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UNMANNED GROUND-BASED ROBOTIC SYSTEMS: CLASSIFICATION AND ANALYSIS

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Abstract. The integration of unmanned ground-based robotic systems into logistics and other automation-intensive sectors has notably expanded in recent years. Despite their increasing prevalence, the lack of a unified classification framework has complicated the systematic selection and deployment of these platforms. This research has been initiated to address this gap by developing the EPAM classification system, which incorporates Environment, Purpose, Autonomy, and Mobility as core multidimensional criteria.

The purpose of this study is to develop a coherent and technically grounded taxonomy for Unmanned Ground Vehicles (UGVs), with a particular focus on logistics and multifunctional applications. The methodology has involved a comprehensive literature review, systematization of existing classification approaches, and a comparative analysis of their scope and limitations. The EPAM framework has been defined in terms of discrete sets of application environments (e.g., paved roads, dirt roads, rough terrains), intended functions (e.g., transport, patrol, combat, supply), autonomy levels (from remote-controlled to fully autonomous), and platform mobility types (wheeled, tracked, legged, hybrid).

Key findings have demonstrated that current classification systems fail to standardize vital technical parameters such as drive configuration, modularity, and autonomy architecture. Therefore, A consistent taxonomy has been proposed, enhancing technical communication between developers and users and supporting more informed decision-making. The novelty of the approach lies in its formalized, multidimensional structure, which enables the coverage of real-world UGV application scenarios and environmental constraints, including transitional terrains, wet surfaces, and complex, obstacle-ridden areas.

A preliminary classification of existing UGV platforms has been initiated to verify and validate the applicability of the EPAM model. This step will serve as empirical support for the robustness and scalability of the proposed system. The practical value of the study is reflected in its potential to foster interoperability standards, enhance procurement specifications, and expedite the development of adaptive UGV platforms for dynamic logistics operations.

Future investigations are expected to focus on refining classification criteria based on operational feedback, integrating Artificial Intelligence (AI)–based perception technologies, and applying the EPAM system in simulation and field-testing environments. The proposed framework offers a foundation for further scientific exploration in ground robotics and operational planning under uncertainty.

Keywords: unmanned ground vehicle (UGV), mechanical engineering, machine design, multi-dimensional classification, robotic systems, logistics automation, autonomous transport, platform mobility, robotics operational context.

Introduction

Modern *unmanned ground robotic systems* (UGRSs) technologies have been increasingly integrated into a wide range of domains that require process automation, operational efficiency, and enhanced safety. Of particular significance is their application in the field of logistics, where these systems have been utilized to perform autonomous transportation of cargo, including evacuation tasks and the delivery of critical resources and materials to inaccessible or hazardous locations. Due to these capabilities, UGRSs are well-positioned to play a crucial role in enabling flexible and rapid response solutions within contemporary logistical operations.

According to the analytical agency *Fortune Business Insights*, the global *unmanned ground vehicle* (UGV) market was valued at USD 3.07 billion in 2023, with projected growth to USD 6.35 billion by 2032, corresponding to a compound annual growth rate (CAGR) of 8.6 % [1]. In contrast, *Precedence Research* forecasts even faster growth, estimating the market to reach USD 3.60 billion by 2024 and USD 8.80 billion by 2034, with a CAGR of 9.35 % [2]. These estimates indicate a stable and increasing demand for UGVs in the near future. Regarding market structure, small-scale UGVs accounted for 58 % of the market in 2024, demonstrating a preference for compact solutions designed for specific tasks. Moreover, 65 % of the market share was held by tracked platforms, which offer high mobility in challenging environments, and 81 % of the systems were operated remotely.

Problem Statement

The significance of UGRSs in military and logistics applications has markedly increased under modern hybrid conflicts, which has stimulated the need for their regulatory forecasting and standardization. As indicated by Zinko et al. [3], the development of UGRSs is regarded as one of the key strategic directions for achieving asymmetric superiority over an adversary. The outlined key vectors for forecasting the development of unmanned systems, the presented vision of the UGRS ecosystem, the conducted SWOT analysis, and the scenario-based forecasting methodology involving a modified branch method as part of a broader foresight analysis [4] confirm the urgent need for unified approaches to the systematization of such systems, particularly in the form of classification models that consider environmental conditions of application, functional purpose, levels of autonomy, and mobility. The development of such a model represents the objective of the present study.

Therefore, the creation of a unified, multidimensional classification framework for UGRSs – based on drive type, structural configuration, and autonomy level would constitute a significant step toward standardization, thereby improving the efficiency of collaboration among all stakeholders involved in the development and implementation of robotic platforms.

Review of Modern Information on the Subject of the Paper

Available sources do not offer a generalized or standardized classification of UGRSs based on key technical parameters such as drive type, structural layout, or level of autonomy. Nonetheless, several isolated classification approaches have been proposed, focusing on intended use (e.g., combat, reconnaissance, transport), type of operational environment (e.g., ground, aerial, maritime), and levels of autonomy, which range from remote control to complete autonomy with decision-making capabilities.

Drive type (e.g., electric, hybrid, diesel) is usually mentioned in the context of energy efficiency analysis but is not incorporated as a component of a systemic classification framework. Similarly, structural layout (e.g., wheeled, tracked, modular) is occasionally used as a selection criterion for specific applications, although no universally accepted formalized approach currently exists. The lack of consistent terminology and a standardized classification methodology often complicates the formulation of technical specifications, leading to misinterpretation of system requirements.

The International Standard Organisation (ISO) 8373:2021 standard [5] contains a glossary of terms and definitions intended for use in ISO documents related to robotics and introduces a fundamental robot classification based on kinematic structure and mobility type:

1. **Manipulators**: *Rectangular / Cartesian robot*: features three prismatic joints; *Cylindrical robot*: includes at least one rotary and one prismatic joint; *Polar / Spherical robot*: This robot is comprised of two rotary and one prismatic joint; *Pendular robot*: contains a universal joint; *Articulated robot*: possesses three or more rotary joints; *SCARA robot*: equipped with two parallel rotary joints; *Parallel robot*: constructed with a closed-loop mechanism, e.g., Stewart platform.

2. **Mobile robots**: *Wheeled robot*: moves using wheels; *Legged robot*: moves using one or more legs; *Biped robot*: moves on two legs in a walking pattern; *Tracked / Crawler robot*: uses tracks for movement; *Humanoid robot*: anthropomorphic in shape and movement;

3. **Mobile platforms:** structures designed for movement, often forming part of Automated Guided Vehicles (AGVs).

4. **Wearable robots**: systems attached to the human body that augment human capabilities.

Siciliano and Khatib [6] propose a general classification and systematization of various robotic systems, which includes: **Industrial Robots**: designed to perform specific tasks such as assembly, welding, painting, or testing; **Mobile Robots**: capable of navigating through space, including autonomous vehicles and robots operating in unstructured environments; **Humanoid Robots**: imitate the human body and can perform human-like motions; **Micro and Nano Robots**: ranging in size from microscopic to nanoscopic, used in medicine (e.g., drug delivery or surgical procedures at the cellular level) and small-scale research; **Parallel Robots** consist of multiple coordinated elements for tasks requiring high precision and speed, which are used in material processing and virtual reality applications; **Biohybrid and Bionic Robots**: integrate living organisms or biological materials into robotic systems, such as robots with biological tissues or bionic prosthetics to restore human functionality.

Further details within the previously described categories of "Mobile Robots" and "Mobile Platforms" are practically absent. In the context of ground-based robots, the term "Unmanned Ground Vehicles" (UGVs) is commonly used. The lack of a recognized classification system for this class of robots motivates the search for and justification of a suitable framework. This study is specifically designed to address this need.

Objectives and Problems of Research

Therefore, creating a unified, multidimensional classification framework for UGRSs – based on drive type, structural configuration, and autonomy level – would constitute a significant step toward standardization, thereby improving the efficiency of collaboration among all stakeholders involved in the development and implementation of robotic platforms.

Main Material Presentation

The authors' expertise suggests that the classification of UGRSs must incorporate the following criteria: *Environment, Purpose, Autonomy*, and *Mobility*. Such an approach allows consideration of both technical and operational aspects, providing a foundational framework for analyzing various systems. The results presented in this study can serve as a basis for further research aimed at optimizing the design and functionality of such systems while ensuring their compliance with modern operational requirements.

A classification system entitled "EPAM" is proposed, which categorizes mobile robotic systems according to the following criteria: *Environment, Purpose, Autonomy*, and *Mobility*. Each of these criteria captures the essential functional and operational characteristics of UGVs, supporting a systematic analysis.

Below, the sets of possible values for each criterion are defined.

The classification of environments for the deployment of UGVs considers a variety of surface types and conditions these vehicles may encounter. Based on recent research, operational environments can be divided into the following categories:

1. **Solid surfaces**: *Paved roads*: asphalt or concrete roads that provide optimal wheel traction and predictable navigation (urban logistics, patrol). Sarwal et al. [7] have investigated the efficiency of UGV operations on such surfaces; *Dirt roads*: Beycimen et al. [8] analyzed terrain traversability. Natural ground surfaces vary in structure, firmness, and the presence of obstacles, such as stones or potholes, in agricultural and engineering applications.

2. **Soft and loose surfaces**: *Sand*: loose soil that complicates traction, particularly for wheeled platforms, while tracked and legged systems exhibit superior mobility (desert missions, reconnaissance) [8]; *Snow covers*: As reviewed by Researcher [9], robotic systems optimized for rugged terrain, snowy or icy terrain that limits traction and requires specific technologies, such as studded tracks (arctic and high-altitude operations).

3. **Wet or unstable surfaces**: *Swamps and bogs*: water-saturated terrain with low load-bearing capacity; tracked and legged platforms are better adapted (rescue and agricultural operations) [8]; *Puddles and colloidal soil mixtures* are shallow water surfaces that pose immersion risks (construction sites, military applications). Ersü et al. [10] systematically reviewed radar technologies applicable to UGVs.

4. **Transitional surfaces**: *Complex terrain*: Maaiveld et al. [11] studied tactical terrain analysis methods. Combinations of solid, soft, sandy, and wet areas create mixed conditions that require adaptive control systems (combat zones, rescue missions).

5. **Obstacles and barriers**: *Rugged terrain*: rocks, ravines, and tree-filled areas requiring enhanced chassis adaptability (forest reconnaissance, mountain operations) [9]; *Water obstacles*: shallow streams and water bodies that can be crossed using special tracks or waterproof electronic systems (military missions, engineering tasks) [8].

The set defined by the Environment criterion ***{E}*** *=* *{****pr*** *(paved road)* – for deployment on paved roads with markings; ***dr*** *(dirt road)* – for deployment on unpaved or dirt roads; ***rt*** *(rough terrain)* – for deployment in off-road conditions; ***o*** *(other)* – for deployment in all different conditions*}*.

Accordingly, platforms may be denoted using the following values: E_{pr} – designed for operation on paved roads, E_{dr} – on dirt roads, E_{rt} – in rough terrain, and E_o – in other environments. Platforms with multi-environment deployment capability may be designated as a subset of ***{E}***. For example, $E_{\{pr,dr\}}$ indicates platforms operable on both paved and dirt roads, while $E_{\{dr, rt,o\}}$ refers to those suitable for any environment except paved roads.

Classification according to **Purpose**:

t *(transportation)*: transport of cargo, resource delivery, and casualty evacuation. An example is the use of UGVs for delivering ammunition, supplies, or medical equipment.

p *(patrol and reconnaissance)*: intelligence collection, terrain monitoring, object surveillance, and perimeter patrol. An example is UGVs equipped with cameras and sensors for real-time data collection and situational awareness, as detailed on Wikipedia [12];

c *(combat)*: execution of combat tasks such as fire support and participation in offensive or defensive operations. Example: Mappes et al. [13] documented instances of fully robotic military operations – 'Ukrainian defense forces conducted the first fully robotic attack;

e *(explosive ordnance disposal)*: detection, neutralization, and removal of explosive hazards, including mines and unexploded ordnance. According to Krivtsun and Kupriienko [14], UGVs can be effectively used for the safe disposal of explosive devices;

s *(supply)*: carriage and use of support modules or systems to assist other operational tasks. Example: UGVs equipped with generators, communication gear, or other logistic payloads;

o *(other)*: specialized applications such as training, demonstration, or experimental tasks. Example: UGVs used in academic programs or prototype testing.

The Purpose criterion is represented by the set ***{P}*** *=* *{****t*** *(transportation)* – for cargo transport, resource delivery, and casualty evacuation; ***p*** *(patrol)* – for patrol missions and surveillance operations; ***s*** *(supply)* – for logistic support (carrying various payload modules); ***o*** *(other)* – for all different applications*}*.

Accordingly, the following notation is applied: P_t – platforms used for transportation, delivery of supplies, and evacuation of wounded personnel; P_p – platforms designed for patrol, surveillance, and reconnaissance; P_s – platforms equipped for support operations, such as mounting application-specific payloads; P_o – platforms intended for other uses, such as training or entertainment, demonstration purposes, or mission-specific tasks.

Platforms with multifunctional roles can be represented as a subset of $\{P\}$. For example, $P_{\{t,\ p\}}$ denotes a platform capable of both transportation and patrol; $P_{\{p,\ s\}}$ indicates a platform for patrol and supply purposes, including configurations for mounting additional modules such as weapon systems.

The classification based on the level of autonomy requires further in-depth analysis of American Society for Testing and Materials (ASTM) standards applicable to unmanned ground systems. This aspect is crucial for ensuring transparency in technical specifications and enhancing communication between developers, customers, and end-users. ASTM F3200-23, titled *"Terminology for Robotics, Automation, and Autonomous Systems"* [15], provides clearly defined terminology related to robotics, automation, and autonomous platforms. The standard covers a broad range of definitions, including terms relevant to unmanned ground platforms, such as levels of autonomy, functional purpose, and performance evaluation methodologies.

The detailed differentiation between levels of autonomy – from remotely controlled and programmable systems to fully autonomous platforms – aligns directly with the proposed Autonomy **(A)** criterion. This framework enables precise categorization of platforms according to their decision-making independence, reflecting the technological realities and operational needs of UGV deployment in both logistics and military domains.

ASTM F3200-23 is based on a consensus-driven approach, which supports seamless integration of the proposed EPAM classification into existing international regulatory frameworks. Moreover, the standard includes terminology that directly corresponds with the proposed Environment **(E)**, Purpose **(P)**, and Mobility **(M)** criteria, thereby significantly enhancing the compatibility and applied relevance of the developed classification model.

SAE J3016 [16] provides further insights into autonomy classification, which outlines various levels of automation and autonomy in unmanned systems. The autonomy levels for vehicles, initially defined by the U.S. National Highway Traffic Safety Administration (NHTSA) in 2013, were later revised and formalized in the International Society of Automotive Engineers (SAE) J3016 standard [16]. This classification system has become a foundational reference in the field of autonomous transportation, ensuring a common understanding among manufacturers, regulators, and consumers. SAE J3016 is employed for vehicle certification, regulatory compliance, and safety impact analysis related to automation technologies.

In addition to the SAE J3016 classification, other frameworks have been developed specifically for UGVs. ASTM Committee F45 has introduced a structured classification system that distinguishes between Automatic, Automated, and Autonomous modes for ground-based platforms, encapsulating varying levels of task execution independence.

According to ASTM Committee F45 [15], the autonomy of UGVs can be divided into three principal categories: **Automatic-UGV**: platforms that follow a predefined route and cannot deviate from it without operator intervention; **Automated-UGV**: platforms with limited ability to modify their route based on environmental changes, while still requiring significant human oversight; **Autonomous-UGV**: fully autonomous systems capable of independent decision-making, route planning, and adaptation to dynamic environmental conditions.

Autonomy levels for UGVs defined by ASTM F45 [15] include: **Level 1**: No autonomy – an operator manually controls the vehicle with no automated functionality (remotely operated platforms); **Level 2**: Shared control – the operator manages core functions, while the system provides partial assistance, such as speed maintenance or trajectory correction. The UGV may perceive its surroundings, but cannot make independent decisions (partially automated logistics platforms); **Level 3**: Automatic-

UGV – movement along a fixed, predefined path using encoded trajectories. Obstacle detection may be available, but autonomous response is limited (e.g., factory AGV systems); **Level 4**: Automated-UGV – capable of deviating from pre-planned routes to avoid obstacles. Environmental processing algorithms allow trajectory adjustment (e.g., Autonomous Mobile Robots used in warehouse operations); **Levels 5–8**: Autonomous-UGV systems with full autonomy in navigation, decision-making, and adaptation. These include advanced sensor integration, AI modules, and embedded decision logic. Typical applications include military operations, logistics, search and rescue, and exploration in off-road environments.

Additional autonomy factors include not only driving control but also: *Navigation* – ability to plan and reroute dynamically; *Decision-making* – capacity to process sensory inputs and make tactical choices; *Organizational interaction* – coordination with other vehicles under centralized or decentralized control; *Environmental complexity* – the capacity to function in structured and unstructured environments.

The ASTM F45 autonomy classification extends the SAE J3016 model by enabling finer granularity across industrial, logistics, and military unmanned platforms. The operational context–mission complexity, environmental dynamics, and operator interaction–substantially affects the level of autonomy required. Continued advancement of autonomous systems necessitates improvements in testing protocols and standardization frameworks [15].

An essential aspect of UGV classification is defining interaction with other unmanned systems, particularly aerial vehicles, which are frequently used in combined operational scenarios. Dinelli et al. [17] review hybrid drone-UGV configurations, highlighting the relevance of a comprehensive classification approach that incorporates multi-agent integration. Factors such as interaction, coordination, and collaborative mission planning between ground and aerial unmanned platforms are crucial for enhancing UGV functionality and ensuring operational effectiveness in complex mission environments.

Adapting the above-mentioned classification approaches for UGVs, a structured classification based on the autonomy criterion is introduced:

The set defined by Autonomy *{A} = {* ***p*** *(programmable)* – programmable systems; ***rc*** *(remote controlled)* – remotely controlled systems; ***a*** *(autonomous)* – autonomous systems; ***o*** *(other)* – other types of control*}*.

Accordingly, the notation includes: A_p – programmable platforms capable of executing various tasks based on predefined algorithms or programmed routines; A_{rc} – remotely controlled platforms operated by a human; A_a – platforms capable of performing tasks independently, including navigation and decision-making based on sensor inputs, AI, and adaptive mechanisms for complex operations in diverse environments; A_o – platforms operated through other control methods, such as bio-interface control systems.

Platforms with hybrid autonomy types are denoted as subsets of *{A}*. For instance, $A_{\{rc,\ a\}}$ indicates platforms that support both remote and autonomous control modes.

The Mobility criterion is defined by the set *{M} = {* ***w*** *(wheel)* – wheeled platforms; ***t*** *(track)* – tracked platforms; ***l*** *(leg)* – legged platforms; ***o*** *(other)* – platforms with alternative mobility systems *}*.

The set *{M}* may include the following values: M_w – platforms with wheeled propulsion; M_t – tracked platforms; M_l – legged platforms; M_o – platforms with alternative movement mechanisms, such as screw drives. Platforms with combined propulsion types are denoted as a subset of *{M}*. For example, $M_{\{w,t\}}$ indicates a wheel-track hybrid platform; $M_{\{w,l\}}$ refers to platforms capable of movement using both wheels and legs.

Subtypes of wheeled platforms include: M_{ws1} – single-wheeled platforms that maintain balance using gyroscopic sensors (e.g., Segway-type); M_{ws2} – two-wheeled balancing robots (similar to hoverboards); M_{wt3} – three-wheeled systems offering increased stability and manoeuverability; M_{wt4} – classic four-wheeled UGVs; M_{wm} – multi-wheeled platforms (6+ wheels) used for enhanced off-road capability. Łopatka et al. [18] investigated the terrain mobility of hydrostatically driven UGVs.

Subtypes of tracked platforms: M_{tc} – traditional rigid-frame tracked platforms with even weight distribution; M_{th} – hybrid wheel-track systems designed for adaptive movement; M_{tf} – flexible tracked platforms capable of shape adaptation for improved terrain navigation. Odedra et al. [19] explored mobility improvements in tracked UGV platforms.

Subtypes of legged platforms: $\boldsymbol{M_{l2}}$ – bipedal humanoid robots for uneven terrain; $\boldsymbol{M_{l4}}$ – quadrupeds offering high stability (e.g., Spot by Boston Dynamics); $\boldsymbol{M_{l6}}$ – hexapods used in research and rescue missions; $\boldsymbol{M_{ln}}$ – multi-pedal robots adaptable to diverse surfaces. Durst et al. [20] provided an overview of mobility modelling for autonomous UGV.

Subtypes of platforms using non-typical mobility methods ($\boldsymbol{M_o}$): $\boldsymbol{M_{os}}$ – snake-like robots employing wave motion for narrow spaces; $\boldsymbol{M_{oj}}$ – jumping robots using impulse propulsion; $\boldsymbol{M_{ot}}$ – screw-propelled platforms effective in sand or snow; $\boldsymbol{M_{om}}$ – magnetic robots capable of moving along vertical or metallic surfaces; $\boldsymbol{M_{oh}}$ – hybrid systems combining multiple mobility mechanisms (e.g., leg-track hybrids). According to Odedra et al. [21], mobility issues of hybrid systems.

The complete set of technical solutions for ground robotic systems is represented as a Cartesian product of the defined sets:

$$\boldsymbol{TR = E \times P \times A \times M}, \quad (1)$$

where $\boldsymbol{TR}$ denotes a technical solution, and $\boldsymbol{E}$, $\boldsymbol{P}$, $\boldsymbol{A}$, and $\boldsymbol{M}$ are the sets defined according to the rules outlined above.

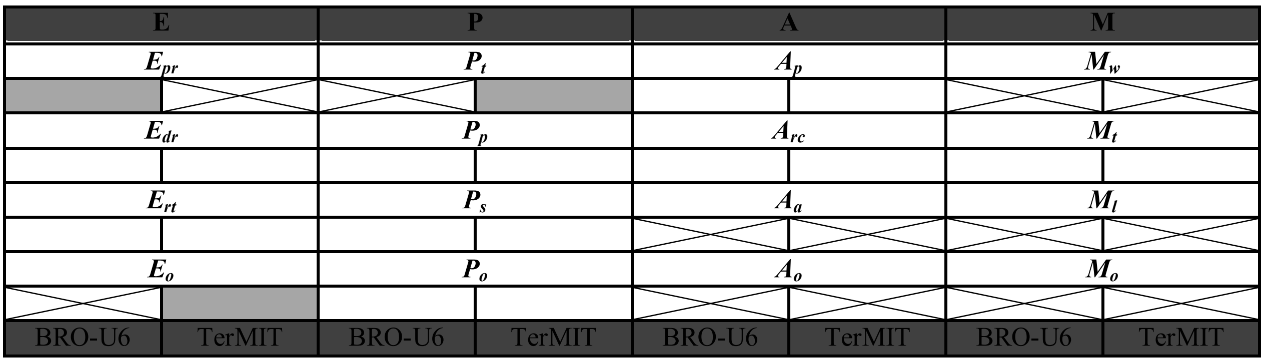
Examples of the identification of two domestic and two foreign ground robotic platforms are presented in accordance with the proposed classification framework.

Classification samples

UGV	Classification description
BRO-U6, Tracked UGV	$\boldsymbol{E_{\{pr,dr,rt\}} P_{\{p,s,o\}} A_{\{p,rc\}} M_{\{t\}}}$
TerMIT – Tracked Modular Infantry Transporter	$\boldsymbol{E_{\{dr,rt,o\}} P_{\{t,p,s,o\}} A_{\{p,rc\}} M_{\{t\}}}$
THeMIS UGV Milrem Robotics	$\boldsymbol{E_{\{dr,rt,rt\}} P_{\{t,p,s,o\}} A_{\{rc,a\}} M_{\{t\}}}$
Rheinmetall Mission Master SP	$\boldsymbol{E_{\{dr,rt,rt,o\}} P_{\{t,p,s,o\}} A_{\{p,rc,a\}} M_{\{w\}}}$

It is evident that comparing platforms is relatively simple when they are equivalent, and it becomes more complex as the divergence between their descriptions increases. Comparing models with identical descriptions should be carried out based on technical specifications, which are beyond the scope of the proposed classification system.

For comparison purposes, we recommend using a conformity matrix, an example of which is provided in Figure, illustrating the comparison of two domestic ground robotic systems: BRO-U6 and TerMIT. The matrix should be constructed in two stages. In the first stage, a qualitative analysis of both systems is conducted to identify common groups of characteristics for comparison and to highlight potential advantages. In the matrix, cells corresponding to features absent in a particular system are "blocked" (crossed-out cells). If the other system possesses the parameter, the corresponding cell is marked as a potential competitive advantage (we propose **shading it in gray**).



EPAM conformity matrix

At the second stage, the content of the unhighlighted cells is filled with technical specifications that can be compared on a unified basis (not shown in the figure), enabling a quantitative comparison.

Based on this analysis, engineers can conclude the advantages and disadvantages of the selected pair of ground robotic systems.

Conclusions

The issue of establishing a basis for comparing various ground robotic systems should be further specified within the "Mobile Robots" class. The proposed classification system "EPAM" is based on four key attributes: **E** – environment of operation, **P** – purpose, **A** – autonomy level, and **M** – mobility type.

A set of possible values has been defined for each attribute, and it has been demonstrated that the description of a specific technical solution constitutes a four-dimensional Cartesian product of these sets. The proposed system's applicability has been illustrated through examples involving both domestic and foreign robotic platforms.

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