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A ROBOTIC DEVICE FOR INSPECTING SMALL DIAMETER PIPES

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Abstract. Inspecting ducts and pipes with small diameters is a recurring task inside the mining industry and presents significant challenges for timely and efficient monitoring. Due to the nature of the materials passing through the pipe, some problems can preclude or reduce the pipe's transport capacity, such as clogging, cracks, or discontinuities. The leading causes of defects in pipelines are the accumulation of residues, mechanical impacts, corrosion, and vibration; therefore, industrial piping systems should always be subject to regular inspection activities. In this sense, the Instituto Tecnológico Vale (ITV) proposes a robotic platform focused on the inspection of small pipe diameters, inspired by the technological principles of other larger visual inspection robots in the mining industry. The proposed platform can inspect pipes as small as 10.5-inches in diameter and visualize anomaly situations using cameras and other embedded sensors. The proposed device composition is mainly low-cost materials, such as PVC and 3D printed plastics. Its primary purpose is to be a functional and still cost-effective platform, easily replicated with off-the-shelf components and additive manufacturing systems. The platform's cylinder-shaped body has IP-67 protection and adaptable locomotion mechanisms using mats and wheels, which can be oriented to overcome specific pipe conditions. In contrast to similar commercial robots, the platform's modular and low-cost design facilitates performing on-the-field adaptations and embedding extra devices such as gas sensors or a LiDAR. The 3D-printed parts reduce up to 70% of the manufacturing costs compared to other ITV robotic platforms. The adjustable software platform using ROS (Robot Operating System) allows for semi-autonomous operation and the possibility of online anomaly identification. This paper presents the robotic's platform design and assembly procedures, demonstrating the feasibility of producing inexpensive alternatives for industrial pipe inspections.

Keywords: Pipe Inspection, Robotic Platform, Mechanical Design, Mobile Robotics, Mining Industry

1. INTRODUCTION

Pipeline systems are recurrent in many industrial activities. For example, pipelines are commonly used to discharge mining tailings or for ore slurry transportation in the mining industry. Due to the fluid's nature, clogging, cracks, or discontinuities are common and preclude or reduce the transport capacities of the pipes. Residue build-up, mechanical impacts, corrosion, and vibration are the main reasons for pipe defects. In this sense, pipe systems need to pass through constant maintenance processes to prevent failures or accidents. One of the main challenges of the continuous maintenance process is performing reliable internal pipe inspections (Sun *et al.*, 2009).

Inspections on ducts and galleries are a recurrent task inside industries to assure the correct functioning of the system. Robotic inspections provide faster and safer inspections and allow the removal of the physical operator from the risks of the confined space.

The Instituto Tecnológico Vale (ITV) has developed the EspeleoRobô, a robotic device capable of inspecting confined spaces. This robotic platform uses a rigid chassis and six independent motors for thrust and can move with different locomotion mechanisms easily replaced through quick-release pins (Azpurua *et al.*, 2019). Nevertheless, due to its external dimensions ($0.55 \times 0.30 \times 0.65$ meters), it cannot inspect pipes and galleries smaller than 22-inch in diameter. Therefore, this article proposes a design of a robotic device capable of visually inspecting ducts smaller than the EspeleoRobô's

original capacity. The methods suggested to seal the robot and guarantee IP-67 protection are based on a previous study developed in the ITV for EspeleoRobô, as presented in Azpúrua *et al.* (2021).

The main objective of this development is to construct a low-cost device with simple mechanical parts that are quickly adaptable and easily manufactured; most components can be 3D printed, and the body is fabricated using a PVC tube. The robot uses electronic components available locally, easy to buy in the national market, and with a lower price when compared with other commercial platforms. The robot design and presented in this paper already has a patent-pending application at Instituto Nacional de Propriedade Industrial (INPI) (de Barros *et al.*, 2021).

2. A REVIEW OF SOME EXISTING PLATFORMS AND ITS LOCOMOTION SYSTEM

According to Fisher *et al.* (2021), sending humans into hazardous environments has obvious safety risks; therefore, using robots to prevent a human from entering dangerous situations has now become a possible solution for safety improvement. Given the characteristics of traditional pipe inspections, this task provides ample opportunity for robotics deployments.

Industries use pipelines to carry several types of fluids. Conditions such as high pressure, risk of explosion, toxicity, and other risks are used to define the materials and dimensions for a pipeline to assure that it can work properly. There is a significant variation in pipe topologies, meaning that some robotic mechanism fits better than others and can be particular for specific situations. Because of this, there are several platforms available in the market with different sizes, methods of locomotion, and purposes.
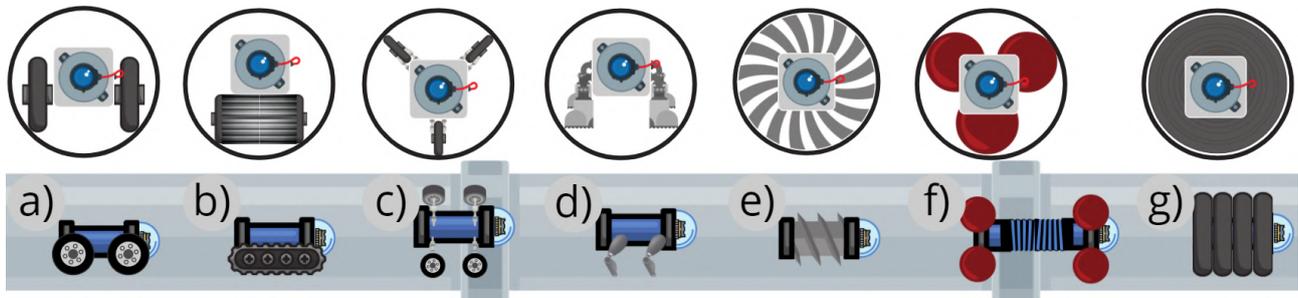

Figure 1: Locomotion system by a) wheels, b) caterpillar, c) wall pressing, d) legged, e) screw, f) inchworm, g) PIG.

Figure 1 show some of the existing methods of robot locomotion inside pipes. The models from a) to f) have traction equipment and are active systems, and the model g) is a passive system and uses the fluid inside the pipes to generate the traction force. Active systems can use several types of traction mechanisms powered by electricity, pneumatic or hydraulic forces. Pneumatic and hydraulic systems have a hose to provide the fluid to assist with the robot's movement. Electric platforms work with unlimited power supply by a cable or batteries for a certain period.

Several studies used the wheel-type robot (Figure 1.a) for pipe inspections. This system is based on a platform over wheels that uses the lower surface of the pipe as a traction track. This model has an excellent performance to inspect pipes built on the same plane or with minimum height differences in the pipeline (Debenest *et al.*, 2014).

In Figure 1.b, the robot uses a caterpillar track-wheel to move. These system advantages are related to the traction force increase once the mechanism has a higher friction surface (Ciszewski *et al.*, 2020). The wall pressing model, represented in Figure 1.c, has a mechanism that forces the rolling system (Wheel or caterpillar track) against the pipe wall. Because of the increase in traction, usually using three support surfaces, this robot can crawl up and down through pipes with high inclinations (Moshayedi *et al.*, 2019).

As the name suggests, legged robots (Figure 1.d) use legs to move between the pipeline. Although, this type of robot is less practical than others once leg systems are considered complex mechanisms, which usually require a more significant space than other systems (Savin and Vorochaeva, 2017). Figure 1.e shows the screw system, which is closely related to the wall pressing model in having a system that requires a larger pipe surface of traction to work. This mechanism usually bases on the structure with angled wheels rotation. This angle makes the structure follow a helical path, resulting in a traction force that moves the platform forward (Ab Rashid *et al.*, 2020).

The inchworm model (Figure 1.f) anchors one side of the mechanism in order to move the other one. Because of the similarity between its and the inchworm movement, they have this nomenclature. The locomotion is possible because the robot center can compress or stretch. The front part of the robot works as an anchor while the center compresses to pull the robot forward. Then the back part anchor and the central part stretch to push the front forward (Kusunose *et al.*, 2020). Finally, PIGs (Pipe Inspection Gauge) are passive platforms driven by the pressure of the traveling fluid inside the pipe. The system is launched from a special base to another to go through a predetermined sector of the pipeline (Rashid *et al.*, 2021).

After presenting a list of the most popular locomotion systems for moving inside a pipeline, this article proposes

a robot design that can operate with wheels and caterpillar tracks. The first design attempt consists of just tracks for locomotion. Nevertheless, to inspect smaller diameters than the caterpillar track without changing the engine, we adapt a more compact and easily replaceable wheel assembly. Those two types of locomotion were selected due to their more straightforward construction when compared with other systems presented, like legs or wall pressing, and their high operation efficiency.

3. ROBOTIC PLATAFORM DESIGN

As a primary goal, the robot's platform design intends to suppress the demand to inspect pipes under 22" inches, the limit of diameter that the current robotic platforms of the ITV can inspect. The secondary goal focuses on inspecting pipelines under challenging conditions, such as discontinuities, flooded sections, obstructions, among others. These conditions considerably increase the risk of failure of an inspection robot.

The proposed mechanism was entirely designed using SolidWorks. We organized these components into modules that can have either structural or locomotion functions. This modular approach guarantees interchangeability between them without needing a complete and unnecessary reassembly of the robot, allowing modifying the traction system directly in the field without undergoing a complex assembly process, which is the main contribution and the innovation of the proposed platform. Figure 2 presents the robot's hierarchical diagram.
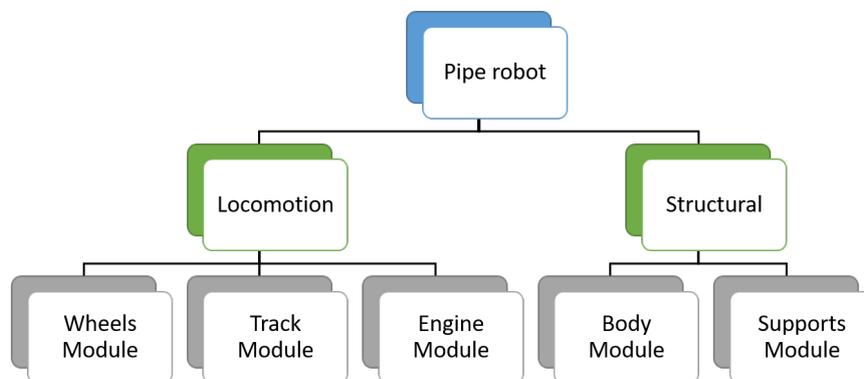

Figure 2: Robot's constructive modules hierarchical diagram.

The design's first step was to select the electronics components embedded in the mechanical body. The layout constraints of the locomotion modules were based on the size and geometry of the compact Dynamixel motors, which are common within robotics applications. Other external components were select due to their water resistance capability. The proposed locomotion system is developed as interchangeable to better adapt to different pipe diameters and operating conditions. Figure 3 illustrates the assembled set with their two possibilities of locomotion system. Also, the robot moves

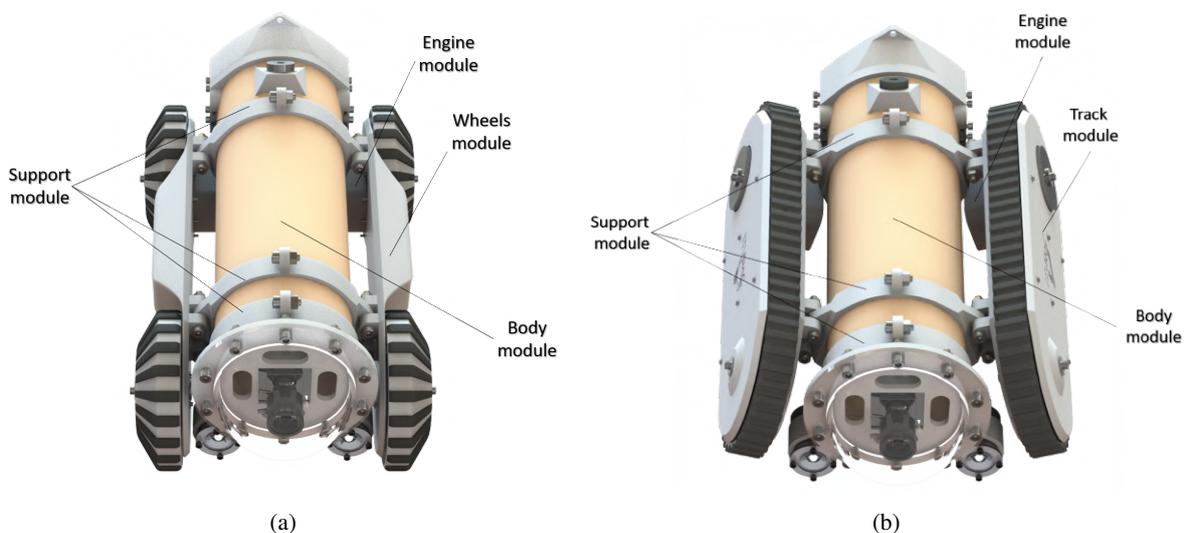(a)   (b)

Figure 3: Robot assembled with (a) wheels and (b) tracks locomotion system.

through wheels and tracks, wheels for pipelines between 10-inch and 14-inch diameter, and tracks for diameter above that as presented in Figure 4.

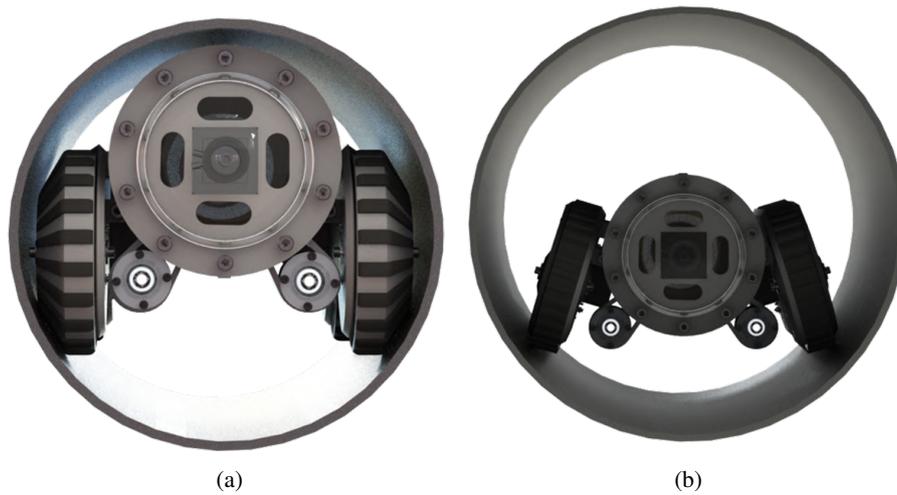(a)   (b)
Figure 4: Pipe robot inside the (a) 10-inch and (b) 14-inch pipeline.

The structural system must have compact mechanics necessary for housing the main electronic components and provide stiffness to the device. We thought of building the robot mostly by additive manufacturing (3D printing), except for structural parts (pulleys and shafts) and those that need tight dimensional assembly tolerances. The 3D printed components make the Pipe robot with a lower production cost (about 70% less) compared, for example, with the EspeleoRobô manufacturing. Commercial and manufactured parts are presented in Figure 5a. The printed ones will be produced in a 3D print inside ITV Robotic's lab and Figure 5b shows the parts printed so far.

(a)   (b)
Figure 5: Pipe robot (a) manufactured and (b) some printed parts.

The current design was found by an Agile development process commonly used in software development: we performed several iterative designs that were first tested using additive manufacturing processes. With the help of inspection specialists, we designed the first version based upon the best inspection platforms of the market, some of those that used wheels or tracks, although they were pricey, used specialized materials and cannot be adapted easily to different pipe situations. After the final testing with only 3D printing materials, the most rugged parts were machined in aluminum, and the custom parts such as bearings and belts were acquired.

3.1 Embedded Equipment

The Espeleorobô inspires the entire electronic system design of the proposed robot. However, due to the small size of the pipes, we changed the electronic components, and the design was adapted to meet the need to inspect an even tighter confined space. Figure 6 presents the diagram of the electronic connections.

The robot has two Dynamixel MX-64AT engines responsible for the locomotion. In addition to offering good performance and small size, these motors offer easy control of parameters such as speed, acceleration, torque, as well as a PID controller and integration with ROS (Robot Operating System) also present. All communication between the engines and the onboard computer is through a Dynamixel U2D2 USB dongle.

As an onboard computer, the system has a Raspberry Pi 4 Model B with a Linux operating system installed, making it practical to manage locomotion, communication, and other peripherals present in the robot. Due to the absence of ADCs (Analog to Digital Converters) in Raspberry's GPIO (General Purpose Input/Output) ports, necessary to read battery level, we use an ADC ADS1115 module to meet this need. The platform software embedded into the Raspberry Pi is developed
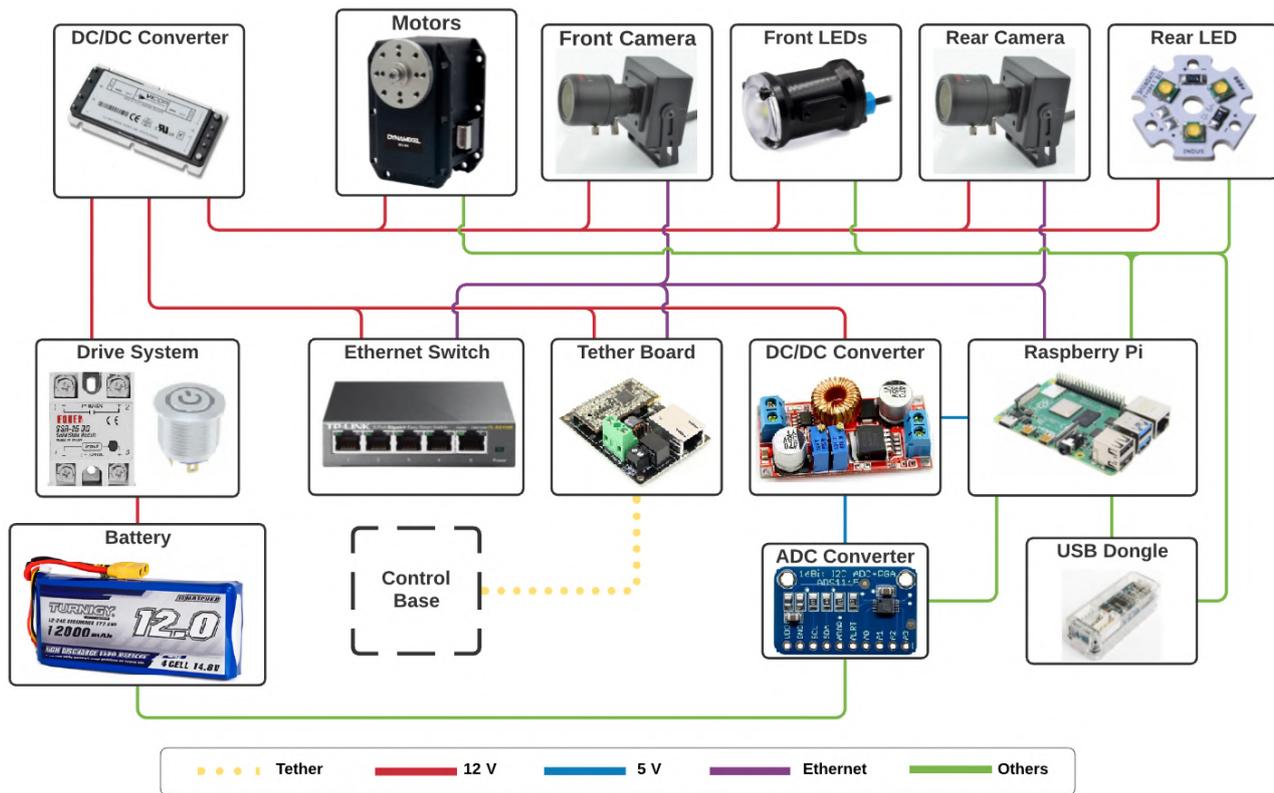
Figure 6: General electrical connection diagram.

under the Robot Operating System (ROS), allowing fast and modular code development.

In order to perform the inspections, we choose varifocal IP cameras in the front and rear of the robot with a wide aperture in image capture and practicality in adjusting the focus, essential attributes for good shooting in very confined spaces. In addition, there are also waterproof Subsea Light LEDs and Indus Star A008 Light Module for front and rear lighting that assist the cameras in capturing images.

As wireless communication is not viable in the robot's environments, communication between the robot and the base is via cable with the Fantom-X Tether, which allows fast communication over distances of more than 300m using a twisted pair cable.

The two cameras, Tether board and Raspberry Pi, communicate via the NETGEAR GS105v2 ethernet switch, which has five ports with Gigabit speed. One ethernet port is still available for more embedded devices if needed.

The system power supply is a 12000mAh 4S1P Turnigy battery that guarantees a good range concerning its weight, and DC/DC converters that regulate the electrical voltage supplied to the electronic components, being an IC XL4015 exclusively for the Raspberry Pi and a Vicor V28A12C200BL for all the rest of the system.
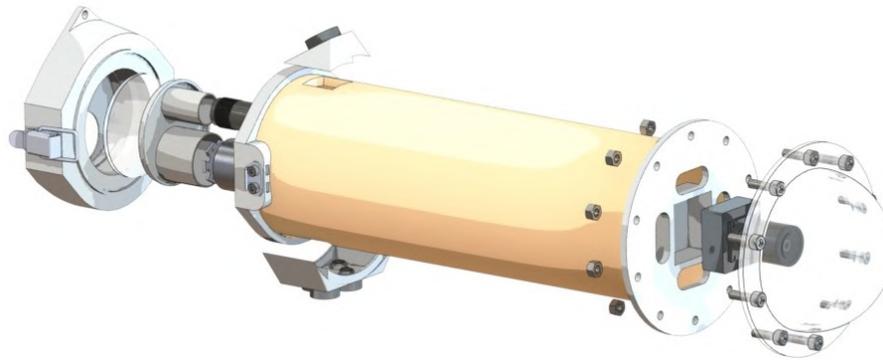
3.2 Body Module

The Body Module consists of a PVC tube with a $110\ mm$ diameter and $6.1\ mm$ thickness with 3D-printed covers attached to the pipe ends. We cut the PVC tube in two different places to positioning the 3D-printed supports for the tether cable ($23 \times 25mm$) and other cables ($60 \times 40\ mm$) used to communicate with external electronic components (motors, LEDs, among others).

The access to the robot's interior is through the rear cover. The outermost part of this cover has a geometry responsible for guiding the tether cable, hold a snap-lock, and provide a camera view in the return operation. Furthermore, the design allows printing this cover with the least amount of material. We bond a polycarbonate plate between these outer and inner cover parts with neutral silicone. The inner part has a place to allocate the LED and camera. The snap-lock mechanism attaches the cover to the body in a fitting similar to airtight jars. We screw one side of the snap-lock in a 3D-printed framed glued to the PVC tube and another to the removable cover.

The body's front cover fixes and protects the camera used for inspection. The cover has a 3D-printed front base, glued to the PVC pipe, and a commercial dome. The front base is responsible for attaching the camera by interference only and fix the dome by screw. The front cover only allows access to the camera. Figure 7a shows an exploded view of the body module.

3.3 Engine Module

The engine module is the same for wheels and track systems, designed to mount easily and quickly on whichever traction module used during the inspection. The engine is cloistered between two covers, and just a drive shaft comes out of this box. We machined one of these covers to assure the required dimensional tolerances for the shaft radial seal and printed the other. An IP-67 sealing grommet seals the cable. The shaft connects to the engine by interference, and screws and nuts fix the engine to the box. It is possible to see in Figure 7b an exploded view of this assembly.

(a) Body module.
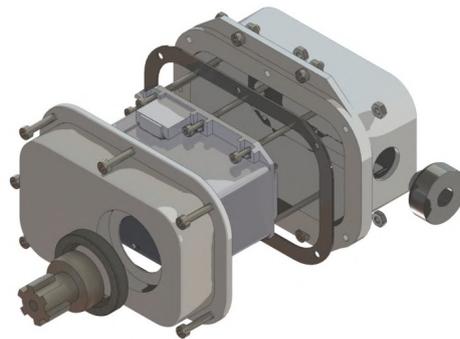
(b) Engine module.
Figure 7: Exploded view of the principal robot modules: (a) body and (b) engine modules.

3.4 Track Module

The tracking module allows inspection on pipes above 14-inch. It consists of two 3D-printed plates, fastened with screws and nuts. The track is an H's tooth profile (1/2-inch pitch) synchronous belt with a double face (teeth on the inner and outer part). Its movement is through three commercial pulleys selected from national catalogs and geometry adjusted to fit the assembly.

The robot has rear axle power, provided by the attachment of the engine module to the pulley. Both the engine and the pulley have splines to connect faster and drive the assembly. Finally, we fix the front axle pulley with a keyway to a machined shaft supported on the printed plates by two bearings.

For applying the necessary tension required for the belt functioning, we installed a mechanism that works as a tensioner. This mechanism is a 3D printed base responsible for withstanding the stretching effort of the belt, guiding a supporting element that has a smaller pulley. Turning a bolt presses the pulley against the inner part of the belt - at the top of the movement module, applying the necessary tensioning force. Figure 8 present the mounting steps of track module: A) represents the tensioner mounting, B) the positioning of the tensioner, pulley support, and engine module at the side plate, C) show the drive pulley setting, D) present the mounting of the pulley responsible for transmitting torque and finally E) are the positioning of support module, the synchronous belt, and outer plater to close the assembly.

3.5 Wheels Module

The wheels module allows inspections on pipes between 10-inch and 14-inch. Their construction is much simpler than the track module. It is only one 3D-printed plate which is the base for the front axle assembly, while we mount the rear one on top of the engine module, analogously to the track module.

In the front axle assembly, the wheel is fixed with a machined shaft. The shaft fits into the bearings with interference,
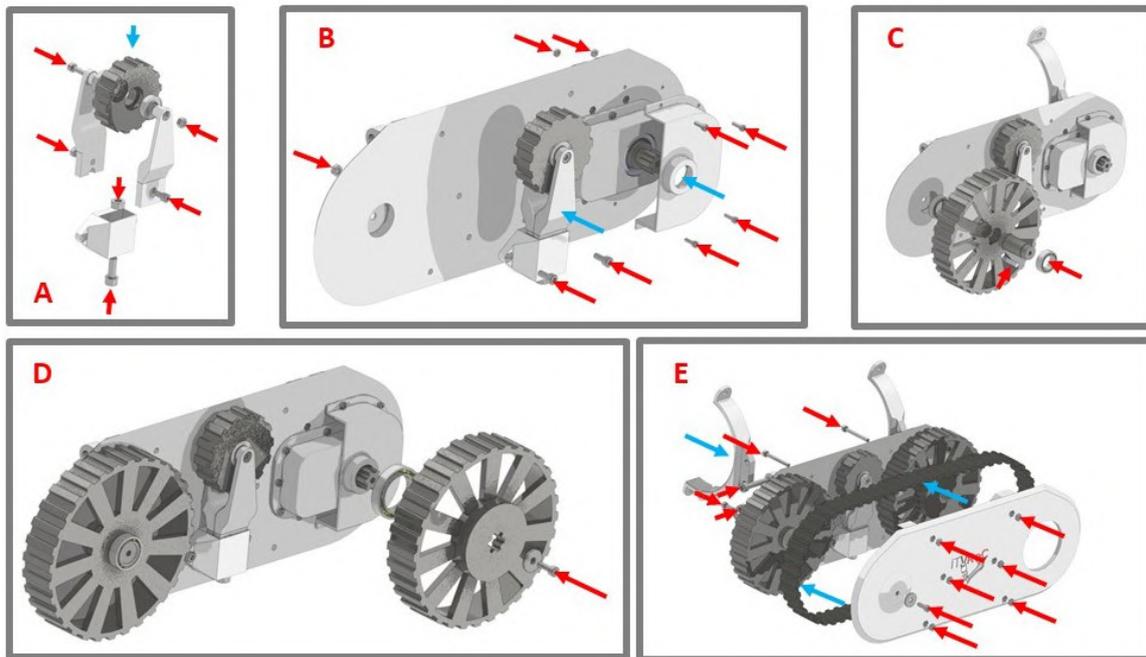
Figure 8: Mounting steps of the track module.

while an elastic ring holds the bearing in a hoop. Finally, we fix this hoop with screws on the printed plate. The hoop was machined to assure dimensional tolerances for a proper fit of the bearings and the elastic rings.

The wheels have three parts: (i) the wheel hub responsible for the interface with the motor rotation axis, (ii) the ABS printed body, and (iii) grooves printed in a flexible material and glued into the printed body. The torque transmission is through splines machined into the wheel hub.

As we told before, the construction of this module is much simpler than the track one. It is possible to see this difference clearly in the Figure 9, which present just three steps: A) is the wheel mounting by positioning the wheel hub and the printed grooves, B) represents the set of supports and the movement assembly (shaft and bearings), and C) the bolting of the wheels mounted in step A to the support assembly.
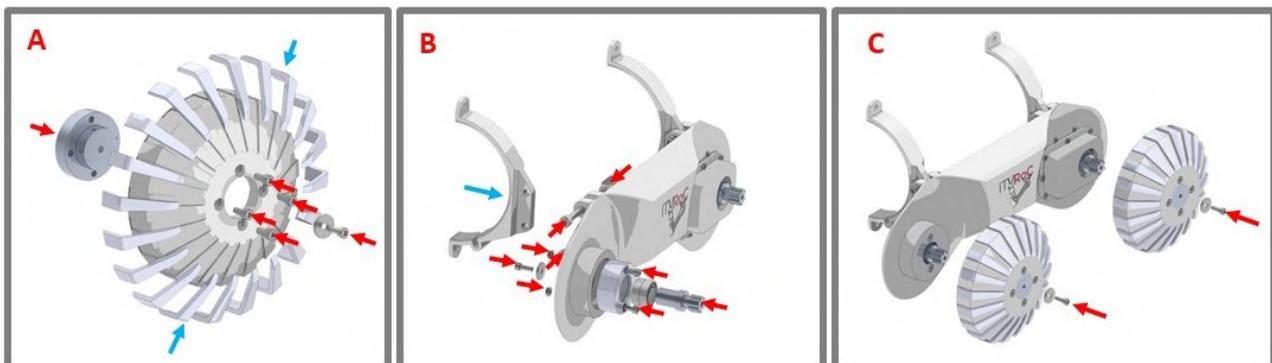

Figure 9: Mounting steps of the wheel module.

3.6 Support Module

The Support Module is the set of parts that attach the Motion Modules and the LEDs responsible for the front lighting to the robot's body. There are three interfaces to attach the support module: (i) the body module, (ii) the locomotion module, and (iii) the LEDs.

The interface of the body module is a pair of brackets in the shape of a clamp - two semicircular rings, with flanges at the ends to screw them, which embrace the robot's PVC body by a bolt. The interface with the motion modules is through two bolted support points. We fit the LEDs into the bracket with a bit of interference and reinforced it with double-sided tape. The supports module needs, at least, for each motion module (tracks or wheels), three pairs of supports for its body's attachment. Therefore, two front pairs, two rear pairs, and two pairs for the LEDs.

We conceived the bracket module to facilitate the quick change between the wheel and track system like the engine

module. An advantage of this system is its manufacturing form (3D Printing), which allows different positioning of the track module by replacing the supports that place this module at different inclination angles, thus providing improved adaptation capabilities for the inspection mission.

3.7 Interchangeable System

As described above, the system was designed for fast swapping between locomotion modules, enabling better adaptation of the robot to the inspected duct diameter. For example, Figure 10 presents the process for swapping the locomotion module. To change from one locomotion module to another is only necessary to unbolting three supports that hold the
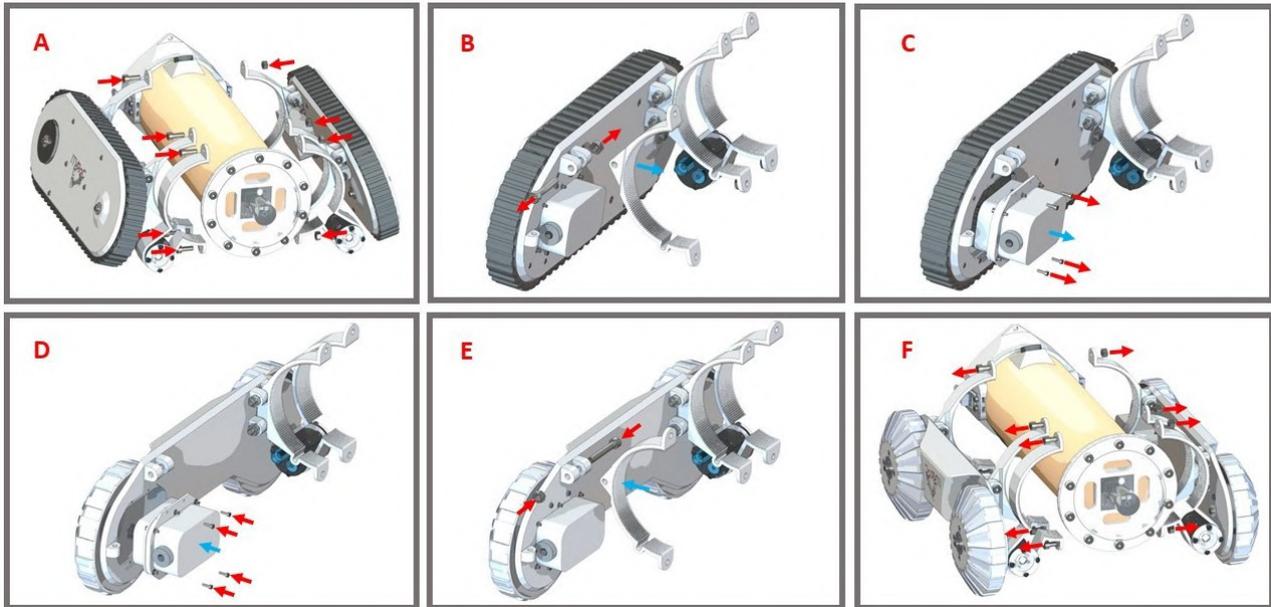

Figure 10: Process for swapping the tracks module to wheels.

assembly in the robot body (Figure 10.a and remove the rear support to allow access to the engine module (Figure 10.b. The next step is removing the engine module and the LEDs from the inner plate (Figure 10.c, and then positioning it in the other locomotion assembly (Figure 10.d, mounting the rear support (Figure 10.e, and finally bolting the supports at the robot body again (Figure 10.f.

3.8 Waterproofing

Depending on the inspection conditions, the robot will face dust, water, or mud. Therefore, IP-67 protection is essential to prevent electronic components from damage. Most of the electronic components are inside the body module. There are three sealing points in this assembly: (i) front cover, (ii) rear cover, and (iii) cable support sealing grommets. We fix the dome with screws under a rubber cord to the front cover bracket on the front cover. The back cover is built like an airtight jar, where the quick-release fasteners are responsible for applying pressure on a nitrile rubber, sealing the system. Finally, all communication cables pass through IP-67 sealing grommets.

For the engine, the seal is done with three methods: a rubber sealing cord between the engine module's covers, a retainer on the drive shaft of the motor module, and an IP-67 sealing grommet for the communication and power wires of the motor. The LEDs used outside the robot already have IP-67 protection, so they do not need extra sealing.

4. CONCLUSIONS AND FUTURE WORK

This paper presents the design of a robotic device for inspecting small diameter pipes, manufactured mainly with commercial electronics components and 3D-printed parts. The robot has an interchangeable locomotion system to allow easy and quick adaptation in the field.

The main objectives that guided the development of the robot were: being a low-cost platform compared to other commercial robots and manufactured inside the ITV lab, easily replicable with off-the-shelf local components, and having IP-67 water and dust protection. The Pipe robot construction costs up to 70% less than the EspeloRobô and other commercial platforms acquired by Vale. Most of the actual commercial inspection robots available have almost all of the electronics components acquired from outside Brazil, which does not occur with the Pipe robot; its electronics components are easy to find off-the-shelf, locally, in Brazil. Sealing tests with similar robots indicate that the proposed solution

will adequately protect the internal components from water damage. The design of this robot already has a patent-pending application submitted by the Vale Patent Office (de Barros *et al.*, 2021) that confirms their systems' innovative construction.

Future work will focus on finishing the robot mounting and field tests to confirm the visual inspection capabilities and the locomotion systems efficiency, which was not possible till the submission date of this article due to the restrictions imposed by the COVID-19 pandemic. Also, we intend to develop a system that automatically positions the tracks in different angles to fit better in pipes diameter between 14-inch and 22-inch, which nowadays is done by manually changing the supports.

5. ACKNOWLEDGEMENTS

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