Novel Modular Self-Reconfigurable Robot for Pipe and Plant Inspection

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***Abstract*—In the last decades, the trend of replacing humans with robots has increased enormously, especially in repetitive or dangerous tasks such as inspection and maintenance. Various inspection robots have been developed so far, but usually those systems are designed for addressing very specific operations. The spread of such devices is mainly limited by the lack in adaptability to different tasks, and by the design restrictions of these robots. Instead, modular and self-reconfigurable robots have proven superior performance in different scenarios. Here, the idea of developing a modular, self-reconfigurable robot for inspection is discussed. The system consists of two modular vehicles with docking modules for reassembling into a snake robot. Thanks to its structure, it overcomes the challenges posed during pipe and plant inspections.**

Keywords–inspection robot; modular robots; self-reconfigurable mobile robot.

I. Introduction

Although robots are becoming very popular in industry, nowadays most of the inspection and maintenance operations on structures and equipments are still largely carried out by human operators. Human-based inspection, however, may not be the optimal solution in terms of costs and time. Preparatory work is often required before starting the operations to access the machinery or the assets and to ensure safety standard for the workers. The reliability and repeatability of the results is another major concern when inspections are performed by humans.

To address the challenges mentioned above, robotic devices have been developed in the last years to perform inspection, especially in industrial plants and in pipeline networks, where major challenges need to be overcome to deal with various problems that could be encountered. For example, the geometrical features of the asset to be inspected may be very demanding, setting sharp constraints in the design of the robots. The environment, where the machinery and the equipments reside, can be very harsh due to the presence of dirt, mud, hazardous substances, staircases, or unexpected obstacles. Finally, even the robot deployment, in some cases, can be a risky operation for humans.

Considering all these issues, a novel modular self-reconfigurable robot is proposed hereafter. Such system is intended to perform inspection of pipelines and industrial plants, travelling autonomously within the environments to reach its targets. Moreover, this system can self-reconfigure into a snake robot to deal with the most advanced tasks.

This paper is organized as follows: Section II presents related works on inspection robots and snake robots; Section III describes the system, analyzing its main features and providing graphical representations of it; Section IV concludes the paper and provides information about next steps in the robot development.

II. Related Works

Within industrial plants, the inspection can be divided into two main groups: inspection of specific machinery and general inspection and monitoring. For machinery, many robots have been developed, such as [1][2]. These robots are very specialized devices, expressly designed for addressing inspection of specific machinery. However, these systems may result ineffective even for different models of the same asset. For general inspection, robots, such as [3]-[5], have been developed. These latter systems show a great flexibility to deal with different scenarios. Such robots consist in assemblies of different robotic devices like mobile platforms with robotic arms on top.

In pipe inspection, usually, robots have to deal with highly constrained environments. In addition to the passive systems whose motion ability is guaranteed by fluid flow, the active systems can be categorized according to the locomotion methods, as in [6][7]. Some of these robots have standard structure, with wheels or tracks for moving and cameras as visual feedback. However, their use can be quite limited. In the same manner, other devices have just one or two modules, but are equipped with complex mechanisms for adapting to pipe networks [8]. In recent years, however, the trend has shifted toward the design of versatile robots with many articulated modules [7].

Since the '70s, many snake robots have been developed, such as [9]-[12]. These robots can move in complex environments coordinating the motion of their parts, using the well-known gaits called lateral undulation and side-winding, see [13]. Due to their slender bodies made of redundant modules, snake-like robots are extremely suitable in performing inspection in constrained environments, as described in [14]-[16].

The unchallenged mobility and adaptability of these robots, however, come at the cost of a high mechanical complexity and a demanding motion control.

III. THE SYSTEM

Modularity and self-reconfigurability are key features for designing multipurpose robots [17][18]. Some robots that have proven to exhibit good performance in surveillance and search and rescue missions are described in [19]-[22]. Here, the robot design is based on these examples, but it introduces important novelties in its mechanical structure and features, which are described throughout this section.

The system consists of two independent vehicles that can self-reconfigure into a snake robot through their docking modules. The vehicles are intended for performing most of the inspection tasks by themselves, so the motion control of individual robots involves only few modules and joints. Nonetheless, the vehicles can deal with complex scenarios or particularly demanding tasks by coupling together and self-reconfiguring into a snake robot. In this way, the mechanical and control complexities of the system increase, but the robot can exploit its redundant kinematics to overcome obstacles, walk through difficult terrains, or climb vertical pipe segments.

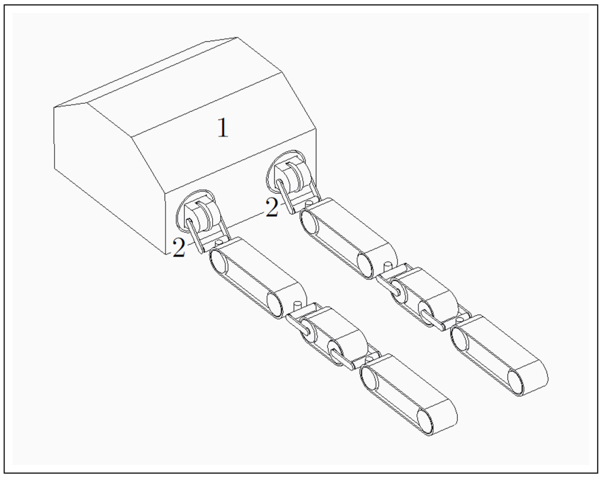

Figure 1. Representation of two vehicles docked at the base for recharging: 1 main base; 2 docking module interfaces.

The complete system includes also a main base. This base is meant for recharging purposes, but eventually it can be used also as a platform for travelling long distances and for deploying the vehicles in proximity of the point of interest. Finally, it is reasonable to assume that, after docking the two vehicles, the main base can use them as manipulators widening the possible fields of application of this system. A graphical representation of the entire system is given in Figure 1.

A. The vehicles

Both vehicles consist of three main modules and a docking module at one extreme, as shown in Figure 2. The modules are connected through active joints that form two specular inter-modules kinematic chains with respect to the central segment. Each docking module is then connected to the front of each vehicle through another kinematic chain.

The vehicle utilizes a combination of active/passive tracks for locomotion. The extreme modules contain all the required electronics and the control boards for actuating the two motors that drive the tracks. The central module has a passive track, it stores the batteries, the sensors for inspection and the pitch joints of the inter-modules kinematic chains. Each inter-modules chain consists of one pitch joint, a link and an active Cardan joint.

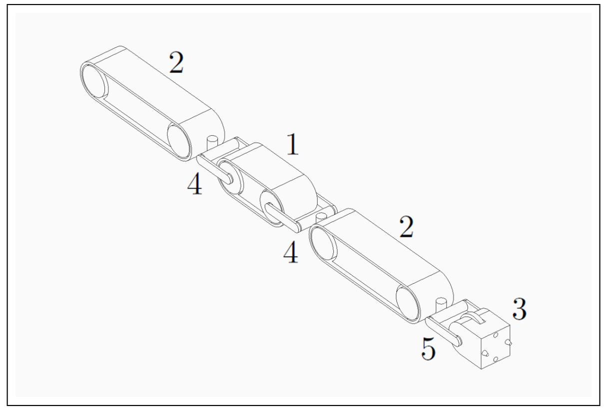

Figure 2. Representation of the vehicle: 1 central module; 2 extreme modules; 3 docking module; 4 inter-modules kinematic chains; 5 docking module kinematic chain.

This kinematics allows the vehicle to steer by rotating its extremes on the horizontal plane, as discussed in the next subsection. On the sagittal plane, the same kinematics allows the robot to adapt to slopes or gaps, overcome obstacles, and climb stairs. By defining proper gaits, the vehicles can perform lateral movements or turn on the spot using its modules as limbs. Moreover, the central part can be displaced vertically to push against pipe walls increasing the grip on its tracks to possibly move in vertical pipes as well.

The docking module kinematics is similar to the one previously described, but the joints are arranged in reverse order: an active Cardan joint, a link and a pitch joint. This sequence is chosen to preserve the symmetry between modules once the two vehicles join together and form the snake robot. The symmetry is crucial for implementing typical snake gaits such as lateral undulation, side-winding, sinus-lifting. In snake robot form, the system can travel easily over rough terrains, can overcome large obstacles and can lift part of its body, as shown in Figure 3.

B. Vehicle kinematics and maneuverability

A preliminary kinematic analysis has focused only on the vehicle, while the docking module and its connecting kinematics have been neglected. Nevertheless, this analysis provides useful information for identifying crucial parameters for the robot design.

The inter-modules kinematics has been computed using the Denavit-Hartenberg convention [23]. As shown in Figure 4, the floating base frame $\{O_b\}$ is located in the central module. Local frames $\{O_{ri}\}$ and $\{O_{li}\}$ are attached on each i^{th} link of the chain, and the additional subscripts $\mathtt{r}$ and $\mathtt{l}$ represent the right and left chain, respectively.

In Table I, the D-H parameters of the right kinematic chain are summarized. The first row represents the fixed transformation from the base frame $\{O_b\}$ to the first joint

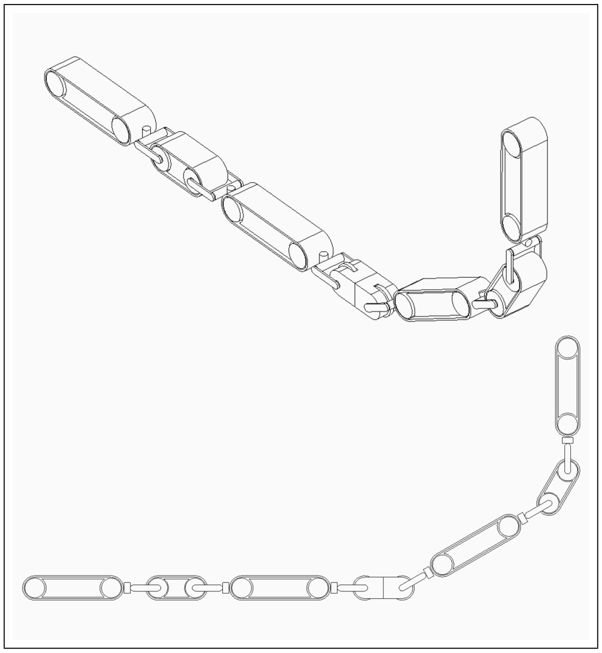

Figure 3. Representation of two vehicles coupled together to form a snake robot. In this mode, the robot can raise segments of the body to overcome obstacles or reach high points.

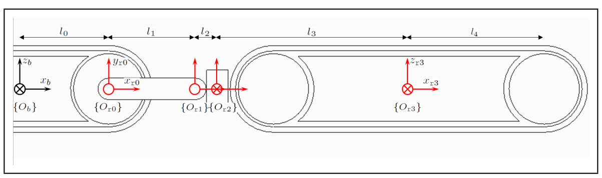

Figure 4. Schematic representation of the right kinematic chain. In black, the base frame $\{O_b\}$. In red, the local frames $\{O_{ri}\}$.

TABLE I. D-H PARAMETERS FOR THE RIGHT KINEMATIC CHAIN

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}

frame $\{O_{r0}\}$, which is translated by l_0 along the x axis and rotated by $\pi/2$ about the same axis. The successive rows describe the translation and rotation transformations defined by the joint variables d_i and θ_i along and about the z axis. The parameters a_i and α_i represent the translation and rotation along and about the x axis. So, l_i is the length of the i^{th} link, while q_{ri} is the angle of the i^{th} joint. Here, the Cardan joint is modeled as two distinct joints with local frames $\{O_{r1}\}$ and $\{O_{r2}\}$, which are shifted by a distance l_2.

Computing the homogeneous matrices from these transformations allows to describe positions and orientations of all the local frames with respect to the base frame $\{O_b\}$. The homogeneous matrix A^b_{r3} of the last frame $\{O_{r3}\}$ serves to identify the robot workspace. The corresponding position vector $\mathbf{p}^b_{r3}$ of the last frame is:

$$\mathbf{p}^b_{r3} = \begin{bmatrix} l_0 + l_1 c_{r1} + l_2 c_{r12} + l_3 c_{r12} c_{r3} \\ l_3 s_{r3} \\ l_1 s_{r1} + l_2 s_{r12} + l_3 s_{r12} c_{r3} \end{bmatrix} \quad (1)$$

Here, l_0, l_1, l_2 and l_3 are the link lengths; c and s refer to the cosine and sinus functions; the subscript $r3$ stands for the joint angle q_{r3}; and the subscript $r12$ represents the sum $q_{r1} + q_{r2}$.

Focusing on the third component of the vector $\mathbf{p}^b_{r3}$, it is possible to compute the maximum height H that the extreme module can reach, as follows:

$$H = \frac{h}{2} - \frac{h}{2c_{r12}} + l_1 s_{r1} + l_2 s_{r12} + (l_3 + l_4) s_{r12} c_{r3} \quad (2)$$

Here, the first term is half the central module height h; the second is the projection of half the extreme module height h onto the global z axis. The remaining part is the third component of the position vector $\mathbf{p}^b_{r3}$ to whom it is added l_4, which is the length from frame O_{r3} to the front wheel. Although this formula does not consider the system dynamics, it gives preliminary information to define how the link lengths affect the maximum height H.

The maneuverability analysis provides further information for defining further design parameters. Although the mono-tread design reduces the number of motors in the vehicle and makes it less sensitive with respect to debris, this feature introduces additional challenges in steering the system. For instance, the skid-steering technique used in caterpillars can not be used here. However, the two active yaw joints allow to rotate the extreme modules on the horizontal plane, as shown in Figure 5. Assuming that all the modules lay on this plane and have uniform tangential velocity v, it is possible to evaluate the curvature radius r_c of the system as follows:

$$r_c = \frac{l_3 + \frac{(l_0 + l_1 + l_2)}{\cos q_{r3}}}{\tan q_{r3}} \quad (3)$$

So, the angular rate ω of the central module is:

$$\omega = \frac{v}{r_c} \quad (4)$$

Equations $(2) - (4)$ depend on the link lengths of the robot. So, increasing the lengths l_1, l_2, l_3 and l_4 ensures to reach and overcome higher obstacles, but, in addition, it increases the curvature radius of the vehicle, thus limiting its maneuverability in constrained environments. Such dualism reinforces the idea of designing a modular, self-reconfigurable robot.

C. The docking module

Various technologies and mechanisms [24]-[27] have been developed for connecting autonomously two or more robotic modules. Some coupling devices are based on activation and de-activation of shape-memory alloys, [24][25], others are based on actuated mechanisms [26][27]. Since these latter seem to provide a good trade-off between connection robustness and power consumption, the vehicles utilize docking devices based on a novel actuated mechanism that is described hereafter.

The docking modules, at the extremes of the vehicles, have passive wheels in place of tracks. Each frame stores the batteries and a gearbox driven by a single motor. The gearbox

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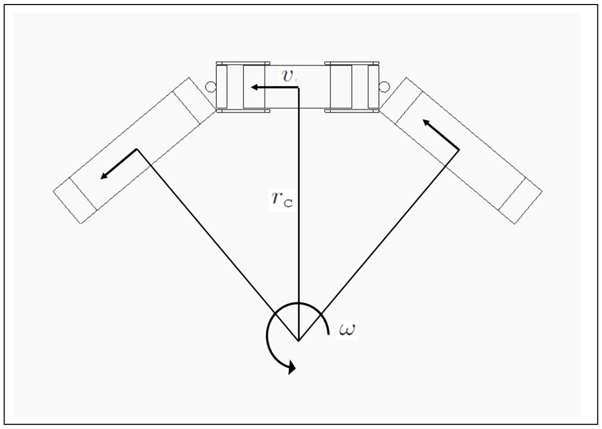

Figure 5. Representation of the vehicle in the C-shape configuration adopted to steer.

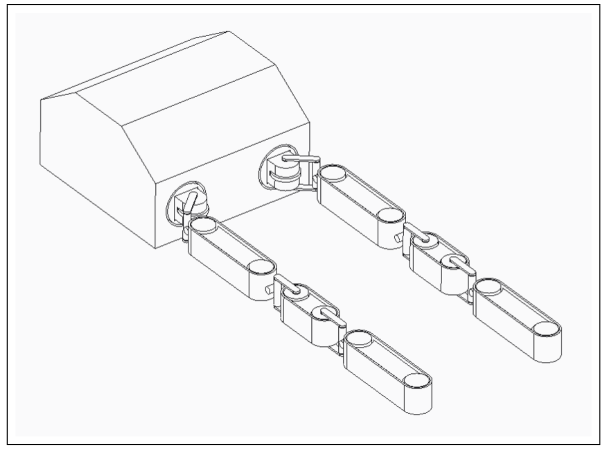

Figure 6. Representation of the vehicles used as manipulator. Once coupled, the roll joints within the base rotate the vehicles in the double arms configuration.

consists of three sprockets: one in the middle, driven by motor; and two lateral with a fixed screw each. The outer faces of each module are complementary, and on each surface there are two tampered pins and two threaded sockets. Hence, one docking module is rotated by $\pm 90\,\mathrm{deg}$ around the global x axis with respect to the other one. When the vehicles get in contact, the motors drive the gearboxes. The lateral gears, besides rotating, slide along the central sprocket pulling out the bolts that tighten to the complementary threaded sockets. Each docking module also includes a camera for vision, a set of infrared transmitters and receivers, and sliding contacts.

D. The main base

The design of the main base is not completely defined yet. However, the primary purpose of this system is to recharge the vehicles. On the base, there are two docking interfaces, which have the same coupling mechanism as the docking modules. These interfaces are driven by roll joints, in such a way that the docking ports in the base can be re-aligned to properly match the configuration of docking modules on the vehicles, as shown in Figure 1.

The roll joints can also rotate the vehicles, which can be used as robotic arms, as in Figure 6. Moreover, it is under consideration the possibility of mounting wheels or tracks on the base. This additional feature can be useful to deploy the vehicles near the point of interest, especially when the inspection has to be performed in very wide areas.

IV. Conclusion and future work

The system described in this work aims at replacing human operators in performing inspection in inaccessible or risky environments, such as pipelines or industrial plants. Modularity and self-reconfigurability are considered as key features to fulfill this purpose.

The proposed device consists of two modular mono-tread vehicles with active joints. The novel mono-tread design reduces the chances to get stuck on debris, but, in turn, it introduces some maneuverability limitations. These drawbacks have been identified and discussed, analyzing the vehicle kinematics and maneuverability. Notably, the motion control of the system, in this configuration, involves only a few modules and joints.

The docking modules, based on the novel mechanism discussed, allow the vehicles to reconfigure into a snake robot or to connect to the main base. As a snake robot, the motion control increases in complexity, but the system can perform advanced operations, such as crossing rough terrains, lifting part of the body or travelling through difficult pipe segments.

The project is still at an early stage, with ongoing simulations to evaluate the performance of such system and to define its design parameters. The definition of dynamic models for the robot as vehicle and as snake is another crucial step toward the development of the proposed system.

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