Multiconfigurable Inspection Robots for Low Diameter Canalizations

E.Gambao, M. Hernando and A. Brunete

Abstract— **Pipe inspection is a very important issue in construction. The inspection of low diameter canalizations is a pending issue nowadays, however it would help to repair and maintain a large amount of installations. In this article the lines that are followed to build a robot that is capable to move inside pipes of less than 26mm and negotiate bends while carrying a camera are described, together with a walk through the state of the art of the robots which are related to the research.**

Index Terms— **microrobot, inspection, modular, multi-configurable.**

I. Introduction

NOWADAYS, the number of pipes around us is very large, including sewer systems, gas pipelines, hydroelectric and nuclear power stations, water, gas and heating pipes in buildings… Among them, there are many low diameter pipes which require to be inspected every year. The cost to inspect such systems can be very high. There are basically two techniques to inspect these pipes: passive and active systems. Passive systems are usually intelligent pigs driven by the pressure difference of fluid inside the pipelines, which are not suitable for many applications (i.e. to be still or go back in the pipe). Active systems are mainly based on robots, which is our case.

Two main application can be found in robotic inspection of pipes: in buildings already built it is a good way to check the structure in case any modification must be done; and in buildings under construction to make sure tasks has been done properly, i.e. assembling, welding…etc.

There are many robots for pipe inspection [6][10], but generally they are conceived for pipes of industrial applications, which have a diameter bigger than 80cm, like gas pipelines or hydroelectric power stations. In this article we propose a small robot to explore pipes with a camera to detect breakages, holes, leaks and any kind of defects in pipes of less than 30mm diameter. 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.

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). These systems can be classified according to the configuration type into manual or automatic, depending on the different number of modules they have into homogenous (only one type of module) and heterogeneous (several types), and according to the configuration, into mobile, lattice or chain. The robotic system described in this paper is manually reconfigurable, heterogeneous and has a chain configuration.

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, different types of modules have been developed, which are described in section III.

Regarding the purpose for which this system was design, low diameter pipe inspection, 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.

II. Description of Microtub.

The goal of the project MICROTUB is to build an autonomous multiconfigurable microrobot for low diameter pipes inspection and maintenance. It is being designed to explore pipes with a camera to detect breakages, holes, leaks and any kind of defects. This microrobot is to be composed of different modules, each of them performing a different task. Thus, multiconfigurability is an essential characteristic, so these modules can be easily interchanged depending on the task.

In first place, different drive modules are being developed due to the different environments in which the microrobot is going to perform the tasks. Two main investigation lines are being followed: worm-like and wheel driven (helicoidal). The other main module is the camera module, which is a two degrees of freedom platform carrying the camera and leds. There are also other modules under research: rotation, batteries and communication. The modules that are already developed are described in next section.

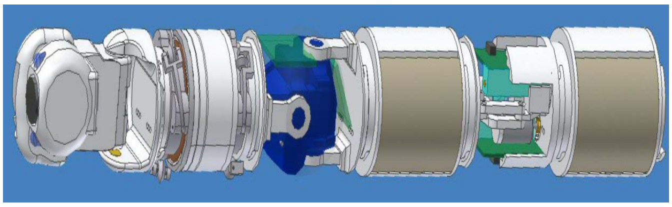

Fig. 1. Model of the MICROTUB

Every module will be 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 process the signals from the sensors and to communicate with other modules and, in case of the master module, to communicate with the user through the PC.

For this microrobot a centralized control has been chosen. There is one master module (a PC by now) that controls the other modules, but for some actions all modules has to cooperate and take decisions at the same time. Thus, the possibility of using distributed control over the onboard control of the modules is under consideration.

Therefore, in order to make the control of the microrobot independent from the modules, a control architecture (for both hardware and software) is being developed [13].

Finally, it is interesting to point out that micromachining and stereolithography have been two of the most used techniques in the building of the robots.

III. MODULES BUILT

A. Helicoidal drive module

This module (fig. 2) was design 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 centered in the pipe.

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.

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 miniaturized conventional motors are being researched.

This module was tested in a 30 cm straight pipe with speeds of up to 30mm/seg. 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 inside pipes.

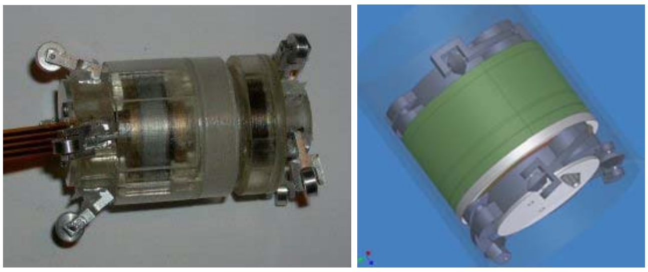

Fig. 2. Picture of the drive module and 3D model of the next version

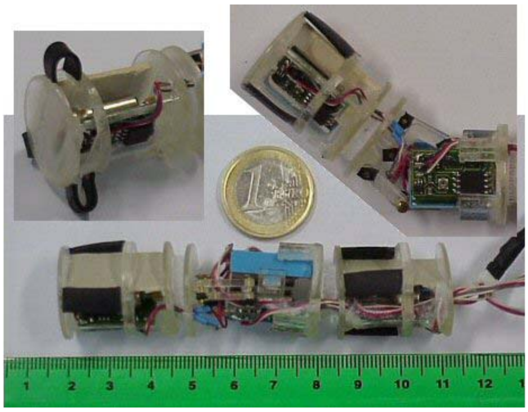

Fig. 3. Picture of the worm-like drive module

This module is being redesigned to a more compact shape (fig. 2, right), by suppressing unnecessary gearhead phases.

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 [14]. 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 microservomotor. 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 droved by a servo) that allows expansion-

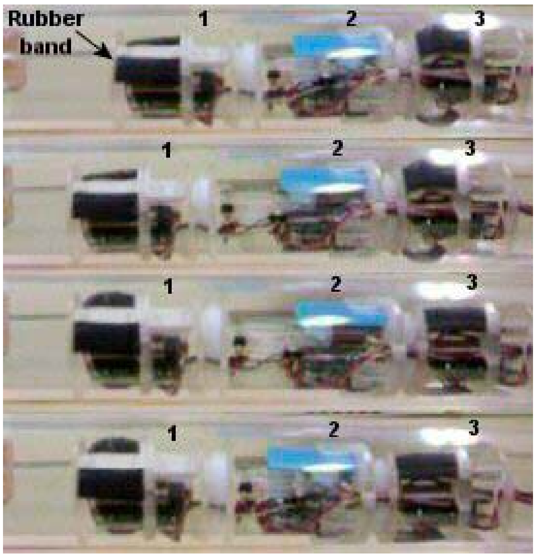

Fig. 4. Sequence of movement

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 [15]). 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/seg

C. SMAs-based worm-like drive module

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

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

The main advantages of this module are: very good relation torque – dimensions (provide a good torque in a very small space), simple electronic circuit, SMAs can act as “Smart Actuators” (resistivity changes depending on the grade of deformation) and great versatility (it can contract-expand and rotate). The main disadvantages are: the power consumption is too high, SMAs act in one direction but they need a ‘rest’ to get back to the initial position (else a spring to get back to that position), assembly requires a lot of precision and appropriate tools, and SMAs have hysteresis.

Due to these disadvantages, we consider that SMAs are better suitable for tasks that require small and discontinuous movements, i.e. latching mechanisms or grippers.

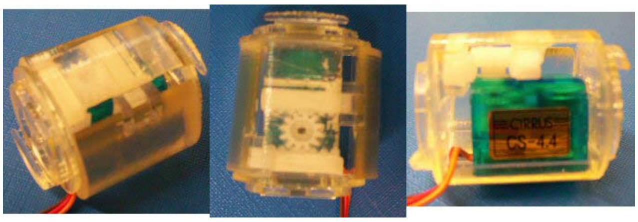

Fig. 5. Different views of the support module

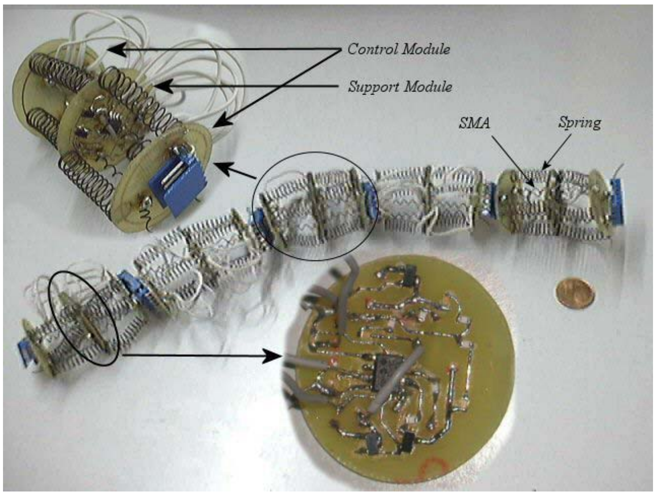

Fig. 6. SMA drive module.

D. Rotation module

The rotation module (fig. 8) is a two degrees of freedom module that allows rotations in the horizontal and vertical planes. Because of the low dimensions requirements (diameter smaller than 26mm) no available commercial servos could be used. Therefore it was built out of the components (axis, gears…etc) of two commercial servomotors and some other parts made by stereolithography.

The integration of the parts was very difficult due to the small dimensions of the components, which required a great precision in both the design and assembling.

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 II

This module is design to get fixed to the pipe through two plates that can be expanded or contracted. It can be used as a more robust alternative to the support module in the worm-like drive module (section B). It has a simple design, being its main characteristics the robustness and small dimensions (25mm diameter and 26mm long).

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

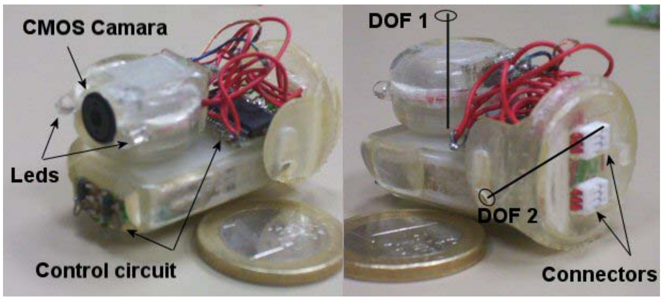

Fig. 7. Picture of the camera module

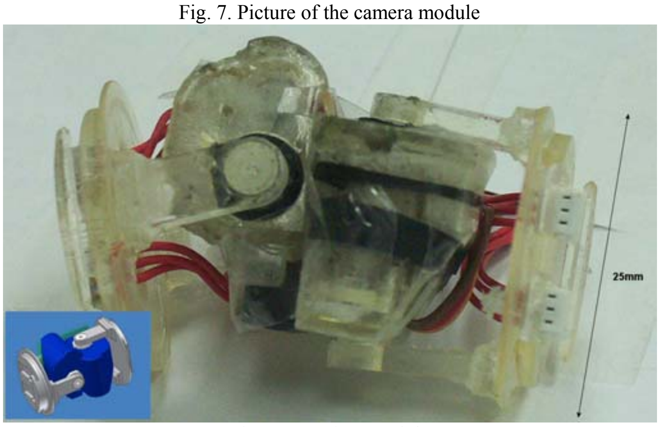

Fig. 8. Rotation Module

F. *Camera module*

This module (fig. 7) 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 camera used is a 8x8x20mm CMOS black and white camera, whose main characteristics are: 320x240 pixels composite video, 20mA@9V, 5V.

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.

G. *Interface board*

The previous modules will have a control circuit onboard (some of them already do, like camera and SMA drive module), that will allow control of the servomotors and communications between them and the central control (PC). The translation between the signals coming from the PC (RS232) and I2C (communication protocol used by the modules) is made in a interface control board (fig. 9).

H. *Graphical User Interface (GUI)*

In order to control the different modules and the camera, a GUI (graphic user interface) has been design (fig. 10). This GUI allows the user to control up to 6 servomotors and 2 leds. It was designed to control the worm-like drive module plus the camera module (2 servos for the camera and 4 servos for the drive module). The GUI displays the image sent by the camera and an 3D model of the estimated position of the two servos of the camera.

In the manual mode, the user can move each servo independently. There is also an automatic mode in which the drive module goes forwards or backwards automatically.
It was done in Visual C++ with MFC. To communicate with the robots it uses the interface board of section G.

IV. MAIN FEATURES COMPARED TO OTHER ROBOTS

In the following subsections the main characteristics of MICROTUB are explained together with the improvements that are being carried out in comparison to the state of the art in pipe inspection robots.

A. *Modularity and Reconfigurability*

The advantages of modularity have been described in the previous sections. Instead of designing a new and different mechanical robot for each task, different copies of simple modules are built. The modules can't do much by itself, but when many of them are connected together, a system that can do complicated things appears. In fact, a modular robot can even be configured in different ways to meet the demands of different tasks or different working environments.

Each module is virtually a robot in itself having a computer, a motor, sensors and the ability to attach to other modules. This is going to be the same in MICROTUB. It is very useful in case any of the modules failed, i.e. selfreparation.

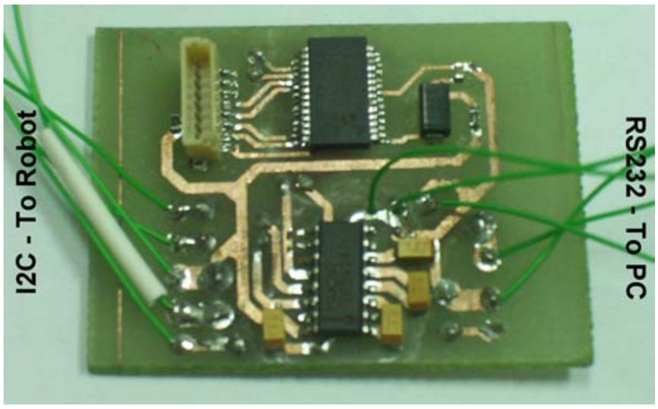

Fig. 9. Interface board

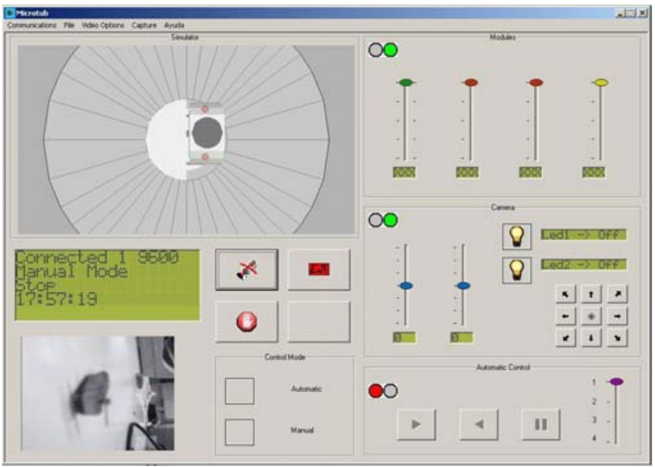

Fig. 10. Graphic Interface

B. Multiconfigurability vs self-reconfigurability

Reconfigurable robots present the ability to change its configuration either manually or autonomously. If the reconfiguration is done autonomously, it is called self-reconfiguration. On the other hand, if the reconfiguration has to be done manually, we talk about multiconfiguration. There is a lot of research in selfreconfiguration, but most of the robots in this field have the same features. Two of the most known robots are Polybot [3] and M-TRAN[4]. These robots present several features that are very interesting: connection mechanism between modules, sensors, power supply…etc. Both PolyBot and M-TRAN are made up of many repeated modules.

These modules attach together to form chains (which can be used like an arm or a leg or a finger), caterpillar, double-thread caterpillar, wheel, 4/6 leg walker, sidewinder, spider …etc depending on the task at hand. Polybot can even perform tasks as moving boxes or riding a tricycle. This is the main advantage: it can change shape and perform a different task.

In the development of inpipe robots, autoconfigurability is not an essential characteristic due to the lack of space inside the tube to change configuration. We believe it is better to talk about multiconfiguration: the robot presents different configurations prior task development. Once the task is started, the configuration must be kept.

C. Homogeneous vs Heterogeneous modules

Depending on the number of modules that the robot is compound of, the robot can be classified in homogeneous (all the modules are the same) and heterogeneous (different modules). MICROTUB could be defined as in [7] as a n-modular microrobot with n from 2 to 5. Polybot and M-TRAN are homogeneous

The man advantage of homogeneous robots is that they are easy to build. On the contrary they are limited to to movement tasks. Heterogeneous robots are more versatile and can perform as many tasks as modules have.

D. Miniaturization

The term microrobot appears nowadays in many articles referring to mini-robots, robots of very small dimensions (millimeters). This is because we are still far from seeing a real “micro” robot (µm). Thus, in this paper we say microrobot when we talk about MICROTUB since for most of the people it is accepted this meaning too.

Keeping in mind that for most of the researches it is not possible to build a real microrobot, it is necessary to miniaturize its components and to make the mechanical and electronic design together to minimize the space (mechatronics). This work is what we have carried out, and it is what makes the design so expensive.

Miniaturization can be seen in many microrobots too, as in the microrobot of DENSO Corporation [2], the Micro Modular Robot of AIST [1], and the three microrobots of the French CNRS: LMS, LAB and LAI [5].

SMAs are extensively used in microrobots because they give a good torque in small displacements. It is used for example in the former robots. Polybot and M-TRAN use shape memory alloy as latches and docking of modules together with infrared emitters and detectors aid. SMAs could be very useful too for grippers and connecting pads.

E. Energy supply

Energy supply is a big problem in mobile microrobots because the available supplied power is very limited. Most of developers adopt batteries or cable as the solution to transfers power supply to the robot. Right now in our robot the power is supplied via cable. But in autonomous microrobots the solution is limited to onboard batteries.

A very innovative solution is presented by DENSO Corporation, which has solved this problem in its Microrobot [2] by developing a wireless energy supply system (together with a low power consumed actuator, high efficient energy conversion device and power management system). The microrobot functions as a complete wireless link system traveling in small pipes at 10mm per second with wireless data communication of 2.5Mbps and wireless energy supply of 480mW. It includes devices such as CCD camera, locomotive actuator, control circuit, wireless energy supply device, and RF circuit installed into a small body of 10mm diameter and 50mm length.

To send energy through radio frequency is a very interesting solution but it is limited to low power devices.

F. Centralized vs Distributed control

Generally most of the robots use centralized control: one agent (PC, one of the modules) tells every module what it has to do in every moment [3][11][12].

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. This is the case of M-TRAN: the robot motion is controlled by all the modules CPUs.

In the prototype 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.

G. Pipe inspection

Pipe inspection is the main task for what the robot is built. Nowadays there are several robots capable of peforming this task, among we can find MRInspect (III y IV) [6], Pipe Mouse by Foster Millar [8], and GMD-Snake2 [9][10]. However, their dimensions are beyond the limits pursued in this paper:

the former robots are design to fit in pipes whose diameter is 88mm (Foster), 100mm (MRInspect) and 135mm (GMD). However, they present very interesting features, which once miniaturized, can be included in our prototype.

The GMD-Snake2 is a snake like robot made of several modules which also implements forward forces generated by hundreds of active scales under the snake bodies, which allow the snake to slide within its curved track. It is also able to move autonomously in a square shaped system of tubes. Based on sensors it is able to detect junctions, intersections, and bends. The detection of junctions, intersections, and bends is a very important issue that we have not taken into account yet. The election of sensors is also a very important matter.

MRINSPECT (Multifunctional Robotic crawler for INpipe inSPECTion) IV has been developed for the inspection of urban gas pipelines with a nominal 4-inch inside diameter. Its steering capability with three-dimensional differentially driven method provides the outstanding mobility for navigation and the new mechanism for steering can easily adjust itself to most of pipelines or fitting, in which other former inpipe robots can hardly travel. Navigation through different diameter pipes is an issue that some of our prototypes already cover: the helicoidal module wheels are able to expand and contract to adjust to smooth changes of diameter, and the worm-like drive module can travel along pipes of diameters from 22 to 35mm.

Another robot that is able to adapt to changes in gas piping is Pipe Mouse, an autonomous inspection system for a live natural gas environment developed by Foster-Miller together with New York GAS and the Department of Energy. Pipe Mouse is a train-like robotic platform. Both front and rear drive cars propel the train forwards and backwards inside the pipeline. Like a train, the platform includes additional "cars" to carry the required payloads. The cars are used for various purposes including the installation and positioning of sensor modules, the system power supply, data acquisition/storage components, location/position devices and onboard micro-processors/electronics. This is the same idea that it is going to have MICROTUB: some modules will act as drive modules while other will be cargo: power supply, communications, camera…etc.

V. CONCLUSION

In this article the lines that have been followed to build an autonomous multiconfigurable microrobot for low diameter pipes inspection and maintenance have been stated. The main characteristics of the microrobot have been explained together with a walk through the state of the art of the robots which are related to the research.

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. Also, the helicoidal module has helped to prove the efficiency of this kind of movement for in-pipe microrobots.

In addition, a camera module and a graphical user interface have been presented. Some other modules (rotation, support) have been presented and will be used in the future version of MICROTUB.

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