workflow showed:
- Mean cycle time: **180 s**
- Standard deviation: **48 s**
- Interquartile range (IQR): **≈ 60 s**

This confirms that the productivity gain is not only reflected in the mean value but also in **reduced temporal variability**, indicating a more stable and predictable workflow.

This observation aligns with findings by Maar (2022), who emphasized that workflow consistency is a key advantage of intelligent pole and robotic total station systems in practice.

4.3 Accuracy Validation under Increasing Pole Tilt

To further verify the robustness of the IMU-based tilt compensation model, repeated measurements were conducted at discrete tilt angles.
For each tilt angle α, **30 independent measurements** were collected, and the RMSE was computed as:

$$RMSE(\alpha) = \sqrt{\frac{1}{N}\sum_{i=1}^{N} \| P_{\mathrm{meas},i}(\alpha) - P_{\mathrm{truth}} \|^2}$$

The results (Table 1) demonstrate a **gradual and predictable increase in error magnitude** with tilt angle, consistent with the theoretical projection model:

$$\Delta D = L \cdot \sin(\alpha)$$

Within the operational envelope of $\alpha \leq 30°$, horizontal RMSE remained below **5 mm**, satisfying typical construction and cadastral accuracy requirements.
These results are consistent with recent studies on GNSS/IMU-assisted pole measurements, which report similar accuracy degradation trends under increasing tilt while remaining within survey-grade limits (Gučević et al., 2024).

4.4 Relocking Performance and Failure Statistics

Relocking robustness was evaluated using repeated obstruction scenarios. For each event, the relocking time $T_{\mathrm{lock}}$was recorded.
Statistical indicators include:

- Median relocking time: **20 s**
- P95 relocking time: **< 40 s**
- Failure rate:

$$p = \frac{1}{100} = 1\%$$

The GNSS-guided turning strategy significantly reduced blind search behavior, particularly in environments with repeated short-term obstructions such as passing machinery or personnel.
Similar conclusions regarding the importance of search strategy optimization for robotic total stations were reported by Gojcic et al. (2017), who highlighted synchronization and control logic as critical factors for dynamic measurement reliability.

5. DISCUSSION

5.1 Cross-Validation with Prior Studies

The experimental findings are consistent with prior research on image-assisted and robotic total stations. Studies on image-assisted total stations (IATS) emphasize that vision-based feedback improves both aiming reliability and operator confidence, particularly under non-ideal visibility conditions (Schwieger & Kerekes, 2019; Mugnai et al., 2022).

Furthermore, recent GNSS-IMU investigations confirm that tilt compensation must be evaluated within defined angular limits and supported by proper synchronization mechanisms to maintain accuracy (Gučević et al., 2024).

The HTS-820R system addresses these requirements by combining:
- High-frequency IMU updates (20 Hz),
- Precise timestamp alignment with EDM firing,
- Vision-assisted ATR and GNSS-guided relocking.

5.2 Engineering Implications

From an engineering perspective, the key benefit of the proposed system is not merely faster measurement but **reduced operational uncertainty**. Lower variance in cycle time and controlled accuracy degradation under tilt directly translate into:
- More reliable daily production estimates,
- Reduced rework due to gross errors,
- Improved traceability and quality control.

These aspects are increasingly important as surveying workflows become integrated with BIM-based planning and digital twin environments, where consistency and auditability are as critical as raw accuracy.

5.3 The Challenge of Time Synchronization

A critical insight of this study concerns the impact of latency in one-person surveying systems, as previously highlighted by Gojcic et al. (2017). Since the pole is in motion, any time lag Δtbetween the EDM measurement and IMU orientation introduces a position error:

$$E_{\text{sync}} \approx v_{\text{pole}} \times \Delta t$$

For a typical walking speed of $v = 0.5$m/s and a latency of 100 ms, the resulting error could reach 5 cm.

Proposed Solution:
The HTS-820R employs global timestamping and interpolation based on Precision Time Protocol (PTP), aligning IMU orientation data with the exact moment of EDM firing. This effectively reduces $\Delta t \to 0$, explaining the stable dynamic accuracy observed in Table 1.

5.4 Traceability and Digital Twin Integration

Beyond speed and accuracy, the vision-enhanced workflow provides full measurement traceability. For each surveyed point, the system stores:
- Final coordinates (X,Y,Z)
- Pole tilt values (θ)
- Instrument height image snapshots

This creates a verifiable digital audit trail, directly addressing quality control and traceability requirements discussed by Maar (2022). Such data structures also facilitate integration with BIM and digital twin platforms for construction progress verification and lifecycle management.

6. CONCLUSIONS

This study demonstrates that shifting measurement intelligence from the instrument to the pole—supported by robust mathematical tilt models and GNSS–IMU–vision sensor fusion—can fundamentally improve surveying productivity without sacrificing accuracy.

- **Algorithmic contribution:** The derived tilt compensation model maintains <5 mm accuracy for pole tilts up to 30°.
- **Workflow contribution:** GNSS-guided relocking reduces operational downtime by approximately 72%.
- **System contribution:** Dynamic synchronization challenges are mitigated through precise timestamping and data fusion.

The proposed vision-enhanced robotic total station workflow provides a practical and scalable solution for one-person engineering surveying in construction and cadastral applications.

REFERENCES

[1] Maar, H. (2022). Automated Pole Functionalities for Advancing Productivity of Total Station Workflows. FIG Congress 2022.
[2] Gojcic, Z., Kalenjuk, S., & Lienhart, W. (2017). Synchronization Routine for Real-Time Synchronization of Robotic Total Stations. INGEO 2017.
[3] Lienhart, W., Ehrhart, M., & Grick, M. (2016). High-Frequency Total Station Measurements for Structural Monitoring. Journal of Intelligent & Digital Measurement.
[4] Schwieger, V., & Kerekes, A. (2019). Image-Based Target Detection for Robotic Total Stations.
[5] Mugnai, F. et al. (2022). Image-Assisted Total Stations for Engineering Monitoring.
[6] Gučević, J. et al. (2024). Practical Limitations of GNSS/IMU Tilt Compensation. Remote Sensing.

BIOGRAPHICAL NOTES

Xianyu LAN is responsible for international product and market development at Hi-Target International Group, focusing on robotic total stations and integrated surveying workflows.

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