Abstract - The inspection of low diameter pipes is a subject of great complexity due to the small operation environment in which the tasks must be developed. Besides, the construction of microrobots for specific pipe inspection is too expensive. In this article, a modular multiconfigurable architecture is presented. The fact of being modular and multiconfigurable makes it capable of performing different tasks and to adjust to different pipes and environments. Different types of modules that can be combined to form a whole microrobot and a control and communication system are also presented.

Index Terms – Microrobot, Modular, Multiconfigurable.

I. INTRODUCTION

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 [15][16].

Multiconfigurable systems are systems capable of having their modules rearranged. This characteristic makes multiconfigurable robotic systems capable of performing much more types of tasks than conventional systems (non-configurable). There are different types of reconfiguration of modules: manual or automatic, homogenous or heterogeneous [2], and according to the configuration, mobile, lattice or chain [17]. The robotic system described in this paper has a chain configuration, is manually reconfigurable and heterogeneous, meaning that the whole system is composed of different kind of modules. It could be defined in [15] as a n-modular microrobot with n from 2 to 5.

One of the most important issues in modular robotics is the control of the modules. In the robotic system described in this paper a centralized control has been chosen. There is one master module that controls the other modules, but for some actions all modules have to cooperate and take decisions at the same time.

In the development of the modules three lines of investigation have been taken: worm-like microrobots, SMA based microrobots and planar micromotor drive module. As a result, three types of microrobots have been developed, which are shown in the following section. In order to integrate all these modules into a single robot, a modular multiconfigurable architecture is under development, and the first results are also shown in this paper.

Although there are piezoelectric materials, hydraulic, pneumatic and thermomechanical microactuators that have been researched and they seem a very good solution in a near future[12][13][14], we propose a solution using micromotors and microservomotors, which are cheaper, more autonomous, demand less power and have a better force/torque relation.

Regarding the purpose for which this system was design, low diameter pipe inspection [3], the size of every module is minimized as much as possible, achieving a final diameter for each module of less than 26mm. This miniaturization adds a great complexity to the design of the modules, because of the limitation in components, electronics and fabrication techniques. Two fabrication techniques used in these prototypes are: stereolithography and micromachining.

A. Stereolithography

Stereolithography, and microstereolithography, in particular, is a relatively new microfabrication process that evolved from the rapid prototyping industry. Its growth, especially in microrobotics, is due to the ability to create complex microobjects from 3D models made with CAD computer programs.

Due to the difficulty in finding microcomponents for microrobots, microstereolithography has turned into one of best providers of components, because its accuracy and reliability.

Stereolithography allows building a part layer by layer by laser induced polymerization. A laser beam is focused and scanned on the open surface of the photosensitive liquid and a solid/liquid transformation occurs locally, which allows creating the shape of one layer of the object. When a layer is finished, fresh resin is spread on top of the already manufactured part of the object, and the light-induced solidification of the next layer is started [4].

The accuracy of this technique is about 0.15 to 0.2 mm, in the horizontal plane, while in the vertical is a little bit bigger, but less than 0.5mm.

Most of the prototypes shown in this article have been made using microstereolithography, in the rapid prototyping laboratory at the U.P.M.
B. Micromachining

The other main technique used in the design of these microrobots is micromachining. Milling machines are very versatile. They are usually used to machine flat surfaces, but they can also produce irregular surfaces or to be used to drill, bore, cut gears, and produce slots. The wheel shown in fig. 2 has been manufactured using a milling machine (amongst other techniques) at the microfabrication laboratory at the U.P.M. Some other designs are already being developed in order to get a stable non sliding wheel.

II. MODULES

A. Helicoidal drive module

This module was designed to be a fast drive module. It is composed of two parts: the body and the rotating head. The wheels in the rotating head are distributed along the crown making a 15º angle with the vertical. When the head turns, it goes forward in a helicoidal movement that pulls the body of the microrobot. The wheels of the body help to keep the module centred in the pipe.

The head is linked to a 3 phase brushless Maxon micromotor through a gearhead, which has been designed in order to get the appropriate reduction (1/24) and speed.

The wheels, its axis and the support system have been manufactured by micromachining, and the other parts (except for the gears) have been made using stereolithography.

The fact that the head of the robot rotates around the robot axis involves the necessity to design a channel for electrical wires that goes through the entire robot to interconnect the front and the rear part of the robot.

The control of the motor was performed in a first step by a Maxon motor control board AECS 35/3. This board supplies the 3 phase signals that the motor demands.

\[ V_x = R \cdot w \cdot \tan \alpha \]

The sequence of movement is as follows (fig. 4):
1. The rear module (3) expands (making pressure against the pipe) and the front one (1) releases.
2. The central module (2) expands straight or in angle.
3. The front module expands and the rear one releases.
4. The central module contracts.

One of the main problems that this board has is the power consumption. It operates at a range of 8 to 30 V, and requires up to 5A. This is a huge power demand, so in next versions a special control board is being design. Also, some similar models but with miniaturised conventional motors are being researched.

This module was tested in a 30 cm straight pipe with different slopes angles. The microrobot was able to go forward even when the pipe was set to vertical position. The helicoidal approach shows itself as a very interesting mean of locomotion for microrobots. The results obtained for this module are shown in the next table (it is also possible to see a video in [18]):

<table>
<thead>
<tr>
<th>Angle (º)</th>
<th>0</th>
<th>15</th>
<th>30</th>
<th>45</th>
<th>60</th>
<th>75</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vel (mm/s)</td>
<td>30</td>
<td>27</td>
<td>22</td>
<td>19</td>
<td>15</td>
<td>13</td>
<td>12</td>
</tr>
</tbody>
</table>

B. Worm-like drive module based on servomotors

This module is composed of two kinds of submodules: expansion module and support module (fig. 3), which allows the microrobot to move as a worm [9]. The support module is used to fix the microrobot to the pipe, so this module does not move. And the expansion module is used to expand the robot (make it go forward), and to turn to right and left (in the next version of this model it will be able to move also up and down). The drive unit is composed of two support modules and one expansion module (fig. 3).

The sequence of movement is as follows (fig. 4):
1. The rear module (3) expands (making pressure against the pipe) and the front one (1) releases.
2. The central module (2) expands straight or in angle.
3. The front module expands and the rear one releases.
4. The central module contracts.
All the modules use a 21x13x9mm microservomotor [19]. It is a linear servo which weights 3.0g, has a maximum deflection of 14mm in 0.15 sec and provides a maximum output force of 200g. The support modules use one servo only and the expansion module uses two.

The support module consists of three rubber bands positioned around the module at 120º from each other, which are bent when the servomotor is activated, exercising a force against the walls of the pipe that allows the module to be still. On the other hand, the expanding module consists of two arms (each of them drowed by a servo) that allows expansion-contraction movements, as well as turns, depending on the relative position between arms.

The module has been tested in different pipes (it is possible to see a video in [18]). The performance obtained is as follows:

- Minimum pipe diameter: 22mm
- Maximum pipe diameter: 35mm
- Maximum angle of rotation of the expansion module: 40º
- Maximum lengthening: 7.5mm
- Average speed at 0º- 90º: 2mm/sec

C. SMAs-based worm-like drive module

This module uses Shape Memory Alloys (SMA) to achieve a worm-like system of locomotion, based on contraction and expansion of the SMAs.

Each module is composed of a support board, a control boards (act as support boards that additionally holds the electronics), SMAs wires to make the contraction and springs to make the expansion when the SMAs releases (fig. 6).

The onboard electronic for this microrobot is based on a PIC SMD (5x5 mm) (fig. 5). At this time, it is possible to put up to 32 modules together. Each module has three degrees of freedom. There are also 4 wires that go through the entire microrobot carrying the control signals.

The main advantages of this module are a simple electronic circuit and a great versatility (it can both contract-expand and rotate). The main disadvantages are the power consumption, too high, and the assembling difficulty.

D. Rotation module

The rotation module (fig. 7) is a two degrees of freedom module that allows rotations in the horizontal and vertical planes. It is based on a 18x18x24mm double servomotor developed from two commercial servomotors. It has a torque of 1.3 Kg-cm in each output. A real picture is not available yet.
The motivations of this module are three: in first place it will allow turning around corners. In second place, it is suitable to hold a camera and allow a two DOF movement of the camera. And finally, a set of this modules put together will allow a snake-like movement.

**E. Support module**

This module is design to get fixed to the pipe through two plates that can be expanded or contracted. It is very useful in worm-like robots.

It is based on a 18mm x 7,5mm x 15,7mm microservomotor of characteristics: 4,4g, 1300g/cm, 0,12s/60º. Two racks are used to transform the circular movement into a linear movement (fig. 9).

**F. Camera module**

This module (fig. 8) is a 2 degrees of freedom structure composed of two servomotors, a camera and two leds for illumination. Thanks to the common interface, it can be assembled to any of the previous modules. The reason why the camera is not symmetric is because it is designed to fit in a 26mm pipe.

The camera used is a 8x8x20mm CMOS black and white camera, whose main characteristics are: 320x240 pixels composite video, 20mA@9V, 7-12V.

The main characteristics of the servomotors are: 6.3mm x 22.25mm x 10.10 mm, 2.85 g, 400g/cm and 0.18 s/60º at 4.8V.

**III. ARCHITECTURE OF THE MICROROBOT**

It is possible to combine the modules presented in section 2 to create a microrobot for low diameter pipe inspection. This microrobot 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 microrobot depending on the task being performed. The previous section has presented different types of drive and rotation modules that can be linked to the camera to do pipes inspection.

There are several reasons why an architecture must be defined: several heterogeneous modules have to be connected and must work together, the modules have to be reconfigurable and it should be easy to connect modules created in the future. For these reasons an architecture of control and design has been developed.

Every module has the same connecting system (fig. 10) in order to make the modules interchangeable. This system allows the modules to be connected in any configuration or position.

There are six wires that go through all the modules:
- 2 for communications (data and clock).
- 2 for power (DC and ground)
- 1 for synchronism
- 1 auxiliary for special applications (i.e. video signal, higher DC power…etc)

Any other module that is to be connected must have this structure.

Apart from the modules, there is a central control, which is the one that give the commands to the modules. In a first step it is a PC, but in future versions it will be one of the modules.

**IV. CONTROL SYSTEM**

**A. Onboard Control**

All the modules are provided with onboard control based on a PIC microcontroller. The tasks of this controller board are to generate control signals (for motors, servomotors, camera, leds…etc), to communicate with other modules and, in case of the master module, to communicate with the user through the PC. In order to perform this communication another board is needed, the interface board, which amongst other tasks converts the signal from RS232 to I2C and vice versa (fig. 11).

**B. Inter-integrated circuit control (I2C)**

I2C a simple bidirectional 2-wire synchronous bus for efficient inter-IC control developed by Phillips. All I2C -bus compatible devices incorporate an on-chip interface which allows them to communicate directly with each other via the I2C -bus. This design concept solves many interfacing problems encountered when designing digital control circuits.
Specific features why I2C is being used in this prototype are:

• It is simple and easy to program.
• Only two bus lines are required; a serial data line (SDA) and a serial clock line (SCL) (fig. 12), which is important to make the interface between modules smaller.
• Each device connected to the bus is software addressable by a unique address and simple master/slave relationships exist at all times; masters can operate as master-transmitters or as master-receivers.
• It’s a true multi-master bus including collision detection and arbitration to prevent data corruption if two or more masters simultaneously initiate data transfer.
• The number of ICs that can be connected to the same bus is limited only by a maximum bus capacitance of 400 pF, so many modules can be connected.

In addition to these advantages, the CMOS ICs in the I2C-bus compatible range offer special features which are particularly attractive for portable systems:

• Extremely low current consumption.
• High noise immunity.
• Wide supply voltage range.
• Wide operating temperature range.

C. Electronic

The basic structure of the control board of the modules is shown in fig. 13. The dimensions of the board are 20x12mm. It is based in a PIC microcontroller (PIC16F767 for most of the modules). It includes Mosfets to drive the motors. It allows the control of up to two servomotors. The camera module allows to control up to two leds additionally.

Due to the small dimensions of the board, there are no connectors but pads for connections (welding).

D. Communication protocol

There are two possible ways of communication between modules in the bus:

• One module can communicate to those close to it (in the front and in the back) through the synchronism line. It is a kind of peer to peer communication, unidirectional. The communication along the microrobot is from module to module, and it seems like passing a baton. Thanks to this protocol, 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 microrobot.
• Protocol I2C. Bidirectional 2-wire synchronous communication amongst all the modules, either between any pair of modules, or from one module to all the others (broadcast).

There are five different types of messages that can be interchanged from the central control and the modules. These messages allow interaction between central control and the modules. These messages are:

1) Initial configuration: the modules answer in order. It is executed at the beginning to check the configuration of the modules. The synchronism line is used as well as I2C.
2) Modular control: the most common messages, commands sent to one module to perform a task. I2C.
3) Global control: messages sent to all the modules at the same time, i.e. stop, accelerate…etc. I2C.
4) Query: demand information from one or more modules that will send a message back. I2C.
5) Sequence: it is a message including several commands that the modules execute in order and delayed respect the previous module. This message is suitable to perform snake movements. The synchronism line is used as well as I2C, plus memory to save the commands prior to execution (fig. 14).
V. FUTURE WORK: DISTRIBUTED AND MULTI-AGENT SYSTEMS

These two extensively known concepts could be very useful in the control protocol of the microrobot [16]. A distributed system is a collection of (probably heterogeneous) automata whose distribution is transparent to the user so that the system appears as one local machine[]. It is possible to consider the microrobot as a distributed system, in which every module do their job but it looks like a whole entity to an external observer.

A Multi-Agent System (MAS) is a system composed of a population of autonomous agents, which cooperate with each other to reach common objectives, while simultaneously each agent pursues individual objectives[]. For the purposes stated in this paper, the agents could be the modules, and the common objectives are the movement of the microrobot inside the pipe.

In the prototypes we have described in this paper, a central control is needed to control the module. Either if it is a PC (as it is now) or one of the modules (in the future), a great intelligence centralized control makes the control much more powerful and easy to implement. The use of distributed systems and multi-agent systems are nevertheless a real alternative for the next prototypes, but so far they have not been implemented in these microrobots.

One of the main goals of this group of investigation is to achieve that the central control is able to manage a not predetermined structure of modules and control it in a optimum way to achieve an objective. That is the reason why a dynamic-cinematic model with a common structure for all the modules is design.

V. CONCLUSION

In this article, several types of modules for pipe inspection microrobots have been presented. The helicoidal and worm-like drive modules have been tested and their results have been described. The helicoidal model is faster and it could be used when a long distance must be done. On the contrary, the modular model provides more control and could be used when turns and rotation must be done. In addition, the helicoidal module has helped to prove the efficiency of this kind of movement for in-pipe microrobots.

Also an architecture for modular multiconfigurable microrobots has been presented, describing the intermodular connectors, the onboard control, the central control and the communication protocol between modules and between modules and central control.

Some of the work that is being performed at the DISAM has also been presented, describing the new prototypes and the improvements that are been developed.

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