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Article

A Small Robot to Repair Asphalt Road Potholes

Salvatore Bruno [1], Giuseppe Cantisani [1], Antonio D'Andrea [1], Giulia Del Serrone [1], Paola Di Mascio [1,*], Kristian Knudsen [2], Giuseppe Loprencipe [1], Laura Moretti [1], Carlo Polidori [3], Søren Thorenfeldt Ingwersen [2], Loretta Venturini [4] and Marco Zani [5]

1 Department of Civil, Building and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy; salvatore.bruno@uniroma1.it (S.B.); giuseppe.cantisani@uniroma1.it (G.C.); antonio.dandrea@uniroma1.it (A.D.); giulia.delserrone@uniroma1.it (G.D.S.); giuseppe.loprencipe@uniroma1.it (G.L.); laura.moretti@uniroma1.it (L.M.)
2 TinyMobileRobots, Sofienlystvej 9, 8340 Malling, Denmark; krk@tinymobilerobots.com (K.K.); si@tinymobilerobots.com (S.T.I.)
3 AIPSS Associazione Italiana Professionisti Sicurezza Stradale, Piazza del Teatro di Pompeo 2, 00186 Rome, Italy; c.polidori@aipss.it
4 Iterchimica S.p.A., Via Guglielmo Marconi 21, 24040 Suisio, Italy; loretta.venturini@iterchimica.it
5 Mark One S.r.l., Via Albert Einstein, 22, FC, Emilia Romagna, 47025 Mercato Saraceno, Italy; info@3dmarkone.com
* Correspondence: paola.dimascio@uniroma1.it; Tel.: +39-0644585115

Abstract: As part of the Horizon 2020 InfraROB project aimed at enhancing road safety through innovative robotic solutions, a compact autonomous vehicle has been developed to repair asphalt potholes. Central to this system is a 3D printer capable of extruding a novel cold-asphalt mixture, specifically designed for patching road surfaces. The printer is mounted on a small robot that autonomously navigates to potholes, while the human operator controls the operation from a secure location outside the traffic area. The system's development involved several key steps: designing the repair mixture, constructing the 3D printer for mixture extrusion, implementing a photogrammetric technique to accurately measure pothole geometry for printing, and integrating the extrusion system with the robotic platform. Two preliminary tests were conducted in controlled environments at Sapienza University of Rome to check the reliability of calculation of the amount of material needed to fill in the potholes. Finally, the entire procedure was tested on an Italian motorway, demonstrating the system's functionality without encountering operational issues.

Keywords: road pavement; pothole repair; workplace safety; autonomous robot; 3D printer; cold-asphalt mixture; photogrammetry

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1. Introduction

Potholes form in road surfaces due to various factors, including climatic conditions (such as humidity and freeze–thaw cycles), traffic loads, and subgrade quality [1,2]. Before potholes spread across the road surface, compromising its quality, patching operations should be carried out promptly. Road managers should prioritize long-term repairs over temporary ones and reserve quick solutions only for urgent situations. Indeed, pothole repair is never a permanent solution but serves to postpone more extensive and costly maintenance. Indeed, water infiltration through pavement layers can worsen the damage by reaching the subgrade, accelerating the deterioration process. Prompt repair is crucial when potholes compromise road safety and drivability [1], as studies have shown that uneven road surfaces and the presence of potholes significantly increase accident rates [2].

Various methods exist for repairing potholes [3–7], ranging from permanent or semi-permanent interventions to temporary emergency procedures. A full-depth patch, considered a permanent repair, involves four key steps:

1. Cutting: Removing the damaged material to a sufficient depth for stable support and shaping the pothole;
2. Tack coat application: Applying a bonding layer to ensure adhesion of the repair material;
3. Filling: Using appropriate materials to fill the pothole;
4. Compaction: Compacting the filled material for stability.

Semi-permanent repair is also a good approach [8,9]. What is interesting about these techniques is the application of the infrared process: the existing asphalt is heated to a high temperature to make it workable, and then, new asphalt is poured on top of it, which blends flawlessly with the old one. Compared to traditional saw cutting, the infrared approach avoids joints that, due to the inevitable infiltration of water, cause rapid deterioration of the patches. Cuts can also be avoided with microwave technology, with which the mixture is heated to heal the road and the pothole itself [10,11].

Temporary repairs, such as thin surface patches, simplify the process by limiting it to cleaning the pothole with compressed air before filling. The throw-and-roll method is often used to temporarily patch potholes. According to [12], throw-and-roll patches made of suitable materials can reduce pothole recurrence by more than 50% and are generally more effective than throw-and-go techniques. The throw-and-roll technique offers simple and rapid patching, reducing work site time [13]. Spray injection is a valuable technique for filling potholes and transverse cracks. Since the spray injection technique does not require compaction, it is one of the most cost-effective patching methods. The throw-and-roll and spray injection procedures are 4 and 2 times faster than the infrared method, respectively.

At any rate, all the previous traditional techniques present safety risks for both workers and road users, particularly when construction sites are set up on active roads. This has driven interest in developing robotic systems that can autonomously perform repairs, minimizing the need for human presence on roadways [14–16]. Instead, the system presented in this paper has been designed to reduce both the exposure of workers to live traffic and traffic disturbance, also increasing road safety.

This research is part of the InfraROB project (Grant Agreement N. 955337), funded by the European Commission's Horizon 2020 research program, which aims to enhance road safety through robotic innovations. Within this framework, a specialized 3D printer was designed to extrude a novel asphalt mixture for filling small potholes. The project encompassed four parallel research tracks: developing the innovative asphalt mixture, designing the 3D printer for extrusion, implementing the photogrammetric technique to represent potholes, and integrating the printer into an existing small robot to create a fully autonomous repair system.

The autonomous system borne from this research project is only a prototype, developed on an existing robot. Constrained by the robot's dimensions, the quantity of material that can be moved is therefore so limited that the studied system can only be used to fill small potholes and a small number of potholes per mission.

2. Materials and Methods

The development of the autonomous pothole repair system followed these key steps:

1. Designing a suitable repair mixture: A mixture was formulated specifically for extrusion through a system integrated into a small autonomous carrier.
2. 3D printer design and construction: A custom 3D printer was designed to extrude the chosen repair material.
3. Photogrammetric technique development: A new method was developed to measure pothole shape and volume, generating the input data needed for the 3D printer.
4. System integration: The components were combined into a cohesive system capable of autonomous operation.

Before detailing these phases, it is important to describe the robot used, as its characteristics significantly influenced decisions regarding the mixture composition and 3D printer design.

2.1. Robot Description

The autonomous carrier, provided by "TinyMobileRobots", is a three-wheeled robot designed for pre-marking road lines. It features a GNSS receiver that provides location data to the operator's tablet via Bluetooth. The robot's compact dimensions—828 mm in length, 688 mm in width, and 491 mm in height—needed specific adaptations to accommodate the extruding system (Figure 1).

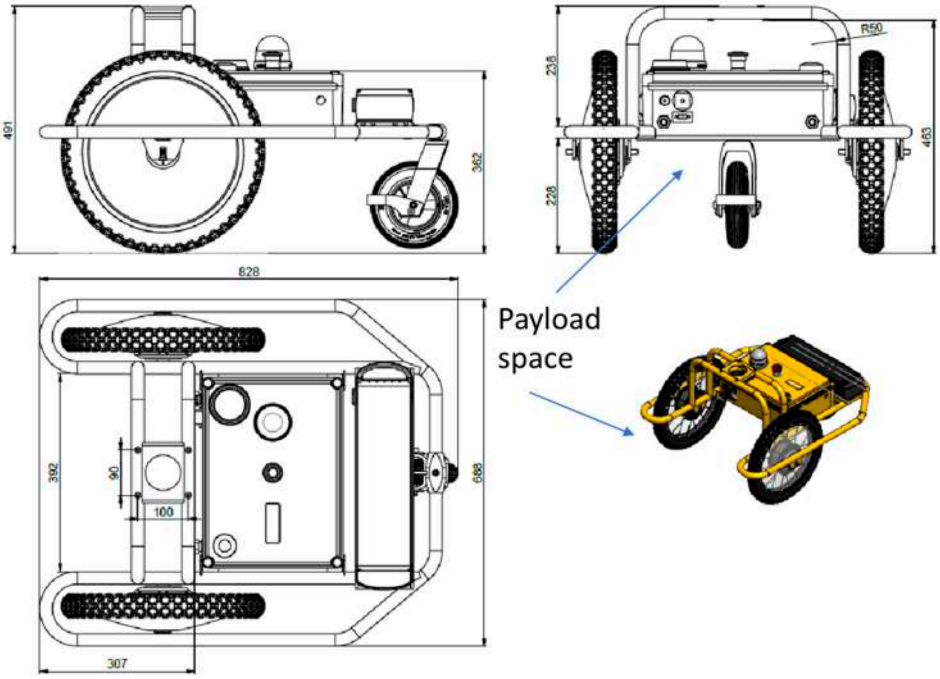

Figure 1. The robot's dimensions [17].

With a weight of 18 kg and a payload capacity of 25 kg, the robot's size and weight constraints dictated the design choices for the integrated 3D printer. The limited space allowed for a printer tank with a maximum capacity of 5 kg of repair material. As a result, the system is optimized to fill potholes with the following specifications:

- Maximum diameter of potholes = 20 cm;
- Maximum depth of potholes = 3 cm;
- Maximum number of potholes per operation = 3.

2.2. Definition of the Repair Mixture

A large set of materials are suitable for filling road potholes; however, after a careful desk study (as detailed in previous publications [18,19]), only asphalt-based materials were considered because they can be used for asphalt and concrete pavements. In addition, because of the limited quantity of material that can be transported due to the robot's small size, maintaining the high temperature required for hot-mix asphalt (160 °C) would necessitate a heating system, thus adding weight and complexity to the robot. For this reason, cold-asphalt mixtures were selected as the most practical solution.

From an environmental perspective, the use of recycled and reclaimed materials is increasingly gaining interest worldwide due to their economic and ecological benefits [20]. Specifically, using reclaimed asphalt pavement (RAP) in pothole repair offers significant cost savings and environmental advantages [21].

Three materials have been selected to deepen the knowledge of their properties for adaption to the 3D printer:

1. Cold-mix asphalt with natural aggregate and emulsion: The mixture is composed of 30% basalt 0/3, 24% basalt 3/5, 45% basalt 5/10, and 1% cement. The emulsion

has been specifically formulated for cold mixing and promotes good workability and adhesion.

2. Cold-mix asphalt with waterproofing bituminous membranes and additives: The mixture is composed of 69% basalt 3/5, 30% RAP 0/8, 1% cement, waterproofing, and a flux oil of vegetal origin (which lowers the viscosity coefficient of bitumen and allows the asphalt mix to be more workable in the long term). The mixture is prepared by adding the bituminous membranes (10% of the total weight of the aggregates) to the basalt. Once the bitumen in the membrane covers the aggregates, RAP, cement, and additives are added. When cooled to room temperature, the mixture is ready for use and is stable for 48 h. Two different commercial types of flux oils are added. The flux oil dosage varies from 25% to 30% of the bitumen's weight according to the desired plasticity, type of bitumen, and particle-size distribution curves used.
3. 100% reclaimed asphalt pavement (RAP) with a rejuvenator: The latter can simultaneously reuse, regenerate, and plasticize the bitumen contained in the RAP. The production of this mixture can be carried out at ambient temperature by adding the additive directly into the mixer after the introduction of RAP. The rejuvenator has the following characteristics:
   - Color = black;
   - Density@ 25 °C = $0.85 \div 0.95$ g/cm^3;
   - Viscosity at 25 °C = $400 \div 500$ cP;
   - Flash point $\geq$ 150 °C;
   - Pour point $\geq$ 0 °C;
   - The material produced with this technology can be stored for up to 72 h before use. In addition, cement and water are added to the mixture.

Extensive laboratory and field tests were conducted on these mixtures, with detailed results reported in previous studies [18,19]. The third mixture, RAP with a rejuvenator, was the only one to meet the target specifications [17–19] based on the experiences made on very busy urban streets. Tests focused on grading, Marshall stability, void content, indirect tensile strength, and particle loss, with variations in additive content (1.5–3.5%) and water content (3.1–5.0%). The maximum aggregate size was limited to 8 mm to suit the dimensions of the potholes targeted by the project. Laboratory tests demonstrated that the selected mixture provided excellent results in terms of indirect tensile strength, Marshall stability, and resistance to particle loss. Field tests involved applying the mixture to actual road potholes. The mixture is compacted by live traffic, and in the first tests carried out, a van was used to run some passes over the pothole just filled. The potholes were then monitored over an extended period. Visual inspections confirmed that the material remained intact, even immediately after application when it was not yet fully cured and had only undergone self-compaction. The final mixture proved to be highly stable during on-site tests and could be applied directly to potholes without prior cleaning or mechanical compaction.

2.3. Three-Dimensional Printer Design and Construction

The design of the 3D printer was constrained by the autonomous carrier's payload capacity and the available space for integration. The Z-axis was omitted from the design to accommodate the targeted pothole dimensions.

The printer is composed of the following key components (Figure 2):

- Tank: Holds the repair material to be extruded;
- Y-Axis Movement: Controls the print head's motion along the horizontal–longitudinal axis, allowing forward and backward movement;
- X-Axis Movement: Controls the print head's motion along the horizontal–transverse axis, enabling left and right movement;
- Electronics: Manages the printer's operations and coordinates the movement and extrusion processes;

- Screw Extruder: The component of the print head responsible for pushing the material out for extrusion;
- Power Supply: Provides electrical power to the 3D printer, with the power cord connected to the autonomous carrier (Figure 3).

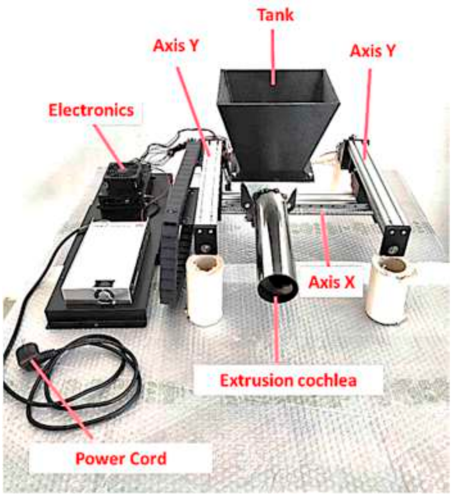

Figure 2. The 3D printer [17].

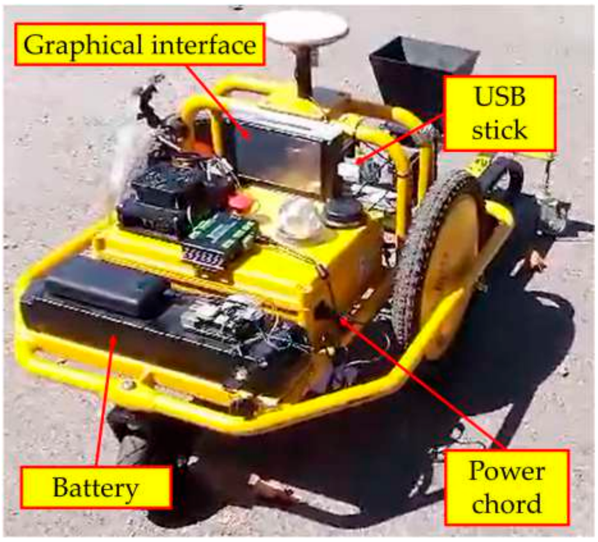

Figure 3. The 3D printer connected to the robot.

The printer is operated through a graphical interface (Figure 3), which allows for user control and monitoring of the printing process.

2.4. Development of the Photogrammetric Technique for Surveying Potholes

To generate a 3D model of each pothole, a hardware platform was developed using Raspberry Pi technology [22,23] whose compact size (88 × 58 × 19.5 mm, similar to a credit card) (Figure 4) allows for easy installation on the robot. A low-cost camera [24] and a GPS module has been integrated with the Raspberry as shown in Figure 5. In recent years, Raspberry Pi has become increasingly popular in road maintenance applications due to its affordability, versatility, and ease of use [25–29].

The RPI 4B and its power supply are mounted at the front of the robot, while a camera, secured with a clamp, is attached to the chassis. A damper is used to minimize vibrations transmitted to the camera. Initial tests indicated the optimal camera placement is 1 meter above the road surface, with a 45° viewing angle from the vertical axis [30].

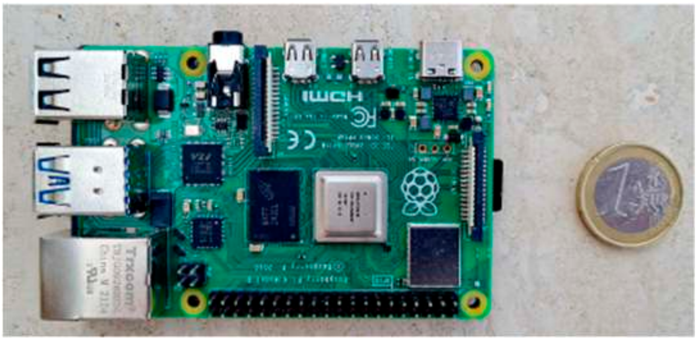

Figure 4. RPI 4B [21].

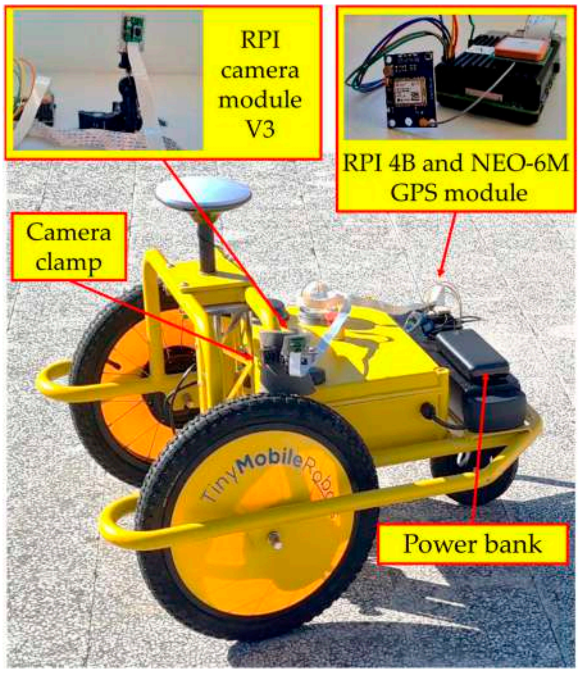

Figure 5. The hardware platform installed on the robot.

As shown in Figure 6, the video acquisition process is designed to center the camera's focus on the pothole, with the robot following circular paths of varying radii (1.0–1.4 m) around the pothole. The robot's speed during video capture is set to 0.4 m/s.

The camera automatically records a video, from which a series of 2D images is extracted, while the GPS module collects location data. These images are then processed using Bentley ContextCapture software [31], which employs photogrammetry techniques to reconstruct the 3D geometry of the pothole through aero-triangulation. The resulting 3D mesh is exported in STL format, which is compatible with the 3D printer. Additional tools within the software allow for the measurement of the pothole's area and volume.

Using the pothole's calculated volume (V) and the properties of the repair mixture, the weight of the material to be extruded (W) can be determined using Equation (1):

$$W = \rho \times V \quad (1)$$

where ρ represents the bulk density of the mixture. The bulk density ρ was measured in previous laboratory work and found to be 2.12 g/cm^3 [18].

Figure 7 summarizes the overall procedure.

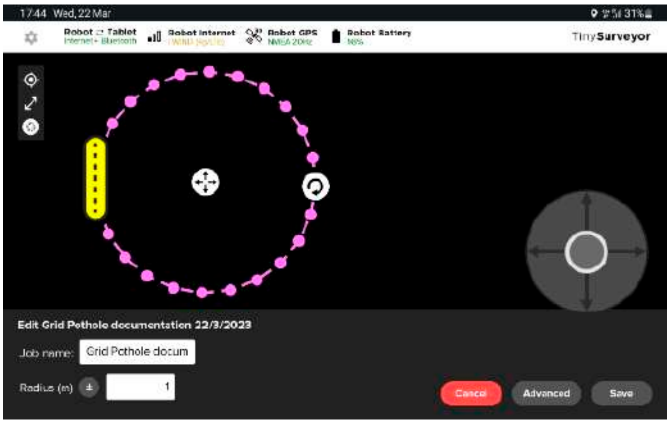

Figure 6. TMR path setting [30].

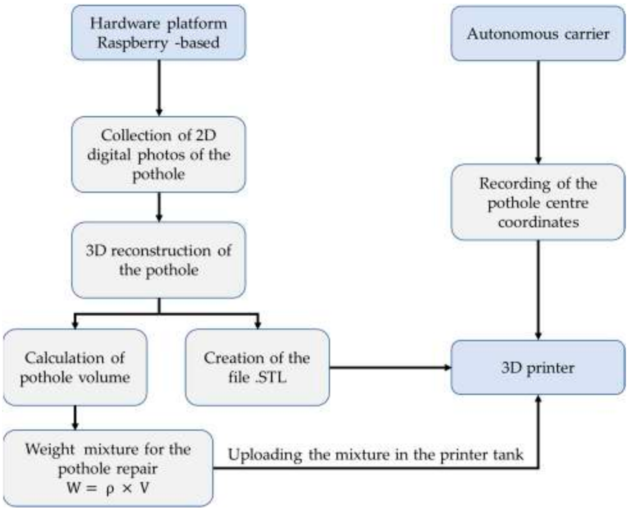

Figure 7. The procedure flowchart.

2.5. System Integration

The integration of the 3D printer with the robot involves two aspects: the physical connection and the software integration.

2.5.1. Physical Connection

The printer is mounted on the rear of the robot using a rigid aluminum frame, which is attached to the robot's tubular brackets (Figure 8). The positioning is carefully planned to ensure that the extruder head is directly beneath the antenna, aligning precisely with the center of the pothole to reduce positioning errors. Due to the off-center placement of the printer, two small support wheels are added beneath the aluminum frame to maintain stability and prevent the printer from tipping over.

All electrical wiring is secured with cable ties, allowing for the maximum movement of the printer during operation without strain on the connections. The printer's power supply is connected to the robot's battery.

To facilitate accurate pothole shape reconstruction, a target of known size is used as a scale reference in the processed images. When the robot reaches a pothole, a target is deployed using a mechanism that inserts a metal stick into the target holder mounted on the aluminum frame, as shown in Figure 8.

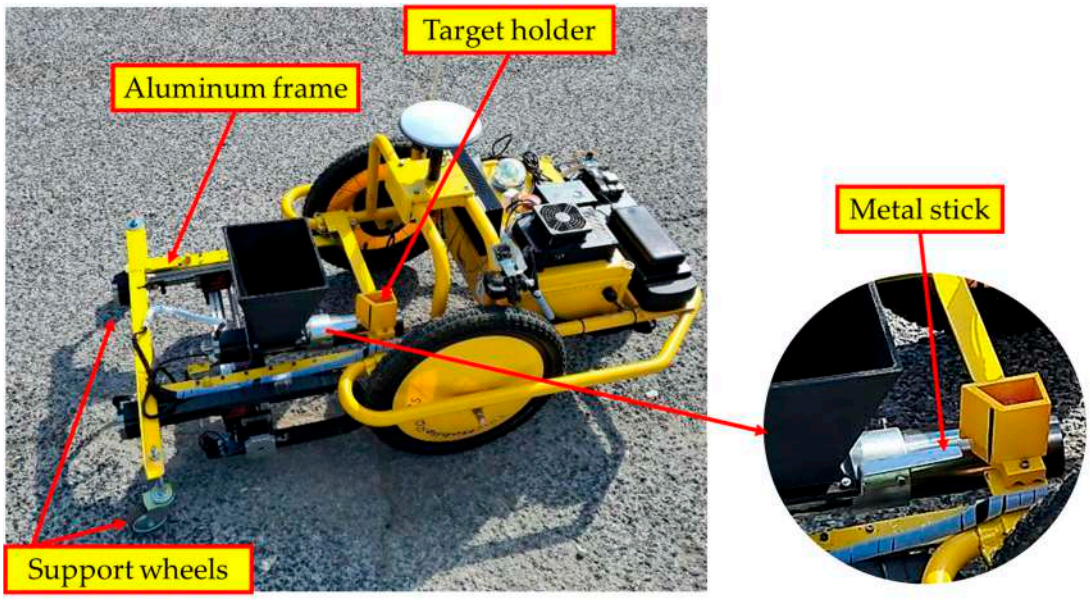

Figure 8. The structural connection of the printer with the robot.

2.5.2. Software Integration

The integration of the software (printer and robot) has been planned to comply with the scheme of the field operations in Figure 9: the van with the robot and the operator arrives on the site and parks in a safe area; the closest escort vehicle "covers" the pothole area. The robot is initialized and starts its operations going to the first pothole, then to the second, and finally returns to the van.

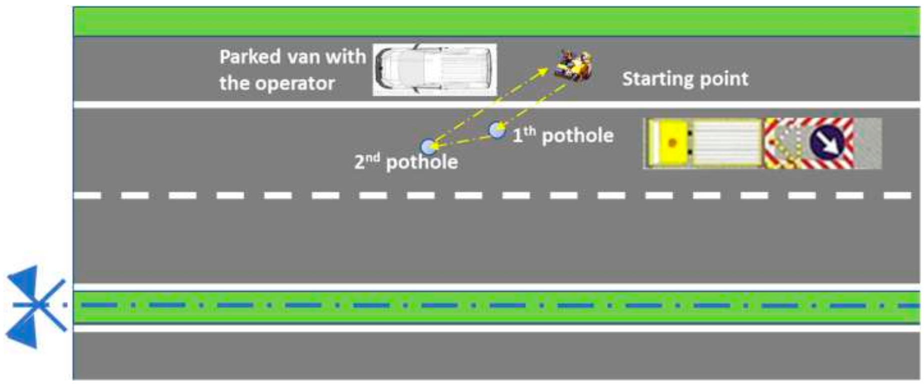

Figure 9. Scheme of the field operations.

The printer is connected to the robot, enabling data exchange via the graphical interface shown in Figure 3. Communication between the robot and the 3D printer occurs over a serial connection, which has been converted to an Ethernet connection via a signal converter.

The process involves repairing multiple potholes, each designated sequentially (e.g., HOLE00, HOLE01), with pregenerated G-code files containing the center coordinates of each pothole set to (0,0). The sequence of operations, outlined in the flowchart in Figure 10, begins with the operator manually centering the robot over the designated potholes to record the position coordinates. Once recorded, the robot returns to the starting point, and the autonomous procedure commences. The robot navigates autonomously to the first recorded pothole and sends an "Enter Connection Mode" command to the 3D printer. The printer responds by homing to its end-stops and entering connection mode, displaying ongoing communication with the robot. The robot then issues a "Select Print File" command, prompting the printer to locate and load the corresponding G-code file for the pothole. The printing process begins with the robot's "Start Print" command, using previously stored offsets to ensure accurate material placement.

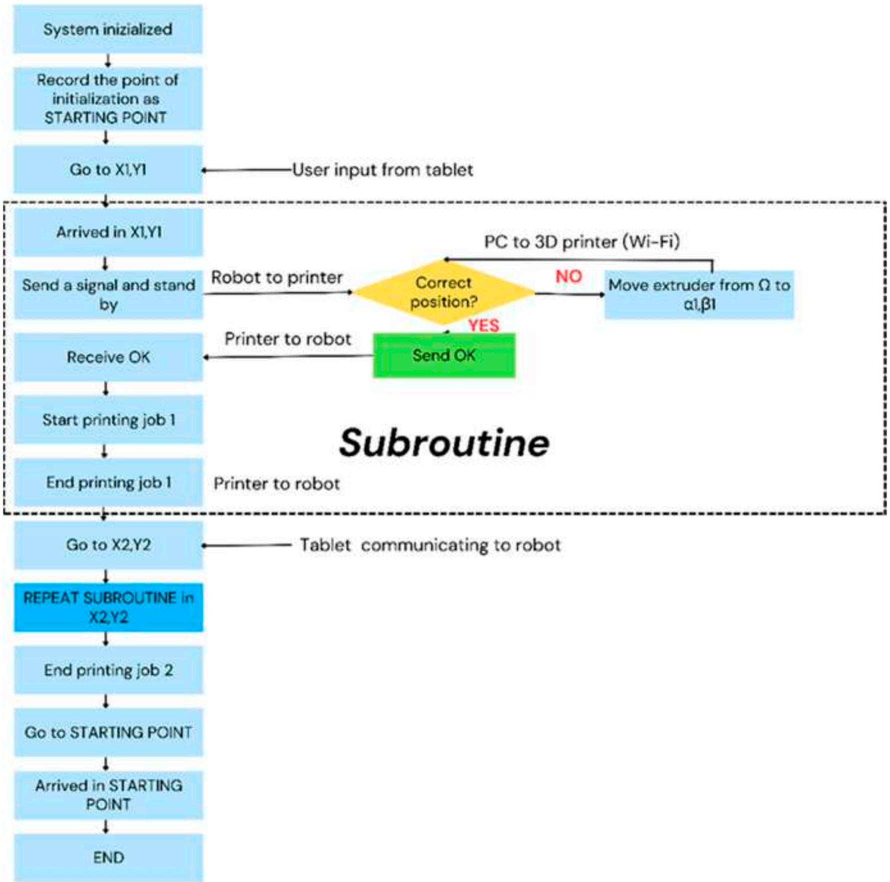

Figure 10. Flowchart of operations of the repair system.

Throughout the printing process, the robot monitors progress by sending a "Status" command every 500 ms. Once the printer completes the task, it notifies the robot, which then issues an "Exit Connection Mode" command to reset the printer to its starting position. The robot then moves on to the next pothole, repeating the cycle for subsequent repairs.

3. Results and Discussion

The robot was tested to assess the performance of the entire procedure, focusing on both the operational efficiency of the system and the accuracy of the data collected. All tests were conducted in controlled environments within the Sapienza University of Rome campus, ensuring the safety of operators by avoiding exposure to road traffic. The following sections detail the testing process and outcomes.

3.1. In Situ Tests

3.1.1. Pothole Monitoring Procedure

Many tests have already been conducted on potholes made of laboratory-built asphalt tiles to verify the accuracy of the calculation of the amount of material needed to fill a hole. These tests are described in detail in Reference [30]. The first in situ test took place at a hospital site affiliated with Sapienza University of Rome, targeting real potholes in the asphalt concrete pavement. The primary goal was to evaluate the pothole monitoring procedure. Pothole detection was carried out using the Raspberry Pi-based system mounted on the robot, as described in Section 2.4, and the results were compared to manual survey measurements (Figure 11).

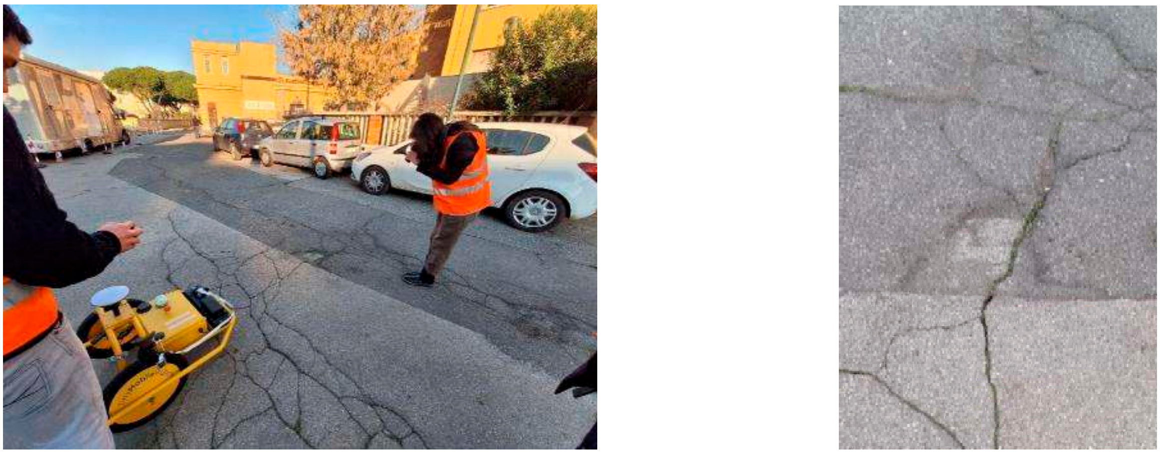

Figure 11. Test at the polyclinic site: manual monitoring of pothole.

The analysis processed both photos taken with the Raspberry system and those taken manually. The photo processing, which took 40 min for each pothole, yielded the same results for shape and volume measurements, confirming the accuracy of the automated system.

The following day, the robot was brought back to the site, loaded with the repair mixture prepared in the laboratory. It was then remotely guided to the previously monitored potholes, and the 3D printing process was initiated. The extruder began dispensing material after a 45 s delay, and the printer followed the recorded geometry of the potholes to fill them accurately (Figure 12a). Once the filling process was completed, an escort vehicle performed the initial compaction by driving over the freshly applied material (Figure 12b). After a 150-day monitoring period, visual inspections showed no signs of material loss from the repaired potholes (Figure 12c). This inspection confirmed the results of numerous in situ tests that we have already described in detail in References [17–19].

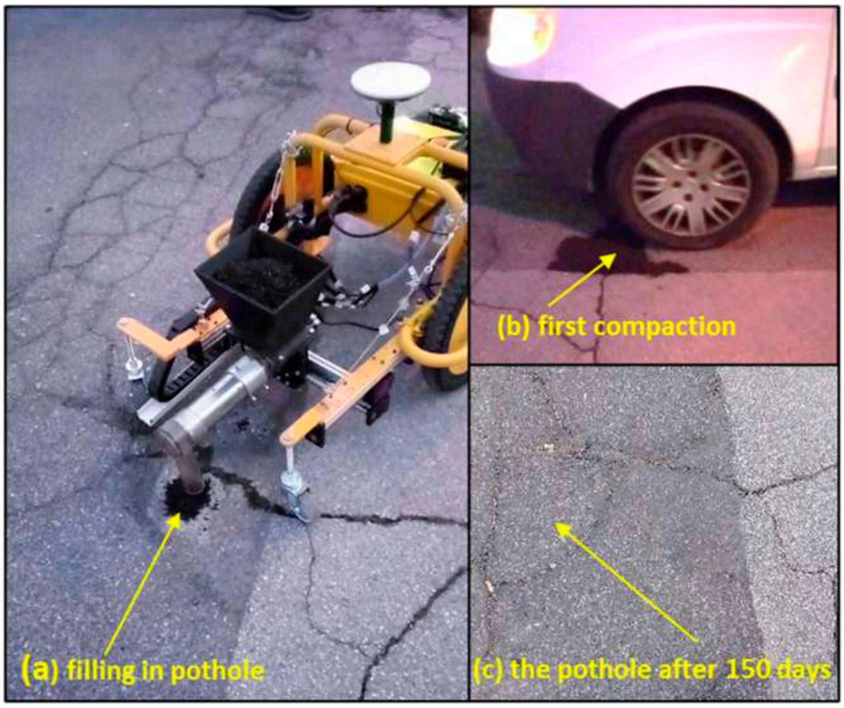

Figure 12. Test at the polyclinic site: pothole repair.

In this initial test, the connection structure between the printer and the robot represented a preliminary setup. However, adjustments were made to the final connection design, as described in Section 2.5.1, to address GPS positioning issues caused by the offset between the antenna and the extruder head.

3.1.2. Checking the Amount of Material

Three potholes were dug in the parking lot of the Faculty of Civil and Industrial Engineering (FCIE) of the Sapienza University of Rome (Figure 13) to verify the accuracy of the calculation of materials. These potholes were documented using the photogrammetric technique outlined in the previous section.

Figure 13. Test at the parking lot of FCIE: plan for the potholes.

The shapes and volumes of the potholes were captured using the photogrammetric technique, allowing for precise calculation of the material weights needed for the repairs. The mixture was then prepared according to these calculations, and each pothole was lined with a thin layer of plastic film. After filling the potholes, the plastic film was carefully removed along with the material, enabling a direct comparison between the calculated and the actual weight of the filled material. The results confirmed the effectiveness of the proposed methodology, as the weight of the material used to fill the potholes closely matched the calculated values, with a relative error of 1% (Figure 14).

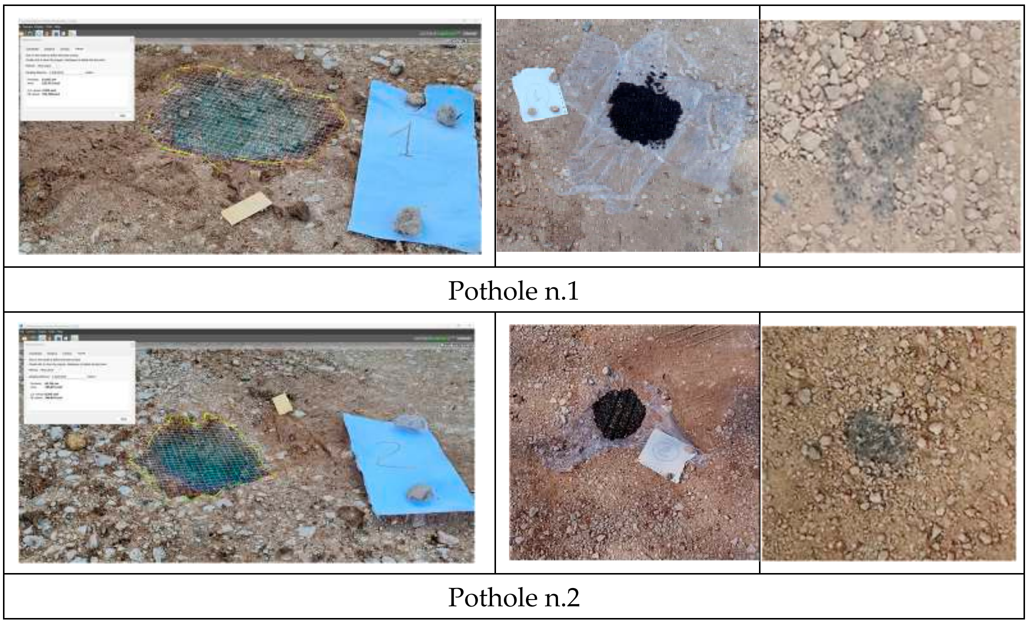

Figure 14. *Cont.*

		
Pothole n.3		
(**a**)	(**b**)	(**c**)

Figure 14. Test at the parking lot of FCIE: (**a**) reconstruction of the potholes and comparison of the material weights for each pothole; (**b**) potholes lined with a thin layer of plastic; (**c**) the potholes after 120 days.

The potholes were refilled with the repair mixture and monitored over a 120-day period. No material loss was observed, confirming the durability of the repairs, as already observed in other tests [17–19]. The tests proved valuable for refining both the monitoring and extrusion procedures. However, these initial tests were conducted by separately controlling the printer and the robot using the manufacturers' respective software. An additional test was carried out to verify the correct operativity of the integrated system composed of the 3D printer with the robot.

3.2. General Test

The final system demonstration took place on 27 September 2024, on a section of the A24 motorway in the "Strada dei Parchi" network near L'Aquila, Italy (Figure 15).

Figure 15. Test site at A24 motorway (Italy).

The demonstration was conducted in two stages to accommodate the mapping of the potholes' geometry and volume, followed by the post-processing of the images collected during the mapping phase. The procedure was tested on two potholes, both surveyed and repaired within the same mission. The robot first navigated to the two potholes to record the GPS coordinates of their centers. It then deployed an object of known dimensions (the orange target shown in Figure 16) to serve as a reference for reconstructing the pothole using photogrammetric techniques. Next, the robot was guided back to each pothole to detect their shapes, capturing video recordings along two circular paths of different radii around each pothole. Figure 16 shows an example image of a pothole during the registration process, as seen in the video. Following the completion of the video recording, the robot returned to the escort vehicle parked at the site's perimeter.

Figure 16. Pothole recording.

The images were processed, and the volume of the pothole was calculated (Figure 17). Given the bulk density (2.12 g/cm^3 [18]), the quantity of material needed was calculated. So, the mixture was prepared, and the robot tank was loaded.

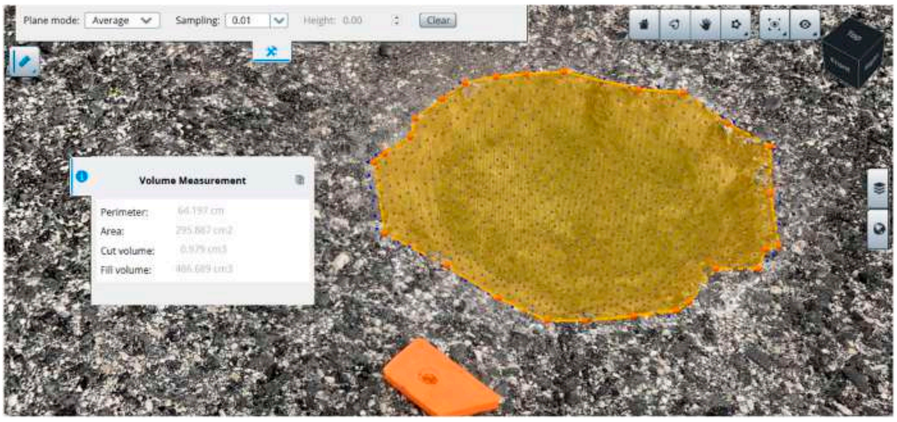

Figure 17. Pothole reconstruction and volume calculation.

The robot was then brought back to the site, and the autonomous procedure was initiated. Using the GPS coordinates recorded during the initial phase, the robot navigated autonomously to each pothole in sequence, filled them with the repair material (Figure 18), and returned to the escort vehicle.

Right after the repairs were completed, the escort van drove over the potholes to smooth out the surface (Figure 19). The mixture did not require mechanical compaction, allowing the road to reopen to traffic without delay, as it did not stick to vehicle wheels. The natural compaction process would be completed by passing traffic over time.

Figure 18. Pothole filling in a pothole.

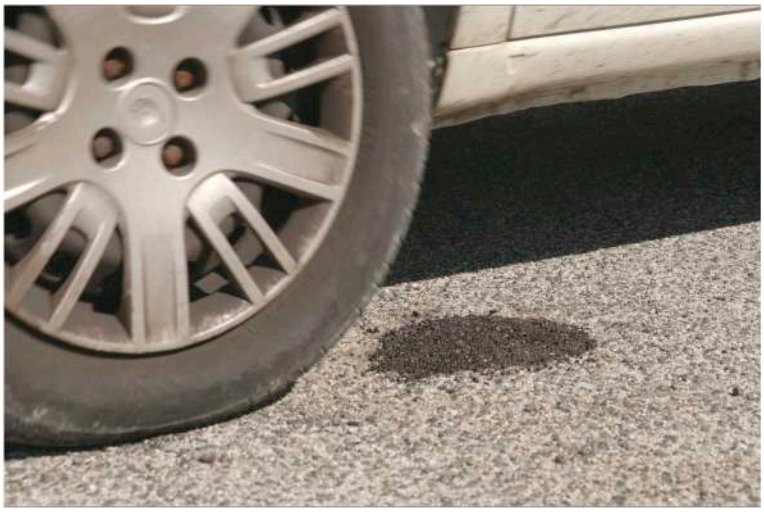

Figure 19. Mixture compaction.

3.3. Cost Estimate

Regarding the system's cost estimate, it is necessary to distinguish the costs of the robot as a tool and the operating costs. For the latter, there is no difference in current operations because, given the small size of the robot, it can be loaded onto a normal service vehicle, the same kind that would transport an operator of a manual service. The advantage consists in increasing safety by keeping workers in a safe area and away from vehicular traffic; the disadvantage is the small size of the potholes that the robot can repair. Manual work would still be required for potholes of a slightly larger size.

The cost of the robot is composed of the cost of the autonomous carrier plus the printing and extrusion device including the printing software. The autonomous carrier is a model available on the market and manufactured by Tiny Mobile Robots for tracing horizontal markings on asphalt, so the innovation of the present work is the printing system and the hardware–software integration.

The high costs incurred during the project, such as orders of custom mechanical parts, software development, etc., can be reduced in the case of series production: a rough estimate can be made by considering a cost equal to 170% of the autonomous carrier currently on the market, whose current price is not exposed due to confidentiality agreements with the above-mentioned manufacturing company.

4. Conclusions

Potholes pose significant social and safety challenges because they contribute to road accidents, vehicle damage, and increased maintenance costs. Addressing these issues promptly is crucial for improving road safety and minimizing disruptions. This paper presented the development of a prototype robotic system for repairing asphalt road potholes, offering an automated solution to tackle these problems more effectively.

This study focused on the following:

- An innovative cold-asphalt mixture was made entirely from RAP with a rejuvenator. The mixture's ability to be compacted by regular traffic offers the significant advantage of reopening roads to vehicles immediately after repairs.
- A 3D printer, specially designed for the Horizon 2020 InfraROB project (Grant Agreement N. 955337), was used to extrude the mixture. It is mounted on the robot with a rigid aluminum frame, positioned to ensure the extruder head is aligned directly beneath the antenna, minimizing GPS positioning errors.
- A photogrammetric methodology was implemented by installing a Raspberry-based hardware platform in the front part of the robot. The platform includes a camera that records a video of the pothole, from which a series of 2D images is extracted, and a GPS to locate the pothole data. The recorded images are then processed to reconstruct the 3D geometry of the pothole through aero-triangulation. The resulting 3D mesh is exported in STL format, which is compatible with the 3D printer. Additional tools within the software allow for measurements of the pothole's area, its volume, and the weight of the material to be extruded.
- The integration of the software controlling both the printer and the robot was completed, enabling the system to operate under a unified software interface managed by a single operator positioned near the test site.
- Two preliminary tests were conducted in controlled environments at Sapienza University of Rome:
    1. The potholes were surveyed to determine their shape and volume using a photogrammetric method, and the required material weight was calculated based on the volume and bulk density.
    2. The accuracy of the process was confirmed by weighing the material used to fill the potholes, which closely matched the calculated amount. The repaired potholes were monitored under traffic for approximately 150 days, with no material loss observed.
- The entire procedure was tested on an Italian motorway, demonstrating the system's functionality without encountering operational issues.

Automatic pothole repair minimizes traffic disturbance, and a mobile construction site can be envisaged. In fact, photogrammetric recording of a pothole takes about a minute, and filling each pothole takes 1 to 2 min. Image processing is performed in a van parked off the road or in an office, if the pothole monitoring is conducted on a different day from the repair.

While this robotic pothole repair system is currently a small-scale prototype adapted to an existing robot, there is potential for the future development of a larger system.

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Conflicts of Interest: Kristian Knudsen and Søren Thorenfeldt Ingwersen are employed by TinyMobileRobots; Loretta Venturini is employed by Iterchimica S.p.A.; Marco Zani is employed by Mark One S.r.l. 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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