



Comparative Study of Air-Ground Robotic Systems and Autonomous Multi-Modal Navigation Techniques

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Abstract: Air-ground robotic systems that combine UAVs and UGVs are widely used in disaster response, firefighting, reconnaissance, inspection, and autonomous navigation. These hybrid systems combine the mobility of the air with the stability and endurance of the ground. This study provides a comparative study of fifteen research papers on hybrid robots based on navigation, localisation, locomotion, firefighting, and autonomous coordination. It includes mechanisms, control strategies, energy efficiency, and GPS-denied navigation techniques. The main trends are topology optimisation, adaptive morphogenesis, multi-sensor localisation, and behaviour-based coordination. The table compares system benefits, limitations and performance. The study concludes that the hybrid robotic systems enhance flexibility and efficiency, but there are challenges in localisation, payload optimisation, and autonomous decision-making [1]–[15].

Keywords: Air-Ground Robots, UAV-UGV Integration, Hybrid Robotics, Autonomous Navigation, Multi-Modal Locomotion, GPS-Denied Localisation, Firefighting Robots, Comparative Study, Morphing Robots, Robotics Control Systems

I. INTRODUCTION

Recent advances in robotics have greatly accelerated the development of hybrid air-ground robotic systems capable of operating across various terrains and environmental conditions. Conventional UAVs can manoeuvre quickly and easily pass obstacles, but they have limited endurance and payload capacity. On the other hand, UGVs offer improved stability and extended operational periods, but face problems in navigating intricate obstacles and inaccessible terrains [1].

To overcome these limitations, amphibious and multi-modal robotic systems, combining aerial as well as terrestrial capabilities, have been developed by researchers. Such systems are especially useful in disaster rescue, firefighting, military reconnaissance, infrastructure inspection, and autonomous exploration tasks [2]. A major advantage of hybrid robotic platforms is their capability to alternate between aerial and terrestrial operation depending on environmental demands [3].

There are several approaches explored in the literature. Passive-wheel-based systems offer simple mechanical structures, but suffer from high friction and instability [4]–[7]. Robots with driving wheels combine the wheels directly into UAV structures for seamless mobility, but they have high power consumption and rollover risks in general [8]. Active-deformation-mechanism-based systems incorporate transformable appendages and adaptive morphologies to improve locomotion flexibility [9]–[11].

Recent studies also showcase the importance of autonomous navigation in GPS-denied environments [12]. Multi-sensor localisation methods use LIDAR, IMU, GPS and Monte Carlo Localisation (MCL), which greatly enhances navigation robustness [13]. Moreover, mission coordination frameworks based on Behaviour Trees enable efficient collaboration among heterogeneous robot teams [12].

This paper presents a comprehensive study and comparative analysis of fifteen research papers focusing on air-ground robotic systems and autonomous navigation technologies.



II. RESEARCH BACKGROUND

Integrated aerial and terrestrial mobility has caught the attention of robotics research, driven by the growing need for versatile autonomous systems. The first robots were designed to move either on the ground or in the skies, not both. However, for mission-critical applications such as search-and-rescue, firefighting and exploration, robots that can adapt to different environmental conditions are needed [1].

These requirements have led to hybrid terrestrial-aerial systems. HyTAQ systems, using a combination of passive wheels and quadrotor UAVs, were used to obtain ground mobility [4]. Later developments introduced the omnidirectional vehicle, such as Skywalker, which improved the manoeuvrability and compactness [6]. Research was pushed further towards adaptive morphogenesis and transformable robotic structures that are capable of reconfiguring their geometry according to operational needs [10].

The M4 Morphobot was a huge advancement, allowing for appendage repurposing and multiple locomotion methods, such as flying, rolling, and walking [2]. Likewise, MTABot used transformable wheels for efficient terrestrial-aerial locomotion [9]. In recent designs such as LoadFlexBot, topology optimisation, internal meshing gears and decoupled control systems have been used to improve structural stiffness and reduce energy consumption [1].

Advancements in localisation and autonomous navigation have enabled these robots to operate effectively in GPS-denied environments. Robust operation was achieved through 3D LIDAR-based mapping systems, probabilistic localisation frameworks, and multi-sensor fusion techniques [12]. Such technologies are essential in indoor firefighting, urban canyons and disaster-stricken environments where GPS signals are unreliable.

The integration of UAVs and UGVs has therefore become a huge research direction in modern robotics due to its potential for improved adaptability and operational efficiency.

III. INCENTIVE BEHIND THE STUDY

The main motivation behind this study is the rapid development of hybrid robotic systems and the growing need for a consolidated comparative understanding of the methods used in the existing research. However, many studies have proposed novel mechanisms of air-ground locomotion, localisation, and autonomous coordination, but a lack of unified comparative evaluation still exists.

Present robotic systems show a large variability in:

Structural design:

- Mechanisms of transformation
- Energy efficiency
- Handling of payloads
- Navigation skills
- Localisation techniques
- Autonomous control strategies

This diversity makes it difficult to identify the most practical approaches for real-world implementation. However, the real-world implementation still encounters challenges such as limited endurance, control complexity, unstable localisation, and high computational demands [1], [12].

The incentive driving this study is therefore:

- To get a systematic analysis of existing air-ground robotic methodologies.
- To compare the strengths and weaknesses of different transformation and control mechanisms.
- To evaluate localisation and navigation techniques in GPS-denied scenarios.
- To identify gaps in research and future directions for next-generation hybrid robotic systems.

IV. COMPARATIVE ANALYSIS

The analysed papers reveal three dominant categories of hybrid robotic systems:

4.1.1 Passive Wheel-Based Systems

Passive-wheel systems use fixed or freely rotating wheels attached to UAV structures. These designs are mechanically simple and lightweight, but they are plagued by instability, high friction and poor adaptability on uneven terrain [4]-[7].



4.2 Systems with Driving Wheels

Aerial platforms equipped with driving wheels have active wheel systems integrated into them. Such systems improve mobility and steering capabilities, but usually increase structural complexity, power consumption and the overall size of the robot [8].

4.3 Active deformation systems

Active-deformation robots use transformable appendages and adaptive morphologies for dynamic reconfiguration [2], [9]–[11]. These systems offer greater operational flexibility, but require complex mechanical architectures and sophisticated control algorithms.

Moreover, the approaches to localisation and navigation differ significantly across the reviewed papers. Modern systems depend more and more on:

- 3D LIDAR mapping
- Localisation using Monte Carlo
- Sensor fusion
- GPS-denied navigation
- Behaviour Tree mission coordination [12]

LoadFlexBot showed significant gains in all reviewed systems in:

- Structural rigidity
- Carrying capacity.
- Energy Efficiency:
- Multi-modal versatility [1]

Likewise, in the challenging urban environments of the MBZIRC, the firefighting robot team performed fully autonomous operations based on multi-sensor localisation and heterogeneous UAV-UGV cooperation [12].

Comprehensive Comparative Analysis of Air-Ground Robotic Systems and Autonomous Navigation Techniques						
Ref.	System / Paper	Methodology / Approach	Key Technologies / Mechanisms	Advantages	Limitations	Results / Outcomes
[1]	LoadFlexBot	Active deformation with topology optimization	Topology optimization, internal meshing gears, decoupled control	High payload capacity, energy efficient, improved structural stiffness, multi-modal adaptability	Complex control system, mechanical complexity, design complexity	Carries 2.5 kg payload, 98.17% energy efficiency in ground mode
[2]	M4 Morphobot	Appendage repurposing for locomotion plasticity	Multi-modal locomotion (flying, rolling, walking), adaptive morphology	Multiple locomotion modes, high terrain adaptability, versatile appendage usage	Large structure, higher mechanical complexity, control challenges	Achieved seamless transitions between flying, rolling, and walking
[3]	UAV Motion Planning (Survey)	Review of UAV motion planning algorithms	Trajectory optimization, path planning, obstacle avoidance	Improved UAV navigation, efficient path planning, better mission success	Computational overhead, algorithm complexity, real-time limitations	Comprehensive survey of algorithms and future directions
[4]	HyTAQ	Passive wheel based hybrid quadrotor	Passive wheels, hybrid aerial-terrestrial structure	Simple mechanical design, lightweight, basic air-ground mobility	High friction, low stability, limited terrain adaptability	Validated hybrid mobility with quadrotor and passive wheels
[5]	Hybrid Aerial-Ground Locomotion	Single passive wheel hybrid locomotion	Single passive wheel mechanism, minimalistic design	Lightweight, minimal design, easy implementation	Limited stability, poor performance on rough terrain	Demonstrated basic air-ground transitions using single passive wheel
[6]	Skywalker	Omnidirectional air-ground vehicle	Omnidirectional wheels, compact structure, agile mobility	High maneuverability, compact structure, smooth transitions	Limited payload capacity, complex control	Achieved agile movement and compact hybrid mobility
[7]	Bimodal Vehicle	Passive wheel integration for adaptive navigation	Passive wheels, adaptive navigation system	Autonomous mode transitions, terrain adaptability	Balance issues, stability control challenges	Successful autonomous navigation in multiple terrains
[8]	Amphibious Fly-Drive Vehicle	Driving-wheel integrated hybrid system	Active driving wheels, dynamic modeling, amphibious capability	Seamless land-air transitions, continuous mobility	High power consumption, complex dynamics, rollover risk	Achieved continuous operation in land and air environments
[9]	MTABot	Transformable wheels for air-ground mobility	Transformable wheels, morphable structure, multi-modal locomotion	Efficient transformation, improved mobility, adaptable structure	Structural complexity, transformation mechanism complexity	Improved efficiency in terrestrial-aerial locomotion transitions
[10]	Adaptive Morphogenesis	Reconfigurable morphology adaptation	Adaptive morphogenesis, multi-environment transitions	High adaptability, environmental adaptation, flexible morphology	High computational complexity, complex design	Achieved multi-environment adaptation with reconfigurable morphology
[11]	FCSTAR	Flying-climbing sprawl-tuned robot	Sprawl-tuned mechanism, hybrid flying and climbing	Multi-mode operation, climbing capability, structural adaptability	Complex transmission system, control complexity	Successfully demonstrated flying and climbing capabilities
[12]	MBZIRC Firefighting Robot Team	Multi-robot coordination for firefighting	LIDAR, IMU, GPS-denied navigation, Behavior Trees (BTs), UAV-UGV team	Autonomous coordination, robust localization, mission autonomy	Heavy computational load, complex system integration	Achieved 7th place in MBZIRC 2020 autonomous firefighting challenge
[13]	MCL3D Localization Framework	Monte Carlo Localization (MCL)	3D LIDAR mapping, multi-sensor fusion, probabilistic localization	Robust localization, works in GPS-denied environments	GPS inaccuracies, sensor noise, computational cost	Reduced RMSE error, improved localization accuracy
[14]	Trans-Rotor	Differential gear joint transformation	Active differential gears, omnidirectional mobility, transformation mechanism	High agility, omnidirectional movement, efficient transformation	Mechanical complexity, gearing system complexity	Improved transformation and omnidirectional mobility performance
[15]	Quadrotor Trajectory Control	Minimum snap trajectory generation	Minimum snap trajectories, quadrotor control systems	Smooth trajectories, stability, high control performance	Requires parameter tuning, computational overhead	Achieved smooth and stable quadrotor trajectory tracking

Fig. 1 Comparative Analysis Table



COMPARISON OF REPRESENTATIVE AIR-GROUND ROBOT DESIGNS							
Design	LoadFlexBot [1]	M4 Morphobot (M4) [2]	HyTAQ [4]	Skywalker [6]	MTABot [9]	Amphibious Fly-Drive [8]	FCSTAR [11]
Configuration (Representative Image)							
	UAV / Crouching / UGV	Flying / Rolling / Walking	UAV / UGV	UAV / Omnidirectional UGV	UAV / UGV (Transformable)	UAV / UGV (Drive-Wheel)	Flying / Climbing / Sprawling
Design Approach	Active deformation with topology optimization	Appendage repurposing (multi-modal)	Passive wheel based hybrid quasikopter	Omnidirectional air-ground vehicle	Transformable wheels for air-ground mobility	Driving-wheel integrated hybrid system	Sprawl-turned mechanism (hybrid flying & climbing)
Degrees of Freedom (Per Leg / Module)	4 DOF	Multiple DOF (reconfigurable)	N/A (passive wheel)	N/A (wheel module)	Transformable (4+ DOF equiv)	N/A (drive wheel)	Multiple DOF (sprawl mechanism)
Transformation Mechanism	Servo motors + limiters + internal meshing gears	Joint reconfiguration and mode adaptation	Passive wheels (folding/rotating)	Fixed wheels for omnidirectional motion	Wheel transformation (extend/retract)	Drive wheels for ground mode	Sprawl mechanism for climbing
Locomotion Modes	UAV / Crouching / UGV	Flying / Rolling / Walking	UAV / UGV	UAV / Omnidirectional UGV	UAV / UGV	UAV / UGV	Flying / Climbing / Sprawling
Max. Payload	2.5 kg	~2.0-2.5 kg (varies)	~1.5 kg	~1.0 kg	~1.5 kg	~1.5-2.0 kg	~1.0 kg
Max. Ground Speed	5 m/s	~3-4 m/s	~2 m/s	~3-4 m/s (omni)	~3 m/s	~3-4 m/s	~2 m/s
Endurance / Energy Efficiency	High (98.17% energy saving in ground mode)	Moderate (multi-modal trade-off)	Low-Moderate (passive wheels)	Moderate (higher energy use)	Moderate-High (efficient transform)	Moderate (higher power use)	Moderate (complex mechanism)
Structural Complexity	★★★★☆	★★★★★	★★★☆☆	★★★★☆	★★★★☆	★★★★☆	★★★★☆
Adaptability to Terrain	High	Very High	Low-Moderate	High (flat terrain)	High	Moderate	High (incl. vertical)
Best Application Scenarios	Inspection, rescue, complex environments	Search & rescue, exploration, versatile missions	Simple inspection, low-cost deployments	Indoor navigation, compact missions	Inspection, agriculture, monitoring	Surveillance, long-range inspection	Climbing inspection, urban environments
Performance Comparison (0 = Low, 5 = High)							

Legend: ★★★★★ Very High ★★★★☆ High ★★★☆☆ Moderate ★★☆☆☆ Low ★☆☆☆☆ Very Low Note: Values are indicative and based on information reported in the respective papers.

Fig. 2 Comparison of the designs

V. OBJECTIVES-BASED OUTCOME

The outcomes of the reviewed studies indicate significant progress in hybrid robotic system design and autonomous navigation.

Objective 1: Increase Mobility on Diverse Terrains

Most of the systems managed to achieve a smooth transition between aerial and ground locomotion modes [1], [2], [9].

Objective 2: Improve Energy Efficiency

Walking on the ground saved considerable amounts of energy compared to constant flying. LoadFlexBot achieved energy-saving efficiency of about 98.17% in ground operation [1].

Objective 3: Independent Navigation

LIDAR, IMU, GPS and Monte Carlo Localisation were combined to enable robust localisation in GPS-denied environments [12], [13].

Objective 4: To increase structural adaptability

Topology optimisation and adaptive morphogenesis improved stiffness, reduced weight and enhanced operational flexibility [1], [10].

Objective 5: Achieve Autonomous Coordination of Multiple Robots

Behaviour Tree-based task coordination and autonomous firefighting activities to enhance mission execution frameworks [12].

However, there are still many challenges to be solved:

- Complex control systems
- High computational demands
- Payload limitations
- Drift in localisation
- Mechanical reliability in severe environments

VI. CONCLUSION

This paper critically evaluates fifteen research papers concerning hybrid air-ground robotic systems, autonomous navigation, and multimodal locomotion technologies. The systems investigated are significant advances in robotics



research through innovations in adaptive morphology, topology optimisation, autonomous coordination and multi-sensor localisation.

Among all the systems, active-deformation-based systems proved to be the most promising category, offering greater flexibility and obstacle-traversal capabilities. Systems like LoadFlexBot and M4 Morphobot showed significant improvements in adaptability, payload capacity, and energy efficiency [1], [2]. Moreover, advances in GPS-denied localisation and mission coordination significantly enhanced the reliability of autonomous operations in complex environments [12], [13].

However, modern hybrid robotic systems still have some key challenges, including control complexity, high computational costs, endurance limitation, and localisation inaccuracies.

Future research should focus on:

- AI-based autonomous decision making
- Lightweight structural materials
- Improved battery
- Real-time adaptive control systems
- Enhanced collaborative multi-robot frameworks

Overall, the integration of UAV and UGV technology represents an innovative direction in robotics with a strong potential for disaster response, industrial inspection, firefighting and autonomous exploration.

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