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Original Research

SIMULATION BASED STUDY OF GROUND MOBILE ROBOTS FOR INSPECTION AND CONTROL OF THE BRIDGE ASSEMBLY PROCESS

BADANIE OPARTE NA SYMULACJI NAZIEMNYCH ROBOTÓW MOBILNYCH DO INSPEKCJI I KONTROLI PROCESU MONTAŻU MOSTU

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Abstract

Nowadays, the inspection of bridges poses a significant challenge for safeguarding critical infrastructures. Recent advancements have seen the integration of robots to replace human personnel in hazardous tasks. These robots, whether operating autonomously or through tele-operation, play a crucial role in monitoring structures and infrastructure, ensuring secure access to areas such as manholes on decks and box girder bridges. Specifically designed for environments deemed dangerous, difficult, or inaccessible to humans, ground mobile robots equipped with appropriate sensors are increasingly deployed for inspection purposes. This paper addresses simulation tests conducted by a hybrid mobile robot. Its compact design and maneuverability enable it to navigate through obstacles, making it suitable for inspecting railway or highway bridge decks as well as confined spaces within box girder bridges. The study includes a survey of existing bridges highlighting key issues to be addressed and presents simulation results for the hybrid rover. Automatic and robotic systems can play an important role for the control during the bridge assembling process increasing the reliability of the structure and improving its operational properties and security.

Keywords: Ground Mobile Robots, Bridge Inspection, Simulation, Structural Health Monitoring

Streszczenie

Obecnie inspekcje mostów stanowią istotne wyzwanie dla ochrony infrastruktury krytycznej. Najnowsze osiągnięcia umożliwiły integrację robotów w celu zastąpienia personelu ludzkiego przy wykonywaniu niebezpiecznych zadań. Roboty te, działające autonomicznie lub w trybie teleoperacji, odgrywają kluczową rolę w monitorowaniu konstrukcji i infrastruktury, zapewniając bezpieczny dostęp do takich obszarów, jak włazy na pokładach i mosty z dźwigarami skrzynkowymi. Zaprojektowane specjalnie dla środowisk uznawanych za niebezpieczne, trudne lub niedostępne dla człowieka, naziemne roboty mobilne wyposażone w odpowiednie czujniki są coraz częściej wykorzystywane do celów inspekcyjnych. W artykule omówiono badania symulacyjne prowadzone przez hybrydowego robota mobilnego. Jego zwarta konstrukcja i zwrotność umożliwiają mu pokonywanie przeszkód, dzięki czemu nadaje się do inspekcji pomostów kolejowych lub autostradowych, a także ograniczonych przestrzeni w mostach z dźwigarami skrzynkowymi. Badanie obejmuje przegląd istniejących mostów, podkreślając kluczowe problemy, którymi należy się zająć, i przedstawia wyniki symulacji dla łazika hybrydowego. Systemy automatyczne i zrobotyzowane mogą odegrać ważną rolę w sterowaniu procesem montażu mostu, zwiększając niezawodność konstrukcji oraz poprawiając jej właściwości eksploatacyjne i bezpieczeństwo.

Słowa kluczowe: Naziemne roboty mobilne, inspekcje mostów, symulacja, monitorowanie stanu konstrukcji

1. Introduction

Robotics and automation play an important role for many applications. Traditionally developed for industrial tasks, such as pick and place, welding, spraying, deburring, just to cite some, robots have been used in a wide range of different domains, such as, service (Sprenger and Mettler, 2015), remote exploration (Shapovalov and Pereira, 2020), agriculture (Acaccia et al., 2003)), and inspection (Ottaviano et al., 2014; Rea and Ottaviano, 2023).

Referring to the inspection of structures and infrastructure, the use of automatic or teleoperated systems allows increasing safety of the operation, reduce time and cost of survey and thus make the process more systematic and prone to be used for preventing critical damages or structural collapses. Moreover, the use of automatic systems allows collecting data from several sensors making the inspection task repeatable and safe.

Referring to infrastructure inspection, the use of Unmanned Aerial Vehicles (UAV) has enormously increased because of their main characteristics, namely wireless transmission, rapid and cost-effective deployment. Recently, the level of autonomy, which was the main drawback, has been enlarged (Amici et al., 2021). Although their advantages and leading role in outdoor inspections, when dealing with confined spaces, pipelines, box girder bridges and in all cases of harsh environments conditions or heavy payloads, alternatives must be considered.

Ground Mobile Robots (GMR) are a type of Unmanned Ground Vehicles (UGV) that are used in combination with or as alternative of UAVs. They can be classified according to the locomotion type; therefore, they can use wheels (Rajendran et al., 2022), legs (ANYbotics, 2024), tracks (Sahari et al., 2022) or combinations of the previous types (Ottaviano and Rea, 2013), the latter are named as hybrid mobile robots.

Wheeled robots are the most common ones, they are robust and energy saving systems, the main drawback is related to the environment, they are effective in almost flat surfaces, being able of overpassing obstacles of limited size. Legged robots have been developed to overcome these limitations, being versatile systems, capable also of climbing slopes and stairs in all kinds of environments. Challenges in their use are related to energy consumption, complexity in control and high costs. Finally, hybrid mobile robots have been developed to conjugate obstacle overpassing capability but maintaining complexity of control and costs limited.

In this paper we are presenting a hybrid mobile rover that was developed for inspection purposes. In particular, we have chosen two different types of bridges to simulate the behavior of hybrid mobile robot in the survey, demonstrating its ability in negotiating different scenarios.

2. Bridge Inspection

Following the bridge collapse in Genoa, Italy, on 14 August 2018, which resulted in the deaths of 43 people, the scientific and professional community has begun to focus intensively on the poor condition of bridge structures. These scientific and professional activities are being addressed both in Italy and in Slovakia. The bridge over Polcevera, or otherwise known as the Morandi Bridge, was put into operation in 1967 after 4 years of construction. The longest span of the bridge structure was 210 m, the total length: 1182 m, and with a pylon height of 90 m, built as prestressed reinforced concrete, it was the top work of the time, named after the designer Riccardo Morandi. An extensive investigation confirmed that the bridge's collapse was due to a lack of maintenance.

The current state of bridge structures in road and rail transport in Slovakia is alarming. This is evidenced not only by the collapsed bridges in the Slovak Republic (Spišská Nová Ves bridge, bridge in Trstena over the Oravica river bridge over the Turiec river, bridge over the Hornád river, but also by the alarming condition of many other bridge constructions. For example, those that had to be closed immediately, because in the process of their reconstruction it was found that their condition was significantly worse than expected. Therefore, a much more complex reconstruction or their removal and the construction of a new bridge (e.g. the bridge in Hlohovec, the Podtureň bridge, etc.) is needed.

In Italy the situation is similar, high number of collapsed bridges demonstrates the gravity of the situation.

In the Slovak Republic, the use of new more modern technologies for bridge diagnostics is lagging. Long-term monitoring of bridges is exceptional in the environment of ŽSR (Slovak railways) and encounters a significant problem with the analysis and evaluation of a large amount of data. A comprehensive Bridge Management System (BMS) has been introduced abroad, which is a means of managing bridges during the so-called life cycle of the object, i.e. from design, construction, operation to maintenance of bridges. In Italy for road bridges was established a new industrial plan for years 2016-2020, where new inspection procedures were defined, and Bridge Management System (BMS) realized (Figuli et al. 2021).

3. Ground Mobile Robot for Bridge Inspection

In this paper a ground mobile rover is considered, as it is shown in Figures 1 and 2; the mechanical design and its main features have been proposed in (Rea and Ottaviano, 2023). The rover is of hybrid type, since it is designed having tracks commanded by 2 DC motors, and legs commanded by an additional DC motor.

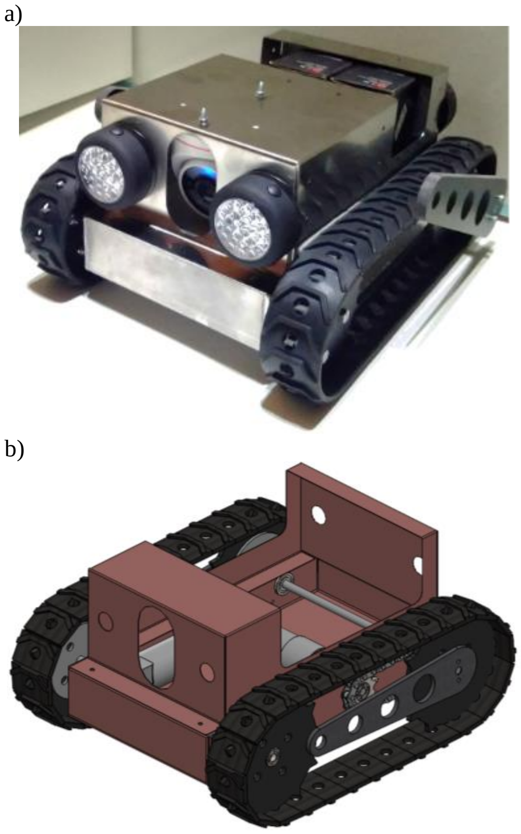

Fig. 1. Ground Mobile Robot: a) a built prototype; b) 3D mechanical design

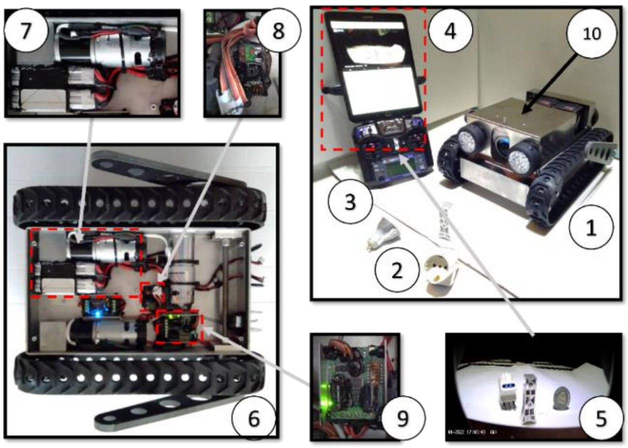

Fig. 2. A scheme of the Ground Mobile Robot: 1) the prototype; 2) objects; 3) Remote Controller; 4) HMI for control; 5) camera view; 6) robot-control boards; 7) motors and battery pack; 8) Spektrum Receiver Mk610; 9) board for control; 10) camera view

Track are used in conjunction with legs when the size of the obstacles to be surpassed is greater than the radius of the tracks.

Figure 2 shows the mechatronic design of the mobile robot, including the HMI (Human Machine Interface) used for teleoperation.

4. Simulation tests

The robot prototype underwent rigorous testing across various operational conditions to assess its engineering viability and performance within real-world scenarios and environments (Rea and Ottaviano, 2023). Specifically, as mentioned earlier, the system underwent testing focused on infrastructure inspection tasks.

4.1. Road Bridges

As road bridges, especially for the important infrastructure, box girder bridges are commonly used worldwide. Box birder bridges are one of types of prestressed bridges. In Slovakia various type of prestressed girders are used for many years and after the years in services the numbers of defects on precast prestressed girder are presented as removed concrete cover, corroded tendons with some ruptured wires, corroded anchors, water leakage through the carriage-way and insulation, overloading of construction, hollow space or voids within concrete caused during casting of the girder, absence of shear reinforcement in prestressed girders, minimal reinforcement ratio was not fulfilled, absence of bonded post-tensioned prestressing, inadequate grouting of tendons and incorrect position of girders on the bearings as is reported in Bujnakova (2017) and Bujnakova (2020). Nowadays another type of box girder bridge is very popular, so called extradosed bridges, number of such types of bridges were constructed lately in Slovakia (Bujňák at al. 2013). For example, a new bridge is in construction in Zilina, over the main railway (see Fig.3). An extradosed bridge combines the main elements of both a prestressed box girder bridge and a cable-stayed bridge. Compared to a cable-stayed, an extradosed bridge uses much shorter pylons than the cable-stayed bridge, and a significantly shallower deck/girder structure than used on the girder bridge. Like any bridge structure, extradosed bridges require regular inspection and maintenance to ensure their long-term performance and safety. Accessing and inspecting the cables and other components of the bridge may pose challenges and require specialized equipment or techniques. The construction of extra-dosed bridges can be more challenging and bring more critical situation. The integration of cables and prestressed concrete elements requires precise coordi-nation and careful execution during construction.

Simulation tests were performed by considering an example of box girder bridge in Fig. 4. The simulation was performed inside the closed elements in the lateral parts in which the floor is inclined. Usually, internal stiffeners are used to reinforce the structure, these elements are considered as obstacles that the robot as to surpass, as it is reported in the numerical simulations of Figs. 5 to 7. Figure 5 shows the motion sequence in which it is necessary to use legs for overpassing the obstacle (the legs are used as propulsive elements). Figs. 6 and 7 reports the actuation for the tracks and legs and kinematic characteristics in terms of velocities and accelerations of the robot center of gravity.

Fig. 3. Box girder bridge: extradosed bridge in Zilina

a)

b)

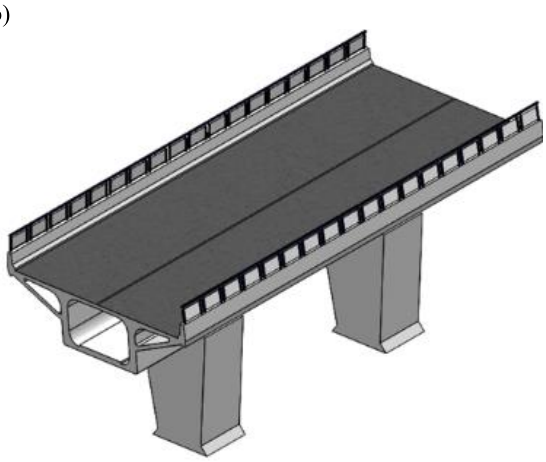

Fig. 4. Box girder bridge example: a) built structure; b) a designed 3D CAD

a) b) c) d) e) f) g) h)

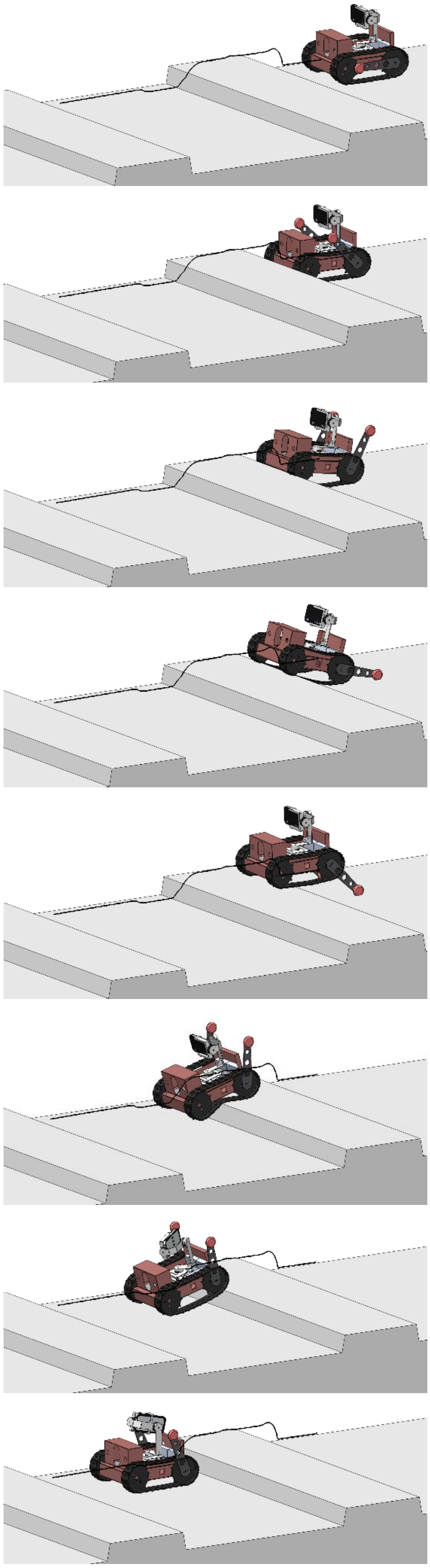

Fig. 5. Motion sequence of the ground mobile robot moving in the box girder bridge

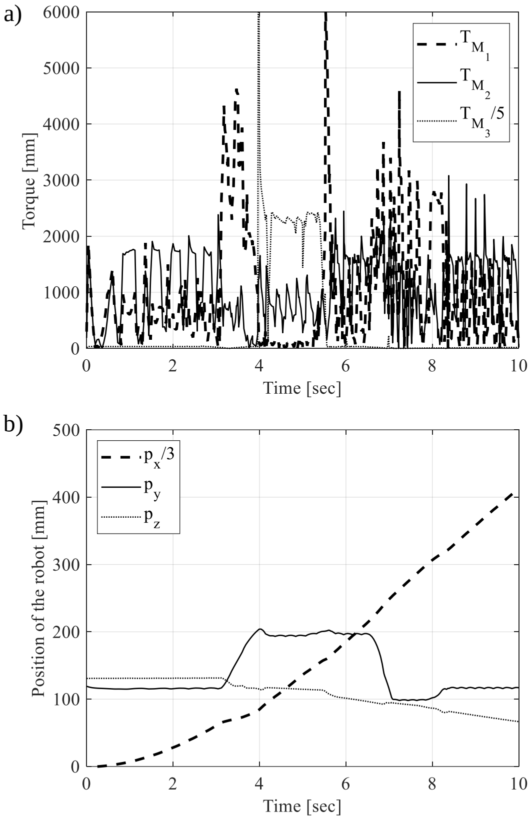

Fig. 6. Simulation results for Figure 5: a) torques for the left and right motors (M_1 and M_2) and legs (M_3); b) coordinates PCM of the center of mass (CM)

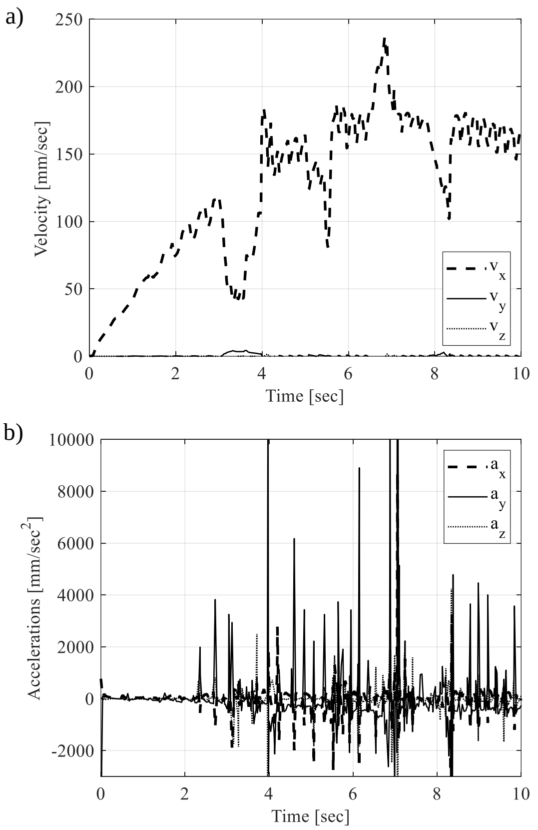

Fig. 7. Results of Figure 5 COM: a) velocities v_x v_y v_z; b) accelerations a_x a_y a_z

4.2. Railway Bridges

Railway bridges are crucial components of railway networks, occupying strategic positions within transportation infrastructure. Over years of use, these structures are subjected to various degradation processes and external influences. Consequently, their durability and reliability diminish over time as a result of these effects (Vičan, J et. al 2015, 2016).

There are 2301 bridges with a total length of 51216 metres registered in railway transport. The average age of railway bridges is more than 60 years. Existing structures need to be inspected to detect any damage and to plan their maintenance.

In Slovakia the high number of bridges are steel structures, mainly as girder bridges for shorter span and truss bridges and arch bridges of special type – girder bridge stiffened by arch.

The simulation tests were conducted in accordance with the specifications to enable the hybrid rover to navigate across the bridge deck. The primary focus of these tests was to identify and navigate over obstacles, with particular emphasis on the rails, as shown in Fig. 9. Numerical results of the simulation are given in Figs. 10 and 11.

Figure 10 reports the velocity and acceleration of the center of gravity of the rover during the motion, Fig. 11 reports the torques for tracks and legs.

Fig. 8. Railway bridge example: a) built structure; b) a designed 3D CAD

The reported simulations can be used to size the actuation and main parts of the robots during the design or verifying the overthrow avoidance when preparing the survey.

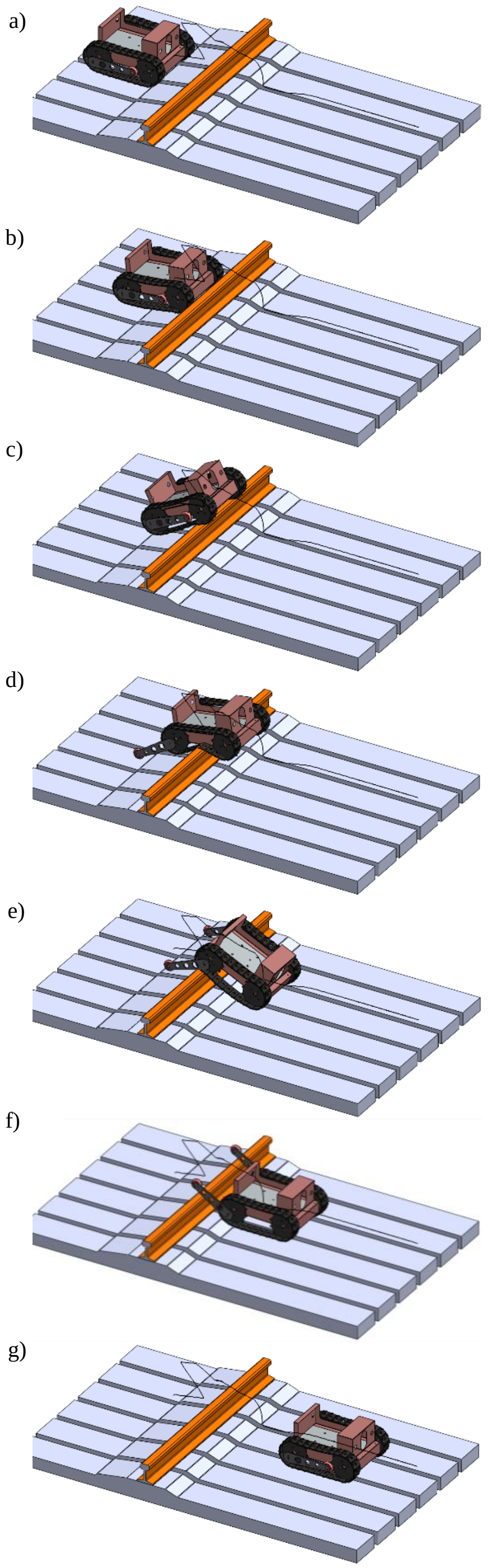

Fig. 9. Motion sequence in the railway bridge

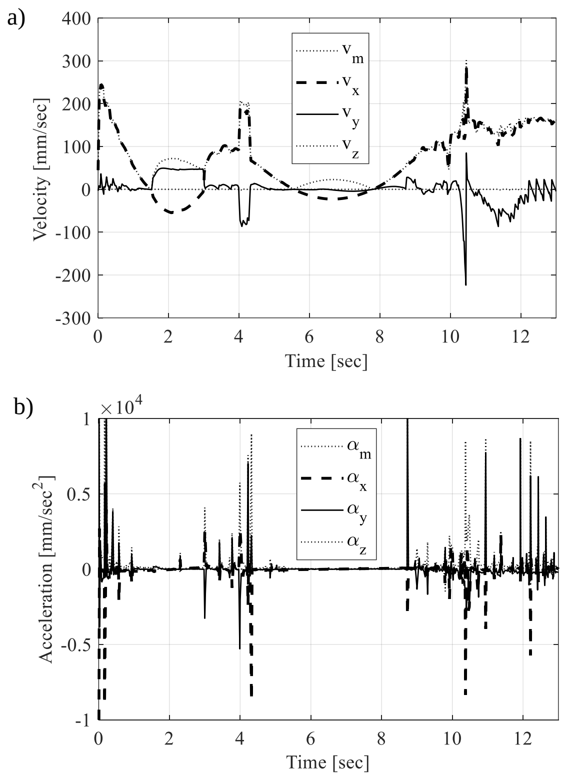

Fig. 10. Results of the simulation in Fig.9: for the center of gravity a) velocity, b) acceleration

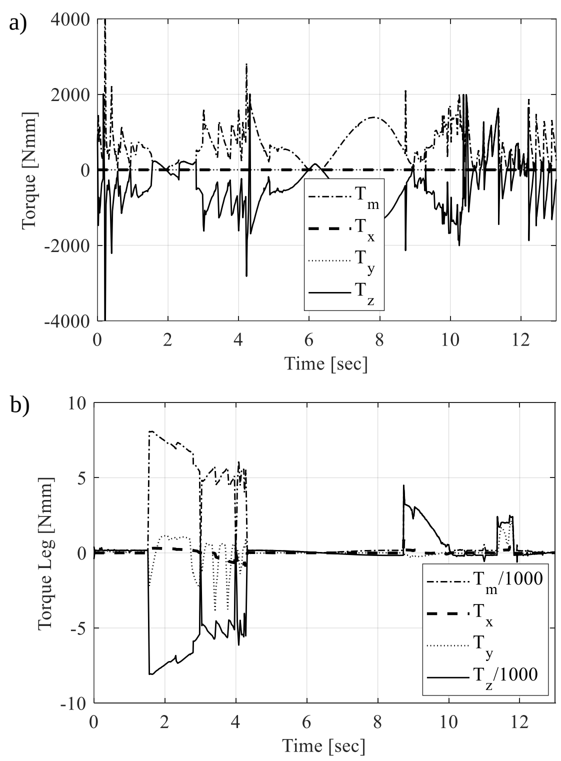

Fig. 11. Results of the simulation in Fig.9: a) torque T_m magnitude and components of tracks; b) for the legs

5. Conclusion

This article proposed the use of ground mobile robots for bridge inspections. In particular, taking into account two types of bridges structures, having different materials, shapes and problems to face, a built rover has been used for simulating the inspection tasks for planning a survey. Simulation tools and models are widely used to design and optimize the system, but also for preparing and optimizing the inspection tasks before they are executed. It is important to highlight that robots can play an important role also during the bridge assembling process for the control, increasing the reliability of the structure and improving its operational properties and security during operational life. In fact, the ground mobile robots can be autonomous or teleoperated platforms on which materials, sensors, robotic arms for manipulation can be integrated for assembling parts, carrying instruments, installing sensors during the assembly process before and after for inspection and further maintenance.

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