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Modeling and Simulation of a Ground Mobile Rover for Inspection Tasks

Pierluigi Rea[1], Erika Ottaviano[2,*] and Maurizio Ruggiu[1]

[1]DIMCM - University of Cagliari, Italy, Via Marengo 2, 09123, Cagliari (Italy)
[2]DICeM - University of Cassino and Southern Lazio, Via Di Biasio 43, 03043 Cassino, Italy

Abstract

This paper proposes design improvements and simulations for an inspection rover developed for inspection tasks. The proposed system is suitable for indoor and outdoor surveys, and due to its compact size and ability to overcome obstacles, it is particularly well-suited for use in confined spaces where human intervention is difficult or nearly impossible. Autonomous or teleoperated systems can replace experienced personnel, navigating complex, unstructured environments that are often hard to access. These systems carry appropriate sensors and manage data, which can be transmitted for further analysis. The survey uses advanced mechatronic systems consisting of robots, instrumentation, and a networking system to operate internal and external sensors. The former is used for navigation, while the latter provides data from the area of interest. This paper focuses on the robotic structure designed for inspection tasks. Building on an existing hybrid rover, the paper examines the mechanical design and simulation of the system to optimize its functionality in motion smoothness and compactness, all while adhering to a low-cost design philosophy.

Keywords: Mobile Robots, Robotic Inspection, Mechatronics, Mechanical Design, Simulation, Structural Health Monitoring

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1. Introduction

Infrastructure monitoring, maintenance, and rehabilitation are critical at the national and international levels. Among various types of civil infrastructure, the need for maintaining and assessing underground facilities has been highlighted in recent studies. Evaluating and monitoring public infrastructure is essential, as large populations rely on these systems daily. Underground and confined areas are commonly used in both civilian and industrial sites. However, they pose significant risks to humans due to hazardous factors such as toxic gases, extreme temperatures, limited space, unhealthy oxygen levels, flooding, and the potential for structural collapse. Security concerns arising from environmental and resource constraints must be addressed to prevent natural or human-induced incidents that could lead to ecological and environmental disasters.

Over time, robotic platforms have been developed to conduct Non-Destructive Evaluation (NDE) of infrastructure [1-3]. However, a limited focus has been on initiatives to advance semi-autonomous or fully autonomous systems. These systems seek to streamline the process of providing routine health monitoring services for civil infrastructure, ultimately reducing time and resource consumption. Given the current landscape, there is an urgent need to develop resilient, reproducible, and cost-effective technological platforms designed explicitly for Structural Health Monitoring (SHM) in civil infrastructure studies.

From the sensor perspective, using contact-based sensors for NDE in civil infrastructure is inherently time-consuming [4, 5]. To overcome this challenge, stochastic, optimal path-planning algorithms are needed. These

*Corresponding author. Email: ottaviano@unicas.it

algorithms should leverage sensor fusion-based decision-making processes to prioritize areas for inspection based on inputs from various sensor modalities. However, it is important to note that a significant portion of existing studies on sensor fusion lacks reliable performance evaluation metrics. Despite the numerous studies aimed at developing sensor fusion techniques, a single sensor is often used to gather information on the examined infrastructure's Structural Health (SH). Moreover, the absence of established safety and security protocols for automated and robotic solutions limits their application in underground monitoring and inspection. Robots must position sensors at the site of interest and be capable of manipulating or placing sensors using specialized robotic hands or grippers [6] designed for the task.

Robotics and automation have become ubiquitous and widely employed across various industrial sectors for production and quality assessment. Over the past few decades, their applications have expanded beyond traditional uses. Robots are now deployed in diverse fields, including service [7], manufacturing, search and rescue [8], agriculture [9], remote exploration [10], entertainment, and, notably, structural inspection and monitoring [11], as well as historical site preservation [12]. The increasing sophistication of intelligent systems is crucial for enhancing daily life activities and improving the security, resilience, and reliability of implemented solutions.

Looking ahead, the use of robotics across various sectors is expected to surge significantly. In particular, the evolution of on-site automation and robotics for inspection is closely linked to smart buildings, smart sensors, and cyber-physical systems. The future holds great promise for robotics in reducing energy consumption and carbon dioxide emissions. For example, robotic maintenance could replace traditional methods, such as helicopter inspections of transmission lines, potentially achieving up to a 95% reduction in energy use [13].

When considering the inspection and monitoring of indoor and underground facilities, Unmanned Ground Vehicles (UGVs) are a necessary solution, particularly in confined spaces and harsh environmental conditions where Unmanned Aerial Vehicles (UAVs) is not feasible. While UAVs are commonly used for outdoor surveys due to their speed, cost-effectiveness, and reliability, they are unsuitable for indoor environments and underground facilities.

UGVs are classified based on the technology they use to navigate the terrain. They can be wheeled [14], legged [15], tracked [16], or a combination of legs and wheels [17] or legs and tracks [18]. Hybrid solutions are particularly well-suited for navigating unstructured environments with obstacles. Energy consumption is also a critical factor, as it directly impacts the robot's autonomy during inspections.

Given these challenges, developing mobile robotic platforms for real-time data collection and transmission capable of monitoring indoor and/or underground structures remotely is highly effective. These robots should be compact to ensure flexibility in indoor or underground environments while also being capable of carrying loads, as they need to be equipped with appropriate sensors and microprocessors for data processing. Additionally, they must be able to navigate complex topological conditions and, if necessary, manipulate or install sensors remotely in intricate indoor or underground scenarios.

In light of these considerations, this paper proposes designing and simulating a new version of a hybrid rover, previously intended for inspection purposes [18]. Specifically, the design improvements focus on integrating a suspension system and redesigning the tracks. Simulation tests were conducted, and this paper will present the results to demonstrate how the robot interacts with obstacles.

2. Design Improvements of THROO (Tracking Hybrid Robot for Overpassing Obstacles)

THROO (Tracked Hybrid Rover for Overpassing Obstacles) in Figure 1 is a robotic system comprising a mechanical framework, a control system, and task-specific sensors and actuators. The mechanical component features a hybrid mobile robot chosen for its optimal balance of flexibility, mobility, energy efficiency, and cost-effectiveness when navigating diverse terrains. Its high payload capacity makes it well-suited for carrying sensors, enabling it to inspect hard-to-reach locations and perform challenging tasks for human operators.

The prototype in Fig. 1a), introduced and described in [18] and [19], has proven effective in inspection applications, especially in industrial sites, due to its remarkable adaptability in overcoming obstacles and maneuvering through cluttered environments.

The original design incorporates tracks and legs, with the tracks used for traversing nearly flat surfaces and the legs explicitly designed for overcoming obstacles. The innovative arrangement of the front and rear pairs of legs allows the rover to surmount obstacles that are up to 110% the size of the tracks [19].

The load capacity is a key feature, as the mechatronic system is designed to transport instruments. In line with the overall project concept, THROO's design features single-degree-of-freedom robotic legs constructed with a 4-bar mechanism powered by a single actuator, as shown in Fig. 1b). This streamlined approach minimizes construction and control complexity.

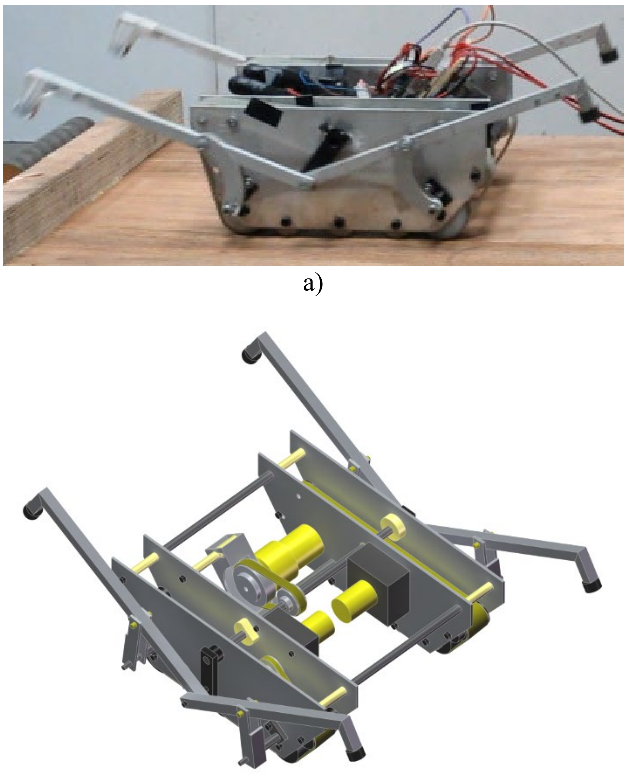
The mechatronic design of the THROO inspection robot can be divided into two key parts based on the design philosophy outlined in [20]. The first part is crucial for robot mobility and operational modes, which can adapt to different environments. The second part is managing an external sensor suite tailored to specific applications. The "internal sensor suite," shown in Fig. 2, is vital in controlling and monitoring the robot's interactions with its environment. Depending on task requirements and cost considerations, three navigation modes are available: pure teleoperation, safeguarded teleoperation, and, for future applications, autonomous navigation. The choice of mode depends on the nature of the task and environmental conditions. The original version of THROO had three degrees of freedom (DOFs)—two for the tracks and one for the front and rear leg pairs. The main characteristics of the prototype are summarized in Table 1.

The rover is teleoperated via a tablet, as illustrated in Figure 2 and Table 2. A comparison among THROO and similar robots for inspection was proposed in [18].

The level of sensorization is linked to the chosen navigation mode and the complexity required for the inspection [19]. The internal sensor suite in Table 2 controls the robot's mobility and navigation. This includes proximity sensors, encoders, GPS, accelerometers, gyroscopes, magnetic compasses, tilt, and shock sensors. Initially, THROO operated in teleoperation mode, benefiting from continuous input from the operator. This mode is advantageous when search parameters are unknown or unstructured or cluttered environments, where visual input is crucial for orienting and maneuvering the robot.

Depending on the task, several external sensors can be added. For outdoor inspection, the rover can utilize a variety of commercially available sensors, as listed in Table 2. These sensors are commonly used in industrial environments, offering robust features while remaining affordable.

Numerical simulations and experimental tests have been conducted to evaluate the performance of the THROO hybrid rover, as detailed in [19].



a)

b)

Figure 1. The old THROO version: a) the prototype; b) the 3D model for simulations**.**

Table 1. Design specifications for THROO

Design Specifications	
Size (L×H×W)	300×200×400mm
Mass	4.5 kg (no batteries)
Max speed	Up to 0.5 m/s
Actuation (tracks)	24VDC 5 Nm, 3.9 W ×2 Torque = 5 Nm
DOFs	3 (4)
Payload	up to 7 kg

Table 2. Sensors' specifications for THROO

Internal Sensors	
Type of sensor	Model
Accelerometer	QTI Ver.2
Gyroscope sensor	BMI160 - Bosh
Gravity sensor	QTI Ver.2
Magnetometer	AKM-09918-Ver1
Lin. Accel. sensor	QTI Ver.2
External Sensors	
Description	Specification
Thermal camera	FLIR: 48MP+5MP Thermal Imagery
Front - Rear camera	Sony: 48MP+19MP
Communication	
Description	Specification
WiFi router (Ethernet/Lan)	TP-LINK Model TL-WN821N
AR6210 DSMX	Spektrum Receiver Mk610
Control	
Description	Specification
HMI Interface /Remote-Controller	Tablet 10" -Samsung

The rover was tested in both indoor and outdoor environments, and it was observed that the presence of tracks on uneven terrain can cause vibrations, which increase the risk of interfering with data acquisition from the external sensors. This issue prompted a discussion about modifying the rover's design while maintaining its overall structure. The proposed modification involves adding a suspension system without altering the original design philosophy, which focuses on using commercial components, ensuring compactness, and providing ease of use.

Figure 3 illustrates the rover with the new suspension system in 3D (Fig. 3a) and front view (Fig. 3 b), which is detailed in Figure 4, and a rollbar designed to prevent the rover from overturning, as shown in Figure 5.

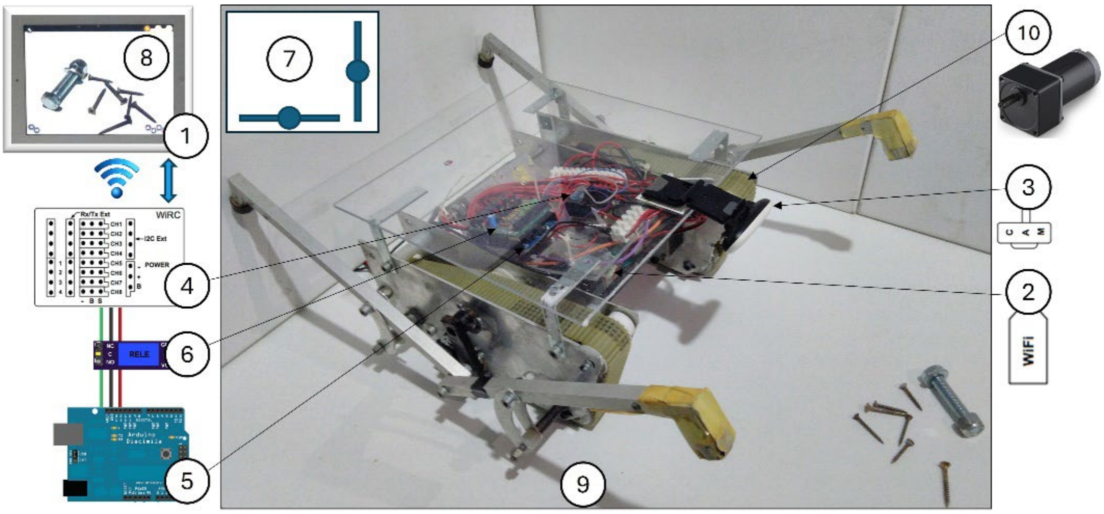
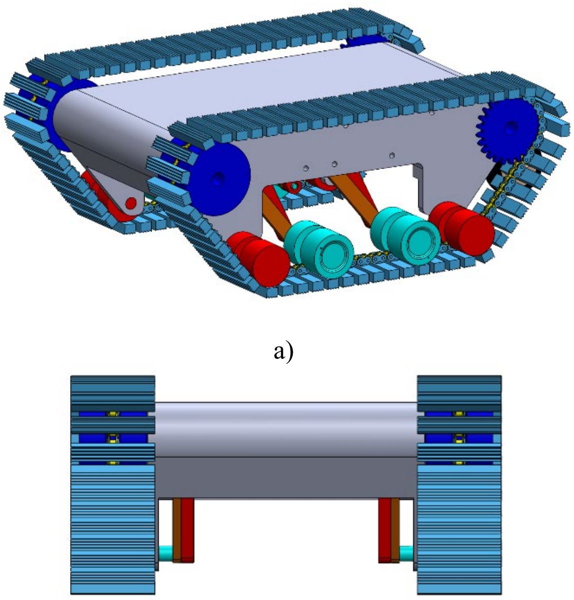


Figure 2. Internal sensors on the THROO robot: 1) Tablet, 2) WiFi router, 3) Camera, 4) Wirc module, 5) Arduino, 6) relay, 7) slider for motor control, 8) camera view, 9) the overall robot; 10) DC motor used.

The model also features a newly designed track to improve simulation accuracy.

The proposed rover is intended for inspection, including sites with unexploded mines. This is one of the primary reasons for maintaining a low-cost design, as there is a risk of irreparable damage to the rover in such environments. The suspension system comprises a fixed frame, two levers of different lengths, and a triangular-shaped link. The triangular structure of the link plays a crucial role, as it connects the chassis to the movable linkage.



a)

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Figure 3. Mechanical design of the novel with a suspension system for THROO: a) The 3D view; b) The front view.

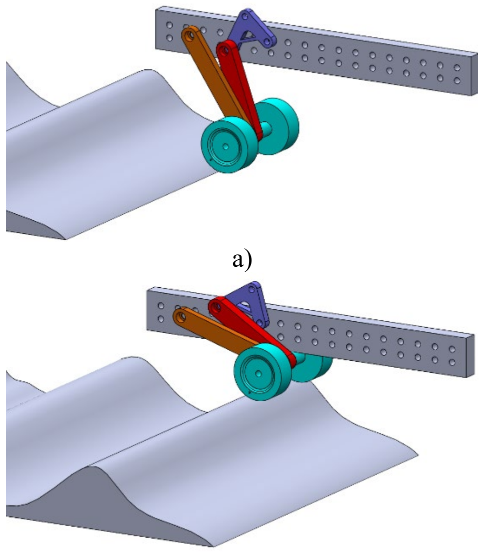

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Figure 4. Mechanical design of the suspension system: a) rest position; b) end-of-travel configurations.

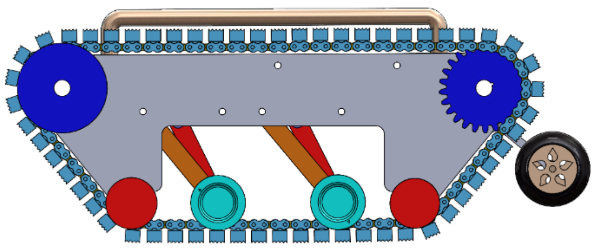


Figure 5. Mechanical design of the chassis with a rollbar to avoid overturning.

The top hole of the link is designed to house the shock absorber, a critical component responsible for controlling shock absorption and oscillations. The suspension elements are positioned inside the chassis to save space and ensure more effective maintenance of the moving components. Figures 4a) and 4b) show side views of the suspension in two configurations: the rest position and the end-of-travel position. Integrating the suspension within the frame offers several benefits. Firstly, it helps reduce the space occupied on the sides of the vehicle, contributing to a more compact overall design. Additionally, housing the suspension parts inside the frame protects them from debris, mud, and other contaminants that could affect the system's performance. The two configurations in Figure 4 demonstrate the suspension's adaptability to variations in terrain or impacts during operation. The rest configuration (Figure 4b) shows the basic arrangement of the suspension elements, while the end-of-travel configuration highlights the maximum excursion the system can achieve in demanding conditions. The overall cost of the prototype is at least 50% less expensive than the commercialized counterparts, sharing approximately the same size and power. Integrating the suspension components within the chassis optimizes space efficiency, enhances protection for the components, and provides a suspension that can precisely adjust to various driving conditions on uneven terrain. The maximum allowed excursion of 70 mm is achieved by limiting the angular range of the connecting rod's movement. The rod will reach its limit at 90° with the ground.

3. Simulations in several scenarios

Several simulations were conducted with the newly designed rover, shown in Figures 3 to 5, using slopes and obstacles like those depicted in Figure 6. The behavior of the new THROO rover was simulated, as seen in Figures 7 and 8, while navigating a scenario presented in Figure 6. The simulation results will provide insights into the designed mechanisms and the mechatronic development by verifying the actuation system.

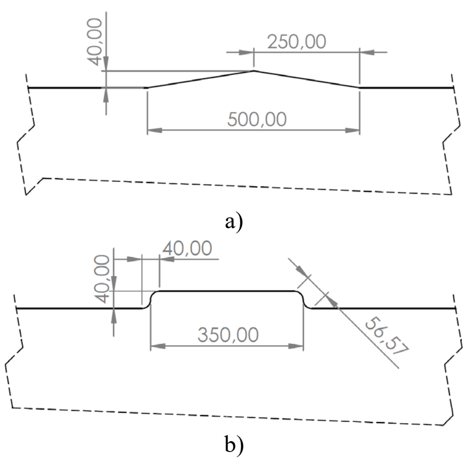


Figure 6. Obstacles in mm for the simulation of the new THROO: a) a slope; b) an obstacle.

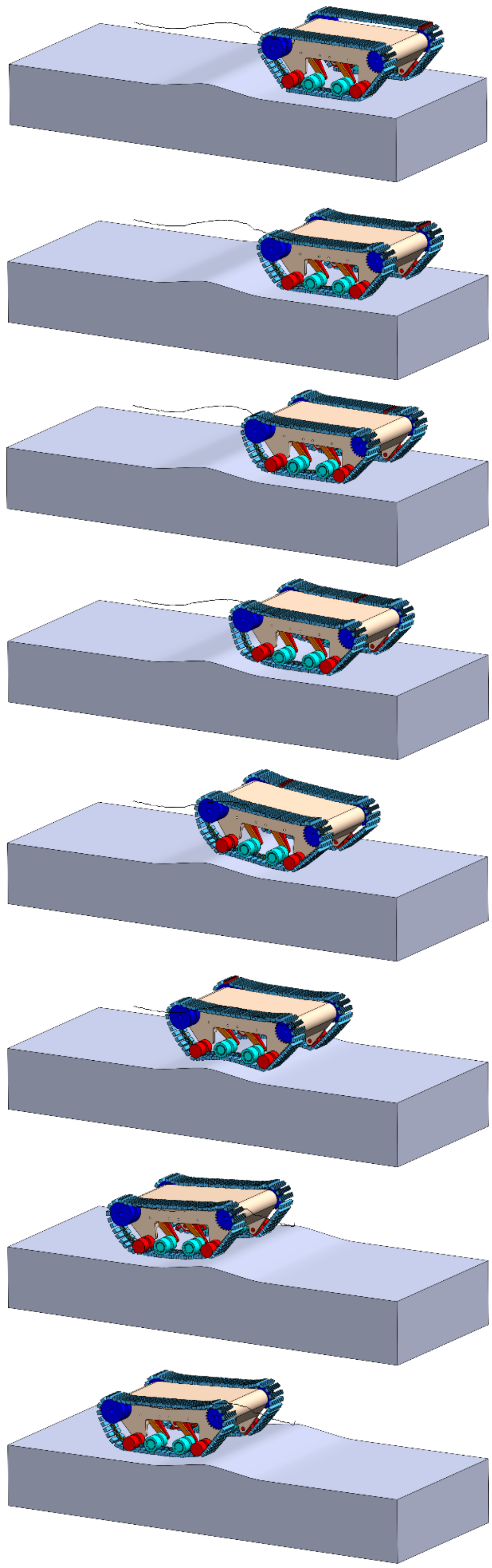


Figure 7. Motion sequence for the slope overpassing represented in Figure 6a).

Simulation results without suspension systems are provided in [18]. A comparison of the system's behavior with and without a suspension system, with simulation tools, demonstrates an improvement of 20% in the performance. Figure 9a) shows the Center of Gravity (COG) velocity while navigating the slope shown in Figure 6a). These results correspond to one of the simulations conducted under various conditions, with the maximum velocity reached during the simulation being 0.25 m/s.

Figure 9b) presents similar results for overcoming the obstacle in Figure 6b). Figure 10 illustrates the linear accelerations experienced by the prototype during the simulations in Figures 7 and 8.

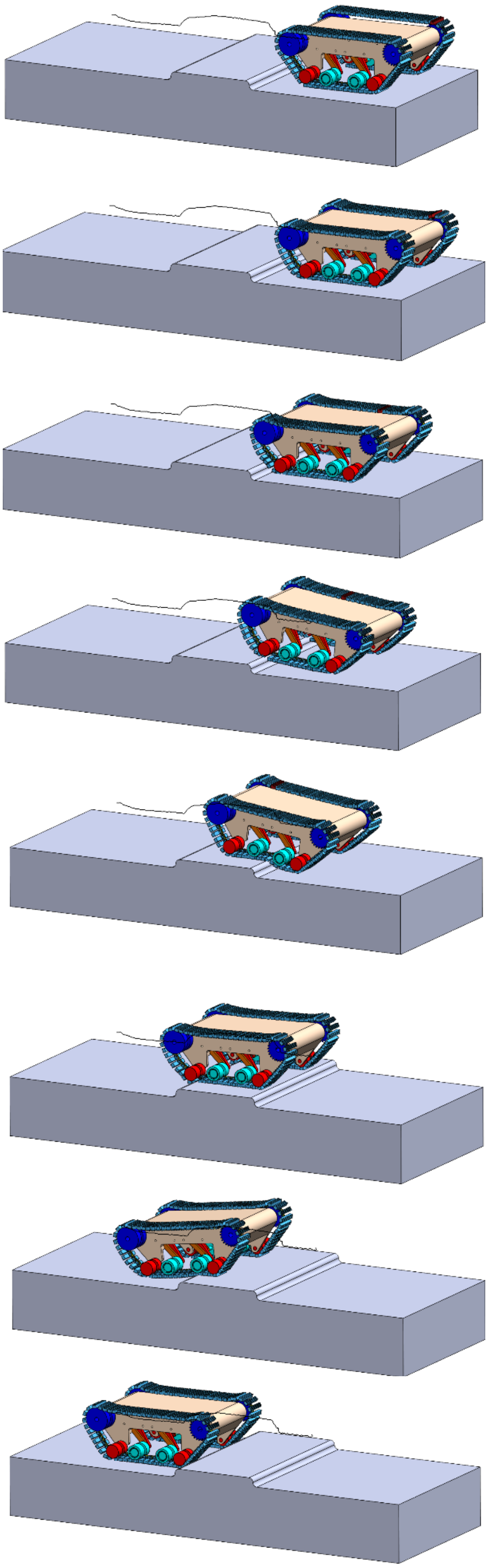
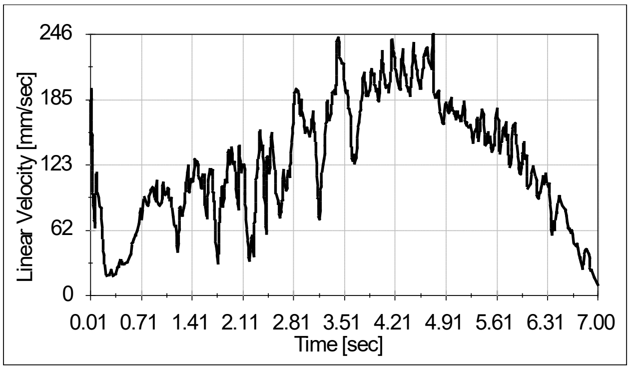


Figure 8. Motion sequence for the slope overpassing represented in Figure 6b).



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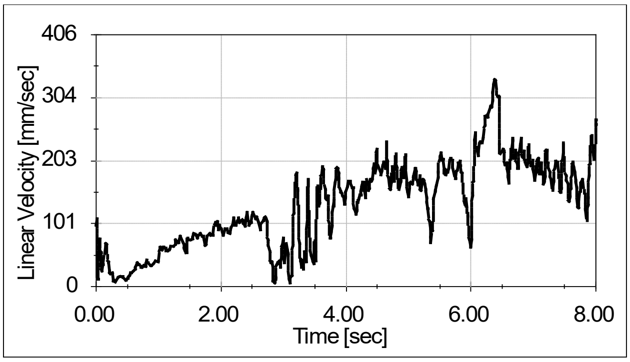

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Figure 9. Numerical results for the velocity of the Center of Gravity: a) results for the simulation in Figure 7; b) results for the simulation in Figure 8.

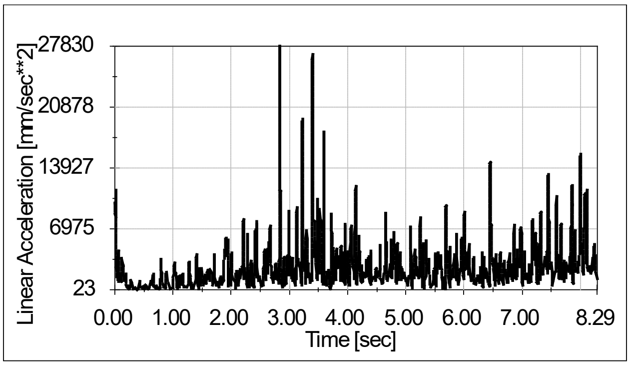

Figure 10. Numerical results of the linear acceleration for the simulations in Figures 7 and 8.

4. Conclusion

Recently, a significant focus has been developing novel monitoring and inspection methodologies, leveraging the widespread advancements in Robotics and Mechatronics. This paper proposes the design and numerical simulation of a hybrid robot designed for inspection purposes, including applications in indoor and underground sites and areas with unexploded mines and ordnance. A suitable 3D model enables the development of realistic simulations and the planning of testing operations in a controlled environment. A suspension system has been designed to optimize the robot's interaction with uneven terrain. Future developments will focus on implementing and integrating the mechanical modifications into the mobile robot. The overall cost of the prototype is at least 50% less expensive than the commercialized counterparts, sharing approximately the same size and power. The low-cost philosophy is highly beneficial when considering the risk of losing the robot due to an explosion in mine zones.

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References

[1] Gkoumas, K, Stepniak, M., et al. New technologies for bridge inspection and monitoring: a perspective from European Union research and innovation projects, Structure and Infrastructure Engineering, 2024, DOI: 10.1080/15732479.2024.2311898.
[2] La, H.M., Gucunski, N., Dana, K., Kee, S.-H.: Development of an autonomous bridge deck inspection robotic system. J. Field Robot, 2017, 34: 1489–1504.
[3] Nguyen, S.T., La, H.M. Development of a Steel Bridge Climbing Robot. In Proc of the 2019 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Macau, China, 2019, 1912–1917.
[4] Gibb, S., La, H.M., Le, T., et al. Non-destructive evaluation sensor fusion with autonomous robotic system for civil infrastructure inspection. J. Field Robot, 2018, 35: 988–1004.
[5] Ahmed, H., La, H.M., Gucunski, N. Review of Non-Destructive Civil Infrastructure Evaluation for Bridges. State-of-the-Art Robotic Platforms, Sensors and Algorithms. Sensors, 2020, 20: 3954. https://doi.org/10.3390/s20143954.
[6] Figliolini, G., Rea, P. Overall design of Ca.U.M.Ha. robotic hand for harvesting horticulture products, Robotica, 2006, 24(3): 329-331 Sprenger, M., Mettler, T.: Service Robots, Business & Information Systems Engineering, DOI: 10.1007/s12599-015-0.
[7] Lixiang, Z., Ze, C., Yan, Y., Chen, Y., Yaoguang, H. Multi-agent policy learning-based path planning for autonomous mobile robots, Engineering Applications of Artificial Intelligence, 2024, 129: 107631, https://doi.org/10.1016/j.engappai.2023.107631.
[8] Habibian, S., Dadvar, M., Peykari, B. et al. Design and implementation of a maxi-sized mobile robot (Karo) for rescue missions. Robomech Journal, 2021, 8(1).
[9] Bordoloi, A. Revolutionizing Agriculture: Harnessing the Power of Robotics. Smart Agriculture. Digital Era in Farming, Elite Publishing House, 2023.
[10] Bellingham, J. G., et al. Robotics in Remote and Hostile Environments, Science, 2007, 318: 1098, DOI: 10.1126/science.1146230.
[11] Smarsly, K., Dragos, K., et al. Mobile Structural Health Monitoring Based on Legged Robots. Infrastructures, 2023, 8:136. https://doi.org/10.3390/infrastructures8090136 .
[12] Rea, P., Pelliccio, A., Ottaviano, E., Saccucci, M. The Heritage Management and Preservation Using the Mechatronic Survey, Int. J. of Architectural Heritage, 2017, 11(8): 1121-1132, DOI: 10.1080/15583058.2017.1338790.
[13] Nagarajan, B.; Li, Y.; Sun, Z.Y. Qin, R.W: A routing algorithm for inspecting grid transmission system using suspended robot: Enhancing cost-effective and energy efficient infrastructure maintenance. J. Clean. Prod., 2019, 219: 622–638.
[14] SmpRobotics: https://smprobotics.com/ (2025).
[15] Anybotics: https://www.anybotics.com/robotics/automate-inspection/ (2025).
[16] Li, Ruiming, Zhang, Xianhong, Hu, Shaoheng, Wu, Jianxu, Feng, Yu, Yao, Yan-an.: Design and Analysis of an Adaptive Obstacle-Overcoming Tracked Robot with Passive Swing Arms. Machines, 2023, 11: 1051. 10.3390/machines11121051.
[17] Ottaviano, E., Vorotnikov, S., Ceccarelli, M., Kurenev, P., Design improvements and control of a hybrid walking robot, Robotics and Autonomous Systems, 2011, 59 (2): 128-141.
[18] Ottaviano, E., Rea, P., Castelli, G.: THROO: a Tracked Hybrid Rover to Overpass Obstacles. Advanced Robotics, 2014, 28(10), DOI=10.1080/01691864.2014.891949.
[19] Rea, P. Ottaviano, E. Design and development of an Inspection Robotic System for indoor applications, Robot. Comput. Integr. Manuf., 2018, DOI: 10.1016/j.rcim.2017.06.005.
[20] Ceccarelli, M., Ottaviano, E., Galvagno, M. A 3-DOF Parallel Manipulator as Earthquake Motion Simulator, Proc. of the 7th International Conference on Control, Automation, Robotics and Vision, ICARCV2002, 2002. 944-949,