REMOVAL SYSTEM FOR UNMANNED GROUND VEHICLES USING A MODULAR ROBOTIC ARM

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A removal system for Unmanned Ground Vehicles (UGVs) equipped with a modular robotic arm designed for hazardous and unstructured environments is presented. The system is based on commercially available solution that enables the manipulation of objects and removal of obstacles in complex terrains, such as disaster zones, battlefields, and industrial sites. The operational environment, teleoperation capabilities, and associated challenges are thoroughly addressed. Recent developments in All Terrain Vehicle-based unmanned platforms are discussed, demonstrating their suitability for rapid and versatile implementation in special-purpose missions. A model of an unmanned platform with an integrated robotic arm is proposed to enhance the existing range of medium-sized UGVs. The system configuration tailored for special-purpose missions is outlined, and kinematic parameters, along with stress tests, are provided to confirm its high adaptability to a diverse range of operational scenarios.

KEYWORDS

Modular robotic arm, Unmanned Ground Vehicles, obstacle removal system, unstructured environment, special mission

1 INTRODUCTION

Unmanned platforms have become essential in operations where human involvement is risky or impractical, such as in military missions, disaster relief, and hazardous material handling [Ying 2021]. These vehicles offer significant advancements in technology, designed to operate on land and perform a wide range of tasks including surveillance, reconnaissance, and complex engineering [He 2023]. UGVs are demanding across various sectors, including the military, emergency response, law enforcement, agriculture, and infrastructure maintenance. Introduced UGVs have different sizes and types to match their specific applications. Small UGVs, typically around 100 kilograms, are ideal for operations in hazardous environments, such as inspecting infrastructure or handling explosives. Medium-sized UGVs, ranging from a few hundred kilograms to over a ton, are suited for tasks like transporting supplies or agricultural tasks. Large UGVs are built for heavy-duty applications, including carrying substantial loads or performing complex construction tasks.

There are generally two approaches to develop UGVs: designing them from concept or adapting existing vehicles. Dedicated UGVs are purpose-built for unmanned operations, designed with specialized features like advanced durability and sophisticated sensors, all specifically engineered to meet the unique demands of their intended tasks. On the other hand, adapted UGVs uses commercially available vehicles that are modified by installing control system, communication equipment, and sensors to perform teleoperated missions [Nowakowski 2023]. This adaptation is more cost-effective and allows for quicker deployment of new unmanned applications.

The functionality of unmanned platform can be extended integrating various equipment, tailored to meet the specific demands of different types of missions [Nohel 2020]. For reconnaissance and surveillance tasks, UGVs are often equipped with high-resolution cameras, thermal imaging sensors, and lidar systems, which provide comprehensive visual and environmental data to support real-time situational awareness and target identification [Konecny 2022]. In hazardous environments, such as chemical spill sites or explosive ordnance disposal scenarios, UGVs may be fitted with specialized sensors like chemical detectors, radiation meters, and robotic grippers designed for safe manipulation and analysis of dangerous substances. For logistics and supply chain operations, UGVs can be equipped with cargo bays, automated loading systems, and GPS navigation for efficient transport of goods and materials across challenging terrains.

Despite the significant advancements in logistics and weaponized unmanned ground vehicles, there is a critical need for UGVs equipped with robotic arms to handle obstacles and risky situations in unstructured terrains [Asadi 2019]. In these operational scenarios, UGVs with robotic arms provide crucial support by enabling remote manipulation of the environment in a disaster zone. Unmanned platform equipped with a robotic arm can clear debris blocking critical pathways, handle unstable materials or safely remove hazardous objects, such as unexploded ordnance or chemical spills, which would be too dangerous for human being. Ability to remotely manage and overcome obstacles improves the UGV's effectiveness and versatility, making it an useful tool in dynamic and hazardous conditions where traditional vehicles might struggle or pose risks.

This study examines the integration of a modular robotic arm with a mid-sized unmanned platform, based on a converted All-Terrain Vehicle (ATV). This adaptation extends the UGV's functionality and modularity, enhancing its ability to operate in unstructured terrains and risky zones, equipped with an onboard obstacle removal system. The presence of the robotic arm not only increases the UGV's operational versatility but also improves its capacity to function safely and efficiently in hazardous environments where conventional vehicles may struggle.

2 OPERATIONAL ENVIRONMENT

The operational environments for Unmanned Ground Vehicles are complex, unstructured, and often unpredictable. These environments are characterized by uneven terrains, diverse obstacles, hazardous materials [Sedlacek 2024].

Figure 1. Obstacles in the unstructured environment

To effectively operate in these conditions, UGVs must be equipped with advanced systems that enable them to navigate, remove obstacles, and manipulate objects, ensuring mission success without direct human intervention. One of the primary challenges UGVs face in these environments is the presence of physical obstacles which can cause collision [Mrowicki 2020]. In disaster zones, for example, collapsed structures, large debris, and rubble can block access to critical areas, impeding search and rescue efforts or supply transport. Similarly, in forests or rural settings, fallen trees, rocks, and dense vegetation can obstruct the UGV's path. In industrial disaster sites or hazardous environments, obstacles may also include dangerous materials such as toxic chemicals, radioactive substances, or unexploded ordnance, which present additional risks to both the UGV and human operators.

To overcome these challenges, solution can be the integration of a modular robotic arm, which allows the vehicle to clear obstacles and manipulate objects especially in autonomous mode. The robotic arm extends the UGV's capabilities by enabling perforce of tasks that would typically require human intervention, such as lifting and moving objects, dismantling barriers, or handling hazardous materials. This is important in situations where the environment is too dangerous for humans to operate directly.

In hazardous environments, such as those involving chemical spills or radiation, the robotic arm allows UGVs to handle dangerous materials safely keeping human operators at a safe distance. This capability is essential in industrial disaster response, where the safe manipulation and removal of dangerous materials are critical to preventing further damage and protecting human life.

3 UNMANNED GROUND PLATFORM CHARACTERISTIC

For research purposes, a mid-size unmanned ground vehicle (UGV) platform was considered as a promising solution due to its versatility and growing global demand for implementation in a variety of tasks. These mid-size platforms are particularly well-suited for operating in harsh and unpredictable environments, where traditional manned vehicles struggle to perform effectively.

The selected UGV platform offers the potential for diverse applications, from disaster response to military operations, addressing the need for adaptable and resilient systems capable of tackling complex missions [Lewinski 2022]. One of the key advantages is their ability to be teleoperated in unstructured environments. Teleoperation allows a remote operator to guide the vehicle with precision, providing fine control over its movements and task execution. The operator relies on high-resolution view and sensor data transmitted from the UGV, which includes real-time environmental mapping through advanced sensors like LiDAR and cameras. This detailed situational awareness is essential for ensuring the vehicle can navigate through challenging terrains while maintaining safe and effective operation where direct human intervention would be too risky.

The growing demand for mid-sized unmanned platforms underscores their increasing significance across various sectors. A promising approach to meeting this demand is through the conversion of All-Terrain Vehicles (ATVs) into autonomous platforms, enabling them to carry out a wide range of special-purpose missions. Two platforms, PERUN (Autonomous Wheeled Vehicle for Reconnaissance and Combat Tasks) [Buzantowicz, 2019] and PAWO (Autonomous Operational Support Platform) [Podkowski 2021], have been successfully tested in Poland, proving the success of this method. These platforms are well-suited for uniformed services engaged in diverse operational roles, including logistics, search and rescue missions, and operations in challenging terrains.

The conversion of ATVs into UGVs offers significant operational advantages including complex tasks in unstructured environments. This conversion process typically involves modifications to four key control mechanisms: accelerator, steering, braking, and shifting—all of which are electrically actuated to enable remote or autonomous control [Yacoub 2018].

A well-designed control system architecture allows for seamless integration of additional equipment through standard communication protocols transmitted via secure radio channels, ensuring that the UGV can be operated safely from a distance in hazardous conditions.

A valuable extension to the proposed UGV platform is the integration of a modular robotic arm, designed to address the lack of such functionality within this platform family in missions that require obstacle removal. In disaster zones or forests the robotic arm can be deployed to clear fallen trees or debris obstructing the vehicle's path. It can also manage hazardous materials that pose risks to human operators, such as unexploded ordnance or toxic substances.

This capability to manipulate objects in complex and dangerous environments makes the UGV an indispensable asset in search and rescue operations, industrial disaster response, and military missions**.**

a) b)

Figure 2. Example of autonomous platform developed on ATV basis: PERU(a), PAWO(b)

4 INTEGRATION OF MODULAR ROBOTIC ARM

In this research, the integration of rotary positioning modules into a selected unmanned platform using the DSM (Drive, Servo, Module) architecture was evaluated. This architecture is characterized by its flexibility and adaptability, which allow for the construction of robotic systems with varying degrees of freedom. The DSM system model supports modularity and easy assembly, enabling the configuration of robotic systems tailored to specific tasks by combining individual modules into more complex functional units suitable for both stationary and mobile applications [Spinea 2024].

It should be underlined that all considered components have been tested and proven effectively in industrial environments, with numerous studies confirming their reliability and operational usability [Semjon 2017]. However, their application in mobile platforms required some analysis and verification of parameters under various conditions.

The core of the DSM architecture involves linking modules through a kinematic chain, which defines how these modules interact to form a functional robotic system. The system model for connecting DSM modules includes components such as the DSM modules themselves, input and interconnect flanges, and output elements [Jaszak 2022]. These components allow for the assembly of units that can serve various purposes, like obstacle removal or object manipulation.

The system's modularity is illustrated in Fig. 3, which shows how connected DSM modules in sequence to create a robotic arm with six degree of freedom (DOF).

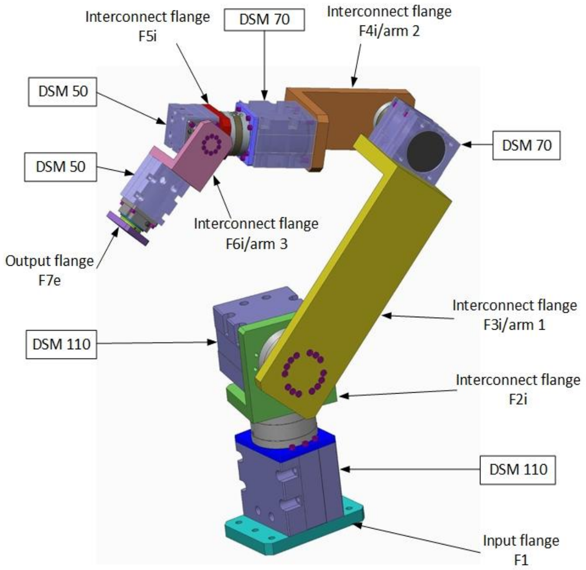

Figure 3. Modular Robotic Arm base do DSM system

This model provides a framework for assembling DSM modules into effective robotic solutions for UGV applications. The connection sequence follows a specific order, beginning with the input flange (F1) and progressing through various DSM modules and interconnect flanges, ultimately terminating at the output element (VR). This configuration enables the robotic arm to execute complex movements and manipulations, making it ideal for tasks in unstructured environments where precise handling is required.

DMS system is based on rotary positioning module (next RPM) shown in figure 4. It is electro servomechanism for drive position (rotary angle or linear displacement). It consists of gearbox, servomotor and sensors in one construction and function compact.

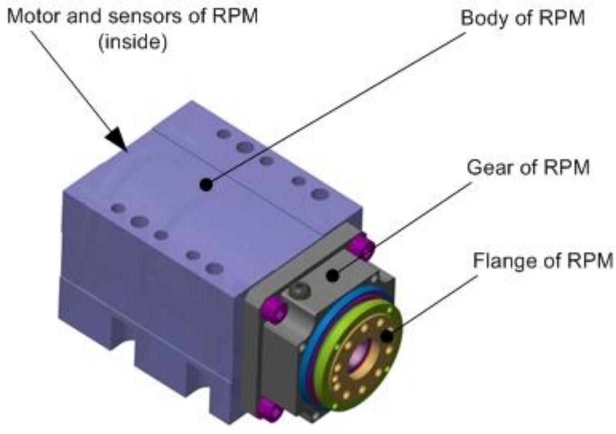

Figure 4. View of RPM module

The key parameters of the DSM modules are presented in Table 1. Each module's size, torque, speed, and stiffness can be selected to ensure optimal performance under different load conditions. The larger DSM 110 module, with a rated output torque of 122 Nm and a maximum tilting moment of 740 Nm, is particularly well-suited for heavy-duty applications requiring significant force and precision, such as lifting or moving large obstacles.

Table 1. Main parameters of DSM system

RPM module	RPM 50	RPM 70	RPM 110
Max. dimension RPM Module [mm]	58x66	80x95	112x135
Max. dimension body of reducer [mm]	55 x 55	Φ 70	Φ 110
Length of RPM [mm]	111	153,6	202
Rated output torque [Nm]	18	50	122
Acceleration and braking torque [Nm]	36	100	244
Rated input speed [rpm]	2000	2000	2000
Cycle effective speed [rpm]	3000	2500	2000
Lost motion [arcmin]	<1,5	<1,5	<1,0
Average angular transmission error [arcsec]	+/- 36	+/- 36	+/- 20
Max. axial force [kN]	1,9	3,7	13,1
Rated radial force [kN]	1,44	2,6	9,3

RPM modules allow for the assembly of functional devices with 2 or 3 axes using connection flanges. To ensure the structural integrity of these connections, FEM analysis was conducted to verify the strength and reliability of each technological unit under operational loads. The DSM architecture further enhances the system's flexibility by allowing customization for various applications. Depending on the specific requirements of the device, the modules can be configured horizontally, vertically, or obliquely. RPM modules provide precise movement control through motor-driven rotary axes, monitored by sensors embedded within the modules and the surrounding environment. This sensor feedback allows intelligent motion control, ensuring that the robotic arm can respond dynamically to changing conditions during mobile operations.

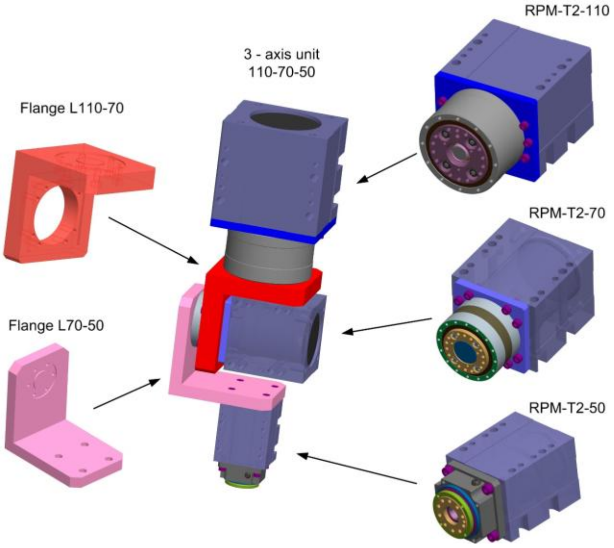

Figure 5. Assembly options of RPM modules

The integration of a modular robotic arm with an unmanned ground vehicle (UGV) platform required a comprehensive, multi-level approach to ensure both functionality and durability. As described in the previous section, an All-Terrain Vehicle was selected as the base for the mobile platform due to its robustness and adaptability. To install the robotic significant structural modifications were required to the ATV's original frame and body, ensuring that the system remains secure and functional during operation. This process involved carefully considering strong bolt connections to prevent the arm attachment from breaking during task execution [Grzejda 2021].

The ATV's chassis was also redesigned to support these new functionalities, featuring a modular frame structure that allows for the quick dismantling. This design facilitates easy maintenance and upgrades, ensuring that the vehicle remains versatile and adaptable to different mission requirements. The redesign included the allocation of space within the chassis for additional components critical to the vehicle's autonomous capabilities, such as drive systems that replace the need for a human operator and computing units that process sensor data for autonomous decision-making.

The robotic arm was strategically positioned at the front of the vehicle (see Fig 6), a decision aimed at optimizing its ability to manipulate objects directly in its path, such as debris removal or handling hazardous materials.

Figure 6. View of integrated modular arm with Unmanned platform

This placement is crucial for ensuring that the vehicle can effectively interact with its environment during operations. This comprehensive approach to integration, from structural modifications to strategic component placement, results in a highly adaptable and robust system capable of performing a wide range of tasks in challenging environments.

To equip the vehicle with autonomous capabilities in unstructured environments, a set of advanced perception sensors was integrated, including an OUSTER LiDAR, a STEROLABS camera as well as GPS-based navigation system. The proposed platform is equipped with an additional camera, complementing the main camera mounted on the front side of the chassis for broad field observation. The additional camera, positioned at the end of the robotic arm, enables close-up views and precise manipulation tasks. This dual-camera setup ensures that operators have access to both a comprehensive overview of the environment and detailed visual feedback for specific tasks, making the system highly effective in performing intricate operations in the field.

The control system of the platform is designed to manage both internal and external data, processing sensor input and receiving commands from the remote control station. It transmits vital measurement data and operational parameters back to the operator, ensuring real-time communication and control over the unmanned platform. The architecture of this embedded control system, which facilitates seamless interaction between the vehicle, robotic arm, and operator, is depicted in Figure 7.

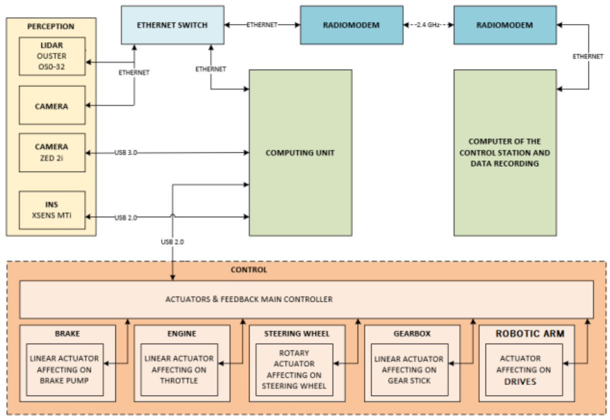

Figure 7. Proposed control system architecture

The proposed modular architecture of the UGV platform is designed to enable the integration of additional detectors or sensors, tailored to the specific requirements of each mission. This flexibility allows the platform to adapt to a variety of tasks, enhancing its effectiveness. The ability to upgrade the UGV with new sensors and technologies ensures it remains capable of handling emerging challenges across diverse applications, whether operating autonomously or through remote control.

5 CONCLUSIONS

The proposed unmanned platform with a modular robotic arm is suitable to carry out special-purpose missions that require object removal in complex environments. The integrated system enables continuous navigation through challenging terrains, such as disaster zones and industrial sites, while allowing for human operator involvement when necessary to address obstacles or hazardous materials. Key applications include search and rescue missions, where the UGV is deployed to operate in high-risk zones, as well as the safe handling of hazardous materials, thereby significantly reducing risks to human operators. The demand for midsize unmanned platforms has grown due to their cost-effectiveness and versatility across a wide range of applications.

The modular robotic arm can be constructed using commercially available parts, offering a flexible and economical solution for functionality extension of various UGV platforms. The combination of DSM modules ensures that the modular robotic arm is not only adaptable but also robust enough to meet the demands of mobile applications.

The architecture proposed in this paper is one of many potential solutions that could be more widely adopted in unmanned systems. This efficient system offers a versatile platform capable of addressing a range of operational challenges in both autonomous and remote-controlled modes, contributing to the advancement of unmanned operations.

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