AUTOMATION AND COMPUTER-INTEGRATED TECHNOLOGIES AND ROBOTICS

UDC 629.735.4:004.9[004.89.027.44](045)
DOI:10.18372/1990-5548.88.20978

Sergiy Dolhorukov

CAD-BASED OPTIMIZATION OF THE MEDIUM-SIZED UNMANNED GROUND VEHICLE

Department of Avionics and Control Systems, State University "Kyiv Aviation Institute", Kyiv, Ukraine
E-mail: sdolgorukov@kai.edu.ua

Abstract—*This paper investigates a multi criteria, computer-aided design system to achieve optimal configurations for unmanned ground vehicles which operate in diverse environments and climate conditions. The core challenge lies in balancing competing design objectives such as cost, payload, reliability and longevity. To address this, a novel design methodology is proposed, integrating an AI-powered CAD system that creates a closed-loop information flow across all development stages, from conceptual design to field testing. This framework was validated through the development of a custom medium-sized unmanned ground vehicle with an integrated motion control system comprised of commercial off-the-shelf components and custom developed parts. Experimental trials in various terrain and climate conditions, including operation in winter, demonstrated high maneuverability, a payload capacity, and a 100 km range. The results confirm the methodology's effectiveness in improving design efficiency and ensuring the seamless integration of mechanical complexity, software, and performance metrics for next-generation unmanned ground vehicles, highlighting the framework's diagnostic strength and its ability to guide targeted R&D.*

Keywords—Unmanned systems, hardware and software integration, system of systems, ground vehicle, computer-aided design.

I. INTRODUCTION

Unmanned Ground Vehicles (UGVs) represent a rapidly evolving field within robotics, extending the reach and capabilities of human operators across diverse and often challenging environments. Driven by the desire to minimize human risk, enhance operational efficiency, and access locations deemed inaccessible or hazardous, UGVs have transitioned from primarily military applications to a wide array of civilian and commercial sectors. From reconnaissance and surveillance to logistics, search and rescue, agriculture, and even planetary exploration, UGVs are increasingly becoming versatile and indispensable tools. At the heart of their operational effectiveness lies their design ‑ a complex interplay of mechanical, electrical, and software engineering that dictates their mobility, perception, autonomy, and mission-specific capabilities. This literature review delves into the critical design features of UGVs, exploring the current state of research, key challenges, and emerging trends shaping the development of these increasingly sophisticated robotic systems. Understanding these design considerations is crucial for advancing UGV technology, optimizing their performance, and broadening their successful deployment across future applications. The design of Unmanned Ground Vehicles is a multidisciplinary endeavor, drawing upon principles from mechanical engineering, robotics, control systems, computer vision, artificial intelligence, and materials science. Existing literature on UGVs extensively covers various aspects of their development, with a significant portion focused on the critical design features that enable their functionality. This review categorizes and examines key design areas as presented in scholarly works, highlighting common approaches, research gaps, and future directions.

Locomotion systems are fundamental to UGV operation, dictating their ability to navigate diverse terrains and overcome obstacles. Wheeled, tracked, and legged locomotion are the primary modalities explored in the literature. Wheeled UGVs, as discussed in numerous studies [1], [2], offer advantages in speed and efficiency on paved surfaces and simpler control mechanisms. Research focuses on optimizing wheel configurations (e.g., Ackerman steering, skid-steer, differential drive), suspension systems for terrain adaptation [3], and tire design for enhanced traction in varied conditions. Tracked UGVs, conversely, are well-documented for their superior off-road capabilities and stability [4], [5]. Literature emphasizes track design for improved traction and reduced ground pressure, as well as

http://jrnl.kai.edu.ua/index.php/ESU

robust suspension systems to manage rough terrains and shocks. Legged locomotion, while still under active development for UGVs, is explored for its potential to traverse highly complex and unstructured environments, including stairs and rubble [6], [7]. Research in this area focuses on bio-inspired leg designs, advanced control algorithms for dynamic stability, and energy efficiency considerations. Hybrid locomotion systems, combining wheels and tracks or legs, are also emerging as a means to achieve versatility across diverse terrains [8].

Efficient power and propulsion are critical for UGV endurance and operational range. Literature widely examines various power sources, including batteries, internal combustion engines (ICE), hybrid systems, and fuel cells [9], [10]. Battery technology, particularly lithium-ion batteries, is prevalent in smaller to medium-sized UGVs due to their energy density and quieter operation [11]. Research focuses on improving battery energy density, cycle life, charging infrastructure, and safety. ICE-based propulsion is explored for larger UGVs or missions requiring extended endurance, although literature acknowledges drawbacks in noise, emissions, and thermal signature [12]. Hybrid systems, combining batteries and ICE, aim to leverage the benefits of both, offering extended range and silent operation capabilities [13]. Emerging literature also investigates fuel cells as a promising alternative for clean and efficient power, particularly for long-duration missions [14]. Power management strategies, including regenerative braking and intelligent power distribution, are also consistently discussed as essential for maximizing operational time [15].

Unmanned Ground Vehicles rely heavily on sensors to perceive their environment for navigation, obstacle avoidance, and mission task execution. The literature extensively covers the use of various sensor modalities. Vision-based sensors (cameras) are widely studied for their rich visual information, with research focusing on monocular, stereo, and depth cameras for 3D environment understanding [16], [17]. LiDAR (Light Detection and Ranging) is another prevalent sensor, providing accurate 3D point clouds for mapping and obstacle detection, particularly in outdoor environments [18], [19]. Radar (Radio Detection and Ranging) is explored for its ability to operate in adverse weather conditions and penetrate foliage, offering robustness in challenging environments [20]. Inertial Measurement Units (IMUs) and GPS/GNSS are fundamental for localization and navigation, with ongoing research addressing limitations in GPS-denied environments and improving localization accuracy [21], [22]. Sensor fusion techniques, integrating data from multiple sensor modalities, are frequently investigated to enhance robustness and reliability of perception [23]. Mission-specific sensors, such as chemical, biological, radiological, and nuclear (CBRN) detectors, metal detectors, and acoustic sensors, are also discussed in the context of specific UGV applications [24].

Control systems are the brain of UGVs, enabling autonomous or remotely operated functionality. Literature explores various control architectures, ranging from purely teleoperated to fully autonomous systems [25]. Teleoperation research focuses on improving human-machine interfaces (HMIs), reducing operator workload, and enhancing situational awareness through sensor feedback [26]. Autonomous navigation is a significant research area, encompassing path planning algorithms, obstacle avoidance strategies (reactive and deliberative), localization and mapping techniques (SLAM - Simultaneous Localization and Mapping), and decision-making under uncertainty [27], [28]. Semi-autonomous or supervised autonomy approaches, combining human oversight with UGV autonomy, are also explored as a practical middle ground [29]. Communication systems are critical for maintaining control and data exchange, with literature examining various communication methods including radio frequency (RF) links, wired tethers, and satellite communication [30]. Research focuses on enhancing communication range, bandwidth, reliability, and security, especially in contested or degraded environments [31].

While significant progress has been made in UGV design, several areas require further research and development. Advanced autonomy, particularly in highly dynamic and unstructured environments, remains a key challenge. Improved energy efficiency and power density are crucial for extending UGV operational range and endurance. Sensor fusion and robust perception in adverse conditions (e.g., low light, fog, dust) need further refinement. Human-robot interaction (HRI) for effective teaming and intuitive control is a growing area of interest. Furthermore, standardization and modularity in UGV design are needed to facilitate interoperability and reduce development costs.

II. PROBLEM STATEMENT

The design of UGVs is a complex and multidisciplinary field, constantly evolving with advancements in robotics, sensors, AI, and materials science. The specific features of a UGV will always be tailored to its intended purpose and operational context.

$$x = \underset{x\in\Omega,\ y}{\arg\operatorname{extr}}\{C,\ W,\ D,\ L,\ R\},$$

x = opt, C = min; W = max; D = min; L = max; R = max, where x is the design parameters; $\{C, W, D, L, R\}$ are the optimization criteria: cost of the UGV; weight of UGV with payload; UGV parameter deviation limits; longevity between major vehicle repairs; reliability, and the corresponding criterion limits

$$\begin{aligned} y = \{ & y_{C_{\min}} \le y_C \le y_{C_{\max}},\ y_{W_{\min}} \le y_W \le y_{W_{\max}}, \\ & y_{D_{\min}} \le y_D \le y_{D_{\max}},\ y_{L_{\min}} \le y_L \le y_{L_{\max}}, \\ & y_{R_{\min}} \le y_R \le y_{R_{\max}}\} \end{aligned}$$

and, $\Omega = \{x | x_i \ge 0,\ x | x_{i_{\min}} \le x_i \le x_{i_{\max}},\ i \in [1, n]\}$, x is a vector of design parameters and constraints represented by a set of n elements. Criteria are weighted according to the task.

For this design, let us define a medium-sized UGV as:

1) Transportable by a light tactical vehicle or standard pickup truck. This limits its overall dimensions and weight.

2) Larger than man-portable that means it cannot be easily carried by a single person for extended periods.

3) Capable of carrying a meaningful payload, manipulator arms or cargo.

4) Intended for missions such as: patrol, reconnaissance, security, light load carriage, EOD (Explosive Ordnance Disposal), potentially light direct fire support.

Design parameters are represented in Table I.

Every decision should be driven by the intended mission. Terrain dictates mobility requirements: wheeled vs. tracked suspension, and environment affects material selection and ruggedization needs. The level of autonomy desired (teleoperation, semi-autonomous, autonomous) will influence sensor requirements, processing power, and communication systems, impacting overall size, weight, and power.

Desired capabilities must be balanced with budget constraints. Sophisticated sensors, advanced autonomy, and high-performance power systems increase cost.

Designing UGV must include ease of maintenance, repair, and logistics in the field. Modular designs and readily available components are beneficial.

TABLE I. UGV DESIGN PARAMETERS

Parameter	**Optimization range**	**Description**
1. Size (Length × Width × Height)	1.5–2.5 m	Length
	0.8–1.5 m	Width
	0.8–1.2 m	Height
2. Weight	200–400 kg	
	400–600 kg	
	400–800 kg	
3. Payload	50–100 kg	
	50–200 kg	
	100–200 kg	
	300–400 kg	
4. Range	50–100 km	Hybrid or Internal Combustion Engine (ICE)
	20–50 km	Battery-powered
5. Power	Batteries	Lithium-ion or similar
	Hybrid	Battery + ICE
	Internal Combustion Engine	Diesel or Gasoline

The ranges provided offer a starting point for designing a medium-sized UGV. The best approach is to clearly define the mission requirements first, then prioritize and trade-off these parameters to achieve the desired performance and capabilities within practical limitations, after that use simulation and testing to validate the design choices.

III. AI AGENTS SYSTEM DESIGN APPROACH

The design and manufacturing process for a medium-sized UGV is a complex, multidisciplinary workflow. The key phases are as follows (Fig. 1):

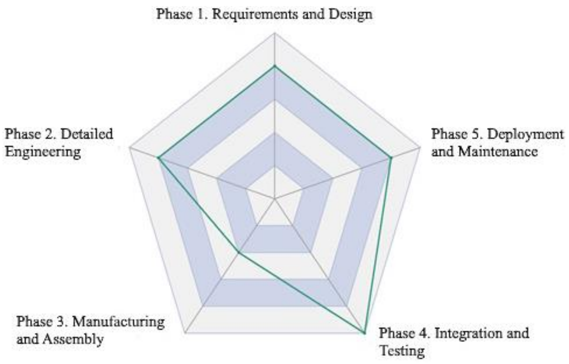

Fig. 1. Components of system design phases

To automate the UGV design process all stages are combined together withing AI powered CAD software environment that ensures information flow during all design stages [32]:

$$\mathrm{UGV}_{CAD} = \langle \mathrm{M}_T, \mathrm{A}_{ST}, \mathrm{R}_\mathrm{D} \rangle,$$

where M are meta agents (A, ..., E), A are agents (1, ..., 19), T is a set of tasks performed by the meta-agent. $T = \{T_1, ..., T_n\}$, where n is the number of different tasks in the UGV CAD system; ST is a set of subtasks performed by agents, $ST = \{ST_1,..,ST_m\}$, where m is the number of different subtasks in the system; R_D shows the relationship dependencies between agents and meta agents.

The agent's function is defined as $S \rightarrow A$, and perception as $S \rightarrow P$, where $S = \{s_1, s_2, ..., s_t\}$ is information from the UGV design environment, $\mathrm{A} = \{a_1, a_2, ..., a_n\}$ is the agent's actions, such that $\mathrm{AI}_\mathrm{agent} = \langle S, A, R \rangle$, where S is the set of all state variables, A is the set of all action variables, R is the reward function.

It combines interaction between hierarchical levels of engineers-designers and intelligent agents with their own behavior models. Then combined system diagram of UGV helps to identify requirements and activities to simulate the system in real world. Usually, SysML main structure of data files consists of functional requirements diagrams, structure diagrams, behavior diagrams and parametric diagrams. All the requirements must be defined in mentioned above diagrams that is managed by the AI-agent that connects user with various digital repositories and creates a closed loop. This way any updates in UGV system model can be immediately verified and implemented in the final product.

A. Requirements definition and conceptual design stage agent specific tasks

1) Mission definition and requirements gathering: patrol, reconnaissance, cargo, EOD, etc. What is the operational environment: urban, off-road, indoor/outdoor, climate conditions. What is required speed, range, payload capacity, endurance, maneuverability, obstacle negotiation, sensor performance. What is required autonomy level (teleoperated, semi-autonomous, autonomous), communication range, deployment methods, environmental conditions (temperature, weather, terrain), stealth requirements (if any). What is required cost targets, size and weight constraints, power consumption limits, reliability, maintainability, safety standards, regulatory compliance, cybersecurity needs.

2) Feasibility study and technology assessment if the requirements are technically achievable with current or near-future technology. Identification of potential technological challenges and risks. Evaluation of the estimated cost of development, manufacturing, and operation. Determination if the project is financially viable. Researching available technologies for each subsystem (locomotion, power, sensors, communication, control). Evaluation maturity, cost, and performance of different options. Considering Commercial Off-The-Shelf (COTS) components vs. custom development.

3) Conceptual design and architecture selection with generation of multiple conceptual designs based on requirements and feasibility study. Exploration of different locomotion types (wheeled, tracked, legged), chassis configurations, power source options, sensor suites, and control architectures. Evaluation of each concept against the requirements and feasibility criteria. Using trade-off matrices, Pugh charts, or similar methods to compare and select the most promising concept(s).

4) Preliminary project planning and creation of a preliminary project schedule with key milestones for design, manufacturing, testing, and deployment phases. Development of a more detailed budget based on the selected concept and technology choices. Definition of the project team roles, responsibilities, and required expertise (mechanical, electrical, software engineers, etc.). Allocation of resources (personnel, equipment, facilities). Identification and assessment of the potential project risks (technical, schedule, budget, etc.) and outlining mitigation strategies.

B. Detailed design and engineering stage agent specific tasks

1) Detailed mechanical design and development of detailed 3D CAD models of the entire UGV, including chassis, suspension, drivetrain, payload integration structures, enclosures, and all mechanical components. Finalization of material selection for all mechanical parts based on strength, weight, durability, corrosion resistance, cost, and manufacturability. Simulation of the finite element analysis model (FEA) to verify structural integrity, stress analysis, vibration analysis, and thermal analysis. Optimization of the design for weight and strength. Creation of detailed manufacturing drawings, assembly drawings, Bill of Materials (BOM), and specifications for all mechanical components.

2) Detailed electrical design of the power distribution network, battery management system (BMS), voltage regulation, and power conditioning circuits. Selection of batteries, motors, motor controllers, and power electronics components based on performance and efficiency requirements. Designing of circuits and interfaces for integrating all sensors (cameras, LiDAR, radar, IMU, etc.). Definition of data acquisition and processing methods. Selection of communication method (RF, wired, satellite), designing of communication protocols, antennas selection and placement, encryption implementation. Control System Architecture (Hardware) design of the embedded control system hardware, selections of microcontrollers, processors, FPGAs, and other electronic components. Schematics and PCB Design development of the detailed electrical schematics and Printed Circuit Board (PCB) layouts for custom electronics. Designing and documenting wiring harnesses for power and signal distribution.

3) Software and control system design and embedded software development for real-time control, sensor data processing, motor control algorithms, and communication protocols. Choosing appropriate operating system (RTOS or Linux-based). Autonomy and navigation algorithms development design and implementation of algorithms for path planning, obstacle avoidance, localization, mapping, and autonomous decision-making. Utilization of sensor data for perception and navigation. Communication protocols and data management implementation. Development of communication protocols for data exchange between the UGV and control station. Designing data logging and management systems. Human-Machine Interface (HMI) design of the control station interface (software and hardware) for teleoperation and monitoring. The main focus is on ergonomics, usability, and situational awareness. Simulation and software testing development of simulation environments to test software and algorithms virtually. Development of unit testing procedures, integration testing, and system-level testing of software components.

4) Prototyping and subsystem testing with rapid prototyping approach is to build prototypes of critical subsystems (locomotion, power, sensor integration) to validate design concepts and identify potential issues early. This is achievable with utilization of 3D printing, breadboarding, and modular components. Subsystem testing and validation with rigorous tests of individual subsystems (mechanical, electrical, software) against design specifications. Verification of performance, functionality, and reliability of each subsystem. Iterative design refinement then must be made based on prototype testing results. The goal is to iterate and refine designs to address identified issues and improve performance. This may involve going back to previous design steps.

C. Manufacturing and assembly stage agent specific tasks

1) Component procurement of all COTS components (motors, sensors, electronics, batteries, fasteners, etc.) from vendors. Managing lead times and supply chain. In-house manufacturing of custom mechanical parts (chassis components, brackets, etc.) using machining, welding, 3D printing, or other fabrication methods as needed. Outsourcing manufacturing of specialized components or large quantities to external vendors (PCB fabrication, custom enclosures, standard cable harnesses). Quality control during manufacturing process. Implementation of quality control procedures to inspect incoming components and manufactured parts against specifications.

2) Mechanical assembly and integration of the mechanical structure, including chassis, drivetrain, suspension, and payload mounting. Installation of wiring harnesses, mounting of electrical components (motors, controllers, sensors, batteries, PCBs), and connection of wiring according to schematics and wiring diagrams. Installation of embedded software and operating system onto controllers. Integration of software components and configuration of communication settings. System-level assembly and integration that combines all mechanical, electrical, and software subsystems to create the complete UGV.

D. System integration and testing stage agent specific tasks

1) System integration power-on and initial checks. Performing of initial power-on tests, voltage checks, and basic functionality checks. Software loading and configuration onto controllers, configuration of communication parameters, and initialization of sensor systems. Basic functionality verification of subsystems functionality: motor control, sensor data acquisition, communication within the integrated system.

2) Functional testing and performance evaluation with mobility and locomotion testing to test mobility performance on various terrains (paved surfaces, off-road, slopes, obstacles). Measuring of speed, maneuverability, turning radius, and obstacle negotiation capabilities. Sensor system testing and evaluation of sensor performance (range, accuracy, field of view, resolution) in different environmental conditions. Calibration and fine-tuning of sensor parameters. Communication system testing of communication range, bandwidth, latency, and reliability. Verification of secure communication and data integrity. Autonomy and navigation testing to test autonomous navigation algorithms in simulated and real-world environments. Evaluation of path planning, obstacle avoidance, localization accuracy, and mission execution performance. Payload testing of the integration and functionality of the payload. Verification of payload operation, data acquisition, and communication. Endurance and power consumption testing to measure battery life, power consumption under various operating conditions, and overall endurance.

3) Environmental and stress testing to test UGV operation in relevant environmental conditions (temperature extremes, humidity, rain, dust, vibration). Verification of ruggedization and environmental sealing (IP ratings). Stress testing of the UGV to evaluate structural integrity, vibration resistance, and shock resistance. Electromagnetic compatibility (EMC) testing to ensure the UGV does not interfere with other electronic equipment and is immune to electromagnetic interference.

4) Safety and reliability testing to rigorously test all safety features, including emergency stop mechanisms, fail-safe systems, and safety interlocks. Verification of compliances with safety standards. Reliability testing to conduct extended operational testing to assess system reliability, identify potential failure modes, and measure Mean Time Between Failures (MTBF).

5) Documentation and finalization of the technical documentation. Finalization of all technical documentation, including design documents, manufacturing drawings, BOM, software documentation, test reports, and user manuals. Project review and acceptance with conduction of a final project review to assess project completion against requirements and budget. Obtaining formal acceptance from stakeholders.

E. Deployment, operation, and maintenance stage agent specific tasks

1) Deployment and user training with deployment planning is to plan for deployment to the operational environment. Considering transportation, logistics, and operational setup. User training of operators and maintainers on UGV operation, control, maintenance procedures, safety protocols, and troubleshooting.

2) Operational deployment and field testing. This includes initial operational deployment of the UGV in its intended operational environment for field trials and real-world validation. Performance monitoring and data collection during this stage is very important. Constant monitoring of UGV performance in real-world operations is conducted, collection of operational data, and gathering user feedbacks.

3) Maintenance and support is routine maintenance procedures. It includes procedures for routine maintenance, inspections, cleaning, and calibration. Repair and troubleshooting procedures development for diagnosing and repairing malfunctions. Provision of spare parts and support for field maintenance. Software updates and upgrades planning for essential embedded software updates, security patches, and feature upgrades throughout the UGV's lifecycle.

4) Continuous improvement and iteration in a feedback loop. Establishment of a feedback loop from operators and maintainers to identify areas for improvement in design, performance, usability, and maintainability. Iterative design updates based on operational feedback and technological advancements, planning for iterative design updates and future versions of the UGV.

IV. EXPERIMENTAL STUDIES: VALIDATION AND HARDWARE EVALUATION

The medium sized UGV was created with the following target parameters. Length is 2.2 meters that allows for good stability and platform size while still being maneuverable in urban and semi-urban environments and transportable. Width is 1.2 meters that balances stability with the ability to navigate through trails, rough terrain and provide payload width. Heigh is 0.8 meters that keeps a relatively low profile for concealment and stability, but high enough to accommodate necessary components and ground clearance for varied terrain. Weight is 250 kg that allows for robust construction, decent payload, and battery capacity while still being transportable and not overly cumbersome. Weight distribution is crucial. Low center of gravity enhances stability, especially on slopes. Maximum payload is 450 kg with best value around 200 kg and UGV can accommodate larger manipulator arms, significant cargo for resupply, heavier weapon systems (if armed configuration is desired), or more extensive sensor and electronic warfare packages. Range is up to 50 km mission battery-powered which is practical range for patrols, reconnaissance within a defined area, and tasks where silent operation is beneficial. Range will be heavily influenced by terrain, speed, and payload power consumption. Operating time is often more relevant (usually it is 4–8 hours of continuous operation). Power choice is Lithium-ion batteries that is most common for medium UGVs, especially for quieter operation and simpler maintenance. Battery capacity is to be sized to meet range and payload power demands.

Table II reports the results in rural environment under variability of loads. We achieved high maneuverability, precision of control, payload capabilities and acceptable speed and range of operation.

The integrated motion control system for UGV was verified during several 4-hour missions and showed limitation of the COTS components and benefits of custom developed modules for power control.

The UGV during test trials is shown in Fig. 2.

TABLE II. UGV EXPERIMENTAL RESULTS IN CROSS-COUNTRY ENVIRONMENT

Wheelbase	Four-wheeled tractor suspension breakaway mechanism
Power	DC motor powered 2 axles of 3000 W each
Speed	up to 30 km/h
Power reserve	up to 100 km
Payload capacity	450 kg
Empty mass	250 kg
Payload on the trailer	1000 kg
Radio and video signal range	up to 5 km without a repeater; up to 20 km with a repeater on an aircraft or on a tethered UAV;
Control Modes	3 speeds, semi-autonomous, IMU navigation, display and logging of the track

Fig. 2. UGV testing in winter conditions at –15° C

The algorithmic and CAD processing requirements for the design team are reduced. The proposed design framework mitigates excessive budget spending, minimizes uncertainties during tests, and ensures integration of COTS components.

IV. CONCLUSIONS

A new architecture for the CAD software environment has been developed, which differs from existing ones in that it combines interaction between hierarchical levels of engineers-designers meta agents and intelligent agents with their own behavior models, which reduces design time and ensures interaction between interested participants in the design process outside of organizations.

A multi-agent approach to UGV design automation has been proposed, which differs from existing approaches in that it uses design agents with elements of reinforcement learning AI to solve multi-criteria decision-making problems, resulting in improved search for design solutions in terms of the use of prior knowledge. The approach not only allows new reward functions to be incorporated flexibly as needed, but also to weigh their relative importance depending on the needs of a specific UGV design task.

The design methodology of the medium-sized UGV incorporated in the design framework yields promising results for the implementation in the automotive industry. A reconfigurable modular design and COTS components ensure scalability, upgrades and advancements for the next generation of medium-sized UGVs. The future for medium-sized UGVs and UGVs in general is exceptionally promising. They are poised to revolutionize numerous sectors, offering enhanced capabilities, improved efficiency, and increased safety across a wide spectrum of applications. As technology matures and costs decrease, we can expect to see a proliferation of UGVs in both military and civilian domains. However, realizing this potential requires proactive and responsible development, addressing ethical concerns, establishing clear regulatory frameworks, ensuring robust cybersecurity, and fostering public trust.

REFERENCES

[1] K. Iagnemma, S. Dubowsky, Mobile robots in rough terrain: Estimation, motion planning, and control with application to planetary rovers. Springer Tracts in Advanced Robotics, vol. 12. https://doi.org/10.1007/b94718.

[2] J. L. Martínez, J. Morales, A. Mandow, & A. García-Cerezo, "A comparison of steering systems for all-terrain robots," *IEEE/ASME Transactions on Mechatronics*, 10(3), 267–277, 2005. https://doi.org/10.1109/TMECH.2005.848295.

[3] H. Gao, Z. Liu, Z. Sun, & G. Liu, "Research on active suspension control of unmanned ground vehicle based on road estimation," *Journal of Dynamic Systems, Measurement, and Control*, 135(6), 2013. https://doi.org/10.1115/1.4024320.

[4] J. Y. Wong, "Theory of ground vehicles," *John Wiley & Sons*, 2001. https://doi.org/10.1002/0471219455.

[5] G. P. MacSithigh, & D. O'Donoghue, "A study of the terrain performance of small tracked unmanned ground vehicles (UGVs)," *Journal of Terramechanics*, 47(2), 105–121, 2010. https://doi.org/10.1016/j.jterra.2009.07.001.

[6] M. Raibert, K. Blankespoor, G. Nelson, & R. Playter, "BigDog, the rough-terrain quadruped robot," *In Proceedings of the 17th World Congress the International Federation of Automatic Control*, 2008. https://doi.org/10.3182/20080706-5-KR-1001.01830.

[7] M. Kalakrishnan, J. Buchli, P. Pastor, M. Mistry, & S. Schaal, "Learning, planning, and control for quadruped locomotion over challenging terrain," *The International Journal of Robotics Research*, 30(2), 236–258, 2011. https://doi.org/10.1177/0278364910388677.

[8] D. Aksaray, & Y. Becerikli, "ARTU: A hybrid wheel-legged unmanned ground vehicle," *IEEE Access*, 8, 58327–58341, 2020. https://doi.org/10.1109/ACCESS.2020.2982823.

[9] S. F. Tie, & C. W. Tan, "A review of energy sources and energy management system in electric vehicles," *Renewable and Sustainable Energy Reviews*, 20, 82–102, 2013. https://doi.org/10.1016/j.rser.2012.11.077.

[10] M. B. Camara, H. Gualous, F. Gustin, & A. Berthon, "Design and new control of DC/DC converters to share energy between supercapacitors and batteries in hybrid vehicles," *IEEE Transactions on Vehicular Technology*, 57(5), 2721–2735, 2008. https://doi.org/10.1109/TVT.2008.915500.

[11] M. Hashempour,, et al., "A review of energy storage systems for robotic applications," *Energy Reports*, 7, 289–304, 2021. https://doi.org/10.1016/j.egyr.2021.01.037.

[12] K. Shojaei,, & S. A. A. Moosavian, "Modeling and control of an articulated unmanned ground vehicle with internal combustion engine," *Robotics and Autonomous Systems*, 60(1), 127–136, 2012. https://doi.org/10.1016/j.robot.2011.09.020.

[13] W. Gao, C. Mi, & A. Emadi, "Modeling and simulation of electric and hybrid vehicles," *Proceedings of the IEEE*, 95(4), 2007, 729–745. https://doi.org/10.1109/JPROC.2006.890114.

[14] L. J. Seballos, A. Serna, & P. Borja, "Fuel cell power systems for unmanned vehicles: A review," *IEEE Transactions on Energy Conversion*, 30(4), 1567–1579, 2015. https://doi.org/10.1109/TEC.2015.2441861.

[15] S. R. Cikanek, & K. E. Bailey, "Regenerative braking system for a military hybrid electric vehicle," *SAE Transactions*, 917–927, 2004. https://doi.org/10.4271/2004-01-1430.

[16] D. Scaramuzza, & F. Fraundorfer, "Visual odometry [tutorial]," *IEEE Robotics & Automation Magazine*, 18(4), 80–92, 2011. https://doi.org/10.1109/MRA.2011.943233.

[17] D. Scharstein, & R. Szeliski, "A taxonomy and evaluation of dense two-frame stereo correspondence algorithms," *International journal of computer vision*, 47(1-3), 7–42, 2002. https://doi.org/10.1023/A:1014573219977.

[18] S. Thrun, W. Burgard, & D. Fox, Probabilistic robotics. MIT press. 2005.

[19] W. Hess, D. Kohler, H. Rapp, & D. Andor, "Real-time loop closure in 2D LIDAR SLAM," *In 2016 IEEE International Conference on Robotics and Automation (ICRA)*, 2016, pp. 1271–1278. https://doi.org/10.1109/ICRA.2016.7487258.

[20] C. Ye, & J. Borenstein, "A new terrain-mapping method for mobile robot, outdoor navigation," *In Proceedings 2002 IEEE International Conference on Robotics and Automation*, vol. 2, 2002, pp. 1528–1533. https://doi.org/10.1109/ROBOT.2002.1014766.

[21] K. Ito, "Radar for autonomous vehicles: A review of recent technology and trends," *IEEE Intelligent Transportation Systems Magazine*, 9(3), 85–98, 2017. https://doi.org/10.1109/MITS.2017.2718818.

[22] F. Gu, & X. Hu, "Navigation in GPS-denied environments: A survey," *IEEE Access*, 8, 55214–55227, 2020. https://doi.org/10.1109/ACCESS.2020.2982181.

[23] O. A. Sushchenko and V. O. Golitsyn, "Data processing system for altitude navigation sensor," *in Proc. 2016 IEEE 4th International Conference on Methods and Systems of Navigation and Motion Control (MSNMC)*, Kyiv, Ukraine, 2016, pp. 84–87. https://doi.org/10.1109/MSNMC.2016.7783112.

[24] O. Sushchenko and A. Goncharenko, "Design of robust systems for stabilization of unmanned aerial vehicle equipment," *International Journal of Aerospace Engineering*, pp. 1–10, 2016. https://doi.org/10.1155/2016/6054081.

[25] O. A. Sushchenko and O. V. Shyrokyi, "H2/H∞ optimization of system for stabilization and control by line-of-sight orientation of devices operated at UAV," *in Proc. IEEE 3rd International Conference Actual Problems of Unmanned Aerial Vehicles Developments (APUAVD)*, Kyiv, Ukraine, 2015, pp. 235–238. https://doi.org/10.1109/APUAVD.2015.7346608.

[26] J. Y. Chen, & M. J. Barnes, "Human-agent teaming for multirobot control: a review of human factors issues," *IEEE Transactions on Human-Machine Systems,* 42(1), 13–29, 2012. https://doi.org/10.1109/TSMCA.2011.2170208.

[27] V. M. Sineglazov, K. D. Riazanovskiy, and O. I. Chumachencko, "Multicriteria conditional optimization based on genetic algorithms.System Research and Information Technologies," no. 3, pp. 89–104, 2020, https://doi.org/10.20535/SRIT.2308-8893.2020.3.08.

[28] V. Sineglazov, E. Chumachenko, and V. Gorbatyuk, "An algorithm for solving the problem of forecasting," *Aviation*, 17(1), pp. 9–13, 2013. https://doi.org/10.3846/16487788.2013.788871.

[29] M. Zgurovsky, V. Sineglazov, and E. Chumachenko, "Classification and Analysis Topologies Known Artificial Neurons and Neural Networks, *Studies in*

Computational Intelligence, 904, pp. 1–58, 2021. https://doi.org/10.1007/978-3-030-54823-9_1.

[30] M. Zgurovsky, V. Sineglazov, and E. Chumachenko, “Classification and Analysis of Multicriteria Optimization Methods,” *Studies in Computational Intelligence*, 904, pp. 59–174, 2021. https://doi.org/10.1007/978-3-030-54823-9_2.

[31] Z. Yan, & H. H. Chen, “A survey on communication technologies for unmanned systems,” *Journal of Communications*, 8(4), 218–228, 2013. https://doi.org/10.12720/jcm.8.4.218-228.

[32] V. M. Sineglazov and S. O. Dolgorukov, “Reinforced Learning for Navigation Equipment Test Table CAD Systems Integration,” 2021 *IEEE 6th International Conference on Actual Problems of Unmanned Aerial Vehicles Development (APUAVD)*, Kyiv, Ukraine, 2021, pp. 90–94, https://doi.org/10.1109/APUAVD53804.2021.9615408.

Received: February 04, 2026
Accepted: March 03, 2026
Published: April 19, 2026

Dolgorukov Sergey. ORCID 0000-0001-7690-0142. Candidate of Science (Engineering). Associate Professor.
Department of Avionics and Control Systems, State University "Kyiv Aviation Institute", Kyiv, Ukraine.
Education: National Aviation University, Kyiv, Ukraine, (2013).
Research interests: computer-aided design, reinforcement learning, neural networks, ground testing equipment, engineering, automation and control systems, computer science.
Publications: more than 20 papers.
E-mail: sdolgorukov@kai.edu.ua

С. О. Долгоруков. САПР-орієнтована оптимізація середньорозмірного безпілотного наземного транспортного засобу

У статті досліджується багатокритеріальна система автоматизованого проектування, призначена для пошуку оптимальних конфігурацій безпілотних наземних транспортних засобів, що експлуатуються в різноманітних середовищах та кліматичних умовах. Основна складність полягає у збалансуванні суперечливих цілей проектування, таких як вартість, вантажопідйомність, надійність та довговічність. Для вирішення цієї проблеми пропонується нова методологія проектування, що інтегрує систему САПР на базі штучного інтелекту, яка створює замкнутий цикл обміну інформацією на всіх етапах розробки, від концептуального проектування до польових випробувань. Ця методологія була перевірена під час розробки спеціального безпілотного наземного транспортного засобу середнього розміру з інтегрованою системою керування рухом, що складається з комерційних готових компонентів та деталей, розроблених на замовлення. Експериментальні випробування в різних умовах місцевості та клімату, включаючи експлуатацію взимку, продемонстрували високу маневреність, вантажопідйомність та дальність ходу 100 км. Результати доводять, що запропонований підхід дозволяє ефективніше проектувати безпілотні платформи нового покоління, успішно поєднуючи складну механіку, програмне забезпечення та технічні вимоги. Розроблена система має високу діагностичну цінність і допомагає чітко фокусувати подальші наукові та конструкторські пошуки..

Ключові слова: безпілотні системи, інтеграція апаратного та програмного забезпечення, системна інженерія, наземний транспортний засіб, автоматизоване проектування.

Долгоруков Сергій Олегович. ORCID 0000-0001-7690-0142. Кандидат технічних наук. Старший викладач.
Кафедра авіоніки та систем управління, Державний університет «Київський авіаційний інститут», Київ, Україна.
Освіта: Національний авіаційний університет, Київ, Україна, (2018).
Напрям наукової діяльності: автоматизоване проектування, навчання з підкріпленням, нейронні мережі, обладнання для наземних випробувань, інженерія, системи автоматизації та управління, інформаційні технології.
Кількість публікацій: більше 20 наукових робіт.
E-mail: sdolgorukov@kai.edu.ua