Novel Modular Self-Reconfigurable Robot for Pipe and Plant Inspection

Authors: Sergio Leggieri[1,2], Carlo Canali[1], Ferdinando Cannella[1], Darwin Caldwell[1]

PRESENTED BY: Sergio Leggieri[1,2].

1) Department of Advanced Robotics, Italian Institute of Technology

2) Department of Management, Information and Production Engineering, University of Bergamo

Email: Sergio.leggieri@iit.it

About the author

Sergio Leggieri is Ph.D. Student at the Italian Institute of Technology (IIT) and the University of Bergamo.

He graduated in "Robotics and Automation Engineering" from the University of Pisa in 2016.

From 2017 to 2018, he worked as collaborator at IIT on the development of a robot for the inspection of power generators, on behalf of "Ansaldo Energia".

His main research interests are in Robotics, Control Systems, Inspection Robotics, and Dynamic Modeling.

About the Italian Institute of Technology

The Italian Institute of Technology, with its headquarters in Genoa, Italy, is a non-profit institution with the primary goal of creating and disseminating scientific knowledge and strengthening Italy's technological competitiveness.

IIT's research endeavor focuses on high-tech and innovation, representing the forefront of technology with possible application from medicine to industry, computer science, robotics, life sciences and nanobiotechnologies.

Introduction

In Industry 4.0 era, mankind has become increasingly dependent on the correct and efficient functioning of many machines and on the goods that these devices produce.

Electricity companies or water/oil/gas suppliers have to ensure the full 24/7 functionality of all the assets, satisfying high safety standard in production processes and in delivery efficiency.

To prevent major breakdown or dangerous failures, such industries need to perform planned inspection and maintenance operations that often result in long downtime and economic losses.

Human-based inspections

Most of the inspections are still performed by human operators. However, such approach often results in a not-optimal solution in terms of costs and time.

According to the targets and the objectives, many issues have to be taken into account during inspections, such as:

- *Preparatory work is often required to reach the assets or the machineries;*
- *Long shutdown or partial disassembly may be needed to reduce risks for operators;*
- *The data collection and evaluation may lack in reliability and repeatability.*

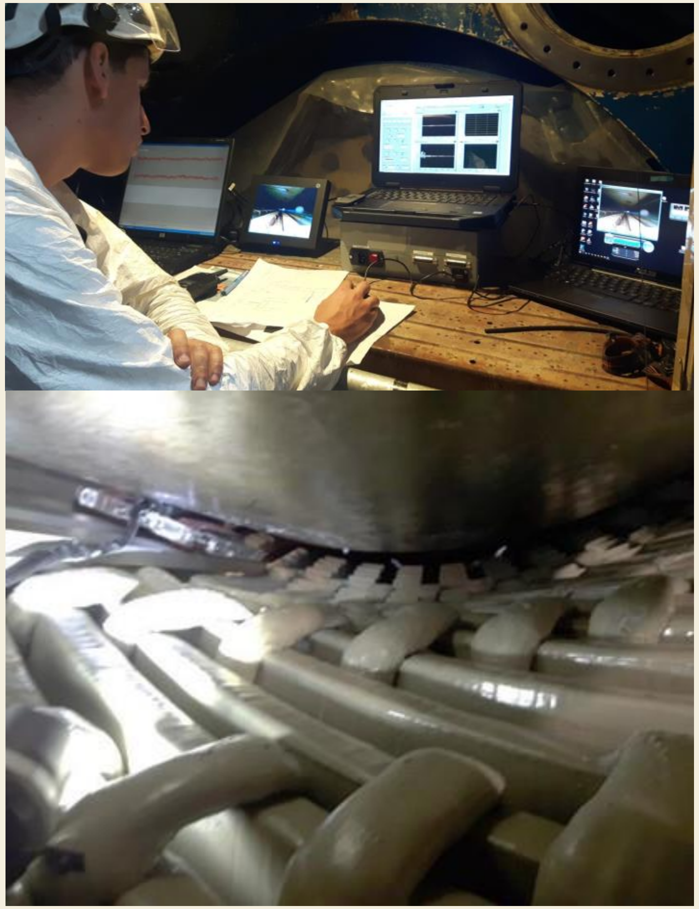
Robot-based inspections

In the last decades, an increasing number of robotic devices have been developed to perform inspections.

Inspection robots aim at: speeding up the operations; reducing costs and downtime; minimizing the risks for human operators.

These systems are designed to perform very specific operations. However, such devices have a reduced capacity to adapt to different scenarios.

For this reason, the spread of inspection robots is still limited in industrial applications.



Plant inspection

Power plants and refineries cover very extensive areas and are composed by many components, such as: buildings; pipes; pressure vessels; tanks; etc.

For the safe and efficient functioning of industrial plants, each component has to be inspected and maintained periodically.

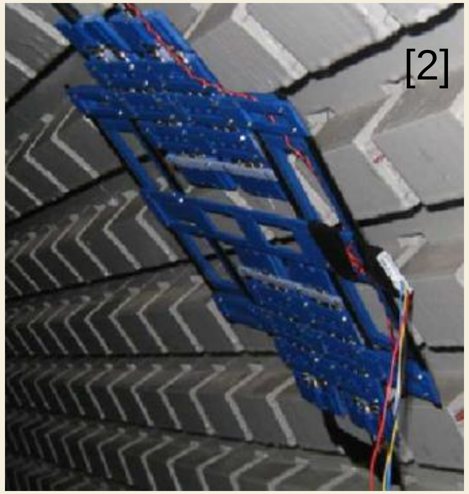
In such facilities, inspection activities may focus on single components or involve the monitoring of the entire plant.

Plant inspection

Performing robot-based inspections on single components requires the use of many specialized robots. These are designed ad hoc to work on a specific machinery and may be inapplicable even to a different version of it.

Plant general inspection requires a different kind of devices. The robots have to operate in wide areas performing data acquisition, while spanning the plant to detect unexpected conditions. Often, these systems are the fusion of mobile platforms, robotic arms and sensors.


[1]


[2]

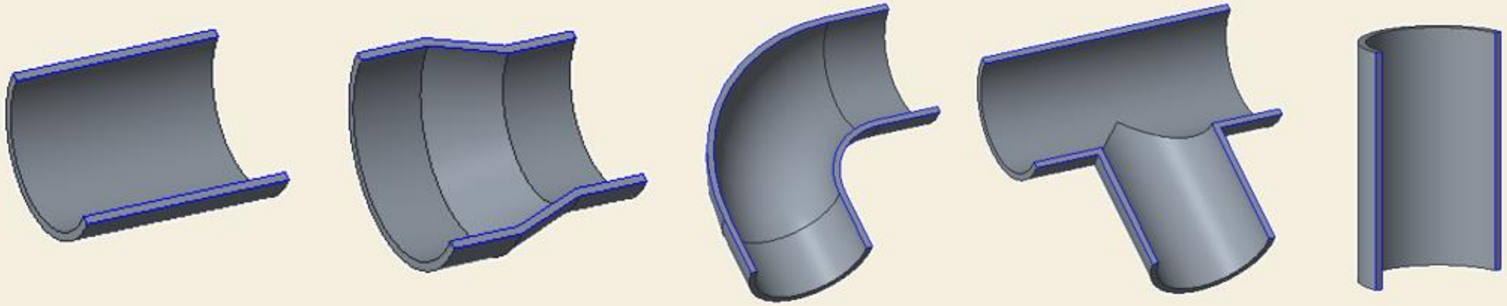

[3]

Pipe inspection

Pipeline networks are spread everywhere in the world and transport fluids of any kind. Damages due to aging, corrosion, fissures or cracks may occur in pipes. The conditions of such structures have to be verified periodically to prevent leakages and possible environmental damages.

Pipeline networks may comprise many different type of segments and junctions:

- *Horizontal sections and changes in diameter are very common;*
- *Elbows and T-sections can be very hard to traverse;*
- *Vertical segments are the most challenging parts.*



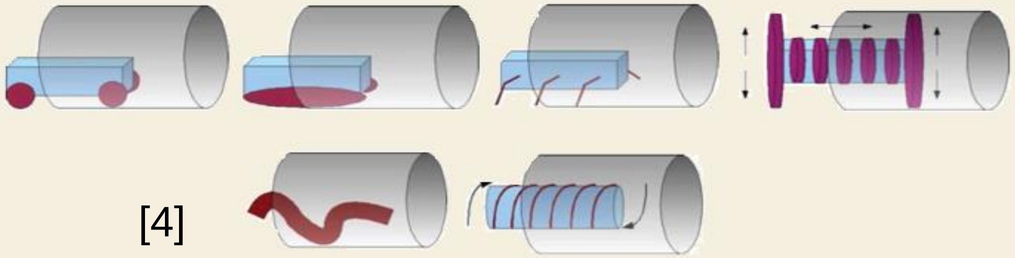
Pipe inspection

The main purpose of pipe inspection robots is to carry cameras and sensors by which the pipe conditions can be assessed. These robots can be divided in two big families:

Passive systems

Pipe Inspection Gauge robots rely on fluid to move, [4]. These systems have a simple structure but a limited range of use, and are unable to stop at specific points.

[4]

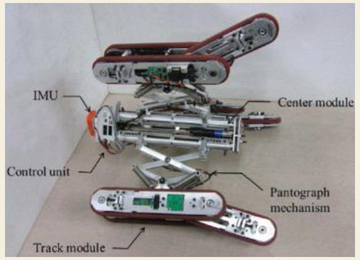


[4]

Active systems

The robots in this family can be further categorized according to the locomotion method, [4].

Robots with one or two modules are very common. Often such systems equip complex mechanisms for adapting to the pipe networks, [5].

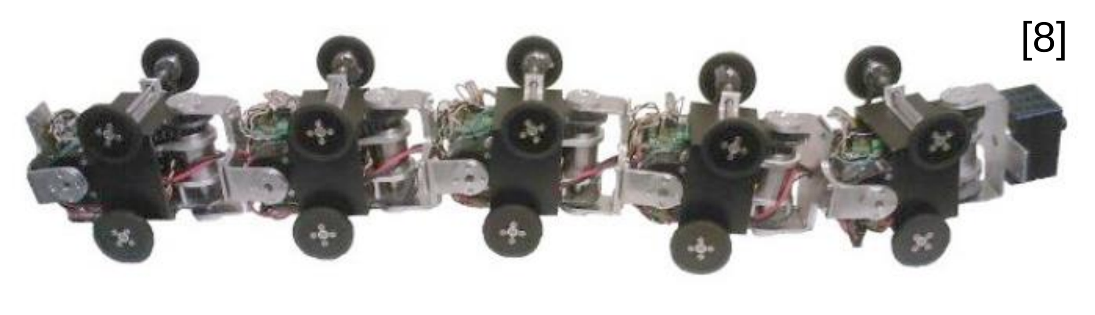


[5]

Pipe inspection

In recent years, the trend of pipe inspection robots has shifted toward the use of more flexible systems with many articulated modules like snake robots, [6].

These robots can move in complex environments coordinating the motion of their parts, [7]. Due to their slender bodies, snake robots are extremely suitable for performing inspections in constrained environments, [8]-[10].



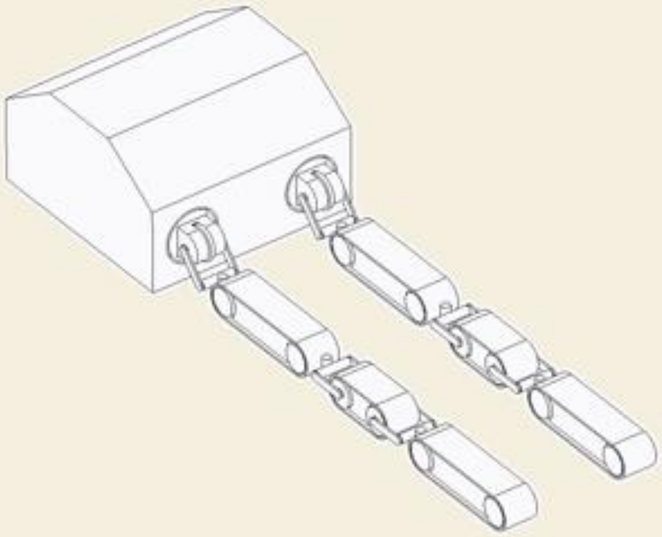
Aim of the work

The purpose of this study is to design a novel robotic system capable of performing a wide set of tasks related to the inspection of pipelines and industrial plants.

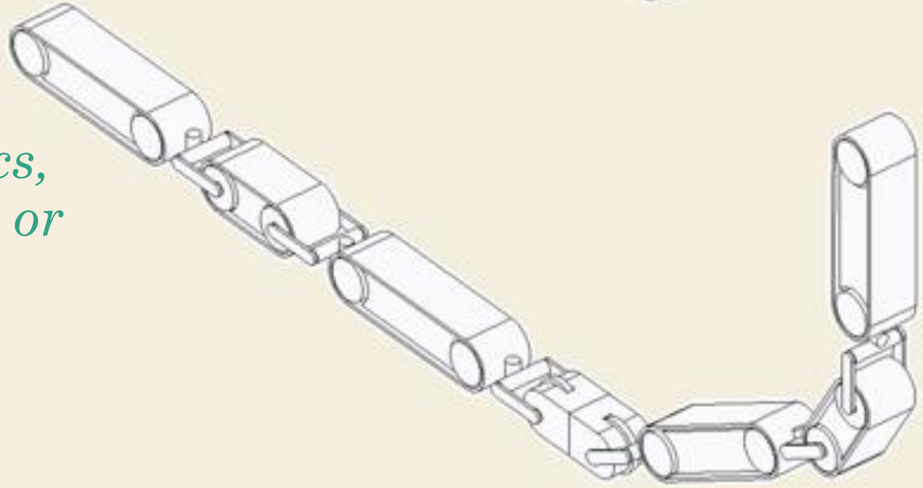
The resulting robot must be able to operate in both confined and open spaces, dealing with harsh environments and unexpected obstacles.

The proposed system

The system consists of two identical vehicles and a main base. Each mobile robot is meant to perform easy inspection activities in pipe and plant.



In case of more complex scenarios or tasks, the vehicles can couple together by using an autonomous docking system, self-reconfiguring into a snake robot.



The snake robot, exploiting the redundant kinematics, can overcome large obstacles, cross difficult terrains or complex pipe segments, and reach targets placed in high positions.

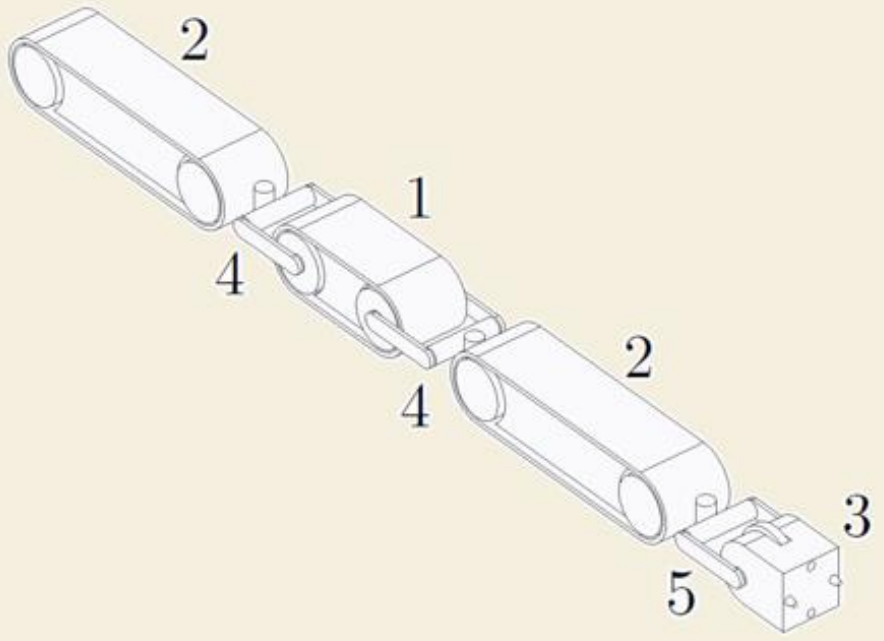
The vehicle: main features

The system comprises three modules (1-2) that constitute the robot body, and a docking sub-module (3) that can be considered as the robot head.

The modules of the robot body are connected through six active joints that form two specular kinematic chains with respect to the central segment (4).

The central section (1) houses the batteries, the main control board, and two actuators. Each extreme modules (2) comprises one motor to actuate the track and the electronics required for control.

The vehicle moves using a combination of active/passive tracks and wheels. Each module has a single track or wheel.

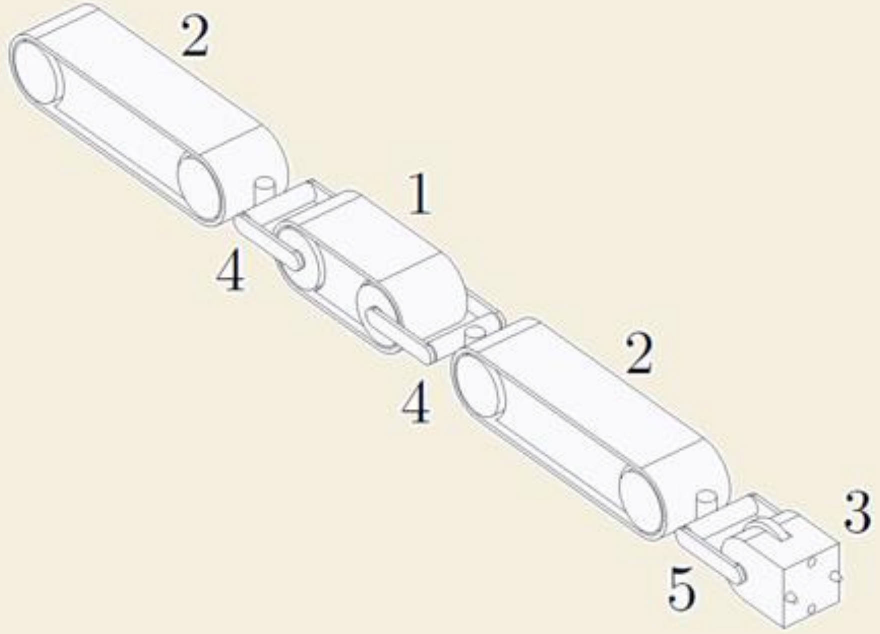


The vehicle: main features

The robot head (3) is connected to the main body through another kinematic chain (5).

The docking sub-module stores additional batteries, the mechanism for coupling, a camera, a set of infrared transmitters/receivers and sliding contacts.

The coupling mechanism consists of three sprockets: the central is driven by a motor, the two lateral beside rotating can slide pulling out the bolts that secure the connection.



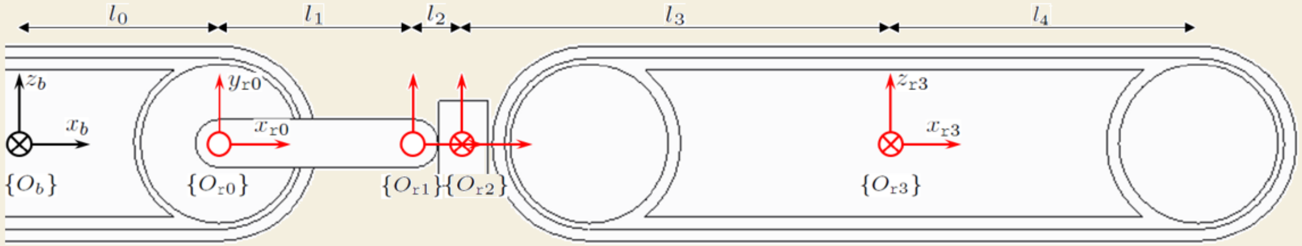
The vehicle: kinematic analysis

A preliminary kinematic analysis has focused only on the robot body with the aim of identifying crucial parameters for the design phase.

The floating base frame $\{O_b\}$ is located in the central segment, local frames $\{O_{ri}\}$ and $\{O_{li}\}$ are attached on each i^{th} link of the right and left kinematic chain, respectively.

The two kinematic chains have been computed using the Denavit-Hartenberg parameters, [11].

Frames	a_i	α_i	d_i	θ_i
$\{O_b\} \to \{O_{r0}\}$	l_0	$\pi/2$	0	0
$\{O_{r0}\} \to \{O_{r1}\}$	l_1	0	0	q_{r1}
$\{O_{r1}\} \to \{O_{r2}\}$	l_2	$-\pi/2$	0	q_{r2}
$\{O_{r2}\} \to \{O_{r3}\}$	l_3	0	0	q_{r3}



The vehicle: kinematic analysis

The computation of the homogenous matrices allows to describe the position and orientation of all the local frames with respect to the base frame $\{O_b\}$ *.*
In particular, the position vector of the last frame $\{O_{r3}\}$ *is:*

$$\mathbf{p}^b_{\mathrm{r}3} = \begin{bmatrix} l_0 + l_1 c_{\mathrm{r}1} + l_2 c_{\mathrm{r}12} + l_3 c_{\mathrm{r}12} c_{\mathrm{r}3} \\ l_3 s_{\mathrm{r}3} \\ l_1 s_{\mathrm{r}1} + l_2 s_{\mathrm{r}12} + l_3 s_{\mathrm{r}12} c_{\mathrm{r}3} \end{bmatrix}$$

From the third component of this vector it is possible to compute the maximum height H that the extreme module can reach:

$$H = \frac{h}{2} - \frac{h}{2c_{\mathrm{r}12}} + l_1 s_{\mathrm{r}1} + l_2 s_{\mathrm{r}12} + (l_3 + l_4) s_{\mathrm{r}12} c_{\mathrm{r}3}$$

This formula shows how an increment in the lengths of each link increases the maximum reachable height H.

The vehicle: maneuverability analysis

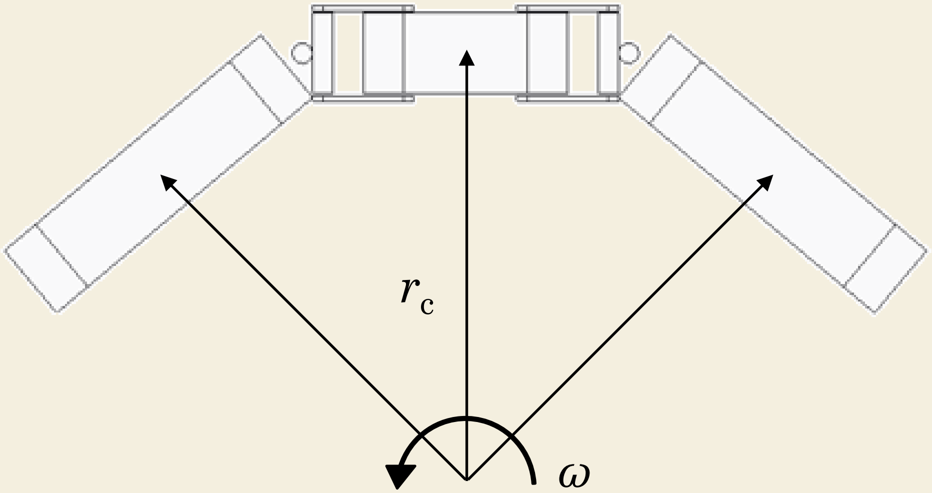
The mono-track design reduces the total motors and makes the vehicle less sensitive to debris. This feature poses additional challenges in steering the robot.

The active joints allow to rotate the extreme modules on the horizontal plane, the curvature radius r_c results:

$$r_c = \frac{l_3 + \frac{(l_0+l_1+l_2)}{\cos q_{r3}}}{\tan q_{r3}}$$

Assuming that all the modules have uniform tangential velocity v, the angular rate is:

$$\omega = \frac{v}{r_c}$$



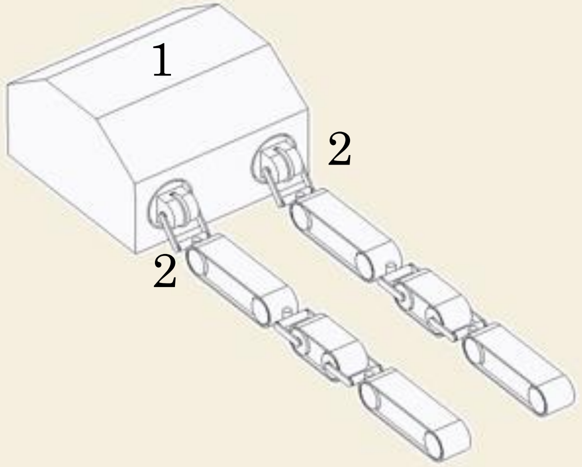
This formula shows how the increment in the lengths of each link increases the curvature radius, thus reducing the maneuverability of the vehicle.

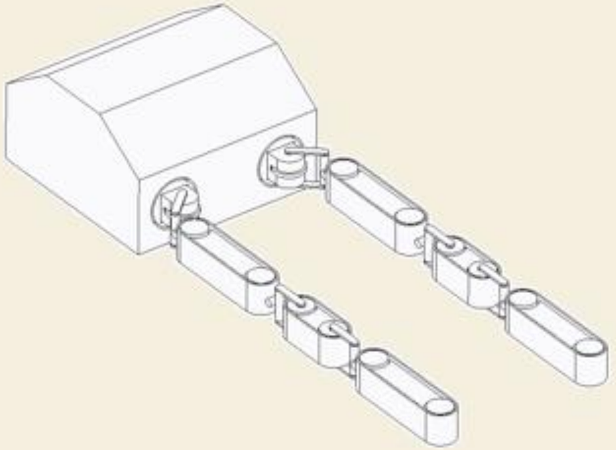
The main base

The design of the main base (1) is not completely defined yet. The primary purpose of this system is to recharge the vehicles.

The two docking interfaces (2) have the same coupling mechanism of the vehicles. Once connected, the vehicles can be rotated by these interfaces and used as robotic arms.

It is under consideration the possibility to equip the base with wheels or tracks, so it can be used to travel long distances and deploy the vehicles near the inspection site.





Conclusions & Future Work

The proposed design is a versatile robot that aims at replacing humans in performing inspections. Modularity and self-reconfigurability are considered key features to fulfill this purpose.

Preliminary analysis on the vehicle kinematics and maneuverability have pointed out the dependence of the maximum reachable height and the curvature radius on the robot length.

The project is still at early stage, with ongoing simulations to define the robot parameters. The definition of dynamic models of the system as vehicle and as snake is the next step toward the development of the proposed robot.

References

[1] A. Pistone et al., “Reconfigurable inspection robot for industrial applications”, Procedia Manufacturing, vol. 38, 2019, pp. 597-604.

[2] G. Caprari et al., “Highly compact robots for inspection of power plants,” Journal of Field Robotics, vol. 29, Gen. 2012, pp. 47–68.

[3] S. Soldan et al., “Towards Autonomous Robotic Systems for Remote Gas Leak Detection and Localization in Industrial Environments”, Springer Tracts in Advanced Robotics, Springer, Berlin, Heidelberg, Jan. 2014, pp. 233-247. in Yoshida, K. and Tadokoro, S., Field and Service Robotics, ISBN: 978-3-642-40685-0.

[4] J. Mirats-Tur and W. Garthwaite, “Robotic Devices for Water Main In-Pipe Inspection: A Survey,” Journal of Field Robotics, vol. 27, Jul. 2010, pp. 491–508.

[5] J. Park, et al., “Normal-Force Control for an In-Pipe Robot According to the Inclination of Pipelines,” IEEE Transactions on Industrial Electronics, vol. 58, Dec. 2011, pp. 5304–5310.

[6] G. Mills, et al., “Advances in the Inspection of Unpiggable Pipelines,” Robotics, vol. 6, Nov. 2017, p. 36.

[7] S. Hirose and M. Mori, “Biologically Inspired Snake-like Robots,” in 2004 IEEE International Conference on Robotics and Biomimetics, Sep. 2004, pp. 1–7.

[8] S. A. Fjerdingen, et al., “A snake-like robot for internal inspection of complex pipe structures (PIKo),” in 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, Oct. 2009, pp. 5665–5671.

[9] J. Borenstein, et al., “The OmniTread OT-4 Serpentine Robot 1 Design and Performance,” Journal of Field Robotics, vol. 24, Jul. 2007, pp. 601–621.

[10] H. Schempf, et al., “Visual and nondestructive evaluation inspection of live gas mains using the Explorer family of pipe robots,” Journal of Field Robotics, vol. 27, May 2010, pp. 217–249.

[11] B. Siciliano and O. Khatib, Eds., Springer handbook of robotics. Springer, Berlin, Heidelberg, 2016, ISBN: 978-3-540-23957-4.