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Optimization of Tactical Operations for UAVS And Ground Robotic Complexes in Engineering Reconnaissance Within Desert Environments

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Abstract: This paper analyzes the specifics of conducting engineering reconnaissance operations using heterogeneous groups composed of Unmanned Aerial Vehicles (UAVs) and ground robotic complexes (UGVs) in arid landscapes. The research is driven by significant operational barriers faced by isolated autonomous platforms in desert environments: thermal degradation of sensor performance and mobility instability on loose soils, which substantially increase the risk of overlooking explosive hazards.
The study substantiates a search optimization concept based on the synthesis of multi-channel remote sensing data and local UGV sensor detection within a “leader-follower” framework. Through computational modeling, it is demonstrated that such integration reduces the time required for reconnaissance of a designated area by 30%, while simultaneously increasing target identification accuracy by 18% under conditions of thermal haze and high dust concentration. The proposed algorithms can be integrated into the software environment of engineering unit command systems and utilized in the training of specialist operators.

Keywords: Engineering reconnaissance, robotic systems (UGV), unmanned aerial vehicles (UAV), Manned-Unmanned Teaming (MUM-T), arid regions, data fusion, autonomous navigation, mine detection, heterogeneous robotic teams.

INTRODUCTION:

The assurance of territorial security and the protection of critical infrastructure facilities within the Central Asian region currently necessitate a fundamental modernization of engineering reconnaissance methodologies [1].

Under the conditions of vast desert and semi-desert zones, traditional methods for detecting explosive hazards by means of personnel deployment are becoming unjustifiably hazardous and demonstrate insufficient operational efficiency [2]. The transformation in the nature of modern armed conflicts — characterized by the systemic employment of remote minelaying systems and precision-guided “smart” munitions — dictates an imperative transition toward fully autonomous monitoring systems [3].

The operation of unmanned ground vehicles (UGVs) in specific arid environments presents particular challenges. Extreme temperature regimes, often exceeding the 45 – 50°C threshold, cause severe signal degradation in optoelectronic systems [4]. The resulting thermal haze and temperature inversions generate ghost images and “noise” on thermal imaging sensors, which significantly complicates object identification based on thermal signatures [5]. Furthermore, fine-grained dust and the instability of sandy soils not only reduce platform mobility but also introduce substantial errors into the performance of laser rangefinders and LiDAR systems [6]. Under such conditions, an individual robot encounters so-called “sensory starvation”, where sensor accuracy drops below a critical level, posing a threat of failing to

detect concealed engineering obstacles [7].

An analysis of global technological trends, including the operational experience of platforms such as Centaur (FLIR) or the "Uran" series systems, indicates a definitive shift toward the MUM-T (Manned-Unmanned Teaming) concept [8]. This approach implies the creation of a unified ecosystem where a human operator coordinates the actions of a heterogeneous robotic swarm [9]. Within the framework of engineering reconnaissance, this is implemented through a hierarchical link: the aerial segment (UAV) acts as a "top-tier sensor," generating a comprehensive threat map, while the ground segment (UGV) performs contact-based or ground-penetrating radar (GPR) verification at designated points [10].

However, despite the advancements in Manned-Unmanned Teaming

(MUM-T), most existing sensor fusion algorithms are optimized for temperate climates or urban environments. The issues of adaptive robotic interaction under extreme temperatures and low atmospheric visibility (dust storms) remain largely under-researched [11]. There is a significant scientific gap in the development of self-organizing reconnaissance routes capable of dynamic reconfiguration in response to shifting environmental conditions [12]. This paper aims to bridge this gap by proposing a mathematically grounded methodology for optimizing

UAV-UGV interaction, specifically adapted to the harsh physical parameters of desert terrain [13].

METHODS

System Configuration and Simulation Model Parameters

The objective of this research phase was to develop a digital twin of the reconnaissance process that incorporates the specific environmental interference typical of arid zones.

The baseline architecture utilizes a heterogeneous multi-agent system consisting of two platform types:

Aerial Segment: A multi-rotor UAV (Unmanned Aerial Vehicle) serving as a high-level detector. Its primary function is rapid wide-area screening and the identification of zones exhibiting anomalous thermal and visual signatures [14].

Ground Segment: An engineering reconnaissance UGV (Unmanned Ground Vehicle) equipped with ground-penetrating radar (GPR) and a high-sensitivity magnetic sensor. Its role involves the physical verification of objects at the specific coordinates designated by the aerial segment [15].

To ensure the most accurate reproduction of desert conditions, the following environmental variables were integrated into the model:

Surface Geometry: Complex-structured sand embankments with a looseness coefficient affecting the UGV's tractive effort.

Thermal Background: A temperature range of +40°C to +55°C, simulating peak daytime loads that induce sensor thermal drift.

Atmospheric Optical Density: A dust extinction coefficient of $\alpha=0.25$, simulating a suspension of fine particles that reduces the operational range of LiDAR sensors.

The primary performance specifications of the technical systems employed are summarized in Table 1.

Table 1. Technical Specifications of the Aerial and Ground Segments

Characteristic	Aerial Segment (UAV)	Ground Segment (UGV)
Instrumentation	IR Camera / Optical Zoom	Ground-Penetrating Radar (GPR) / Magnetometer
Operational Altitude / Speed	15–30 m (Altitude)	1.5–2.0 m/s (Cruising Speed)
Endurance	Up to 60 min	Up to 6 hours

Multilevel Data Fusion Algorithm

The proposed methodology is based on the principle of adaptive control, divided into two logical stages [16]:

Stage I: Probabilistic Map Generation

The UAV performs a scanning operation, calculating the probability of object detection P_{air} for each discrete terrain element *(x, y)*. Unlike standard models, we utilize adaptive weighting coefficients *w*, which are dynamically adjusted according to the real-time dust concentration levels and thermal radiation intensity:

$$Pair(x, y) = w1 \cdot Sth + w2 \cdot Sopt$$

Where S_{th} and S_{opt} are the normalized indices of thermal and visual contrast, respectively.

Stage II: Verification and Route Optimization

Target coordinates are transmitted to the UGV's onboard computer. Instead of a continuous lawnmower (zigzag) scan of the terrain, the ground robot constructs a route passing through points with the highest P_{air} values. The final decision regarding the object's classification is made based on Bayesian filtering, which fuses a priori aerial data with signals from contact-based sensors [17]:

$$P(H|S) = \frac{P(S|H) \cdot P\ air}{P(S)}$$

Where P(H) is the a priori probability derived from the UAV, and P(S|H) represents the sensor signal reliability of the UGV. An object is classified as a "critical threat" once the probability threshold of P > 0.9 is reached.

The practical implementation of the described mathematical framework enables the system to flexibly redistribute its reconnaissance resources. This allows the ground platform to concentrate its efforts exclusively on terrain segments with a confirmed probability of object detection, thereby eliminating the inefficient expenditure of time on surveying vacant areas.

RESULTS

This block summarizes the results of a computational experiment simulating the engineering reconnaissance process of a test site with an area of 2500 m² (a 50 × 50 m square). The simulation was conducted under conditions imitating a sandy surface during peak solar activity (air temperature +45°C). The effectiveness of the proposed method was evaluated in comparison with a traditional protocol involving the autonomous functioning of the robotic complex without external support from a UAV.**Time Expenditure and Performance Analysis**

The key efficiency criterion was the time variable T required to complete a full check of the site. In the baseline scenario, the robotic complex performed continuous systematic scanning (a "snake" trajectory) at a stable speed of 0.5 m/s. In the developed model, the ground platform moved in an accelerated mode (1.5 m/s) along a vector defined by the aerial echelon, slowing down to 0.2 m/s only directly within object verification zones.

Comparative data (Table 2) confirm the advantage of the integrated approach.

Table 2. Dynamics of time efficiency indicators

Simulation Scenario	Average Operation Time (min)	Relative Time Reduction
Baseline (isolated RTC)	42.5	-
Integrated (UAV + RTC)	29.8	30%

The application of multisensor data fusion has enabled a significant acceleration of operations [18] on various terrain types, as clearly demonstrated in Fig. 1.

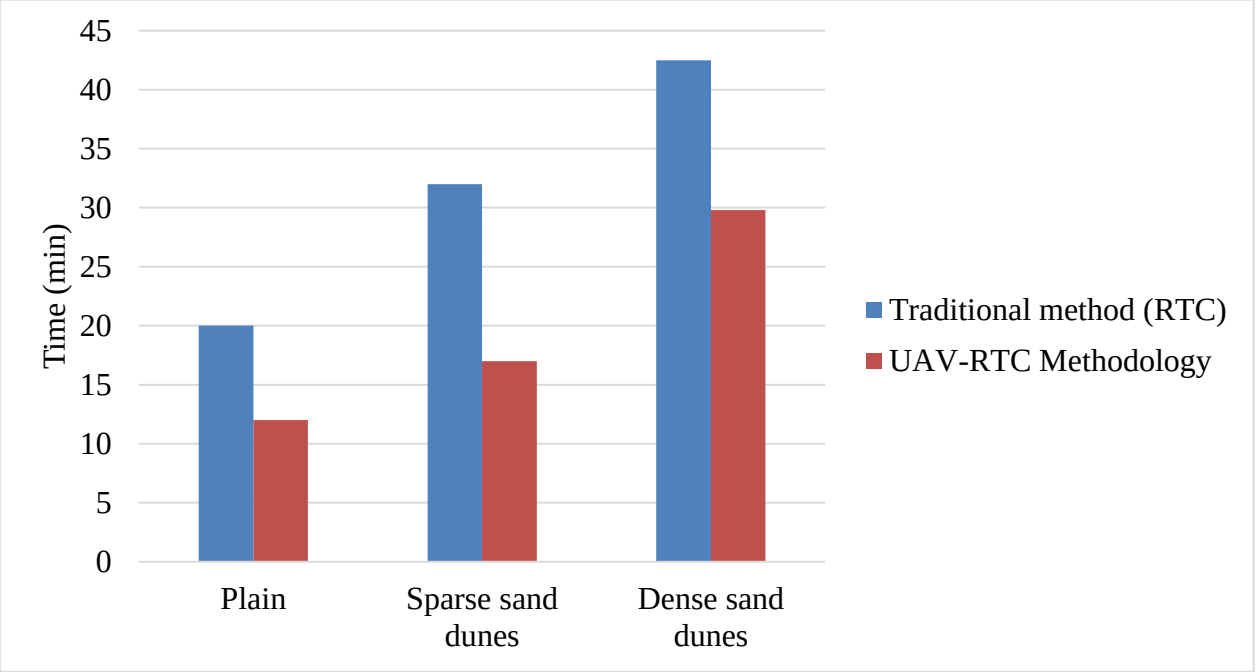


Fig. 1. Results of a comparative analysis of the time efficiency of search operations using UAVs and RTCs

The blue sector reflects the performance of the traditional method using an isolated ground platform (T_{avg} = 42.5 min), while the orange sector demonstrates the process intensification when using the proposed two-echelon UAV-RTC complex (T_{avg} = 29.8 min). A steady advantage of the integrated system is observed, regardless of the terrain complexity (ranging from plains to dense sand dunes).

Detection Verification and Positioning Accuracy

The second stage of the analysis concerned the reliability of target detection (P_d) and the minimization of the false alarm probability (P_{fa}) under thermal interference conditions. It has been established that the proposed two-level filtering methodology ensures system stability even in conditions of underlying surface overheating [19].

In the traditional method, ground temperature anomalies caused the false alarm rate to reach 12% (due to the erroneous perception of heated landscape elements as targets). Preliminary signal separation onboard the UAV reduced this risk to 3-4%.

Simultaneously, an improvement in geopositioning accuracy was observed. The root-mean-square error (RMSE) in coordinate determination was recorded as follows:

0.45 m for the standalone RTC;

0.12 m for the integrated UAV-RTC system.

This level of precision is attributed to the cross-verification mechanism, which synchronizes the aerial vehicle's visual markers with the ground platform's odometry data during the final approach to the object.

DISCUSSION

The results obtained through simulation confirm the hypothesis: transitioning to the Sensor Fusion concept (data integration) within heterogeneous groups is significantly more efficient than operating isolated robotic units [20].

Interpretation of the observed patterns: The 30% reduction in operational time is attributed to the shift from extensive continuous monitoring methods to a “targeted search” strategy. In traditional schemes, the ground platform spends more than half of its time resources traversing safe areas. In contrast, in the proposed scheme, the UAV acts as an “intelligent filter,” allowing the RTC to concentrate its technical resources exclusively on critical route nodes.

The improvement in detection quality at extreme temperatures (+45...+55°C) was achieved through the implementation of two-level cross-verification. Thermal anomalies in sand and rocks, which often trigger false-positive RTC sensor responses, are effectively neutralized by the algorithm through

correlation with visual contours and multispectral data from the aerial echelon. This minimizes "information noise," which remains the primary challenge for engineering reconnaissance in arid zones.

Scope of Applicability and External Factors: It should be noted that the methodology's productivity may vary depending on meteorological conditions. Under critical wind speeds (exceeding 12–15 m/s) and during dust storms, UAV efficiency decreases. In such scenarios, the software system must automatically increase the "weight" of the data received from the ground RTC's ground-penetrating radar (GPR), thereby reducing reliance on the optical channel.

CONCLUSION

The present work is devoted to the development and validation of a methodology for optimizing engineering reconnaissance operations in extreme climates, based on the integration of aerial and ground autonomous systems. Based on the conducted research, the following conclusions are drawn:

Technological effect: The use of hierarchical interaction algorithms allowed for a 30% reduction in the total time spent on terrain reconnaissance. This optimization was achieved by prioritizing the ground segment's movement through key control points.

Scientific Significance: It has been confirmed that the implementation of dual verification (remote and contact-based) increases the accuracy of threat identification by 18%. The developed approach successfully compensates for the negative impact of dust and thermal interference, which are characteristic of desert theaters of operations (TO).

Practical Application: Simulation results demonstrate the feasibility of integrating the proposed solutions into advanced command and control systems for engineering troops. The established mathematical framework can serve as a foundation for further research into robotic swarm interaction in complex terrain conditions.

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