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Research on design and implementation of innovative UGV modular platform in mine action programs

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Abstract

This research paper focuses on the development of an innovative system applying the UGV (Unmanned Ground Vehicle) modular platform in the fields of humanitarian demining, where the scientific research process demonstrates the multifunctional application of such systems, or similar ones, in civil protection sectors. The use of the UGV platform enables more efficient mission completion in scenarios where human lives are directly at risk, such as demining operations. The UGV platform, with its modular design and development approach, represents a modern method for the advancement of such systems, offering multi-operation and multifunctional applications.

Keywords: Humanitarian demining, UGV (Unmanned Ground Vehicle), Civil protection

1. Introduction

The resolution of the global issue of residual landmines and unexploded ordnance (UXO) has always been one of the most strategically demanding tasks. Apart from posing significant risks to safety, it also presents a substantial challenge in terms of accessibility to difficult and demanding terrains. The problem of residual mines and UXO is inherently significant and complex; when coupled with challenging terrain, the issue escalates to an extreme level. Systems for mine and UXO clearance have been in existence for many years, especially mechanical systems that have proven to be among the most effective and efficient solutions. These systems not only enhance operational effectiveness but also provide exceptional protection to personnel on the field. Research regarding this topic can be found ie. in [1,2,3,4,5,6,12].

A large majority of minefields and UXO are estimated to be located in highly demanding terrains with uneven topography. Bosnia and Herzegovina, a country heavily affected by the residual mine and UXO problem, exemplifies this issue, particularly due to its challenging topography. This serves as the foundation for the scientific research presented herein, which proposes a potential solution. The demanding topography of Bosnia and Herzegovina poses a unique challenge to resolving the residual mine and UXO problem. Existing solutions available on the market are effective only on slopes not exceeding 15 to 20 degrees, which is significantly below the gradient of the terrain where minefields are located in Bosnia and Herzegovina. Over the past few decades, from the 1990s to the present day, several innovative solutions for demining in challenging terrains have been developed. However, none have reached the stage of serial production. Difficult and uneven topographical areas are still cleared primarily using manual detection and removal methods, which carry a high risk for field personnel. While manual methods, alongside mechanical approaches, remain among the most effective demining techniques, they come at a considerable cost to human safety. The primary objective of designing and developing solutions that facilitate mine and UXO clearance is to prioritize the protection of human lives.

2. Machines that save human lives

In our previous paper [6] we elaborated on the issue of landmines both globally and in Bosnia and Herzegovina, with a particular emphasis on the most effective methods for detecting and removing mines and UXO in terrains with challenging topography. Machines that save lives are precisely those systems based on mechanical demining principles, which have demonstrated both effectiveness and efficiency. According to an analysis conducted by the Croatian Mine Action Centre (HCR), performed in accordance with the International Mine Action Standards (IMAS) and national Mine Action Centres (MAC), it has been shown that a single demining machine can accelerate the demining process by 50%. This equates to replacing the work of three sniffer dogs (biosensor detection method) or the efforts of two demining teams (16 individuals) [1].

2.1. Economic factor

In addition to accelerating the demining process for a given area, mechanical systems directly protect and save human lives by eliminating the need to expose trained personnel to direct danger. Moreover, the accelerated process enables a reduction in suspected mine-explosive areas, which significantly impacts the number of potential casualties. This is particularly critical, as a large portion of suspected mine-contaminated areas in Bosnia and Herzegovina is still located near populated regions. The protection and preservation of human lives, as previously emphasized, remain the most important priority. However, another crucial factor that justifies the use of mechanical demining systems, especially in terrains with demanding topography, is their economic efficiency. Demining is an inherently expensive process. Training sniffer dogs and educating personnel also represent significant financial challenges. However, when considering the overall effectiveness and operational outcomes of the three main methods, mechanical demining proves to be the most economically viable.

Although the initial budget and resources required to procure a mechanical demining system are substantial, such a system demonstrates long-term cost-effectiveness. A well-functioning system, operating year-round regardless of weather conditions or terrain, with regular maintenance and repairs, becomes a financially sound investment. More importantly, such a system might save even a single human life - a value that is truly immeasurable. The economic feasibility of mechanical demining systems is further reinforced by their versatility. Many systems can be repurposed for other applications if needed. For instance, a single system with multiple attachments can be simultaneously utilized for mine-clearing operations and firefighting missions, thereby further justifying its economic value [1].

Using advanced systems such as mechanical demining paired with advanced detection technologies can significantly improve the cost-effectiveness and efficiency of mine action programs. Here's how these methods compare to traditional approaches.

Cost-Efficiency:

- Reduced labor costs: advanced technologies reduce reliance on manual deminers, who require extensive training and are often the most significant recurring cost in demining operations.
- Faster clearance rates: mechanical systems like flails, tillers, and excavators can clear larger areas more quickly, reducing the time and, consequently, the overall costs of operations.
- Precision from advanced detection: technologies like ground-penetrating radar (GPR), drones with multispectral imaging, and AI-enhanced metal detectors minimize false positives, saving time and resources.

Enhanced Safety:

- Minimized risk to humans: mechanical systems and autonomous vehicles reduce the need for personnel to work in close proximity to landmines, decreasing the risk of injury or death.
- Improved detection accuracy: advanced sensors reduce the likelihood of missed mines or unnecessary excavation caused by false positives, making the process safer and more predictable.

For example here is a comparison between traditional and advanced system demining, and although it costs more at the beginning, on a larger scale, where minefields are on a wide spread of an uneven and hard-to-reach terrain, mechanical demining is more cost-effective.

- Traditional Methods:
  Manual demining can cost \$1–\$4 per square meter and take years for heavily mined areas.
- Advanced Systems:
  Costs range from \$2–\$10 per square meter initially but scale better in larger operations due to increased efficiency and time savings [2].

It is also worth noting that, since the entire study is primarily based on data collected from the territory of Bosnia and Herzegovina, where minefields are located in particularly challenging terrains, the case study has demonstrated that mechanical demining paired with GPR detection has significantly improved the conditions in the field, improving clearance rates in regions with heavy contamination.

3. Multifunctional and multimodal solutions available on the market

Year after year, demining systems continue to improve, particularly those that perform simultaneous detection and clearance, thereby increasing their level of efficiency. The market for mechanical demining systems is not significantly diverse when it comes to the applied methods, which are primarily based on milling systems and digger systems. The key differences lie in the total effective width of operation and the depth of excavation.

Detection system technology plays a pivotal role in enhancing clearance systems. With advancements in technology and the application of AI software for data analysis, it is possible to create highly detailed vehicle navigation maps with minimal deviations. It is important to note that civilian and humanitarian demining systems are essentially derived from military demining systems, which have been further refined to enhance their efficiency. This distinction forms the basis of the differences between military and humanitarian demining. According to the International Mine Action Standards (IMAS), based on United Nations (UN) guidelines, humanitarian demining must achieve an accuracy rate of 99.6%.

Therefore, demining systems, particularly those dedicated to humanitarian demining, must be designed to meet international IMAS standards to ensure the highest possible efficiency. Over the past two decades, the market for demining machines has seen the emergence of so-called modular platforms or modular vehicles. These serve as base stations to which specific attachments - such as mechanical demining systems - can be connected. The advantage of such systems lies in their efficiency and cost-effectiveness, as previously mentioned since they can be reallocated and adapted for other purposes depending on the need.

The most common applications of these systems are as follows.

1. Military operations. Military applications have continued to drive innovation in UGV (Unmanned Ground Vehicle) technology. The Gulf War in the early 1990s highlighted the need for unmanned systems to perform dangerous tasks such as bomb disposal and reconnaissance. This led to the development and deployment of UGVs such as iRobot's Pack Bot and Foster-Miller's TALON. These UGVs were extensively used in conflicts in Iraq and Afghanistan for tasks like detecting and neutralizing improvised explosive devices (IEDs).
2. Civil and commercial use. In recent years, UGVs have found applications across various civilian and commercial sectors. In agriculture, UGVs are used for precision tasks such as soil analysis, planting, weeding, and harvesting, ensuring high efficiency and accuracy. In the logistics industry, UGVs

automate warehouse operations, transport goods, perform inventory checks, and manage logistics. In the construction industry, UGVs are employed for tasks such as surveying, material transport, and heavy equipment management, improving both safety and productivity.

3. Humanitarian and rescue missions. UGVs have also proven invaluable in humanitarian efforts and disaster response. They are deployed in disaster zones for search and rescue operations, debris removal, and supply delivery. Their ability to operate in hazardous environments makes them essential for tasks too dangerous for human rescuers. For instance, UGVs were heavily utilized following the Fukushima Daiichi nuclear disaster in Japan for damage assessment and cleanup operations in areas with high radiation levels.

DOK-ING MV-4 (Fig. 1) is one of the world's most renowned light-class robotic systems, designed for demining operations and explosive ordnance disposal (EOD). Its low profile and robust structure make it highly resistant to detonations from all types of anti-personnel mines and UXOs of similar explosive intensity. Additionally, it is capable of withstanding explosions from anti-tank mines.

Figure 1. DOK-ING MV-4 [7]

HOME x HOWE Thermite robotic firefighters (Fig. 2) are among the most capable and durable firefighting robots on the market. Designed to mitigate life-threatening situations, these tools provide fire suppression, situational awareness, and intelligence gathering for first responders. Thermite robotic firefighters are essential allies in high-risk, hazardous environments.

Figure 2. HOWE x HOWE robotic UGV [8]

The Aardvark GEN 2 (Fig. 3) is an advanced unmanned ground vehicle (UGV) specialized in humanitarian demining and other demanding engineering tasks. Developed by Aardvark Clear Mine Ltd, this system is designed to deliver a high level of safety and efficiency in mine clearance operations.

Figure 3. Aardvark GEN 2-concept [9]

MILREM ROBOTICS Multiscope UGV (Fig. 4) is a fast, cost-effective, and flexible solution for the mining sector, helping companies keep workers away from hazardous locations while saving time and energy. The UGV can be remotely operated to access dangerous areas or utilized for automated transport of heavy equipment and materials.

Figure 4. MILREM ROBOTICS Multiscope UGV-Firefighting UGV [10]

TEXTRON RIPSAW M5 (Fig. 5)combines the speed of innovation with proven program performance, making it combat-ready. As the 5th generation of the RIPSAW series, the M5 delivers speed, mobility, and unmanned capability. It can maneuver silently and keep pace with current and future maneuver forces, pushing capabilities beyond human formations.

Figure 5. TEXTRON RIPSAW M5 UGV platform [11]

3.1. UGV (Unmanned Ground Vehicles)

Unmanned Ground Vehicles (UGVs) are robotic systems that operate on the ground without human presence. They can be remotely controlled or operated autonomously, utilizing various sensors and control algorithms for navigation and task execution. UGVs come in diverse shapes and sizes, tailored to specific applications, ranging from small, portable reconnaissance robots to large, rugged vehicles for heavy-duty tasks. These vehicles are equipped with advanced technologies such as GPS, LiDAR, cameras, and communication systems, enabling efficient operation in various and often challenging environments [1].

3.1.1. History of UGV (Unmanned Ground Vehicles)

Early beginnings

The concept of unmanned vehicles dates back to the early 20th century. One of the first recorded uses of unmanned vehicles occurred during World War I with the development of remotely controlled tanks and torpedoes. These early systems were primitive by today's standards but laid the foundation for future innovations.

World War I and the interwar period

During World War I, the British Army experimented with the "Wickersham Land Torpedo," a remotely controlled explosive device. Although it was not widely adopted, this early experimentation demonstrated the potential of unmanned ground systems for military applications. During the interwar period, several nations continued to develop remotely controlled vehicles, primarily for military purposes. The most notable among them was the German Goliath tracked vehicle, used during World War II. It was a small, wire-guided vehicle designed to deliver explosives to enemy positions.

Modern era: 1990 to present

The modern era of UGV development began in the 1990s, with significant technological advancements and a broader range of applications beyond the military. Progress in electronics, computing, and sensors has enabled the development of more sophisticated and capable UGVs.

3.2. Use of UGVs in humanitarian demining

The modern approach to addressing the problem of landmines and explosive remnants of war (ERW) worldwide increasingly relies on the application of Unmanned Ground Vehicles (UGVs). These systems offer significant advantages in efficiency and safety, particularly in the context of humanitarian demining. UGVs provide essential functionalities that enhance the demining process.

The Application of UGVs in Humanitarian Demining is following:

1. Minefield detection
   UGV systems equipped with advanced sensors (for detecting metal, heat, or explosive substances) enable rapid and precise mapping of minefields, eliminating risks to human lives.
2. Explosive device neutralization
   UGVs with specialized manipulators allow for the safe removal or neutralization of mines and ERW, ensuring high precision and safety during operations.
3. Terrain mapping
   UGV systems facilitate detailed mapping of minefields, recording data on the locations of mines and explosive devices, thereby streamlining the planning and execution of demining operations.

The advantages of UGVs are numerous**.** In mine action operations, UGV systems offer a rather broad spectrum of benefits:

1. Enhanced operational efficiency by performing multiple tasks simultaneously.
2. Reduced human exposure to hazardous environments.
3. Increased adaptability, as the same UGV base can be repurposed for different missions.

Their utility extends beyond demining. Analysis of existing innovative systems in the market reveals a wide range of applications, particularly in civil protection. UGVs have become indispensable in various aspects of civil protection, including:

1. Search and rescue
   UGVs are deployed to locate individuals endangered by natural disasters such as earthquakes, floods, or hurricanes. Their ability to access hazardous or hard-to-reach areas makes them invaluable tools for saving lives.
2. Firefighting
   Equipped with sensors for detecting fires and hazardous gases, UGVs enable firefighters to respond rapidly and manage fires more effectively.
3. Disinfection
   UGVs can be employed to disinfect public spaces or surfaces in response to outbreaks of infectious diseases, such as COVID-19. Their autonomy ensures efficient disinfection without exposing humans to risk.

By integrating UGVs into these critical operations, organizations not only enhance safety and efficiency but also leverage advanced technology for broader societal benefits.

3.2.1. Efficiency and reliability of UGVs

Efficiency

The efficiency of Unmanned Ground Vehicles (UGVs) pertains to their ability to perform tasks with minimal loss of time, energy, and resources. Key factors influencing efficiency include:

1. Energy management
   Efficient UGVs optimize battery usage and energy consumption. Advanced energy storage systems and regenerative braking are common features that enhance energy efficiency.
2. Navigation and path planning
   Advanced navigation systems utilizing algorithms for optimal route planning reduce travel time and energy consumption. Techniques such as Simultaneous Localization and Mapping (SLAM) are widely applied to improve navigational efficiency.
3. Task execution
   UGVs equipped with multifunctional tools can perform various tasks without the need for equipment replacement, thereby enhancing overall task efficiency.

Reliability

Reliability is a critical aspect of UGV performance, particularly in applications where failure can have significant consequences. Reliability encompasses the ability of a UGV to consistently perform its intended functions under specified conditions. Key factors include:

1. Mechanical reliability
   This involves the robustness of a UGV’s physical components, including the chassis, wheels, tracks, and manipulators. Studies have shown that mechanical failures, such as those related to propulsion systems or actuators, are common but can be mitigated through regular maintenance and robust design.
2. Reliability of sensors and control systems
   Reliable sensors and control systems are essential for accurate navigation and operation. Failures in these systems can lead to navigation errors or issues in task execution. Advances in sensor fusion and fault-tolerant control systems have significantly enhanced the reliability of these critical components.
3. Communication Reliability
   For teleoperated UGVs, reliable communication systems are essential. Issues such as signal loss or interference can disrupt operations. Improvements in communication technology, including the use of redundant communication channels, have been implemented to address these challenges.

4. Conclusion on designing an innovative UGV system

The future of addressing tasks that carry significant risks to human safety and have the potential to cause unnecessary consequences on the ground lies in the implementation of autonomous or teleoperated (remotely controlled) systems such as UGVs (Unmanned Ground Vehicles). Additionally, the future of vehicles designed for executing specialized missions also resides in the UGV segment. Investments in the scientific and design aspects of UGV development will ensure easier operation and execution of more complex missions, particularly those involving direct human danger. Integrating AI technology into autonomous navigation will enhance the operational effectiveness of UGVs while also improving control systems. This positions the human operator as a supervisor overseeing the entire operation, whether it be humanitarian demining, rescue missions, firefighting, or similar tasks.

Power Systems and Propulsion in UGVs

Analyzing current market solutions, we gain valuable insights into the power supply and propulsion mechanisms of UGVs, which form the vehicle's core and are crucial for uninterrupted mission execution. Despite the global industry's gradual shift towards complete electrification to reduce CO_2 emissions, UGV propulsion systems must retain fossil fuel-based power sources, particularly for applications such as humanitarian demining or rescue missions, where uninterrupted power supply is vital.

The rationale is straightforward: in remote and challenging locations far from communication networks, it is more practical to deliver one ton of fuel than to install electric cables spanning hundreds of meters or even kilometers.

Key Design Principles for Innovative UGV Solutions

The design of an optimal and innovative UGV system can be summarized into five key points:

1. Vehicle dimensions
   Compact vehicle dimensions that allow passage through dense vegetation and rugged terrain, comparable to the size of an average off-road vehicle, are essential for accessibility.
2. Modular platform
   A modular platform enhances cost efficiency for repairs and maintenance, facilitates multifunctional use depending on the installed module, and accelerates development time by treating each segment as an independent module (e.g., propulsion, power, or operational module).
3. Versatility in missions
   A thoughtfully designed platform capable of handling a wide range of tasks, including military operations, civil applications, humanitarian missions, and rescue operations, ensures adaptability.
4. Vehicle as a power station
   UGVs powered by internal combustion engines, combined with electric generators, can serve as mobile power stations during natural disasters.
5. Development for future use
   Applying the modular principle to smaller vehicle segments allows for future development and expanded application.

Innovative Development in Collaboration with Federal Civil Protection

The development and research process for creating this innovative solution was conducted in collaboration with the Federal Administration of Civil Protection, specifically the Demining and Explosive Ordnance Disposal Sector. This partnership led to the realization of a multifunctional solution suitable for a variety of missions and tasks, or alternatively, as a power supply unit. Feedback from trained personnel with decades of experience in mine action operations played a critical role in identifying both innovative and efficient methods for mechanical demining, particularly in challenging terrains with complex topography, such as those found in Bosnia and Herzegovina. Below is an illustration of the conceptual design (final sketch) that led to the further development of the modular UGV platform.

Figure 6. Ideation sketch that was the final stage of the final design

5. Development of the UGV modular platform

By defining the UGV design through sketches and developing each element of the modular platform, we advance to the next stage of design and development: constructing a 3D software model. The 3D software model provides a comprehensive view of the vehicle's form, allowing us to make necessary adjustments to enhance functionality. As mentioned earlier, the design follows the principle of a modular UGV platform. In line with this principle, each element or module is modeled individually in 3D before assembling the final model. Figure 7 features numbered modular platform elements. Dimensions are presented in Fig. 8.

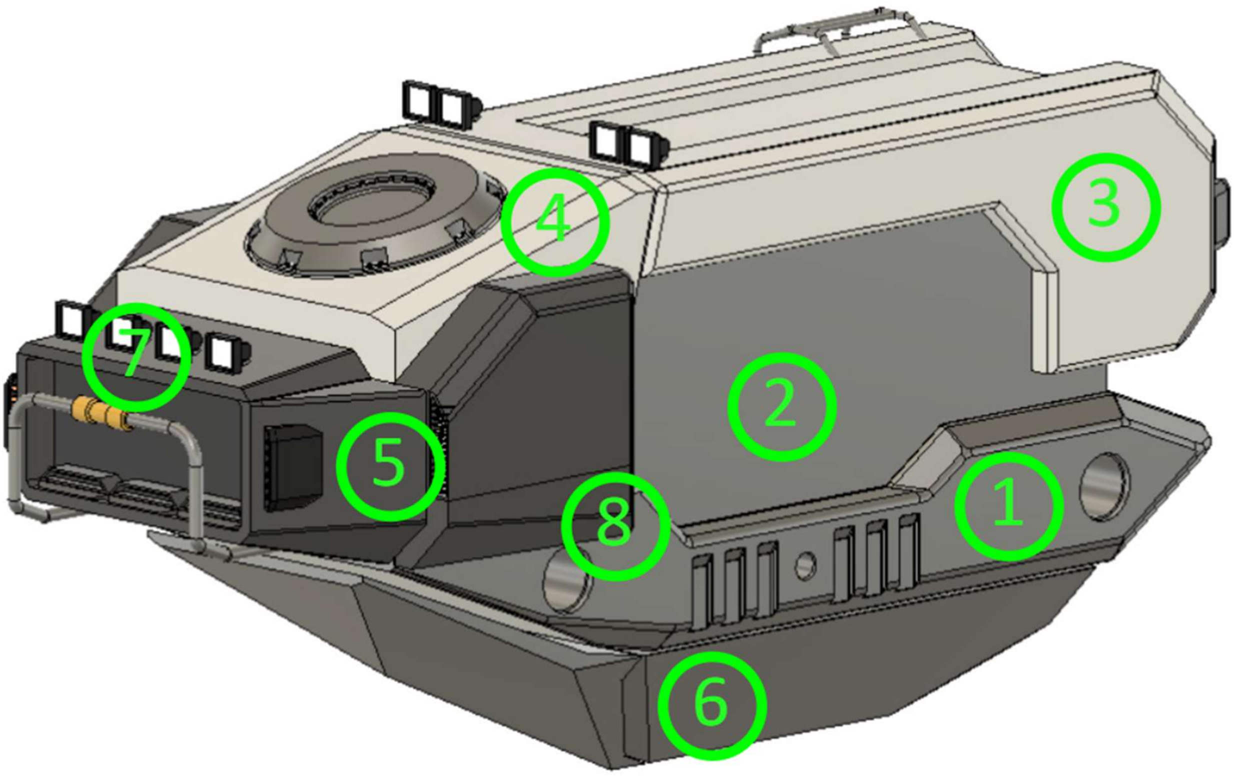

Figure 7. The final design of UGV modular platform-modular segments

1. Main load-bearing platform
   The foundational structural element that supports all components of the UGV, ensuring stability and strength during operations.
2. Central drive system
   The core propulsion system responsible for powering the vehicle is equipped with robust engines or motors suitable for varied terrains and tasks.
3. Protective roof covering
   A shield that safeguards internal components from environmental hazards and potential impacts.

4. Module base
   A modular framework designed to securely house interchangeable mission-specific components.
5. Protective bullbar with integrated radars, scanners, and cameras
   A front-mounted protective structure equipped with advanced detection and navigation technologies to enhance situational awareness and operational safety.
6. V-hull (external module for blast wave deflection)
   An externally mounted feature designed to deflect explosive shockwaves away from the vehicle, providing additional safety in hazardous conditions.
7. Other vehicle parts (lights, supplemental radar systems, ladders, etc,)
   Ancillary components that enhance the vehicle's functionality and operational flexibility.
8. Vehicle structure
   The overall framework that integrates all components is designed to provide durability, balance, and adaptability.

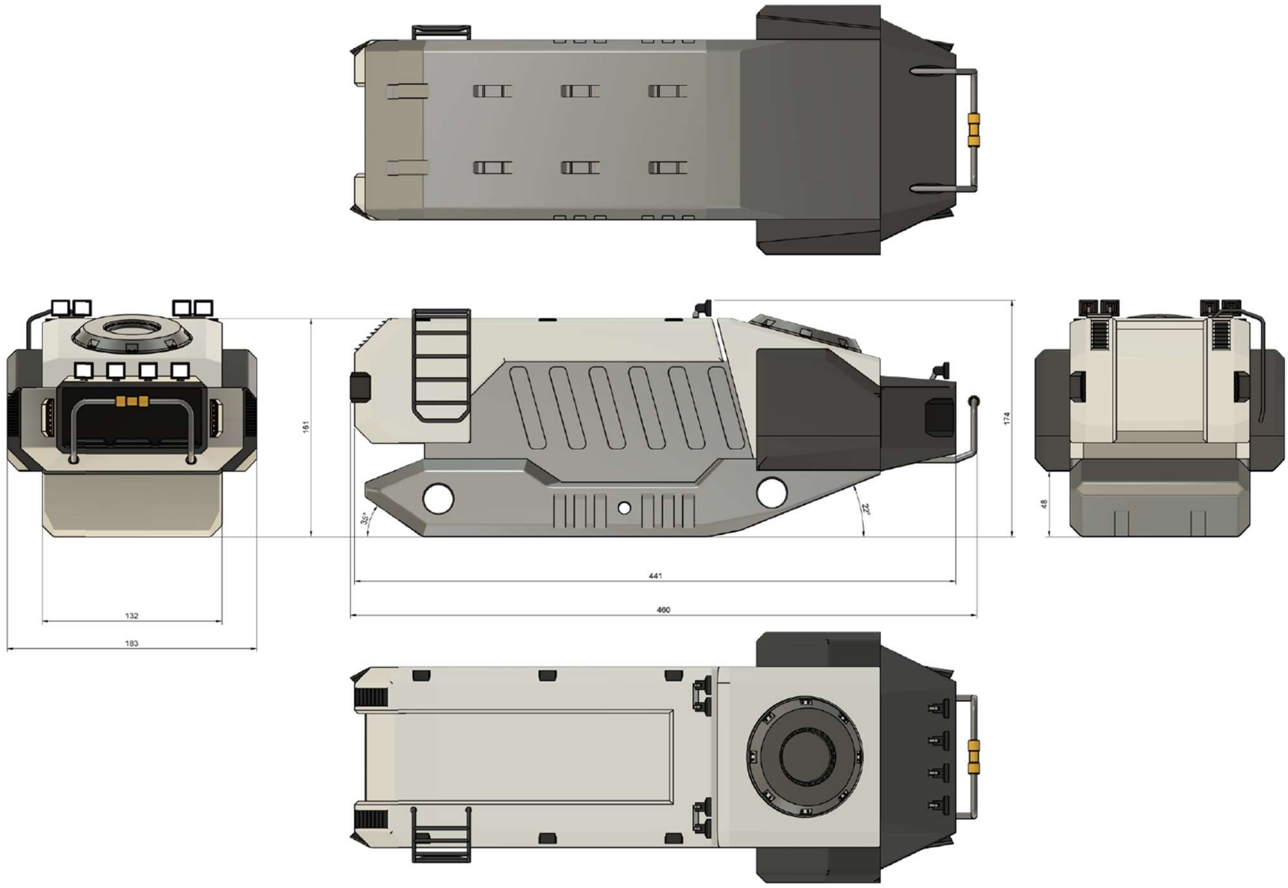

Figure 8. Dimensions of the UGV Vehicle

By finalizing the decision to develop a UGV modular platform, the focus on modularity ensures both cost-effectiveness in production and accelerated development timelines. The platform is divided into subunits, with each part treated as a separate module. This approach not only expedites the development process but also simplifies the replacement and modification of specific components.

One of the critical reasons for adopting a modular design and development approach is to streamline repairs, maintenance, and replacement of individual segments, ultimately extending the product's lifespan. For instance, if the front section of the vehicle, such as the bullbar, sustains damage, there is no need for a comprehensive repair or replacement of the entire vehicle. Instead, only the damaged part - in this case, the front protective bullbar - would be replaced. This modular design philosophy significantly enhances the platform's practicality, adaptability, and long-term operational efficiency.

5.1. Technical specifications of the UGV modular platform

During the 3D software modeling process of the UGV, the primary focus was placed on the vehicle's compactness. Since the UGV is intended for deployment in extremely challenging terrains and hard-to-reach locations, compactness was emphasized not only in the vehicle's dimensions but also in its overall architecture, including the propulsion and generator systems, as well as the hydraulic system. In the illustration below, the total dimensions of the vehicle are shown, which correspond to the average size of a passenger car commonly seen on roads. The designed UGV's dimensions do not exceed the standard road lane width (2.5 meters).This compact design ensures the UGV's adaptability and maneuverability in confined or difficult-to-access environments while maintaining efficiency and functionality.

5.1.1. Structural development of the UGV modular platform

The design of the UGV vehicle was based on the principle of modularity, applied to the vehicle's operational framework as the core platform (base station). The vehicle's architecture was tailored to the modular principle, meaning the vehicle is composed of modules to facilitate easier troubleshooting, part replacement, and regular maintenance.
The vehicle's construction (Fig. 9) adhered to the modular approach and was divided into several components:

1. Base structure: The primary load-bearing and structural element—this part of the construction handles the heaviest loads.
2. Sub-structure: A structure mounted onto the base structure, serving as a framework for attaching panels and specific components necessary for the vehicle's full functionality.

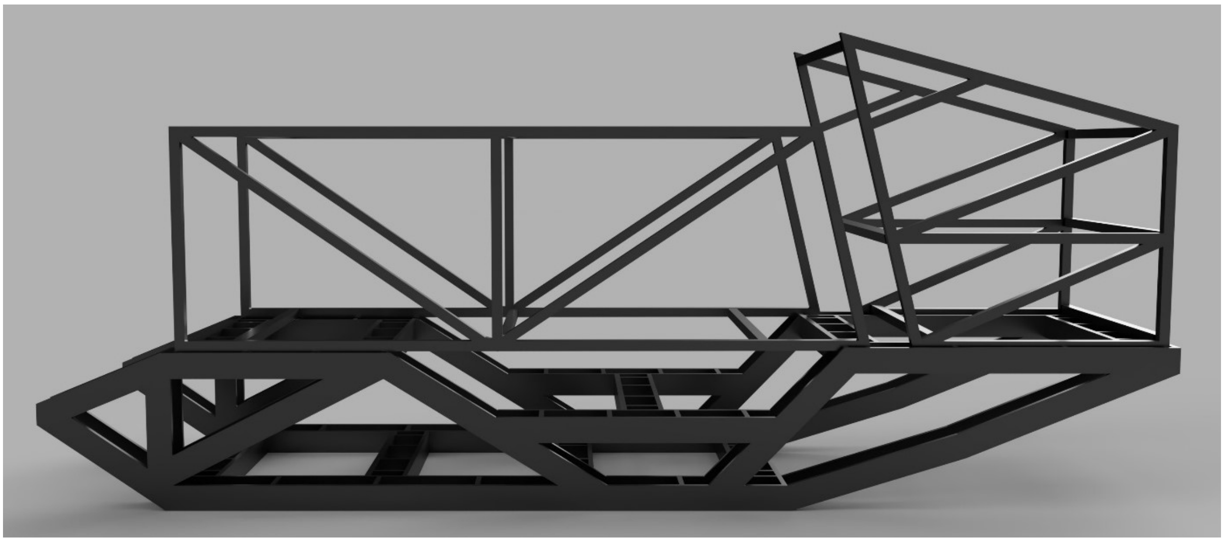

Figure 9. Structural development, the first version of the UGV structure

The development of the structure is tailored to the segments and the final design of the modular UGV platform, along with all its associated components, as previously outlined. The structure was designed based on the principle of triangle application to ensure uniform distribution of load forces. The final version of the construction, after a series of adaptations and various technical and technological implementations, was built using hot-rolled steel U-profiles with dimensions of 100x50x5 mm. The reason for selecting already existing profiles was to influence the manufacturing time, economic feasibility of both the construction and the entire project, and, most importantly, the reduction in weight, which can significantly affect the vehicle's final performance.

After selecting the profiles, a series of adaptations to the initial construction were made, followed by the generation of a 3D model of the structure for visualization, technical documentation preparation, and model preparation for numerical (FEA) analysis. Using software for generating and numerically analyzing the 3D model (SolidWorks), an FEA analysis was conducted. Upon detailed review of the FEA analysis, certain adaptations to the model were necessary. After the modifications, the analysis results showed passing results with maximum loads of up to 15 tons, which is three times higher than the nominal calculated operational load on-site. The static analysis of the final version of the construction is performed in three phases (Figs. 10-12), addressing the three most critical possible scenarios for the fixation of the structure:

- 4 fixations (all 4 wheels touching the ground),
- 3 fixations (3 wheels touching the ground, 1 wheel in the air),
- 2 fixations – diagonal (2 wheels touching the ground, 2 wheels in the air).

The most critical phase is the 2/2 variant, where 2 fixations are diagonal, as this is when the maximum twisting of the structure occurs. This is where the largest displacements in the FEA analysis (Figs 13 and 14) are most evident.

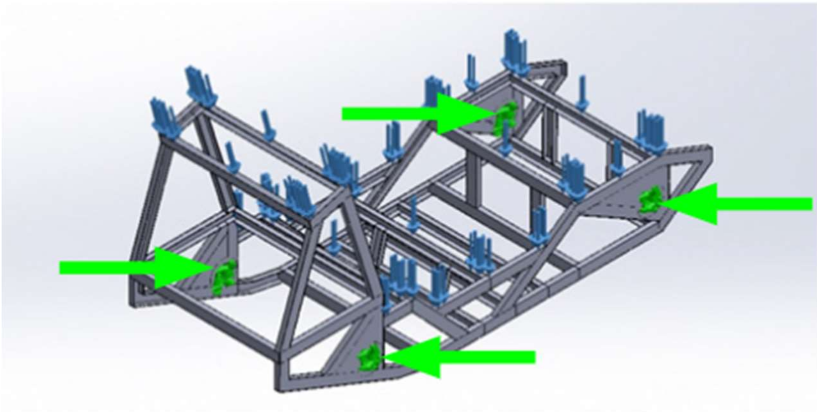

Figure 10. Analysis in the case of 4 fixations

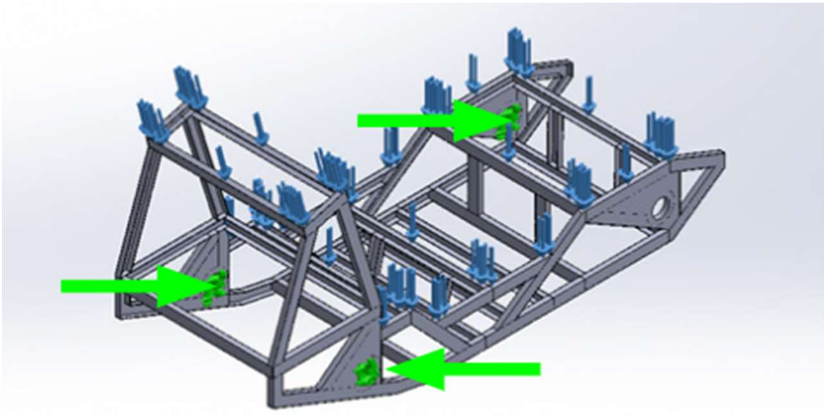

Figure 11. Analysis in the case of 3 fixations

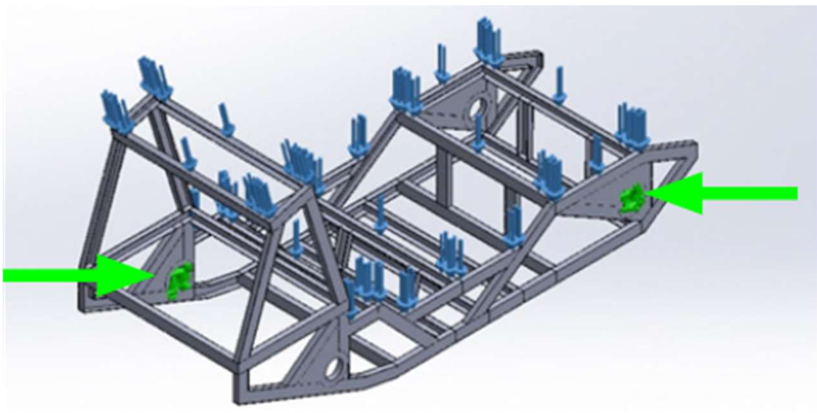

Figure 12. Analysis in the case of 2 diagonal fixations

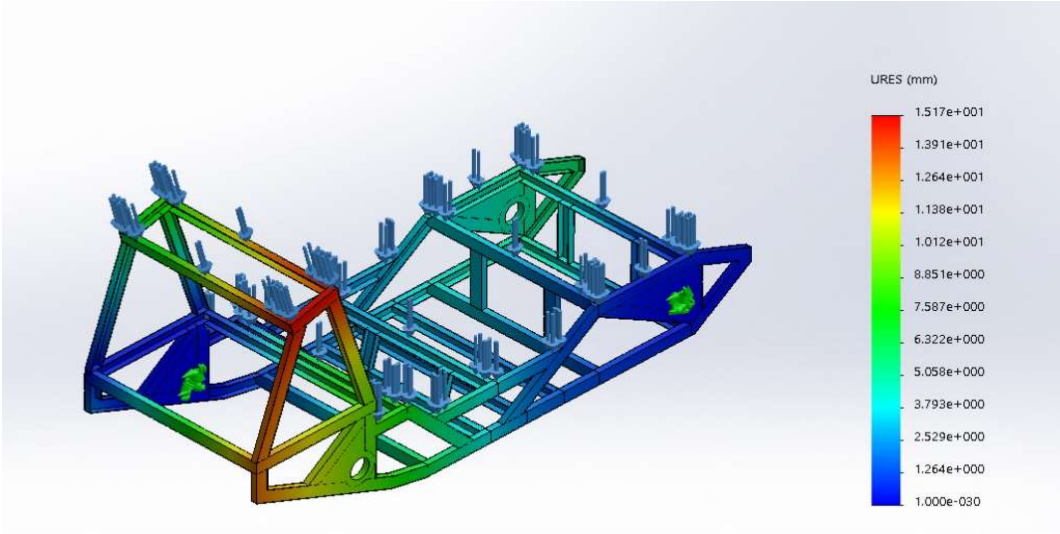

Figure 13. Displacement of construction in static analysis with 2 diagonal fixations

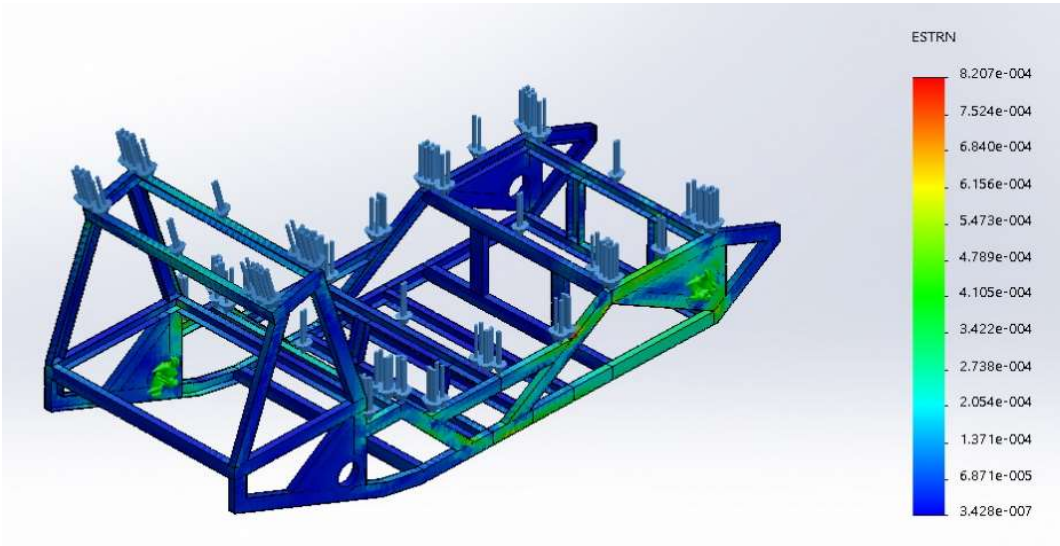

Figure 14. The strain of construction in static analysis with 2 diagonal fixations

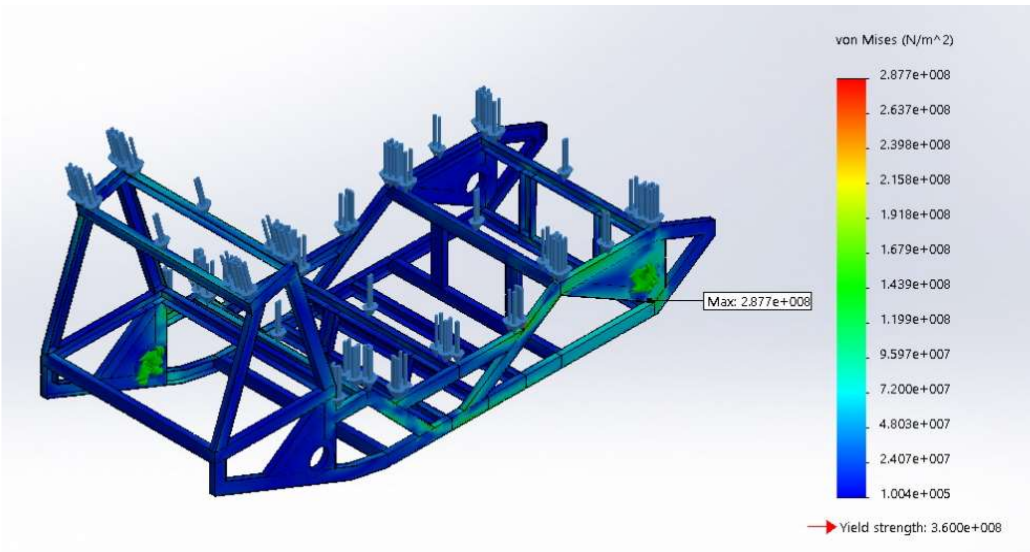

Figure 15. The stress of construction in static analysis with 2 diagonal fixations

The final version of the construction is presented in Figs 16 and 17 (back and frontal view).

Figure 16. The final version of the construction (back view)

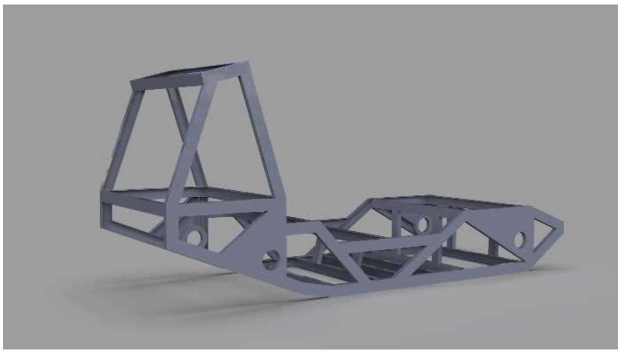

Figure 17. The final version of the construction (frontal view)

5.1.2. Propulsion system of the UGV modular platform

The propulsion system of the UGV (Unmanned Ground Vehicle) utilizing an internal combustion engine (ICE) represents a robust and efficient solution for operations in hard-to-reach areas (Fig. 18). These engines are renowned for their ability to deliver high power and reliability, even under extreme conditions such as low temperatures, dusty or muddy terrains, and steep gradients. The internal combustion engine is paired with a generator that converts the engine's mechanical energy into electrical energy. This generator powers the vehicle's electrical components, including sensors, communication equipment, and auxiliary systems, thereby enhancing the UGV's autonomy and operational range. Additionally, the integration of the ICE with a generator enables the vehicle to supply electrical power in emergency situations, addressing the energy needs of remote settlements or critical institutions requiring a stable power supply. This dual functionality significantly increases the versatility and utility of the UGV platform in various mission scenarios.

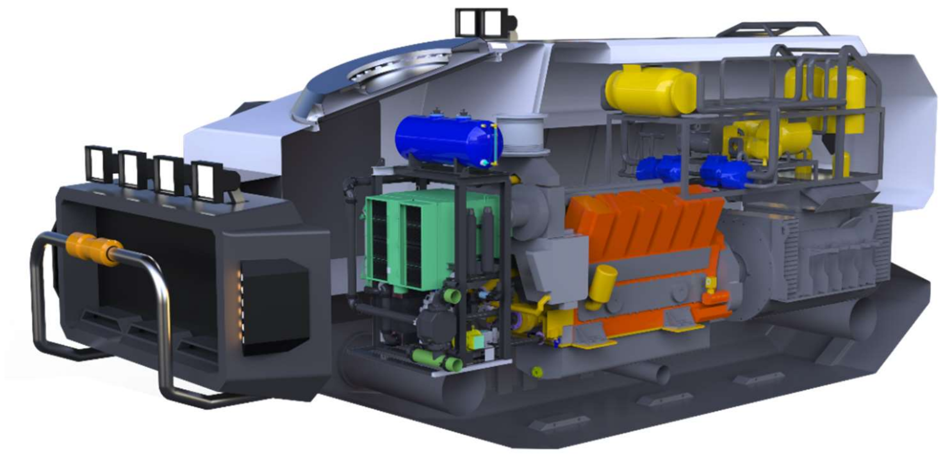

Figure 18. Propulsion system of UGV modular platform, sectional view, internal combustion engine paired with electric generator

The advantages and benefits provided by an internal combustion engine (ICE) as a propulsion system, as previously noted, lie in its effectiveness during critical situations where uninterrupted vehicle operation is essential for the success of a specific action or mission. Another significant advantage is the closed-system design, allowing repairs and urgent maintenance to be performed directly in the field if necessary. This feature enables parts from one vehicle, damaged during an operation, to be transferred and utilized in a less-damaged vehicle.

The development of the vehicle's structure is another distinct segment of the design process, critical for the serial production of such systems. Due to the confidentiality of data related to the comprehensive development and structural analysis, this aspect will be omitted from the scope of this scientific paper. However, it is worth noting that the structure has been tailored to align with the overall design and developed in accordance with the active loads that may occur during specific operations or missions in challenging terrains.

5.1.3. Characteristics of the UGV vehicle

After defining the objectives, as well as the design and development of the base platform, the vehicle's power transmission systems to the ground are included among its key characteristics. Most production vehicles currently available on the market utilize tracked systems for power transmission to the ground, which is the most efficient solution for off-road vehicles of this type. However, as this work focuses on the design and development of an innovative solution aimed at ensuring seamless or facilitated functionality and operability on terrains with more demanding topographies, in addition to the traditional tracked power transmission system, a so-called robotic arm system is being developed. This system includes independently powered wheels at each of the vehicle's four drive points, enhancing its adaptability and performance in challenging environments.

5.1.3.1. Track-Based Power Transmission System

The track-based power transmission system is one of the most economical and efficient methods for transferring power to the ground in off-road vehicles. In addition to providing excellent traction on various surfaces, tracks enable the vehicle to overcome steeper inclines, which conventional off-road tires cannot achieve. The UGV is equipped with 35 cm wide rubber tank tracks, driven by two high-torque electric motors. This configuration (Fig. 19) ensures exceptional traction in all situations and across diverse types of terrain.

Figure 19. Side view of UGV modular platform with track-based power system

Through the development of a modular system, we successfully lowered the center of gravity of the modular platform closer to the ground. This adjustment benefits the vehicle, particularly when utilizing the track-based power transmission system. With this improvement to the center of gravity (Fig. 20), we achieved enhanced stability, allowing for increased tilt angles of the vehicle, including lateral tilt angles as well as the approach and departure angles at the front and rear of the vehicle.

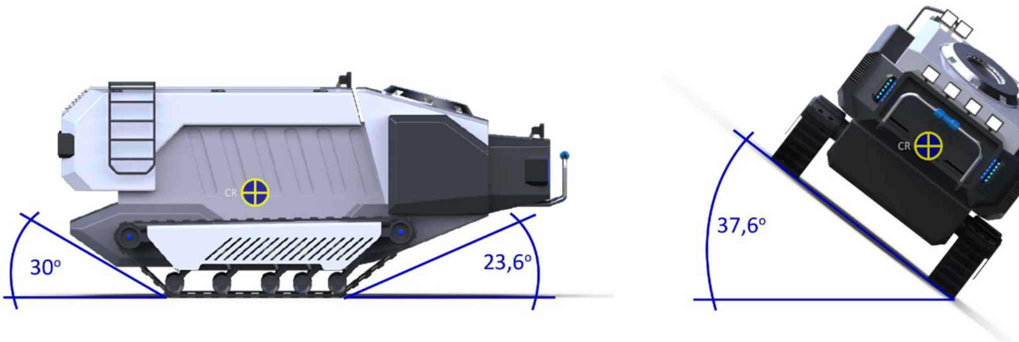

Figure 20. Approach, departure, and tilt angles

5.1.3.2. Power Transmission System Using Robotic Arms with Independent Power Supply and Integrated In-Wheel Motors

The power transmission system based on robotic arms with an integrated in-wheel motor system offers several advantages when operating on challenging terrains:

1. Increased ground clearance
   This system allows for dynamic adjustment of the vehicle's ground clearance, enabling it to traverse obstacles and rough terrain more effectively.
2. Extended wheelbase (stability)
   By extending the distance between axles when needed, the system enhances vehicle stability on uneven surfaces.
3. On-site servicing and repairs
   The modularity of the robotic arms facilitates repairs and maintenance directly in the field, minimizing downtime during missions.
4. Independent power supply for each wheel
   Each wheel is powered separately, enabling adaptive traction control and directing power to the wheels with the most grip for improved performance in challenging conditions.
5. In-place rotation
   The robotic arms (Fig. 21) and in-wheel motors allow the vehicle to execute precise, on-the-spot maneuvers, including 360° rotation, greatly enhancing mobility in constrained environments.

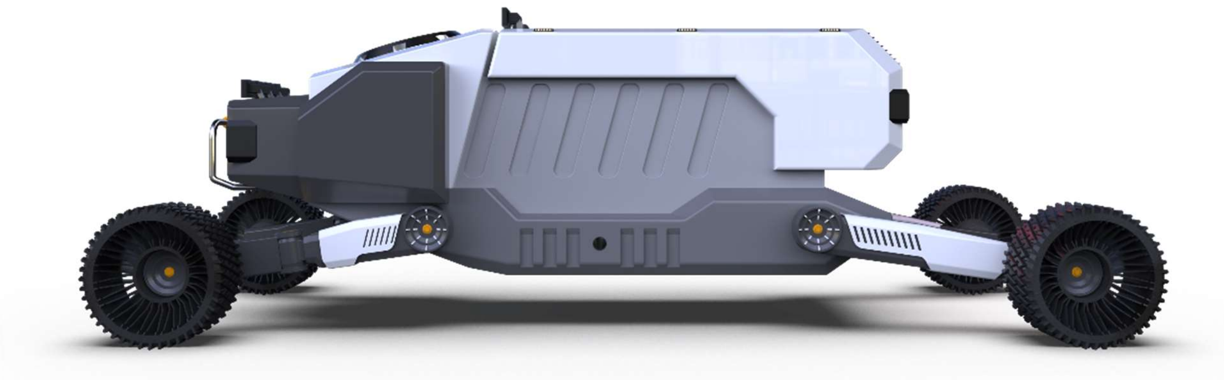

Figure 21. Side view of UGV modular platform with robotic arm power system with integrated in-wheel ev motors

Robotic arms, in addition to the in-wheel system, are also equipped with airless tires, which are highly suitable for this type of vehicle (Fig. 22). Airless tires are systems with an internal structure composed of a network of reinforced rubber elements, providing additional suspension to the vehicle. Unlike conventional pneumatic tires, which require repair in the event of punctures, airless tires can overcome obstacles without the risk of bursting. Furthermore, damage to the sidewalls of airless tires does not affect the vehicle's operational capacity as it would with conventional tires. Consequently, the lifespan of airless tires is significantly longer.

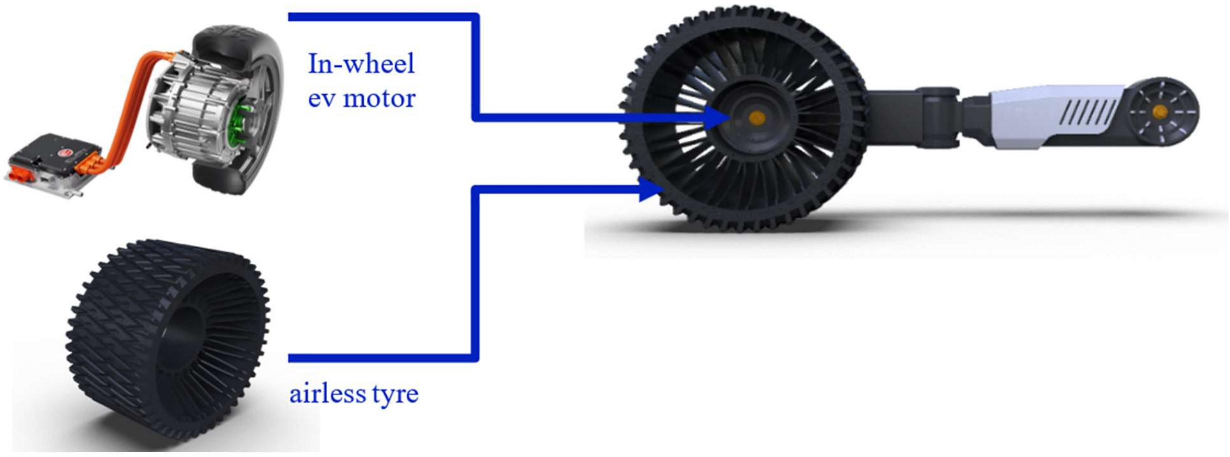

Figure 22. Detailed view of robotic arm power system

Independent power supply for the robotic arm system and their independent rotation at the articulated joint with the platform allow for adjustments to the vehicle's height (joint rotation angle of up to 85°). The vehicle can increase its ground clearance within a range of 2.2 m to 4.2 m (Fig. 23). This capability, combined with unrestricted movement, enables the vehicle to position itself on any incline and overcome specific depressions, protrusions, or obstacles in the terrain when required.

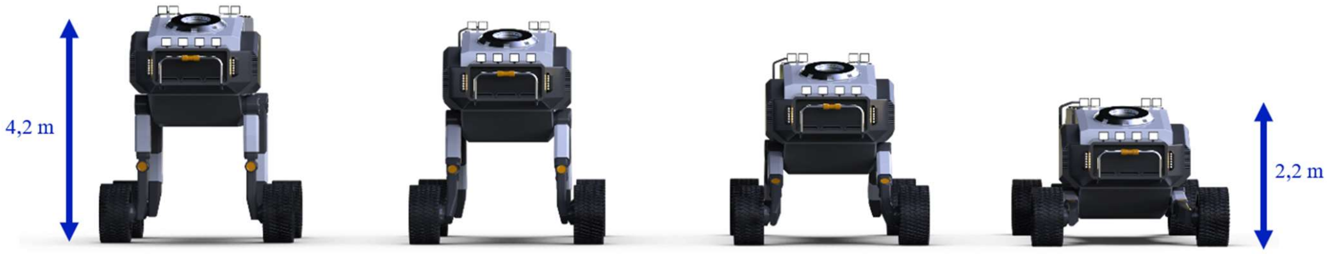

Figure 23. UGV modular platform with variable height

6. Modules for UGV operations

In the previous sections, we elaborated on the three primary domains where UGV modular platforms and vehicles are applied. With this in mind, we design and develop modules necessary for performing specific operations and tasks. The following modules are being developed:

1. Multi-functional robotic arm module with interchangeable tools
2. Mechanical demining module – variable flail mechanism
3. Mechanical demining module – independently positioned flails and milling mechanism
4. Firefighting module – water cannon

Since the UGV modular platform is equipped with a generator paired with an internal combustion engine (ICE), it is capable of generating electrical power. Beyond serving as a power station during emergencies—such as natural disasters causing interruptions in electricity supply—the platform can also function as a charging station for drones, as well as a take-off and landing station. With this in mind, we design a drone capable of carrying loads of approximately 80 kg. However, in reference to our earlier research [6], the drone's primary role is to detect landmines, minefields, and unexploded ordnance. It is equipped with detection systems such as NQR (Nuclear Quadrupole Resonance) or LiDAR. Additionally, the drone can be outfitted with infrared cameras and systems for detecting fires or locating missing persons in difficult-to-access terrains.

Modular Attachment System

Before discussing the designed modules, it is important to briefly explain the module attachment system (Fig. 24), which is critical for the seamless, efficient, and rapid deployment of a single vehicle to the field. Modules are connected to the vehicle via a rotating turret located at the front of the vehicle. This turret has a load capacity of over 5 tons and includes hydraulic and electrical connectors to power the modules. The module attachment turret is angled at 15° to avoid any potential conflicts during the rotation of the module's arm, ensuring smooth and efficient operation.

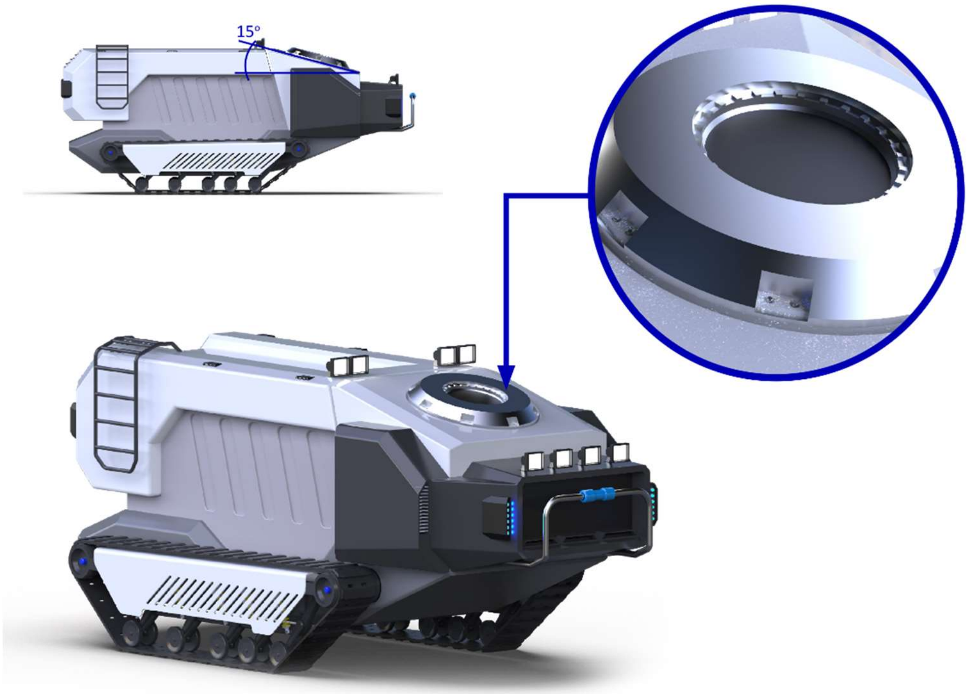

Figure 24. Module attachment system, rotary turret

Different types of modules, when not in use, are stored on a docking structure located within the facility. The modules are secured to the structure using hydraulic clamps. Once the vehicle approaches the desired module needed to perform a task or mission, the hydraulic clamps release the module, allowing it to be lowered into the docking turret on the vehicle, as shown in Figure 25.

Figure 25. Construction for storing modules with a mechanical gripper fixation system

6.1. Multifunctional robotic arm module with interchangeable end

The multifunctional robotic arm module (Fig. 26) is designed to provide full control and maximum mobility, closely resembling the system of an excavator arm. However, in this specific case, the module features independent rotation at its base, relative to the vehicle's position. It is also equipped with a central telescopic system with a maximum extension of up to 3 meters. With the ability to change its end-effector, the module can be easily repurposed. In addition to a digging bucket, it can be equipped with a hydraulic breaker for construction purposes, a water cannon for firefighting, or a winch for lifting loads. The image below illustrates the operational angles of all joints, along with their maximum rotations.

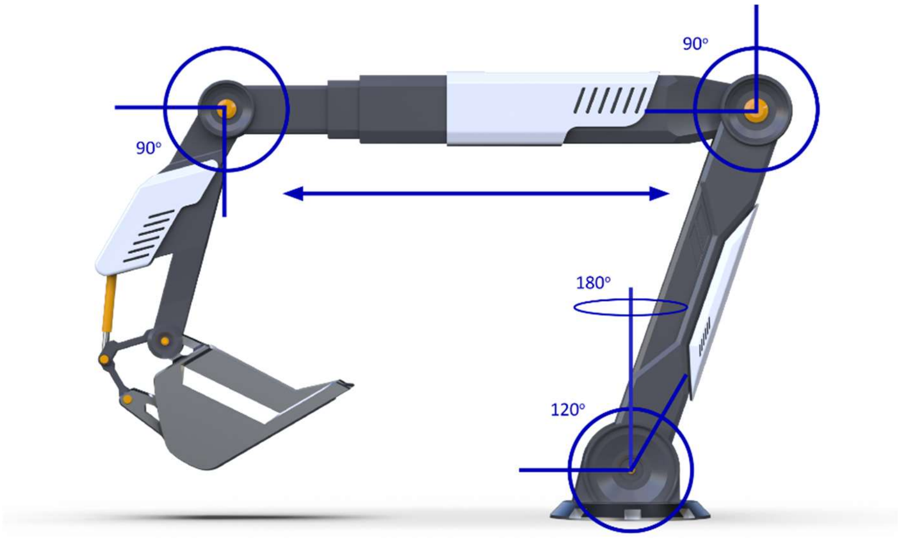

Figure 26. Side view of multifunctional robotic arm module with interchangeable end, operative movements of the joints

6.2. Mechanical demining module – the principle of variable flails

The mechanical demining module (Fig. 27) operating on the principle of variable flails essentially involves the independent movement of flails along the Z-axis (Fig. 28). These flails are divided into three independent systems, which can be positioned relative to one another autonomously. A key innovation of this system is its ability to adapt to terrain, enabling the complete mechanical removal of mines in depressions and protrusions, thus increasing operational efficiency in challenging environments. The system operates based on previously scanned areas, utilizing detection systems carried out by drones. These drones perform topographical scans of contaminated terrain, detecting mines and creating a 3D terrain analysis. This analysis guides the positioning and movement of the flails, ensuring precise and efficient demining.

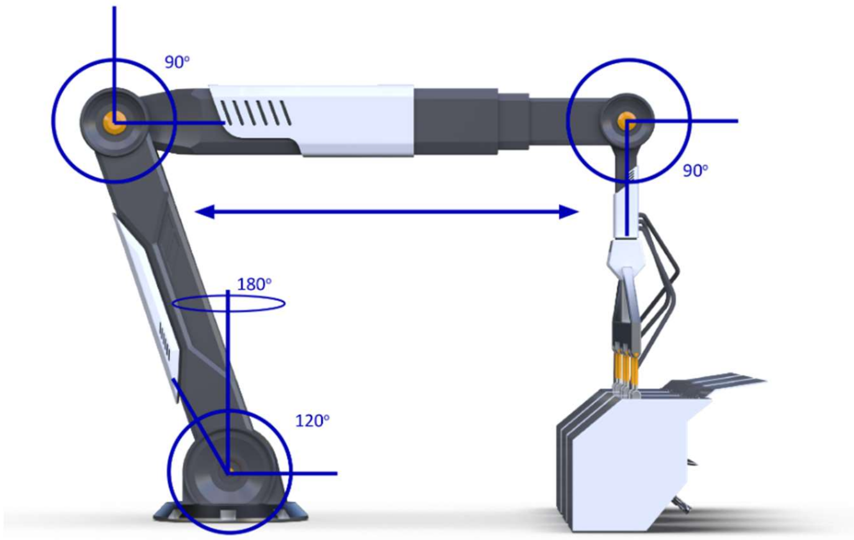

Figure 27. Side view of mechanical demining module, operative movements of the joints

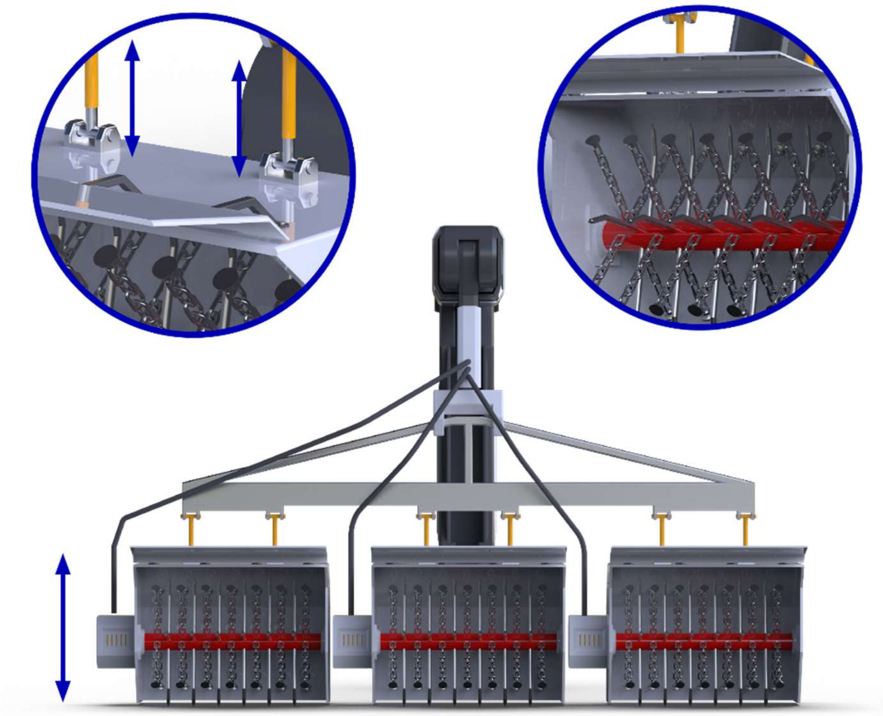

Figure 28. Front view of mechanical demining module, detailed view of height adjustment

By simultaneously combining detection and mechanical mine and UXO (Unexploded Ordnance) removal, the data accuracy and applicability are ensured, preventing unnecessary issues or critical situations in the field that could compromise the functionality of the vehicle or endanger personnel. This approach addresses potential terrain changes, as topography at specific sites can shift, leading to the displacement of mines or UXOs. This displacement is often caused by soil erosion due to heavy rainfall, which may result in landslides that further bury or shift mines and UXOs. The presented system integrates detection using LiDAR technology (Fig. 29), allowing real-time terrain scanning and mine detection. This setup aligns with the research detailed in our earlier paper [6], which highlights the advantages of such integrated systems. The illustration below demonstrates the system's operational method, showcasing its synergy with simultaneous mine detection using LiDAR.

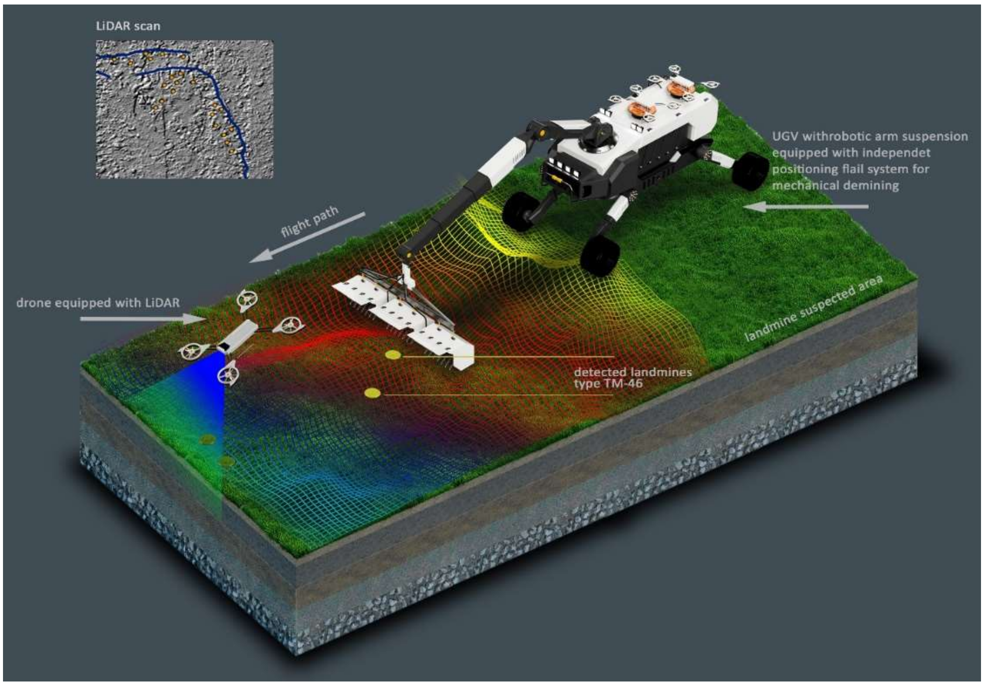

Figure 29. Principle of operation of the module for mechanical demining (principle of variable flail system) integrated with LiDAR scan of ground and detection of landmines and UXO

6.3. Mechanical demining module – the principle of independent positioning of flails and tiller

The mechanical demining module (Fig. 30), which operates on the principle of independent positioning of the flails and the rotary cutter, allows for various work speeds and different digging depths. The primary role of mine destruction is assigned to the chain mechanism, i.e., the flail system. The rotary cutter, as the secondary system, is there to complement any gaps that may arise during the mechanical removal of the flail system.

Independent positioning and movement of the flails and rotary cutter in relation to the digging depth provide greater efficiency compared to the classic arrangement with two flails. The combination of the flails and the rotary cutter provides certain advantages when digging different types of soil. According to the demining requirements, the digging depth and the number of rotations are adjusted to achieve a higher technological speed and better operational efficiency. Each segment of the cutter rotor can have multiple heads positioned at a relative angle of 120°. The segments are phased so that the cutting heads form three spirals that begin from the center of the rotor and symmetrically expand to each side [1].

Destruction of high-destructive power mines must be carried out by the primary tool – the chain mechanism with a large radius, which will not be damaged. The rotary cutter, as the secondary tool, is suitable for adjusting the digging depth and fully clearing the mines.

In short, the combination of the flail system as the primary and the tiller system as the secondary tool provides the following advantages:

1. More flexible handling of different working conditions with two independent working tools.
2. The ability to independently adjust the digging depth and the number of rotations of flail and tiller.
3. Adaptation to actual demining conditions.
4. Two tools, the flail, and the rotary cutter, provide double efficiency.
5. High reliability in the destruction of different types of mines.
6. The most destructive anti-tank mines are destroyed by the chain mechanism, avoiding significant machine damage.
7. The rotary cutter is lighter than the second flail, saving material and motor power.
8. The rotary cutter destroys the smallest parts.
9. The rotary cutter can be adjusted to determine the final digging depth of the soil. [4]

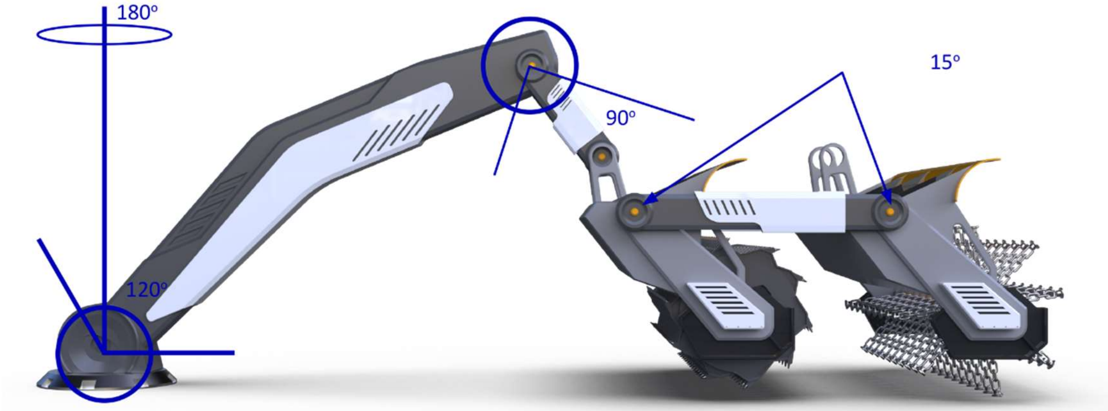

Figure 30. Side view of mechanical demining module, operative movements of the joints

The combination of a tiller system and flail system in mechanical demining does not require special terrain analysis and topographic scans, as in the case of the variable flail principle. The system works by positioning the flails relative to the rotary cutter, or the rotary cutter relative to the flails, depending on the terrain and soil composition, in order to increase the effectiveness of mine and UXO removal, which may be buried or further covered with soil deposits during the mechanical removal process. The system can also be paired with airborne terrain scanning for the presence of mines and UXOs, and, using the detection system, generate a detailed movement path for the vehicle.

Figure 31 shows the principle of mechanical demining using a system of independent positioning of flail and tiller system, integrated with aerial drone multi-sensor detection systems, such as LiDAR and GPR sensors.

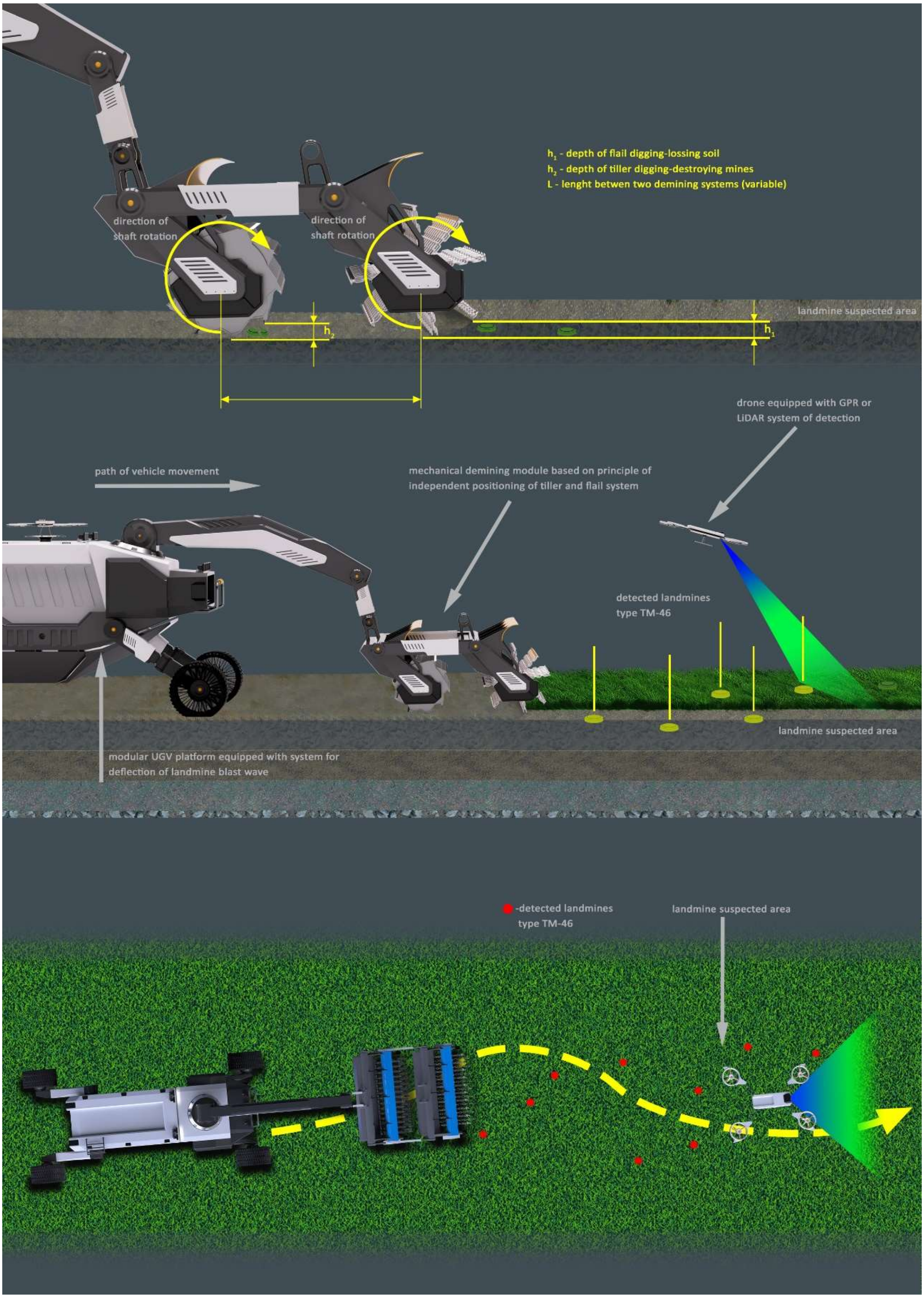

Figure 31. Principle of operation of the module for mechanical demining (principle of independent positioning of flails and tiller), integrated with aerial detection sensors for landmines and UXO

Figure 31 shows how can smart algorithms predict the exact movement of the UGV to the exact location where the mines are placed. With the modern approach, first of all, landmine detection systems, which are a crucial part of mechanical demining, the percentage of success of mine action programs is significantly higher, up to 50%. Mechanical demining based on the principle of independent positioning of the flail and tiller system, works by adjusting the depth of digging each tool. For example, the primary tool is the flailing system, used for the unveiling, digging out the soil around the landmine, as well as destroying it. The secondary tool, the tiller system is there to fulfill possible fails of the flailing system, such as that mine can be much further buried, or the remains of the landmines after detonating. The flail system will destroy every bits and pieces of the landmine.

6.4. Water cannon module for firefighting

The water cannon module (fig. 32) designed for firefighting purposes enhances the versatility of the UGV platform, positioning it primarily as a tool for protecting both people and the environment. The advantages of using such systems in firefighting lie mainly in preventing potential injuries or fatalities during operations involving highly dangerous fires, particularly in structural fires where the collapse of buildings or their structural elements could pose additional risks to personnel on site.

UGV systems in firefighting are not a new concept; robotic UGV systems of smaller dimensions have been used over the past decade, primarily as firefighting tools directly connected to a water hose supplied by a fire truck. The system discussed here operates in two modes: it can either connect directly to a fire truck or a hydrant as a water source or utilize its onboard reservoir, with a capacity of 5 tons, for water or foam. Having an onboard reservoir for water or foam allows the UGV system to operate effectively in critical areas, such as structural fires or fires in terrains with challenging topographies. In such scenarios, the vehicle would be remotely controlled from a safe distance for personnel and equipped with thermal cameras to identify and suppress any "hidden" hotspots in the fire.

Figure 32. Water cannon module attached to a tracked UGV modular platform with red-white livery

7. Conclusions

The implementation of UGV systems in the domain of demining represents a crucial innovation in addressing one of the most serious humanitarian challenges – unexploded landmines. The application of mechanical demining, combined with the innovative system of mechanical demining with independent positioning of flails and tillers, brings significant improvements in efficiency and safety during demining operations. This advanced approach allows precise control over the tools and provides greater flexibility in operational conditions, reducing risks to human life and accelerating the land clearance process.

The UGV modular platform designed in this work adds further value to mine action efforts, as its modularity allows for easy adaptation to different operational requirements and specific working conditions. With the ability to integrate various modules, the platform can be tailored for use in different scenarios, not only for demining but also for civil protection tasks such as responding to natural disasters, search and rescue operations, and other operations requiring high precision and safety.

Furthermore, the implementation of such systems in industry can contribute to technological advancement, stimulate innovation, and enhance the economic efficiency of a country. By introducing UGV platforms into various sectors, such as environmental protection, construction, and even defense, competitiveness is increased, and infrastructure is improved. In this way, UGV platforms can become a key factor in advancing industry and the economy, while also contributing to the safety and well-being of society as a whole.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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