Design considerations and prototype implementation of a piezoelectrically driven micro-vehicle for the internal inspection of small diameter pipes

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Abstract: - The initial design and the prototype implementation of a micro-vehicle is presented. This micro-vehicle is capable of moving internally and simultaneously inspecting pipe systems with a diameter between 40mm to110mm. The driving motors are chosen to be of ultrasonic piezoelectric type, due to their high torque and compact design characteristics. The structure of the vehicle is modular, based on a number of carriages, each one responsible for a specific task (e.g. traction, micro-camera support, electronics support, etc). It can carry a color micro-video camera for providing optical images from the inside of pipes. Initial power and force calculations are provided, leading to promising estimates for motion distance and travel speed.

Key-Words: - Visual Inspection, microrobots, micro-vehicles, piezoelectric motors, pipe-inspection.

1 Introduction

Internal inspection of small diameter pipes is becoming of increasing importance in a range of engineering applications, such as telecommunication piping systems, water, oil or gas piping supply systems, or tube systems of industrial boilers and reactors. This necessity gave rise to the development of a number of mechanisms, able to move internally in piping systems for inspection and even for repair needs. A comprehensive review and analysis of such systems is performed in [1]. As a result of this analysis, most of these systems actually concern pipes with large diameters, (e.g. large oil or gas transfer lines).

A limited number of developments have been reported, concerning small diameter pipe inspection mechanisms. An interesting development is reported in [2], describing a microrobot, able to move in diameters between 16 to 20 mm. It is based actually on a electro-pneumatic “inchworm” locomotion mechanism. This type of mechanism restricts the usage of the robot for small length pipes, with relatively small speed. Most of the systems analyzed in [1], which are capable of inspecting small diameter pipes, suffer from a number of drawbacks, such as limits in the smaller tube diameter to be inspected (e.g. above 10cm), limits in the pipe length to be inspected (e.g. below 100m), or limits in the inspection speed.

In a first attempt to realize a more effective solution to this problem, a design and a prototype construction of an inspection micro-vehicle is presented in this paper. The micro-vehicle under consideration, shown in Fig. 1, is theoretically capable of moving inside pipes with an internal diameter between 40mm and 110mm. Its travel speed can be up to 22cm/sec and its travel distance can be more than 100m.

Figure 1: A general view of the prototype of the proposed micro-vehicle

2 Motion equipment

2.1 Motor operating principle

The restriction in the pipe diameter -and consequently in the overall available space- is the most dominant factor for the selection of the driving motors, as well as for the overall shape of the micro-vehicle. Taking into account the space restrictions mentioned, ultrasonic piezoelectric motors have been selected as the driving motors. Piezoelectric motors, compared to conventional electric motors, produce higher torque at low rotation speed, make use of friction forces instead of electromagnetic forces, their equivalent inertia is much smaller, and they provide more power for the same volume [3].

Their function is based on an electric field, which is created when strain causes a polarized state in the crystal. An ultrasonic motor is a type of actuator that uses mechanical vibrations in the ultrasonic rage as its drive source. When a bar of metal is vibrated, traveling waves are generated, as shown in Fig. 2.

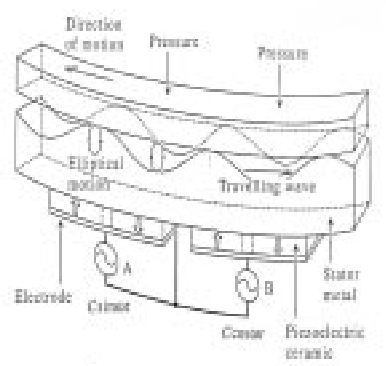

Figure 2: Operating principle of an ultrasonic piezoelectric motor [3]

In order to achieve this kind of waves, the edges of the metal are connected to form a ring. By mounting two sources of vibrations at the appropriate intervals, waves can be created, traveling in only one direction. One of them will generate a vibration given by Ccos(ωt), while the other will generate a vibration of Csin(ωt), lagging the previous one by 90 degrees, as shown in Fig. 2.

When a rotor is pressed against the stator section, a rotational motion opposite in direction to that of the progressing wave is imparted to the rotor. The stator carries traveling waves and drives the rotor. When the drive voltage is removed, the rotor shaft remains in place, due to the friction force arising from the rotor being pressed against the stator.

The main parts of an ultrasonic motor are the rotor, the stator and the piezoelectric ceramic. Points on the surface of the former ring move elliptical trajectories with an amplitude of several micrometers. Figure 3 shows the construction of a stator.

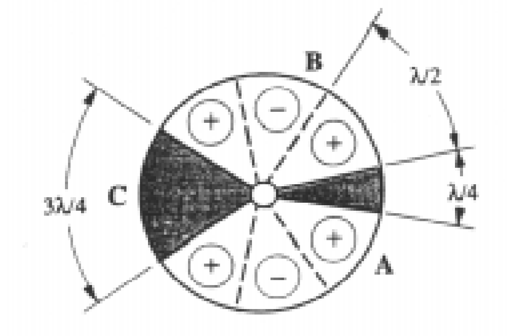

Figure 3: Stator ring and electrode arrangement for a typical piezoelectric motor [5].

The equivalent electrical circuit for single-phase ultrasonic motor is shown in Fig. 4.

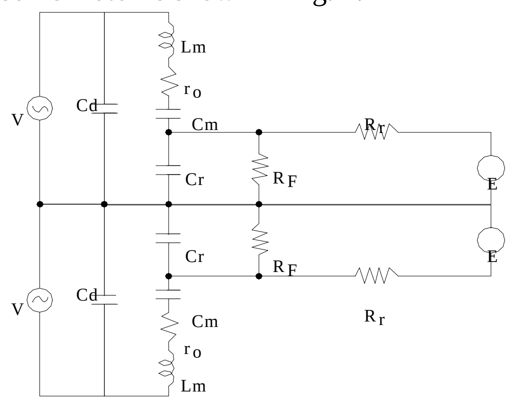

Figure 4: Equivalent electrical circuit for a typical piezoelectric motor [3].

The elements in this equivalent circuit have the following meanings:

C_d: Blocking capacitor, acting as a regular dielectric.
C_r: Equivalent capacitor, representing the stator's strain created in response to the reaction by the load torque.
R_r: Resistor representing frictional and viscous losses in the bearing and other related parts.
R_f: Resistor representing losses due to sliding between the stator and the rotor.

2.2 Technical characteristics of the selelcted motor and motion controller

The piezoelectric motors used, are shown in Fig. 5 and have an external diameter of 30.3mm and a total length of 25mm [6].

Figure 5: View of the piezoelectric motors used [6]

The advantage of this kind of motor is the presence of a high torque at low rotation speed. So it is not necessary to use a reduction gear. Each motor can continuously operate in a rage of rotation speed between 25 and 250rpm, with a corresponding output torque up to 0.05Nm for 250rpm. Due to the existing pressure between the stator and the rotor, the piezomotor preserves its high holding torque (0.1Nm) and acts as a brake. Pairs of bevel gears in a ratio 1:1 can transfer the rotation axis by 90^0. Further technical details of the selected motor are presented in Table 1.

Table 1: Technical characteristics of the selected motors [6]

Motor size	30mm Dia, 11mm Thick
Shaft size	4mm Dia, 14mm Long
Mounting Holes	M2 threaded holes on a 14mm BCD,90°apart
Rated Torque	0.05Nm
Holding Torque	0.1Nm
Time Responce	$\leq 1m\sec$
Direction of rotation	CW,CCW
Operating life	2,000 Hrs

Table 2: Technical characteristics of the selected controllers for the motors [6]

REQUIRED INPUT POWER	24 VDC, 0.7 AMPS
Driver Output	110VAC,2phase, 50KHz
Switch	On/Off
Start / stop control	CW, OFF, CCW
Speed Control	Variable, B10 KΩ, 0.1W potentiometer
Temperature range	-10 to +55°C

The selected motor controllers, with corresponding technical characteristics presented in Table 2, is able to regulate both the direction of rotation (Clockwise, Counter-clockwise), as well as the rotation speed.

3. Structural elements

The micro-vehicle is of modular construction, consisting of three different types of parts-carriages. The main carriage type supports two piezoelectric motors and the mechanism of traction.

The front carriage carries the micro camera and the lighting equipment, and the last one carries the balun, necessary for the CCTV signal transmission over a distance of more than 2200 feet.

This type of modular partition of the micro-vehicle has been deliberately selected, in order to provide the model with suppleness, allowing it to drive through arched pipes. The first and the last carriage are made of a special aluminum alloy (FORTAL-T651) with density 28.1 kg/dm^3 and elasticity 72000 Mpa and the rest of the construction are made of St 32, which provides durability and allows welding.

3.1 Micro camera carriage

It is a rectangular 3mm thick 50mm long and 20mm wide aluminum plate placed on four wheels, which are attached on two 3mm diameter shafts. Its Top view and its perspective view are shown in Fig. 6 and Fig. 7 respectively.

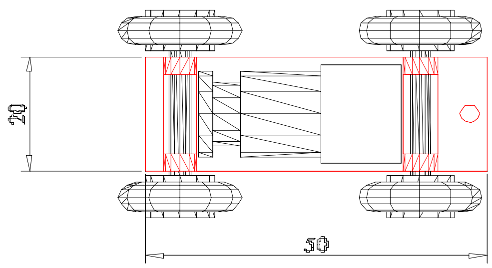

Figure 6: Top view of the micro-camera carriage

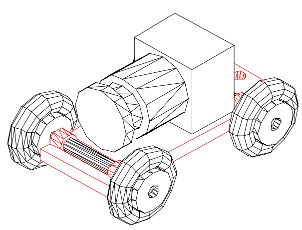

Figure 7: Perspective view of the micro-camera carriage

3.2 CCTV Balun carriage

It is quite similar to the micro camera carriage with the major difference that it is now longer (99mm) and it has a cable connector at the backside, in order to stabilize the various transmission cables. Its Top view and its perspective view are shown in Fig. 8 and Fig. 9 respectively.

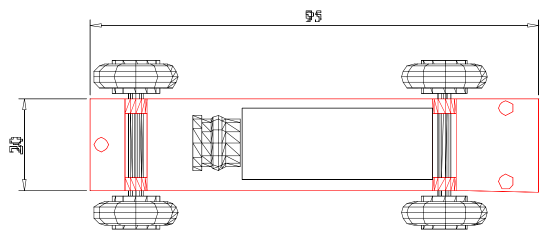

Figure 8: Top view of the balun carriage

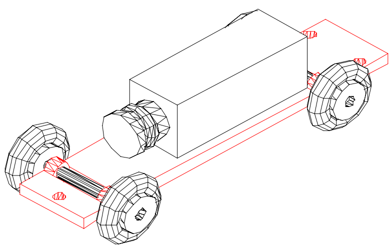

Figure 9: Perspective view of the balun carriage

3.3 Traction carriage

It holds the thrust mechanisms, responsible for the motion of the whole construction. Its perspective view is shown in Fig. 10.

The carriage chassis, whose top view is shown in Fig. 11, has four rectangular holes, which have been created to provide space for the placement of two piezomotors and their corresponding bevel gears.

Its width is 30mm, its length is 149mm, its thickness is 3.6mm and it is made of St 32. This material renders easier the welding procedure, which is necessary for connecting to the chassis, the additional special elements, used to support the motors.

Views of these elements, which are attached to the traction carriage chassis, are shown respectively in Figures 12 to 15.

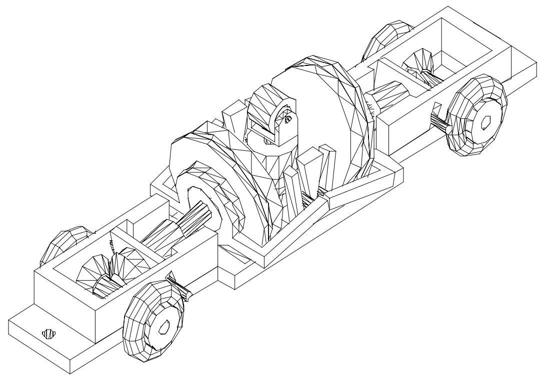

Figure 10: Perspective view of the traction carriage

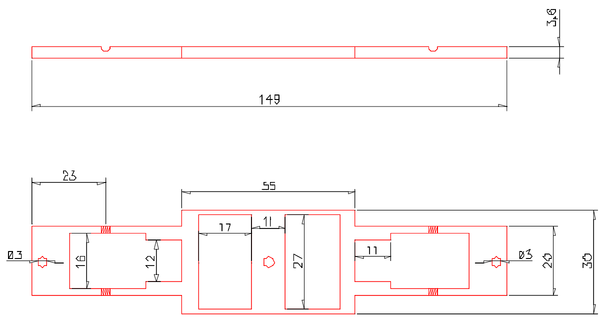

Figure 11: Top view of the traction carriage chassis.

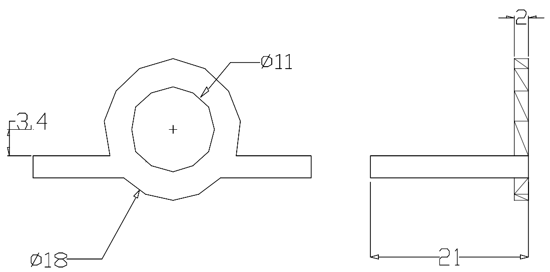

Figure 12: Front and side view of the motor mounting rings.

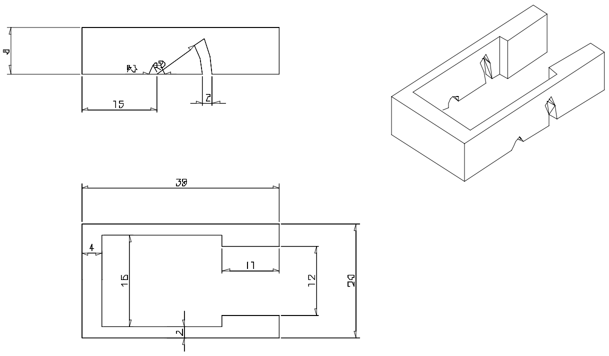

Figure 13: Views of the gear box covers

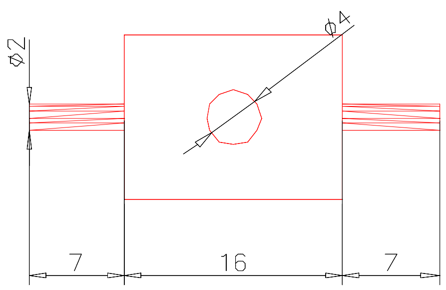

Figure 14: View of the gear box input axis lifting plate.

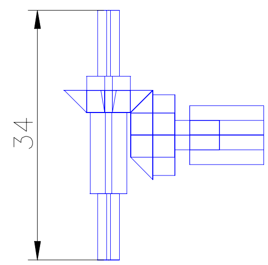

Figure 15: View of the gear pair arrangement.

The basic concept in the design of these elements is the easy assembly of the traction carriage elements, as well as the capability of rotating the piezomotor axis, with respect to the gear box axis. This rotation is necessary, every time there is a need to change the inclination of the motor, in order to be adapted to a specific pipe diameter.
In order to achieve a better fixing of the carriage against the inside pipe walls, a special device is provided on the carriage, which is shown in Fig. 16.

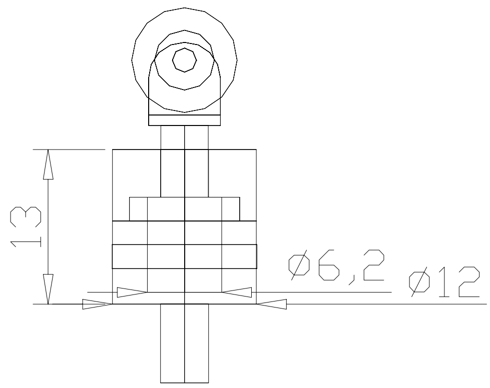

Figure 16: Traction and fixing wheel device.

This device consists of a hollow cylinder, a spring placed in the cylinder and a wheel attached on a metal part, which is in contact with the spring so that the wheel is pressed against the upper part of the pipe. The device actually increases the vertical force applied on the wheels so that, for a significant fraction coefficient, the tractive force of the wheels (fraction) is bigger than the tractive force of the motor. In order that the carriage can be used to the various pipe diameters under consideration, the height of this device can be varied. This is achieved by using a series of additional concentric cylinders of an appropriate height, so that the wheel of the device will still have contact with the inner surface of the pipe.

4. Microcamera characteristics

A color micro-camera from ALMEX is used for visual inspection. Its dimensions are 17X17X30mm and is mounted on a carriage in front of the main part of vehicle. It has a high resolution of 330TVL EIA, 380 TVL CCIR, an imager of 1/3 inch, a sensitivity lower that 3LUX@f1.5 and an operating temperature -23C to +40C. Its supply is 6VDC and for the transmission of the signal two CCTV baluns are used with pair of braided cables. A number of LEDs are used for the appropriate lightening inside the pipe, mounted in front of the micro-camera. The power supply can be also implemented, using two lithium batteries, in order to reduce the total number of cables.

5 Power and travel distance indicative calculations

Taking into account an efficiency degree of appr. 90% for the bevel gears and for the other types of losses, the total mechanical power output for two piezomotors on a traction carriage is estimated to be equal to 2X1.18W or 2.34W at 250rpm (worst case, according to [6]). Thus, for a wheel with a diameter of 17mm, the maximum total force available on the wheels, is equal to F_m = 10.5N for a travelling speed of 0.22m/sec.

In order that the traction wheels do not slip, a minimum force must exist in the spring of Fig. 16, calculated according to:

$$B=Fm/\mu \qquad (1)$$

where μ is the traction coefficient with a typical value equal to 0.8 [7]. Equation (1) leads to a minimum value of B=13.1N. For this reason, a spring with a stiffness k equal to 15000N/m is selected, assumed to act under a deformation of 1mm.

During its operation, the micro-vehicle must drag additionally behind it a piece of unwrapped electrical cable of a certain length L_T. Assuming negligible inertial forces, due to the small carriage mass and acceleration, the total force, which the carriage traction mechanism should provide, must overcome the friction forces F_f:

$$F_f = (M_V g + 2B) f_r + L_T m_c g f \qquad (2)$$

where M_v is the total mass of the vehicle, g is the gravity acceleration, B is the force acting on the spring of the device of Fig. 16, m_c is the mass of the dragged cable per unit length, L_T is the length of the unwrapped cable, f_r is the rolling coefficient and f is the friction coefficient. Typical values of the rolling and friction coefficients are respectively $f_r =0.01$ and $f=0.2$ [7]. Typical values for the masses are $M_v=0.2Kg$ and $m_c=44.25gr/m$ for a UTP10 type of cable. Since all other parameters are known in eq. (2), a maximum cable length of L_T = 117m could be anticipated, further reduced to L_T = 100m, allowing a safety factor for inertial and other effects.

In case that the travel distance must exceed 100m, several traction carriages can be combined, due to the modular structure of the micro-vehicle.

6. Conclusion and future research

One prototype of the system has been tested, indicating areas of possible future improvements. One area of future research involves the application of piezomotors of smaller diameter size (eg. of external diameter of 15mm). Due to the modular structure of the micro-vehicle, additional measuring equipment could be used in accompanying carriages, such as distance or inclination measurements. Also, the motion controller could be included in the micro-vehicle, allowing longer motion intervals, due to the reduced cable weight. Improvements in the mechanical structure are possible, like waterproof sealing, or more compact construction.

In any case, the design concepts applied for the construction of the described prototype, provide a reliable and promising base for future research.

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