Journal of Automation and Control, 2017, Vol. 5, No. 2, 50-53
Available online at http://pubs.sciepub.com/automation/5/2/4

DOI:10.12691/automation-5-2-4

Friction Difference as Principle of Robot Locomotion

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Abstract Paper deals with friction difference principle, which is used as basic principle of robot locomotion. Piezoactuator is used as driving unit for locomotion. Structure of robot is described and also steady state velocity is derived.

Keywords: *friction difference, pipe, locomotion, piezoactuator*

Cite This Article: Alexander Gmiterko, Ľubica Miková, Ivan Virgala, Tomáš Lipták, and Michal Kelemen, "Friction Difference as Principle of Robot Locomotion." *Journal of Automation and Control*, vol. 5, no. 2 (2017): 50-53. doi: 10.12691/automation-5-2-4.

1. Introduction

There are many technical devices which involve pipe systems and constrained spaces (nuclear power plants, heat exchangers, chemical plants, oil and gas industry devices, etc.). As a prevention of accidents and disasters, it is necessary to inspect these systems for any cracks and damages. Internal inspection from inner side of pipe is very often only one possible way to inspect these systems. For several years in the world the considerable effort is aimed on research and development of miniature robots able to move in tubes for inspection and maintenance, res. for cable drawing. In case of tubes with small diameter the minimal size of conventional drives is used as an actuators limit in the miniaturisation. In addition the conventional wheel or caterpillar drive inclines to slipping, when inside wall is choked by dust [1-20].

This study deals with mobile miniature robot, which uses expansion and contraction of piezoelectric actuator.

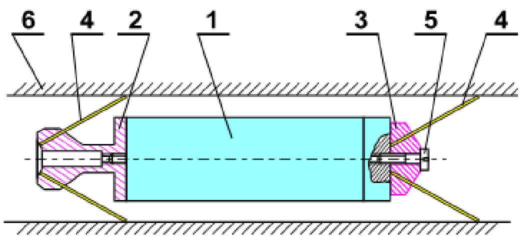
2. Robot Arrangement

Figure 1 shows the structure of the miniature mobile robot for movement in thin tube. It consists of one piezostack, mounted from thin piezoelectric layers [6] and two groups of thin bristles.

Piezostack is used as electromechanical transducer. It converts electrical energy form to mechanical form. The stack is mounted from thin piezoelectric layers and it can generate very large forces but typically extends only a few microns per actuator length. Whenever, the piezoelectric actuator should be operated with a preload. The effect of the preload is to minimize any excess compliance at adhesive layers or mechanical interfaces.

Another condition is that applied voltage must be under the maximal operating boundary. Every peak can be reason of non-returnable damage.

Both groups of bristles include three elastic bristles attached at the same angle. Bristle is made from elastic material. Dynamic friction between the elastic bristle tips and wall of tube differs according to slide direction.



1 – piezoactuator, linear motor; 2 – head bristle plate; 3 – back bristle plate; 4 – bristles; 5 – screw; 6 – pipe

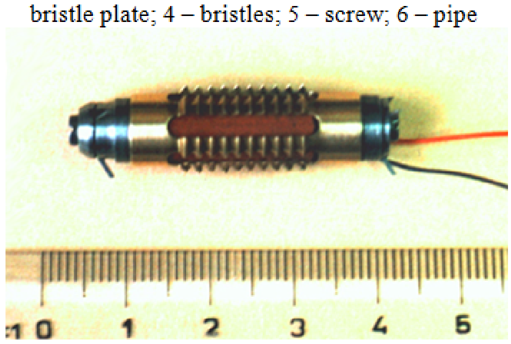


Figure 1. The structure of the miniature mobile robot

So used piezostack generates linear vibration under the applying of suitable modulated voltage and mechanical preload. After extending of piezostack robot elongates some microns along its body in forward direction and in backward direction. In this situation, there is a place for using the difference of friction between bristles and wall surface. Dynamic friction in forward direction is smaller then in reverse direction. Difference between these frictions is base of robot motion. If this difference is zero then robot will not be able to move. Robot moves by this principle and does very short step. The length of this step is approximately equal.

3. Steady Velocity of the Robot

This section derives the steady velocity Vs of the miniature mobile robot by extending Hamilton's principle for the steady piezostack vibration. The physical interpretation of the extended Hamilton's principle is that robot moves to minimize the total work done by the robot, which includes work W_{IW} done on the inner wall and external work W_E.

When the piezostack vibrates (Figure 2), the velocity of the bristle tip in the axial direction is given approximately as

$$v_1 = v_s + v_b(\omega)\cos(\omega t) \tag{1}$$

$$v_2 = v_s - v_b(\omega)\cos(\omega t) \tag{2}$$

where

ω - angular frequency

v_s - steady velocity

These velocities over time are shown in Figure 3.

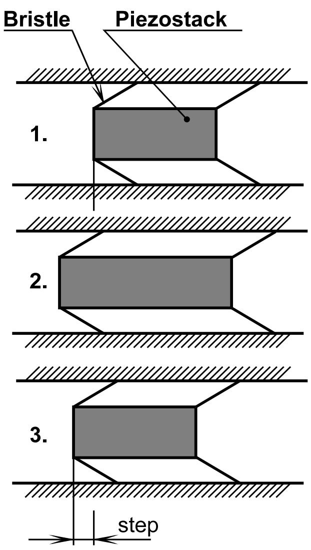


Figure 2. Piezostack vibration - Robot locomotion principle

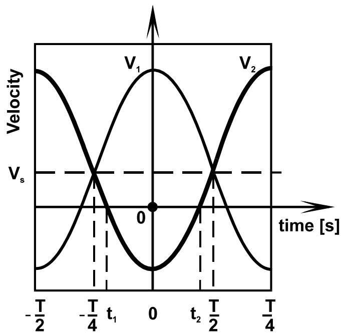


Figure 3. Velocities of the bristles over time

Time points:

$$t_1 = -\frac{1}{\omega}\arccos\left(\frac{v_s}{v_b}\right) \tag{3}$$

$$t_2 = \frac{1}{\omega}\arccos\left(\frac{v_s}{v_b}\right) \tag{4}$$

are obtained from equation (1) and (2) when $v_s = 0$.

The total work W done by the robot is given as follows:

$$W = W_E + W_{IW}. \tag{5}$$

The work W_{IW1} done by the bristle 1 on the inner wall is given as

$$W_{IW1} = \int_{-\frac{T}{4}}^{t_1} N_0\mu_2 v_1 dt - \int_{t_1}^{t_2} N_0\mu_1 v_1 dt + \int_{t_2}^{\frac{T}{4}} N_0\mu_2 v_1 dt. \tag{6}$$

The work W_{IW2} done by the bristle 2 on the inner wall is given in following form:

$$W_{IW2} = \int_{-\frac{T}{4}}^{\frac{T}{4}} N_0\mu_2 v_2 dt \tag{7}$$

where N_0 is a force of the elastic bristle tip against the inner tube wall. μ_1, μ_2 are the equivalent coefficients of dynamic friction

The external work is given as

$$W_E = \frac{F v_s T}{2} \tag{8}$$

Where F is the tractive force.

Steady velocity v_s is obtained from following equation

$$\frac{d\left[\int_{-\frac{T}{4}}^{\frac{T}{4}} W dt\right]}{dv_s} = 0. \tag{9}$$

From equation (9) we can obtain following analytical solution for the steady velocity

$$v_s = \frac{\pi\left[2(\mu_1 - \mu_2) - \frac{F}{N_0}\right]}{4(\mu_1 + \mu_2)} \cdot v_b. \tag{10}$$

This result indicates, that the steady velocity is depending on

1. the equivalent coefficients of dynamic friction v_1 and v_2,
2. piezostack vibration velocity v_b,
3. the force N_0 of the elastic bristle tip against the inner tube wall.

4. Regulated Bristles

Passive bristles have been used also for elimination of influence of pipe geometric deviations to normal force (also friction force) between bristles tips and inner pipe wall. The vertical locomotion of in-pipe robot with passive bristles could be problematic if values of geometric deviations overcome certain limits. The robot falls down if deviations causes increasing of inner diameter and robot loses stability inside pipe. The robot will be blocked inside pipe if geometric deviations cause the too large decreasing of inner pipe diameter.

Bristles with regulated properties (Figure 4) would be a significant contribution to solving of these mentioned locomotion problems. It means that bristles should become to controlled compliant parts. Principle of controlled bristles leans on fact that bristle properties changes to suitable values for obtaining of higher locomotion efficiency.

For locomotion based on friction difference, it means that normal force between bristle and pipe wall is decreased when bristle should move in forward direction inside pipe. Bristle, which moves backwards, should have increased normal force (also friction force) between the bristle tip and pipe wall. Consequently, normal force and also friction force is decreased in front bristles and increased in back bristles when actuator elongates. Situation changes when actuator contraction occurs, front bristles have higher normal force and back bristles have lower normal force.

This algorithm will increase friction difference between forward and backward moving of bristles and in causes increasing of robot locomotion velocity and traction force.

Also influence of geometric deviations could be eliminated with these regulated bristles. Sensing of normal force gives feedback information about the actual value of normal force, which can be compared with desired value of normal force. The regulation error can be compensated with any suitable regulator.

Regulated bristles enable to achieve higher efficiency and also prevention of robot blocking inside pipe (Figure 4). Another contribution is overall lower consumption of energy.

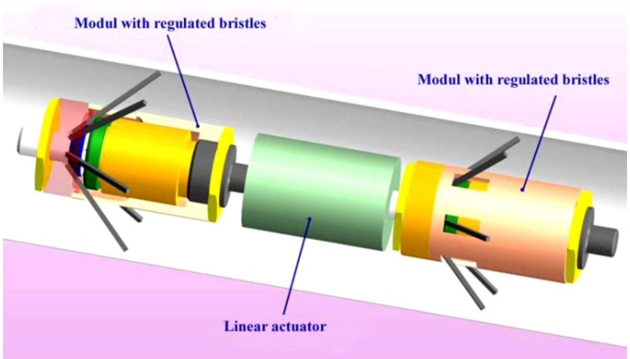


Figure 4. Regulated bristle robot concept

Passive bristle is pure mechanical system and it is not able to fully compensate geometric deviation. Regulated bristle module will involve also sensors, actuators, regulator and suitable control algorithm. Weakness of pure mechanical systems will be compensated through the mechatronic conception (Figure 4) of robot with regulated bristles. The bristled in-pipe robot becomes to intelligent machine with several useful properties.

The robot (Figure 4) consists of two modules with regulated bristles and one module with linear actuator for operation of elongation and contraction.

Change of the bristle angle or change of displacement of bristle tip is possible to realize through the compliant mechanism (Figure 4). The concept is coming from lever mechanism with combination of reduced cross-section of material. Piezoelectric actuator force is applied to compliant mechanism and it is used for regulating of normal force value applied to inner pipe wall. Compliant mechanism consists of three bristle connected with middle rosette. There is no problem with attaching of bristles as before (Figure 4). The compliant part is inserted into case with preloaded piezoactuator (Figure 5).

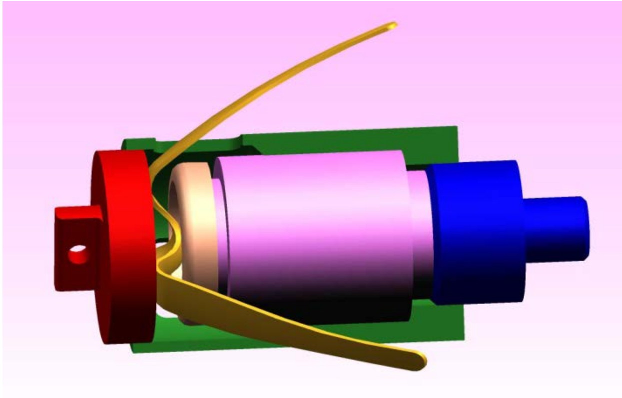


Figure 5. Concept of module with regulated bristles

Completed design of in-pipe robot with regulated bristles is shown on Figure 6.

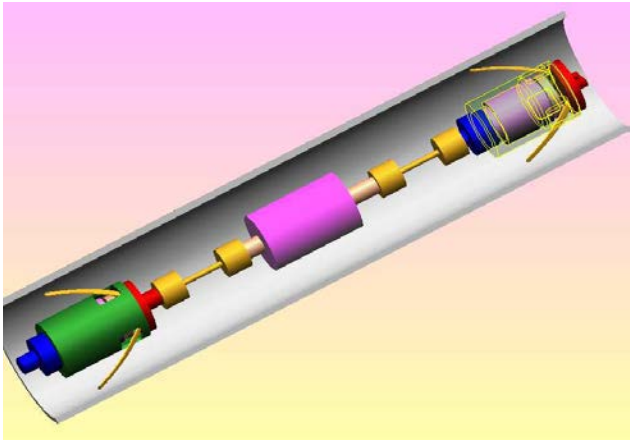


Figure 6. Completed design of in-pipe robot

5. Conclusion

On base of above theory, we have implemented simple one module functional model of this robot which is shown at Figure 1. The next phase is experimental verification of above assumptions.

Future work will be concerned to adaptive in-pipe robot with ability of more range adaptation to inner diameter change.

Regulated bristles are the way how it is possible to improve the pure mechanical solution of in-pipe robot.

There are several examples where mechatronic adaptation of product solved the weakness of mechanical products [21-26].

Acknowledgements

The work has been accomplished under the research projects No. VEGA 1/0872/16 financed by the Slovak Ministry of Education and project “Design and realization of pneumatic manipulator” financed by the Faculty of Mechanical Engineering at the Technical University of Kosice. This contribution is also the result of the project implementation: Centre for research of control of technical, environmental and human risks for permanent development of production and products in mechanical engineering (ITMS:26220120060) supported by the Research & Development Operational Programme funded by the ERDF.

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