A 2 DoF Servomotor-based Module for Pipe Inspection Modular Micro-robots

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Abstract—A 2 degrees of freedom module for pipe inspection modular micro-robots based on servomotors is presented in this article. A mechanical and electrical description of the module is also given, including the kinematics and the close control loop design to detect obstacles (walls). The main configurations in which it can be used are described as well: snake-like robots and chain multi-configurable modular robots. The different pipes and elbows it can move on are also shown.

I. INTRODUCTION

Pipe inspection robots are specific purpose robots with a very complicated development due to the convergence of several disciplines in its design. Especially, the development of a multi-configurable pipe inspection micro-robot (meaning by micro-robot a reduced dimensions robot dedicated to exploration and maintenance of low diameter canalizations) starts from the knowledge given by different lines of investigation: low dimension robots (let’s say micro-robots), modular and re/multi-configurable robots, and pipe inspection robots amongst others[3][4][8]. There are quite a few reliable robots for pipe inspection tasks[3][4][8], but only a few are designed for low diameter pipes[9][10].

Modular robotic systems are those systems that are composed of modules that can be disconnected and reconnected in different arrangements to form a new configuration enabling new functionalities. Some of the advantages of modular systems are versatility, simplicity, robustness and low cost.

The module described in this article is a rotation module designed for commercial pipes of 40mm diameter or higher. It can be assembled as a part of a heterogeneous multi-configurable modular robot or a set of these modules can be assembled together to form a snake-like robot.

As a part of a heterogeneous multi-configurable modular robot it will provide two degrees of freedom for rotation (pan and tilt). As part of a snake-like robot, these modules will act as a drive module that will allow the robot to crawl through the pipes.

The structure of the article is as follows. In section II the mechanical design of the module will be presented, including concepts, kinematics and a description of the servomotors. In section III the electronics used for control and sensing will be presented. In section IV the different configurations in which it can be used are presented and some example configurations are given.

II. MECHANICAL DESIGN

The rotation module has been designed with two purposes: the first one is to be used as a rotation module for chain multi-configurable robots. The second one is for snake-like robots. For both of these applications it is necessary to have a mechanism to connect and disconnect the modules easily and to pass the wires for communication and supply from one module to the next. This is achieved by the connectors shown in fig. 1.

Each module is composed of two servomotors, two connectors (one male and one female) and the electronics for control, sensing and communication. Each motor provide one degree of freedom. Both together provide rotation in two perpendicular planes.

The servomotors come from commercial ones but have been redesigned to have a more compact size. The gearset of the servomotors have been rearranged (see fig. 2) and placed in a new cover to save space. The torque given for each degree of freedom is $0.43 Kg * cm$, down shifting the torque given by the servomotors (1.3Kg * cm) by 50%, an acceptable result.

Each module is able to raise up to two other modules of the same weight.

A. Kinematics

The homogeneous transformation matrix of the module has been defined following the Denavit Hartenberg convention [1]
(a) Default configuration
(b) Rearranged configuration

Fig. 2. Gearhead

TABLE I

<table>
<thead>
<tr>
<th>a_i</th>
<th>d_i</th>
<th>α_i</th>
<th>θ_i</th>
</tr>
</thead>
<tbody>
<tr>
<td>q_1</td>
<td>-L_2</td>
<td>0</td>
<td>π/2</td>
</tr>
<tr>
<td>q_2</td>
<td>-L_1</td>
<td>0</td>
<td>-π/2</td>
</tr>
</tbody>
</table>

(see eq. 1 to 3), according to the reference system shown in fig. 3 and the parameters defined in table I.

\[
A_1^0(\theta_1) = \begin{bmatrix}
\cos\theta_1 & 0 & -L_2\cos\theta_1 \\
\sin\theta_1 & 0 & -L_2\sin\theta_1 \\
0 & 1 & 0
\end{bmatrix}
\]

\[
A_2^0(\theta_2) = \begin{bmatrix}
\cos\theta_2 & 0 & -L_1\cos\theta_2 \\
\sin\theta_2 & 0 & -L_1\sin\theta_2 \\
0 & 1 & 0
\end{bmatrix}
\]

\[
A_0^2 = A_1^0(\theta_1) \cdot A_2^0(\theta_2) =
\]

\[
= \begin{bmatrix}
c\theta_1c\theta_2 - s\theta_1 - c\theta_1s\theta_2 - L_1c\theta_1c\theta_2 - L_2c\theta_1 & \\
c\theta_1c\theta_2 - s\theta_1 - c\theta_1s\theta_2 - L_1c\theta_1c\theta_2 - L_2c\theta_1 & \\
0 & 1 & 0 & 0
\end{bmatrix}
\]

\[
A_2 = A_1(\theta_1) \cdot A_2(\theta_2) =
\]

\[
= \begin{bmatrix}
\cos\theta_2 & 0 & -L_1\cos\theta_2 \\
\sin\theta_2 & 0 & -L_1\sin\theta_2 \\
0 & 1 & 0
\end{bmatrix}
\]

\[
A_0^2 = A_1^0(\theta_1) \cdot A_2^0(\theta_2) =
\]

\[
A_0^2 = A_1^0(\theta_1) \cdot A_2^0(\theta_2) =
\]

\[
= \begin{bmatrix}
c\theta_1c\theta_2 - s\theta_1 - c\theta_1s\theta_2 - L_1c\theta_1c\theta_2 - L_2c\theta_1 & \\
c\theta_1c\theta_2 - s\theta_1 - c\theta_1s\theta_2 - L_1c\theta_1c\theta_2 - L_2c\theta_1 & \\
0 & 1 & 0 & 0
\end{bmatrix}
\]

(3)

To refer the system to the coordinate system XYZ situated at the origin, it is just enough to apply a translation in the X axis, obtaining the matrix (4)

\[
T = \begin{bmatrix}
1 & 0 & 0 & -L_1 \\
0 & 1 & 0 & 0 \\
0 & 1 & 0 & 0 \\
0 & 0 & 1 & 0
\end{bmatrix}
\]

\[
= \begin{bmatrix}
c\theta_1c\theta_2 - s\theta_1 - c\theta_1s\theta_2 - L_1c\theta_1c\theta_2 - L_2c\theta_1 & \\
c\theta_1c\theta_2 - s\theta_1 - c\theta_1s\theta_2 - L_1c\theta_1c\theta_2 - L_2c\theta_1 & \\
0 & 1 & 0 & 0
\end{bmatrix}
\]

(4)

\[
\theta_2 = \arcsin(-z/L_1) \\
\theta_1 = \arcsin(-x/(L_2 + L_1\cos(\theta_2)))
\]

(8)

(9)

Fig. 3. Reference system for Denavit-Hartenberg

\[
x = -L_2\cos(\theta_1) - L_1\cos(\theta_1)\cos(\theta_2) - L_1 \\
y = -L_2\sin(\theta_1) - L_1\sin(\theta_1)\cos(\theta_2) \\
z = -L_1\sin(\theta_2)
\]

(5)

(6)

(7)

The coordinate systems have been chosen in order to have the same orientation in the end-effector and in the reference system. In this way, if several modules are connected together, the homogeneous transformation matrix of the whole system can be computed by multiplying the homogeneous transformation matrix of every single module (eq. 10).

\[
T_n^0 = T_1^0 \cdot T_2^1 \cdot ... \cdot T_{n-1}^{n-1}
\]

(10)
TABLE II
COMPONENTS WEIGHTS

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight(g)</th>
<th>NElemnts</th>
<th>Total Weight(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link Bar</td>
<td>1.958</td>
<td>4</td>
<td>7.832</td>
</tr>
<tr>
<td>Male connector</td>
<td>8.514</td>
<td>1</td>
<td>8.514</td>
</tr>
<tr>
<td>Female connector</td>
<td>8.965</td>
<td>1</td>
<td>8.965</td>
</tr>
<tr>
<td>Upper cover</td>
<td>3.993</td>
<td>2</td>
<td>7.986</td>
</tr>
<tr>
<td>Lowe Cover</td>
<td>4.246</td>
<td>2</td>
<td>8.492</td>
</tr>
<tr>
<td>Lid</td>
<td>3.795</td>
<td>2</td>
<td>7.59</td>
</tr>
<tr>
<td>Servomotor</td>
<td>3.75</td>
<td>2</td>
<td>7.5</td>
</tr>
<tr>
<td><strong>Total weight</strong></td>
<td></td>
<td></td>
<td><strong>56.879</strong></td>
</tr>
</tbody>
</table>

B. Weights and Dimensions

One of the requirements in the design of the rotation module was to be light. Its parts have been made in resin by stereolithography and will be fabricated in a more resistant material in the future. The weight of every module is 56,879g. A detailed table of weights is shown in table II.

The diameter of the module is less than 27mm and the total length, including connectors is 46mm. It is able to go through commercial pipes of 40mm diameter or higher.

III. ELECTRICAL DESIGN

The electrical design of the module has been done under two premises: simplicity and low-consumption. For that reason a low consumption microcontroller has been chosen (NanoWatt technology).

Every module is provided with an electronic control board (with a low consumption PIC microcontroller PIC16F767) which is able to perform the following tasks:

1) Control of two servomotors
2) Communications via $I^2C$
3) Sense position and consumption of each servomotor

Position and consumption sensing allow to perform a close loop control (see fig. 4). This can prevent harms (i.e. overheating) to the servos when they try to reach an unreachable position (due to obstacles, for example). The position and consumption of each servo is measured continuously. When the servo wants to reach a position but the consumption is too high, this means that an obstacle (or a wall) has been detected, and so the servo is stopped.

A small circuit has been designed to sense the consumption of the servomotor by means of a resistor of low value and a capacitor ($470\mu F$) in parallel to stabilize the voltage. The voltage at the resistor will be measured through the analog-to-digital conversor (see fig. 5).

To sense the current position of the servomotor, the potentiometer itself of the servomotor is connected to the microcontroller by means of a cable connected from the variable part of the potentiometer to the analog-to-digital conversor. It is very important that the potentiometer is linear to be able to get the current position from the measured voltage.

Power consumption is shown in table III. It is very important to have low consumption in order to make robots autonomous or avoid overheating. As it is possible to see, the consumption of the module at rest is very low.

An electrical bus goes through all modules carrying 6 wires:
- Power (5v) and ground
- $I^2C$ communication: data and clock
- Auxiliary line
- Synchronism line

$I^2C$ has been chosen as opposed to other protocols (like CAN) because only two bus lines are required and it is integrated in small microcontrollers.

The synchronism line is used for low level communication between adjacent modules. It is a kind of peer to peer communication, unidirectional. The communication along the micro-robot is from module to module, and it seems like passing a baton. Thanks to this line, every module can be aware of which other modules are close to him, and the central control of the robot is able to know which is the configuration.
of the micro-robot.

The auxiliary line is not defined in this module. It can be used, for example, to carry the video signal from a camera (see [2]).

IV. CONFIGURATIONS

At this moment there are six modules working that can be used, as previously stated, as rotation modules for chain multi-configurable robots and as elements for snake-like robots.

A. Homogeneous modular robot (snake-like)

1) Principles: A snake-like or serpentine configuration (fig. 6) can be obtained by connecting several rotation modules together. Serpentine robots offer a variety of advantages over mobile robots with wheels or legs, apart from their adaptability to the environment. They are robust to mechanical failure because they are modular and highly redundant. They could even perform as manipulator arms when part of the multilinked body is fixed to a platform. On the other hand, one of the main drawbacks is their poor power efficiency for surface locomotion. Another is the difficulty in analyzing and synthesizing snake-like locomotion mechanisms, which are not as simple as wheeled mechanisms (but nowadays a lot of research has been done in this field[7]). For straight pipes, wheeled robots are much more convenient. But for pipes with a lot of curves and bends, snake-like robots can be a very interesting solution.

Four common modes (gaits) of locomotion in snakes are: serpentine, side-winding, concertina, and rectilinear [5][6].

Serpentine locomotion is the most common method of travel used by snakes. Each point of the body follows along the S-shaped path established by the head and neck, much like the cars of a train following the track. The key property of snakes in achieving serpentine locomotion is the difference in the friction coefficients for the tangential and the normal directions with respect to the body. In particular, the normal friction tends to be much larger than the tangential friction, leading to avoidance of side slipping.

Sidewinding is similar to serpentine, but the snake actually lifts parts of its body and sets them down again. Sidewinding causes the snake to move diagonally relative to the S shape.

In concertina locomotion, the snake bends its body like an accordion and then lifts and straightens itself out to move forward.

Rectilinear locomotion lets the snake move straight ahead with its body stretched out by playing with its muscles and skin.

The most suitable locomotion gait for pipes turns out to be serpentine and concertina locomotion. Inside the pipe there is not much space for sidewinding, and rectilinear locomotion is not feasible at all, due to the characteristics of the robot.

Serpentine locomotion is more suitable to negotiate bends and for straight stretches when the friction between the robot and the pipe is strong enough. If the friction is small, or to climb pipes, concertina locomotion is more appropriate.

2) Snake-like configurations: The snake-like configuration is a very versatile robot which can adopt several shapes. In fig. 9 different configurations are shown: Vertical wave (fig. 9(a)), horizontal wave (fig. 9(b)), circle (fig. 9(c)) and helix (fig. 9(d)). Due to the 2 dof the robot can adopt many 3D configurations.

The robot has not yet been extensively tested, but some
initial tests have been carried out. The robot fit in pipes of 40 mm diameter (fig. 8) and is able to negotiate 90° angles (fig. 7).

3) GUI: A GUI has been implemented for the control of snake-like robots (fig. 12). With it, it is possible to:
   • simulate movements
   • telecontrol the robot
   • record sets of movements and send them to the robot for later execution.

B. Heterogeneous modular robot (chained)

It is possible to combine several heterogeneous modules to create a micro-robot for low diameter pipe inspection. This micro-robot is conceived to explore pipes with a camera to detect breakages, holes, leaks and any kind of defects. Due to the great variety of pipes that can be found, it is very useful to reconfigure the micro-robot depending on the task being performed. This idea is shown in fig. 10.

Nowadays, there are some prototypes already developed, but they can not work together yet. This prototypes are shown in fig. 11 and are: helicoidal drive module, worm-like drive module, support module, camera module.

V. CONCLUSION

In this article, a 2 degrees of freedom module for pipe inspection modular micro-robots based on servomotors has been presented. A mechanical and electrical description of the module characteristics has been presented, including the
kinematics, torque, consumption and close control loop design to detect obstacles (walls), as well as the main configurations in which it can be used: snake-like robots and chain multi-configurable modular robots. The different pipes and elbows it can move on have also been shown.

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