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CERERE PROJECT: A PRACTICAL AND METHODOLOGICAL FRAMEWORK FOR DESIGNING AN OPTIMAL UGV FOR PRECISION AGRICULTURE IN WATER-LIMITED ENVIRONMEN

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Abstract
This paper summarises a research and development activity that integrates new technologies, innovative approaches, and advanced methodologies to design a multifunctional rover. The simulation and analysis techniques presented allowed the development of a highly customizable design that can meet specific functional and operational requirements. The rover featured in this report is designed for use in both off-road and urban environments. The rover features an optimized mechanical design that ensures stability, quiet operation, and reliability, making it suitable for a range of scenarios. Thanks to the modular approach and advanced simulation techniques, the design can be quickly adapted to the client's specific needs, reducing development time and offering tailored solutions across other performance levels. The use of the rover in scenarios with limited water resources is reported in the article. The use of such a solution enables the optimisation of water use through advanced monitoring strategies and targeted interventions. In such a way, sustainable and accurate management of water resources can be ensured.
Keywords: Unmanned Ground Vehicle, Precision Agriculture, Agricultural Robotics, Multibody Dynamics, Control Systems.

INTRODUCTION

Unmanned Ground Vehicles (UGVs) are a category of vehicles designed for ground operations. UGVs can be either remotely controlled by an operator or autonomous, meaning they can navigate and make decisions independently using sensors and artificial intelligence algorithms [1]. The development of the first UGVs began in the late 19th and early 20th centuries, with evidence of their use dating back to 1912. One notable early model was an "Electric Dog" tricycle that could follow a light source. Initially, these vehicles were primarily used in military applications [2]. UGVs are used in several sectors: a) Military and defense; b) Industrial and logistics; c) Civil and rescue; and e) Agriculture. One of the most interesting sectors is agriculture, where these vehicles are used for precision agriculture and smart water use. Autonomous UGVs are used for field operations such as data collection, fertilization, optimal water resource use, and soil and plant sampling [3]. These issues are addressed in [4], which describes the Agri.q rover, which features a structure capable of moving over uneven terrain and mounts a robotic arm for precision operations. Another UGV of considerable interest is Vitibot's Bakus development. With its design, the rover can move between vineyards, conduct plantation surveys, and intervene where necessary [5]. In the military context, rovers are used for ordnance defusing, surveillance, and

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operational support in high-risk contexts [6]. Several examples can be found in the literature. THeMIS, developed by Milrem Robotics, is a hybrid diesel-electric vehicle used for operational and combat missions, carrying armaments and heavy loads while maintaining high mobility [7]. THeMIS is designed according to STANAG 3542 standards. Such a vehicle can handle slopes of up to 60 percent and side slopes of up to 30 percent, providing excellent mobility over rough terrain. Another example of a UGV employed in the military is iRobot's PackBot. It has been used in various missions such as chemical weapons detection [8], in transporting wounded [9]. Another sector where UGV use is increasing is the construction industry.

Such use enables automation of complex tasks, such as site preparation, monitoring, and intervention, in harsh environments. These solutions reduce worker risk and improve operational efficiency. They are also handy for structural monitoring by reducing the costs of such operations. Usually, inspections and monitoring are carried out using lifting platforms, but they are expensive and there are lengthy operational interruptions [10]. During the design of these systems, one aspect that should not be underestimated is the choice of an appropriate locomotion system, which directly affects the vehicle's performance in terms of grip, stability, speed, and obstacle clearance. The two main configurations are wheels and tracks. Wheeled systems are widely used on paved roads and compact terrain and have several advantages: a) Less friction, b) Simplicity of construction, and c) Greater range. Track systems, on the other hand, provide greater grip, stability on rugged terrain, and even load distribution. However, they have some disadvantages, such as higher energy consumption, lower speed than wheeled vehicles, and faster mechanical wear and tear.

METHODOLOGY AND STAGES OF UGV DEVELOPMENT

The design methodology adopted for the platform's development is a structured, systematic process aimed at obtaining an optimal solution from a functional and performance perspective. The entire flow consists of eleven main phases: a) Functional requirements analysis; b) Definition of the system's outline dimensions and graphical mockup; c) 2D system pre-dimensioning; d) Kinematic analysis; e) CAD modeling; f) Multibody analysis; h) Structural FEM analysis; i) Definition of electronic components, h) Integrated electromechanical analysis; i) Sustainability and life cycle analysis. Design begins with functional requirements analysis, including operational needs, performance constraints, and environmental conditions. From this stage, the rough dimensions of the rover are derived, defined based on transportability, logistics, and modularity. To ensure multimodal transport and ensure a high degree of transportability, the following dimensions are defined: Length 1480 (mm), Width 1215 (mm), and Height 927 (mm). The creation of a mockup is the starting point for the structural and functional design of the new self-driving tracked UGV, based on skid-steer architecture and specially developed hybrid suspension. The rover is structured around a load-bearing chassis designed to optimize the protection of internal components and the use of the top surface. There is a battery housing inside the chassis, positioned so as not to take up space on the top surface, protecting the electronics from dust, water, and other adverse environmental conditions and ensuring safety and reliability. The top surface remains free and accessible, allowing the installation of additional instruments (robotic arms, sensors, modular payloads) for different missions. This configuration offers operational flexibility

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and allows the rover to be adapted to various scenarios without compromising internal protection. The conceptual graphical mockup of the rover, intended to define the system's overall architecture, is shown below. The rover uses a hybrid suspension system that provides stability, camber control, and even load distribution across the tracks. It combines elements of the MacPherson and Double Wishbone systems, optimized for a tracked vehicle's needs.

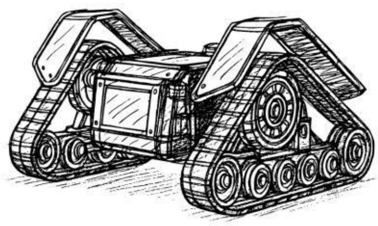

Fig. 1. *Conceptual Graphical Mockup of UGV*

Each track is connected to the chassis by three main components: a) The Main shock absorber connects the track to the chassis, absorbing shock and vibration; b) Lower arm: provides longitudinal and transverse track position control; c) Upper pendulum: adjusts camber and maintains it at zero degrees, ensuring even wear and optimum ground contact. To simplify locomotion and reduce complexity, the electric motor and gear motor are mounted directly on the crawler track. In this way, the motor follows track movements, improving dynamic response, and no universal joints or flexible shafts are required. The drive unit integrates a compact planetary gear, specifically developed to achieve the required reduction ratio in a small space while maintaining high efficiency and reliability. This solution allows the transmission to be concentrated on the track itself, reducing space requirements and simplifying maintenance. For clarity, below is a graphic mockup of the locomotion system.

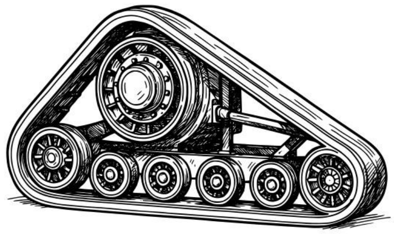

Fig. 2. *Conceptual Graphical Mockup of Locomotion Systems*

An initial 2D static analysis follows, which helps identify loads and critical structural points. This data feeds the predimensioning phase, which guides the subsequent three-dimensional CAD modeling phase. CAD modeling enables the creation of a realistic, accurate rover model, which is subsequently used for multibody analysis (MBD). At this stage, a full body was used to represent the overall geometry of the main frame and to study the system's dynamic behavior by calculating the constraint reactions at the contact and support points.

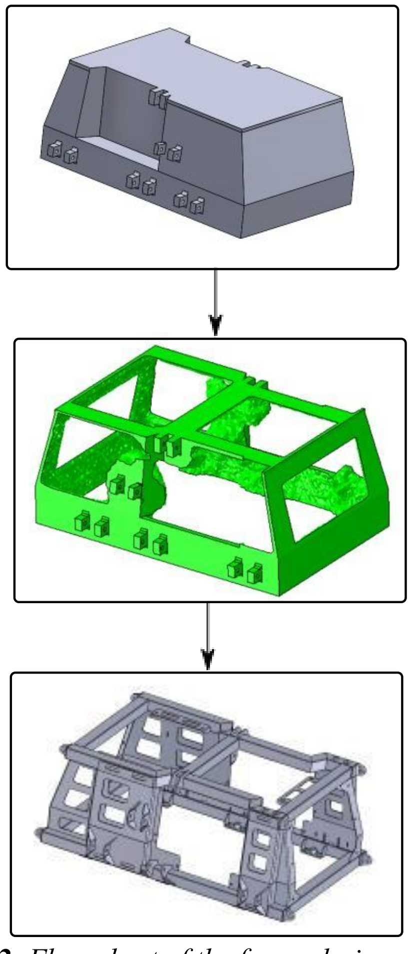

Fig. 3. *Flow chart of the frame design process*

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These reactions were then imported and applied as loads in the FEM analysis, allowing the actual stresses on the structural components to be evaluated. Using FEM, the frame geometry was optimized, reducing unnecessary mass and improving overall stiffness. Subsequently, based on the results, a geometry that could be realized with commercial components was developed, providing a better balance between lightness, strength, and the subsystems' integrability. Starting from the CAD model as a solid body, a topological optimization is carried out, and the structure shown in the intermediate step is obtained. After that, the final CAD model is created, taking into account which elements are commercially available for fabrication.

The electronic component definition phase aims to identify and select the devices required to control the rover's propulsion and energy management. Electronic components, such as motors, can be included in the multibody code to perform electromechanical simulations and validate design choices. Finally, the sustainability analysis aims to reduce the vehicle's environmental impact throughout its life cycle. Design choices follow green design principles such as energy efficiency and energy recovery; ease of maintenance and disassembly; and reduced fuel consumption and emissions. Life Cycle Assessment (LCA) tools are also used to assess environmental performance and to quantify future improvements.

TECHNICAL DESCRIPTION OF UGV

The rover, shown in Figure 4, features a robust, modular mechanical structure that enables operation in complex environments.

Fig. 4. *Virtual Prototyping of UGV*

The supporting structure consists of an electro-welded steel tubular frame, which provides high mechanical strength. The overall dimensions of the vehicle are: height 233 (mm), width 1215 (mm), and length 1211 (mm) with an empty weight of about 400 (kg).

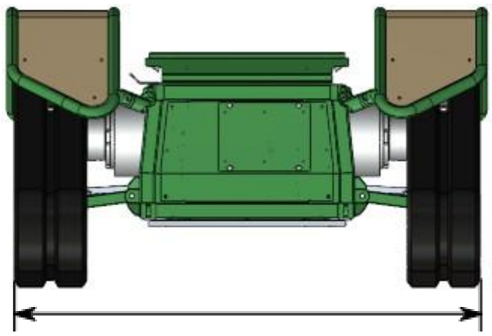

Fig. 5. *Frontal View of UGV*

This configuration ensures a good compromise between compact stability and load capacity.

The locomotion system is based on rubber tracks, shown in Figure 6. This system is chosen to improve its stability and load distribution, reducing ground pressure.

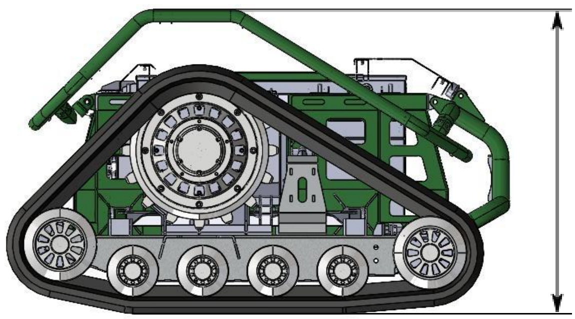

Fig. 6. Lateral View of UGV

A spring mechanism and adjustable shock absorbers achieve suspension. The rover is also equipped with a trailer hitch system and a modular, customizable load floor. The latter can be configured to meet operational needs, enabling the transport of materials and equipment, or the installation of robotic arms or sensors for monitoring, sampling, or targeted intervention.

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OVERALL ARCHITECTURE OF THE CONTROL AND PERCEPTION SYSTEM

The whole architecture of the control system is reported in Figure 7. The design is organized into distinct but connected functional levels. A battery powers the entire system, distributing energy to the power modules (Drive I and Drive II). These modules regulate the current to the electric motors (Motor I and Motor II). The drivers get command signals from two control units that use the Arduino MEGA 2560 microcontroller. These units serve as middleware between the onboard computer and the motor drivers.

common ground, ensuring a stable electrical reference and reducing signal noise. The middleware facilitates communication and interaction between the NVIDIA onboard computer and the motor driver. The onboard computer manages data processing and control logic. The motor driver physically controls the rover's motors. The middleware processes data from the onboard computer and translates it into commands the motor driver can understand. This allows for the integration of different communication protocols and improves system flexibility. To extend the system's perception and autonomy capabilities, a high-performance NVIDIA Jetson TX2 computing module has been added to the basic architecture to

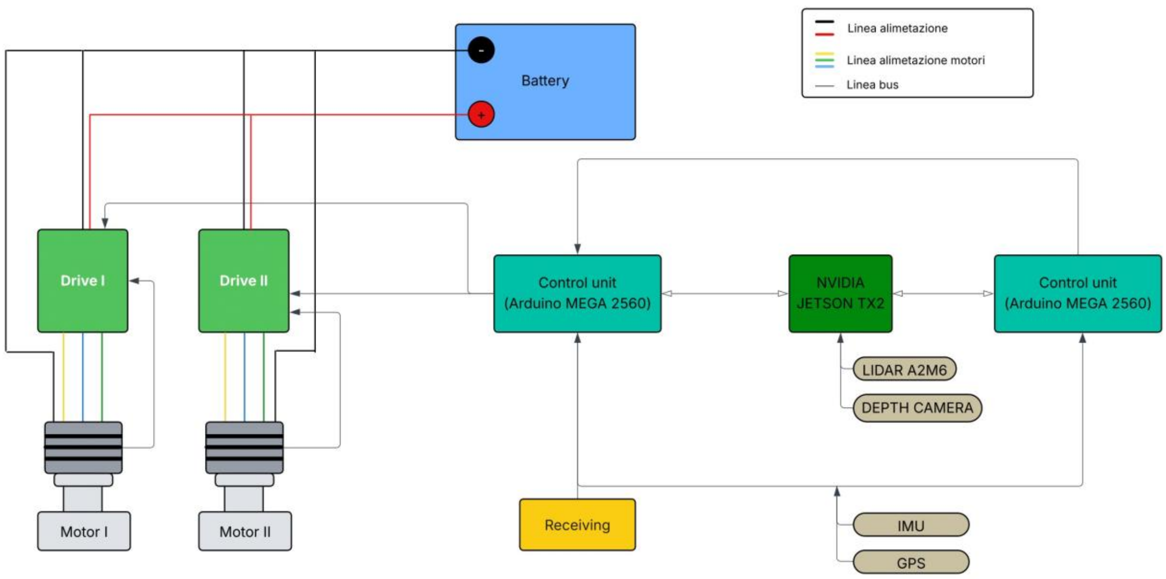

Fig. 7. Hardware Systems

These units serve as middleware between the onboard computer and the motor drivers. They manage low-level control through bus signals and directional signals to coordinate the motors. Additionally, they connect to a receiving module to acquire external commands. Connected to the Arduino is a GPS module with 1-3 meter accuracy for global positioning, and an IMU unit that manages the robot's orientation, contributing to the system's overall positioning. All components share a

manage advanced vision and navigation sensors, such as the A2M6 Lidar, a laser scanner connected directly to the onboard computer, and a depth camera. These sensors, connected directly to the NVIDIA module, provide three-dimensional data and environmental information, which are processed in real time for obstacle detection and scene reconstruction. The results of this processing are transmitted to the two Arduino units, which operate in parallel and perform complementary control and interface functions. In the software

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implementation, each microcontroller is programmed in the embedded C language to perform specific real-time management and control tasks. In particular, each microcontroller processes commands from the cognitive level and converts them into specific control signals for the respective power drivers and electric motors. This configuration distributes the computational load across the two microcontrollers to improve the system's responsiveness and robustness. The multi-level division of perception, processing, and control ensures high efficiency, modularity, and operational reliability, enabling the system to achieve robust, scalable autonomous behavior. To illustrate the system's planning and control, as well as the integration among the various modules and connections, a flowchart is presented in Figure 8.

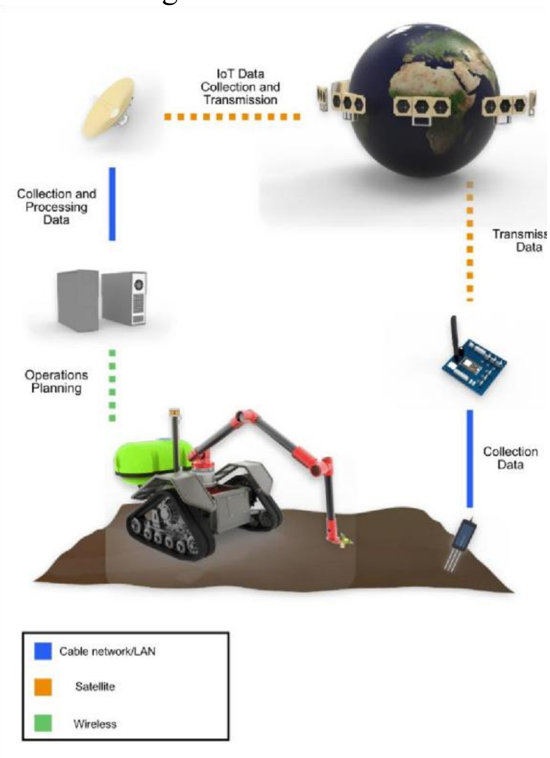

Fig. 8. *Flow Chart of the project*

To ensure reliable long-range communication within the multi-level system, a dedicated space segment has been implemented. In particular, the satellite constellation component, based on picosatellites produced by Apogeo Space, a private Italian constellation dedicated to the Internet of Things (IoT), enables continuous data exchange between the UGV and remote control centers. These satellites, typically measuring 10 × 10 × 3 cm and weighing less than 1 kg, fall into the picosatellite category and are deployed in low Earth orbit (LEO) to minimize latency and energy consumption (Figure 9).

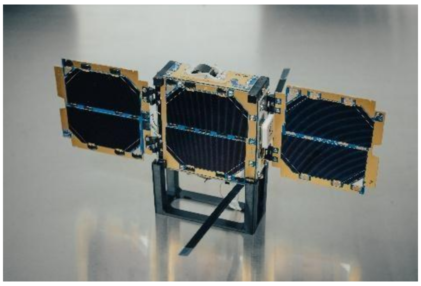

Fig. 9. *Satellite*

The constellation is designed to offer global coverage and to operate collaboratively among dozens—up to 96 units expected to be completed by 2027—accelerating revisit time and enabling two-way communication for small data packets from sensors and IoT devices. From a technical standpoint, each unit integrates miniaturized solar panels, a compact satellite bus, and a 169 MHz communication module, with a typical payload of 10 bytes (including an identifier and timestamp). Each satellite passes over a ground station, providing an average communication time of around 6 minutes. Thanks to its low orbital profile ≈ 0 k and modular structure, this approach provides a scalable platform for the UGV that can transmit data even from remote areas disconnected from terrestrial infrastructure, ensuring a resilient connection with the space constellation. Furthermore, adopting a proprietary protocol and AES -256 encryption ensures the security and integrity of transmitted data.

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Fig. 10. *Ground Satellite Antennas*

Therefore, this system enables the implementation of a lightweight, dedicated satellite communication network that can be seamlessly integrated into the UGV context, allowing the vehicle to send small telemetry or sensor packets via satellite with high reliability, even in challenging operating conditions.

For interfacing between the UGV and the picosatellite constellation, an Apogeo Space satellite modem was adopted, designed for the transmission of small data packets in IoT architectures based on LEO orbits. The device, shown in Figure 10, is the onboard unit responsible for connecting to Apogeo's proprietary satellite network. The module is based on a low-power architecture and integrates a 169-MHz-band transceiver compatible with the Apogeo protocol, enabling communication with the constellation's satellites during visibility windows. The board has a UART/USB interface for connecting to microcontrollers or SBCs (Single Board Computers) for the UGV. It supports an optimized message format with a 10-byte payload, node ID, and timestamp. The modem is also equipped with a high-gain external antenna and power management circuits for sleep mode during periods of inactivity, reducing power consumption and ensuring continuous operation in remote environments. Integrated AES 256 encryption protects transmitted data and provides robustness against interference and attacks.

Thanks to these features, the Apogeo modem is an efficient solution for lightweight and secure satellite connections. It can be seamlessly integrated with autonomous mobile systems, such as UGVs, enabling real-time telemetry and sensor data transmission without terrestrial infrastructure.

CONCLUSION

This paper falls within the authors' research range, from multibody simulation of mechanical systems to nonlinear identification and control. The proposed methodology for system design is based on analytical and numerical tools, making it applicable to a wide range of systems. In this case, the rover is designed for automated irrigation of plants in areas with reduced water availability. The goal is to ensure efficient and sustainable use of water resources. An additional advantage is the use of a communication network based on satellite IoT signals, which enables the rover to maintain high reliability and operational continuity. In addition, the elaborate approach to machine automation is not limited to new projects, but can also be integrated into existing, operational machines. This feature makes the technology highly scalable, versatile, and easily adaptable to different application contexts. The goal is to develop new technological apparatuses that combine efficiency, reliability, and operational safety.

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