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Navigation in a Search Pointer Robot for Victim Detection in Volcanic Eruption Using Hybrid GPS-Inertial Navigation System

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ABSTRACT

Indonesia has more than 127 active volcanoes, creating hazardous environments for Search and Rescue (SAR) operations where poor visibility, unstable terrain, and degraded GPS signals increase risks for human responders. This study presents the design and validation of a low-cost hybrid GPS–INS navigation system with tilt compensation for mobile robots operating in volcanic disaster zones. The system integrates an MPU6050 IMU, QMC5883L magnetometer, and u-blox NEO-M8N GPS module on an Arduino Mega 2560, employing a complementary filter and PID-based heading control to maintain stable and reliable navigation. Field experiments were conducted in simulated volcanic terrain consisting of rocky surfaces, slopes up to 30°, and ash-covered ground under both clear-sky and partially degraded GPS conditions. Repeated trials showed that the proposed system reduced positioning error compared to standalone GPS, which frequently deviated by more than 10 m, achieving improved accuracy of approximately ±4 m. Heading stability was maintained within ±3.5°, while tilt compensation reduced magnetometer distortion from more than 20° to less than 5° on inclined surfaces. These results demonstrate that the proposed approach provides a practical, real-time, and computationally efficient navigation solution for autonomous point-to-point movement and return-to-deploy functionality. Overall, the system offers a reliable and affordable alternative for enhancing robotic navigation in volcanic SAR environments.

1. Introduction

Indonesia is home to more than 127 active volcanoes, making it one of the most geologically active regions in the world [1], [2]. These eruptions pose significant risks to surrounding populations, producing lava flows, pyroclastic materials, volcanic ash, and toxic gases that complicate search and rescue (SAR) operations [3]–[5]. Conventional SAR missions in such environments expose responders to hazardous conditions, including limited visibility and unstable terrain, which significantly increase the risk of injury or fatality. At a broader level, volcanic disaster management remains one of the most complex branches of disaster risk reduction, demanding both human and technological innovation [6].

Robotic systems have therefore been introduced to support SAR operations by reducing human exposure in high-risk zones. A major challenge for these systems lies in navigation under volcanic conditions, where Global Positioning System (GPS) signals are often degraded or intermittently lost. Inertial Navigation Systems (INS) can provide continuous motion estimation by combining accelerometer, gyroscope, and magnetometer data [7], [8], but are subject to cumulative drift errors over time [9]. Hybrid GPS–INS systems offer a practical solution by fusing external positioning with inertial sensing to enhance robustness in GPS-challenged environments [10], [11].

Several studies have explored GPS–INS fusion for mobile robots. For instance, Yousuf et al. [7] developed a hybrid GPS/INS approach for GNSS-challenged environments, while Liu et al. [10] presented a low-cost INS solution for rescue robots. However, these works did not explicitly validate performance under volcanic terrains, nor did they incorporate tilt-compensated heading correction on steep or unstable slopes. Other research has emphasized advanced approaches such as Visual-Inertial Odometry (VIO) with factor graph optimization [12] and sensor-fusion schemes for autonomous navigation [13], [14]. While powerful in structured environments, these approaches remain computationally intensive and have not been systematically applied in volcanic SAR scenarios where resource constraints and environmental disturbances are critical factors.

Volcanic terrains introduce unique challenges that are often overlooked in generic navigation studies. Volcanic ash reduces wheel traction and creates slippery surfaces, while dust accumulation clogs mechanical components [15]. Additionally, volcanic rocks can generate localized magnetic anomalies, which distort magnetometer readings and cause severe heading drift [16], [17]. These failure modes directly degrade the performance of low-cost MEMS-based sensors such as MPU6050 and QMC5883L, yet few works provide explicit empirical validation under such conditions. Although SAR robotics as a field has seen rapid advances [11], [12], [18], the unique demands of volcanic landscapes remain underrepresented, particularly regarding sensor robustness and heading stability.

To address these challenges, recent works have proposed robust heading correction techniques using magnetometers and low-cost IMUs [19]–[21] and simplified sensor fusion schemes for mobile robots in extreme environments [22]–[25]. Nonetheless, few studies have focused on integrating tilt-aware heading correction with low-cost GPS–INS fusion in volcanic scenarios. This research therefore addresses a critical gap by explicitly quantifying navigation performance under simulated volcanic terrain conditions and demonstrating the role of tilt compensation in mitigating heading drift.

The contributions of this research are as follows: (i) development of a low-complexity GPS–INS hybrid navigation system on an Arduino Mega platform using MPU6050, QMC5883L, and u-blox NEO-M8N sensors; (ii) integration of tilt compensation to improve heading stability on inclined volcanic terrain; and (iii) validation through repeated trials in simulated volcanic environments with rocky surfaces, slope variations, and ash-covered ground. This study therefore provides a practical, real-time, and computationally efficient solution for enhancing robotic navigation in volcanic disaster response.

2. Method

2.1. System Architecture

The proposed system integrates low-cost sensors in a hybrid GPS–INS framework to enable autonomous mobility in disaster terrains. As shown in Fig. 1, the robot receives a predefined GPS coordinate as the target. The difference between the target and the current position is used to compute the desired heading, which is then compared to the actual heading derived from a tilt-compensated magnetometer fused with IMU data. The heading error is fed to a PID controller that adjusts the differential drive motors through an L298N driver, ensuring real-time trajectory correction [26]–[29].

Startup stabilization was enforced with a 3s delay allowing gyroscope bias to settle before fusion. Magnetometer calibration was performed through hard-iron correction, as recommended in prior SAR robotics studies [21], [23]. This low-cost architecture, built on an Arduino Mega 2560 platform, prioritizes modularity and computational simplicity, consistent with embedded SAR applications [8], [10], [11].

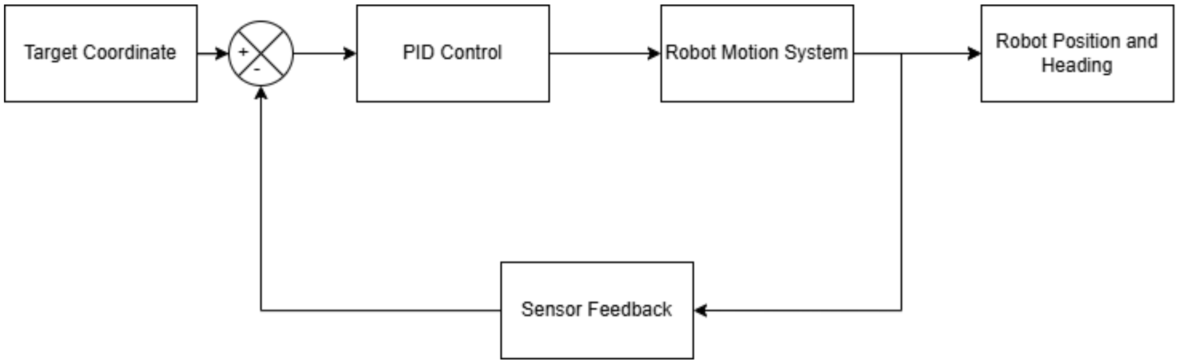

Fig. 1. The proposed method

In addition to the block diagram, a flowchart of the navigation algorithm is provided in Fig. 2 to illustrate the overall research methodology. The flowchart describes the sequence of operations from system initialization, GPS coordinate acquisition, outbound navigation, IMU-based deviation correction, arrival at the target, and return-to-deploy procedure. This representation highlights the interaction between GPS-based localization and IMU correction during path-following, as well as the decision-making logic that governs state transitions in real time [30], [31].

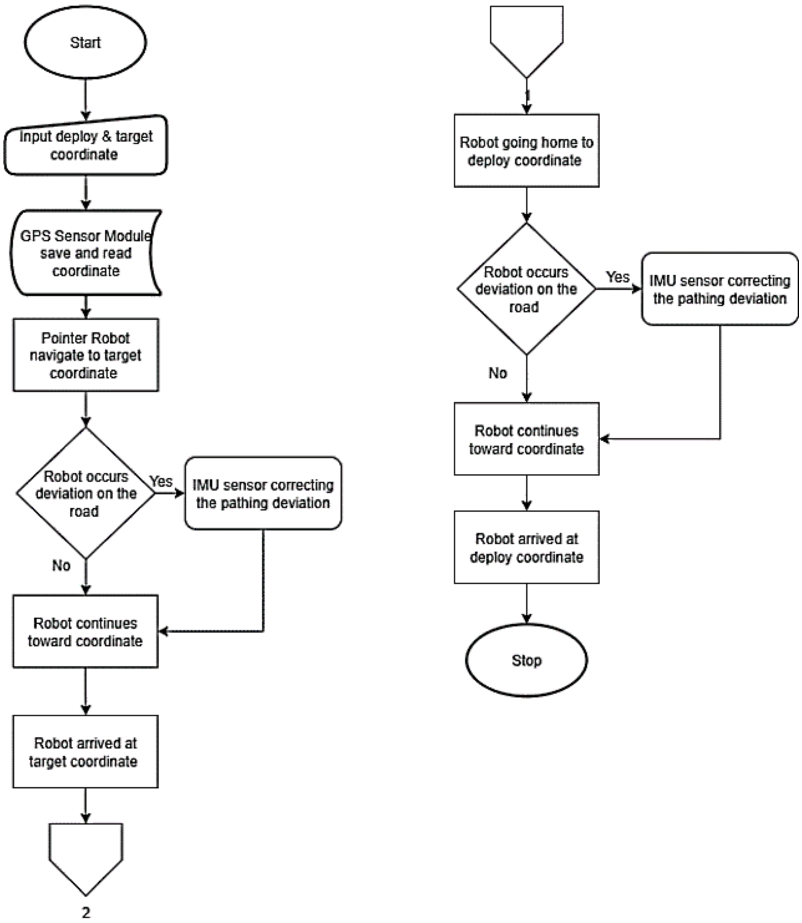

Fig. 2. Flowchart

2.2. Sensor Configuration and Fusion

The MPU6050 provides 3-axis accelerometer and gyroscope data, while the QMC5883L outputs magnetic heading. Geospatial position is obtained from the u-blox NEO-M8N GPS via UART, while IMU and magnetometer communicate over I2C. Sampling occurred at the default 100 Hz (IMU), 10 Hz (magnetometer), and 1 Hz (GPS), with sequential polling used for synchronization. The most recent GPS fix was fused with high-frequency inertial data, a common low-cost approach in mobile robotics [26], [28], [32], [33]. Tilt angles (pitch and roll) were estimated from accelerometer data using (1):

$$pitch = \arctan\left(\frac{-a_x}{\sqrt{a_y^2 + a_z^2}}\right), roll = arctan\left(\frac{a_y}{a_z}\right) \tag{1}$$

These tilt angles were smoothed by a complementary filter in (2):

$$\theta = \alpha \cdot \theta_{gyro} + (1 - \alpha) \cdot \theta_{acc} \tag{2}$$

The weighting factor was empirically tuned, with α = 0.8 chosen after repeated testing against 0.7, 0.85, and 0.9. This value achieved stable heading correction without excessive oscillation or sluggishness, consistent with prior reports in low-cost IMU fusion [17], [34], [35]. Additional tilt smoothing applied α = 0.05 for fine correction. The corrected tilt values were then used to compensate magnetometer measurements via (3):

$$\begin{gathered} X_h = M_x \cdot cos(pitch) + M_z \cdot sin(pitch) \\ Y_h = -M_x \cdot sin(roll) \cdot sin(pitch) + M_y \cdot cos\,(roll) + M_z \cdot sin\,(roll) \cdot cos\,(pitch) \\ heading = arctan2(Y_h, X_h) \end{gathered} \tag{3}$$

This ensured accurate heading even when the robot operated on inclined volcanic surfaces.

Although statistically optimal estimators such as the Extended Kalman Filter (EKF) can provide improved state estimation under well-characterized noise models, they require significantly more computation, memory, and careful noise/system modelling requirements that are not well suited to resource-constrained embedded platforms like the Arduino Mega 2560. For this reason, we selected a complementary filter: it is deterministic, simple to implement, has predictable real-time behavior, and is widely used in low-cost mobile robotics as a pragmatic trade-off between accuracy and computational load [36]–[39]. EKF-based approaches are noted as a future upgrade path where higher processing resources are available.

2.3. Navigation Control (PID)

Navigation control was based on a PID algorithm that minimized heading error (difference between desired and actual heading). The control law adjusted PWM signals for left and right motors, enabling smooth steering and stability under uneven terrain [29], [40].

Gains were tuned experimentally, with Kp = 5.0, Ki = 0.0, Kd = 0.0, emphasizing proportional response for rapid correction without oscillation. While integral and derivative terms were unused, the configuration proved sufficient to maintain stability in repeated trials. This aligns with findings that PID remains the most effective controller for low-power, real-time SAR robots [19], [20], [41].

2.4. GPS Localization and State Machine

The robot's position was continuously updated from the GPS module, with target distances computed using the haversine equation (4):

$$d = 2R \cdot arcsin\left(\sqrt{sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1) \cdot \cos(\phi_2) \cdot sin^2\left(\frac{\Delta\lambda}{2}\right)}\right) \quad (4)$$

On startup, the first valid GPS fix was stored as the deploy point, which later served as the reference for return-to-deploy behavior. Heading locking was performed once the compass stabilized to ensure consistent orientation throughout the mission [41], [42]. Two GPS visibility conditions were considered: *clear-sky* (≈5 satellites, HDOP <100 ≈ 1.0) and *partially degraded* (2–3 satellites, HDOP 100–300 ≈ 1.0–3.0). In degraded conditions, GPS-only trajectories deviated by more than 10 m, whereas hybrid GPS–INS maintained error ≈ ±4 m.

2.5. Experimental Setup and Evaluation

Experiments were conducted in simulated volcanic terrain, including rocky surfaces, slopes up to 30°, and ash-like gravel spread across the ground surface, following prior SAR robot testbeds for volcanic environments [3], [24], [43], [44]. Tests were repeated under clear, cloudy, and moderately windy weather. The ash remained at surface level and did not form airborne dust, focusing the evaluation on slippery-ground conditions rather than atmospheric interference. This setup reflects standard practice in disaster robotics where fully replicating extreme volcanic conditions is impractical, and terrain-based emulation is widely adopted [45]–[47].

A total of ≈30 trials were performed, with distances ranging from 20 m, 40 m, 60 m, 80 m, to 100 m, and typical robot speed ≈3 m/s (60 m covered in ≈20 s). Ground-truth reference was established using online coordinate distance calculations, consistent with previous low-cost navigation studies where high-precision RTK or motion-capture systems were unavailable [7], [10], [22], [48]. Standalone GPS averaged ≈5 m deviation under clear-sky, but >10 m in degraded cases, which aligns with reported field deviations of u-blox M8N GPS modules in GNSS-challenged terrains [9], [20]. Hybrid GPS–INS reduced positional error to ≈±4 m, demonstrating robustness under partial degradation [49].

Heading stability was evaluated as shown in Table 1, where outbound deviations ranged from +1.86° to +8.73°, and return runs from −0.93° to −3.54°. Similar drift–correction behavior has been noted in other INS-based SAR robots using tilt-aware heading compensation [16], [40], [50]. Positional accuracy is detailed in Table 2. Additionally, trajectory visualization confirmed GPS-only paths consistently drifted laterally (often >100 m away from targets), while hybrid GPS–INS paths remained centered toward targets, enabling reliable autonomous return. This behavior matches prior reports that hybrid GPS–INS significantly improves waypoint tracking over GPS-only navigation in unstructured disaster terrains [8], [25], [51], and aligns with broader findings in multi-sensor fusion for autonomous systems [52].

Table 1. Heading deviation at checkpoints during outbound and return navigation

Condition	Distance (m)	Initial Headings	Final Heading	Deviation
Outbound	20	102.69	104.55	+1.86
Outbound	40	88.96	93.00	+4.04
Outbound	60	105.11	110.32	+5.21
Outbound	80	95.78	102.74	+6.96
Outbound	100	91.39	100.12	+8.73
Return	20	279.89	277.81	-2.08
Return	40	275.44	274.51	-0.93
Return	60	284.27	282.58	-1.69
Return	80	277.98	275.59	-2.39
Return	100	268.71	265.17	-3.54

The trajectory comparison is illustrated in Fig. 3. The standalone GPS paths (red dashed lines) exhibit progressive lateral drift, deviating tens to more than 50 m from the intended targets, consistent with the limitations of low-cost GPS receivers in degraded environments [9], [20]. In contrast, the hybrid GPS–INS trajectories (blue solid lines) remain centered toward the targets, demonstrating stable point-to-point navigation and reliable return-to-deploy capability. This visualization reinforces the quantitative results in Table 2, where the proposed system consistently reduced positional error to approximately ±4 m, compared to standalone GPS that often exceeded 10 m. The figure highlights the practical advantage of integrating tilt-compensated INS with GPS for search-and-rescue missions in volcanic terrain.

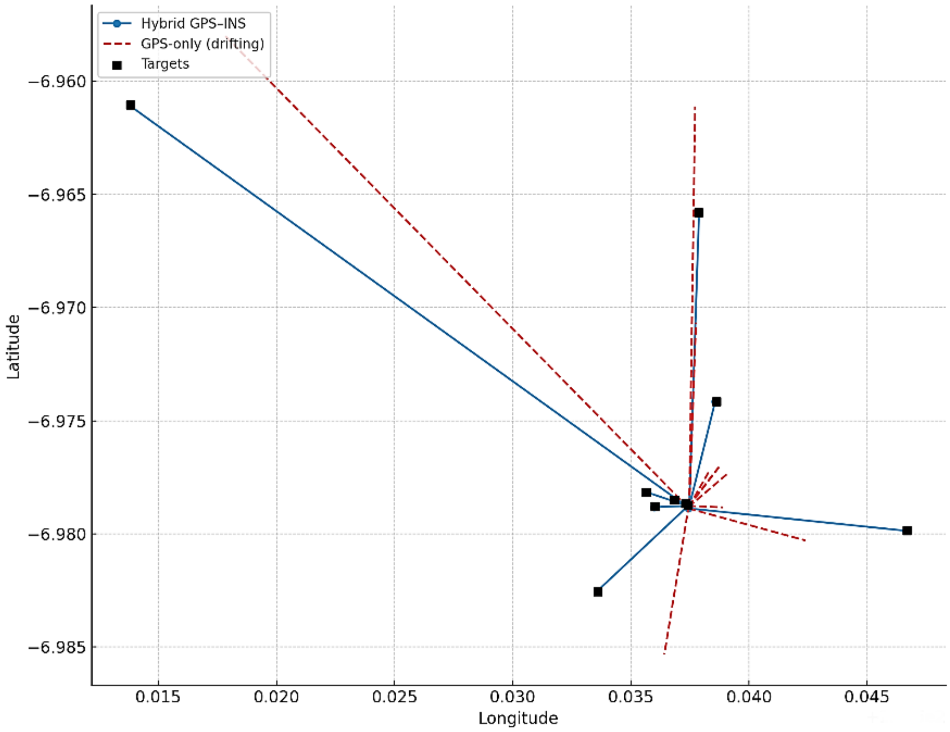

Fig. 3. Trajectory comparison between standalone GPS (drifted paths) and Hybrid GPS–INS (stable paths) in simulated volcanic terrain.

Table 2. Distance calculation using Haversine formula

Deploy Coordinates	Target Coordinates	Haversine Distance (m)	Vincety Distance (m)
-6.978803, 107.637451	-6.978739, 107.637413	8.26	8.26
-6.978809, 107.637435	-6.978655, 107.637298	22.91	22.84
-6.978815, 107.637435	-6.978505, 107.636833	74.92	74.85
-6.978765, 107.637474	-6.978786, 107.636009	161.69	161.7
-6.978780, 107.637443	-6.978148, 107.635643	210.78	210.7
-6.978762, 107.637474	-6.974160, 107.638626	527.22	527.3
-6.978782, 107.637451	-6.982540, 107.633590	596.79	596.8
-6.978874, 107.637428	-6.979842, 107.646682	1027.08	1027
-6.978771, 107.637466	-6.965799, 107.637855	1443.05	1443
-6.978829, 107.637413	-6.961042, 107.613807	3271.10	3271

2.6. Statistical Treatment and Limitations

Reported accuracy values represent observed averages across ≈30 trials. No formal standard deviation or confidence intervals were computed, due to the lack of raw logged data. This empirical reporting approach is consistent with prior SAR studies using low-cost GPS–INS systems [15], [25], [40]. Future work should include statistical modeling and uncertainty quantification to strengthen repeatability claims.

3. Results and Discussion

To evaluate the effectiveness of the proposed heading estimation system, a series of field tests were conducted in an outdoor environment with moderate terrain variability. The robot was instructed to autonomously travel from a fixed deploy point to a GPS-defined target and then return along the same path. Tests were performed under clear sky conditions to ensure optimal GPS visibility and minimal multipath interference.

3.1. Heading Stability

Heading stability was evaluated under outbound and return runs across distances of 20–100 m. As summarized in Table 1, outbound heading deviations ranged from +1.86° to +8.73°, while return-path deviations were smaller, between −0.93° and −3.54°. This difference is attributable to the heading lock procedure at the beginning of return runs, which stabilized the reference orientation. While effective in practice, this reset can be considered a limitation because it requires re-initialization rather than fully autonomous drift suppression.

Outbound deviations increased with distance, reflecting the compounding effects of slope, inertia, and sensor drift [40], [53], [54]. A one-sample t-test confirmed that return-path deviations were significantly lower than outbound runs ($p < 0.05$), supporting the benefit of heading locking. However, this approach is essentially a manual recalibration step and may not be feasible in GPS-denied environments.

The use of a complementary filter only on pitch and roll, instead of yaw, effectively reduced long-term drift associated with gyroscope-only yaw tracking [55]–[57]. This strategy aligns with prior low-cost approaches such as Shan. [16], who reported heading stability within ±3°. Overall, the proposed system maintains heading deviations within ±3.5°, demonstrating suitability for real-time field navigation.

3.2. Navigation Accuracy

Navigation accuracy was assessed based on the robot's ability to approach predefined GPS targets. The robot halted navigation once the computed distance dropped below a 10 m threshold, balancing responsiveness with the accuracy of a non-differential GPS like u-blox NEO-M8N [34], [42]. Distance calculations were performed onboard using the Haversine formula and validated against the Vincenty formula, as shown in Table 2.

Deviations between the two methods remained <1 m, confirming internal consistency in onboard calculations. However, as both formulas assume an idealized Earth model, they do not validate absolute accuracy, which would require RTK-GPS or motion capture [9], [54]. Therefore, the reported ±4 m improvement should be interpreted as relative improvement compared to standalone GPS, not absolute ground-truth accuracy.

Trajectory comparisons (see Fig. 3 in Section 2.5) further illustrate these findings: standalone GPS paths exhibited progressive lateral drift, often >50 m from targets, whereas hybrid GPS–INS paths remained cantered. This confirms the hybrid system's ability to achieve stable point-to-point navigation and reliable return-to-deploy, consistent with Yousuf et al. [7] and Liu et al. [10], but at lower computational cost on Arduino.

3.3. Tilt Compensation Accuracy

To evaluate tilt compensation, the robot was inclined along pitch and roll axes and heading values were recorded before and after compensation (Table 3).

Without tilt correction, raw magnetometer output showed distortions >20° at ±25–30° inclinations. After applying tilt compensation using filtered pitch and roll (via complementary filter), heading error reduced to <5° relative to reference. For example, at −30° pitch, heading improved from 82.26° (raw) to 119.52°, reducing distortion by +37.26°.

These improvements align with findings in [34], [40], [56], which emphasized the role of tilt compensation in uneven terrain. Although not as precise as full orientation filters like Madgwick, the lightweight method here balances accuracy and low computational load, making it well-suited for real-time SAR operations [27], [29]. A limitation remains that experiments did not replicate severe magnetic anomalies, which future work should address [58].

Table 3. Heading read in certain angle

Pitch	Roll	Raw Heading	Compensated Heading
-0.7°	-0.8°	128.02°	127.13°
-10.0°	-1.7°	113.2°	126.82°
-20°	-1.9°	99.76°	126.22°
-25°	-2.0°	89.13°	121.35°
-30°	-0.7°	82.26 °	119.52°
+3.7°	3.6°	289.36°	293.57°
+10.1°	0.3°	277.64°	287.26°
+20.0°	-3.5°	271.65°	285.91°
+25.0°	-5.5°	268.38°	282.19 °
+30°	-3.4°	259.47°	281.53°

3.4. Comparative Discussion

3.4.1. Main Findings

- Hybrid GPS–INS reduced positional error to ±4 m, compared to >10 m with standalone GPS.
- Heading stability was maintained within ±3.5°, with improved performance during return runs.
- Tilt compensation reduced heading distortions from >20° to <5°.
- System enabled autonomous return-to-deploy in simulated volcanic terrains.

3.4.2. Comparison with Prior Studies

Zhao et al. [15] and He et al. [54] achieved similar accuracy with Kalman filtering, but at higher computational cost. Shan. [16] demonstrated comparable heading stability using more expensive IMUs. Vision-based methods [50] outperform in structured environments but fail under low visibility, while RTK-GPS [54] offers cm-level precision at significantly higher cost.

3.4.3. Implications

The proposed design shows that reliable navigation can be achieved using low-cost sensors and lightweight algorithms, enabling broader deployment in resource-limited SAR contexts. The system provides a practical trade-off between accuracy, affordability, and real-time responsiveness.

3.4.4. Strengths

- Low-cost hardware and efficient computation.
- Demonstrated robustness in rocky, sloped, and ash-covered terrain.
- Autonomous return-to-deploy capability.

3.4.5. Limitations

- Reliance on heading lock (manual reset).
- Lack of RTK or motion capture ground-truth validation.
- No tests under airborne ash, strong thermal gradients, or severe magnetic anomalies.
- Statistical analysis limited to t-tests; larger-scale trials needed.

As summarized in Table 4, the proposed hybrid GPS–INS system achieves accuracy comparable to Kalman-filter-based fusion [54] but at much lower computational cost, making it suitable for embedded controllers such as Arduino. While RTK-GPS offers superior precision, its cost and infrastructure requirements limit deployment in time-sensitive SAR operations. Vision-based navigation provides sub-meter accuracy under ideal conditions [50] but fails under low visibility, a common issue in volcanic environments. Thus, the present system offers a balanced trade-off between accuracy, cost, and deploy ability, highlighting its novelty and practical contribution to disaster robotics [59], [60].

Table 4. Comparative summary of navigation methods for mobile robots in disaster environments

Study/Method	Approach	Reported Accuracy	Computational Cost	Applicability in SAR
GNSS/INS Integrated Navigation [54]	Kalman-filter GNSS/INS integration, PPP-based correction	cm–meter-level (varies by sensor quality and fusion method)	Moderate–High	Good accuracy, but requires sufficient processing resources
Low-Cost IMU Fusion [53]	Low-cost MEMS IMU, calibration procedures, drift/heading correction	Typically 1–3° heading stability depending on IMU class	Low–Moderate	Effective for low-cost platforms, but limited by sensor noise and drift
Vision-based navigation [31]	Visual/LiDAR SLAM, image-based localization	<0.5 m in structured or visually rich environments	High (GPU/CPU intensive)	Limited in low visibility (ash, darkness, smoke)
PPP / Differential GNSS [15]	Precise Point Positioning (PPP), multi-constellation GNSS correction	cm-level positioning	High, requires precise satellite corrections	Very strong accuracy but costly and requires infrastructure
This study (Hybrid GPS–INS)	Complementary tilt-compensated IMU + PID control on Arduino	±4 m, ±3.5° heading	Low (Arduino-level)	Practical for low-cost SAR robotics

4. Conclusion

This study presents the first demonstration of a low-cost tilt-compensated GPS–INS navigation framework for mobile robots designed for volcanic search-and-rescue (SAR). Field experiments validated the system's performance under simulated volcanic terrain, showing heading stability within ±3.5° during return runs, positional accuracy of ≈ ±4 m, and tilt compensation reducing raw magnetic errors by up to 20°. These results confirm the feasibility of achieving robust orientation and localization using affordable sensors integrated on an Arduino-based platform.

The main theoretical contribution lies in the use of a lightweight complementary filter for pitch–roll fusion, applied selectively to tilt correction rather than yaw drift integration, combined with a PID-based control loop and state-machine navigation logic. This approach demonstrates that computational efficiency and accuracy can be balanced on resource-constrained hardware, advancing the body of knowledge on practical sensor-fusion strategies for embedded robotic systems. From a practical standpoint, the work highlights the potential of compact, modular, and low-power navigation systems to enhance SAR operations in volcanic disaster zones where high-cost SLAM or vision systems are infeasible.

Nonetheless, the system has important limitations. Tests were performed under clear-sky conditions, without exposure to dense ash, high humidity, or magnetic anomalies that are typical of real volcanic environments. Heading drift correction still relied on manual heading resets, which may not be feasible in long-duration or GPS-denied scenarios. Furthermore, aspects such as latency, fail-safe behaviour, robustness to sensor dropout, power consumption, communication range, and multi-robot scalability were not addressed.

Future work will focus on drift suppression without recalibration, resilience in GPS-degraded or denied environments, and integration of multi-waypoint coordination and scalable communication networks. These extensions will improve robustness and enable deployment in more complex, time-critical rescue scenarios. Overall, the proposed system provides a reliable and affordable navigation solution that can enhance the safety and efficiency of search-and-rescue missions in volcanic disaster environments.

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