THE PIPES MOBILE INSPECTION ROBOTS

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Summary

In this paper, the design of a tracked in-pipe inspection mobile robot with a flexible drive positioning system is presented. The robot would be able to operate in circular and rectangular pipes and ducts, oriented horizontally and vertically with cross section greater than 200 mm. The paper presents a complete design process of a virtual prototype, with usage of CAD/CAE software. Mathematical descriptions of the robot kinematics and dynamics that aim on development of a control system are presented. Laboratory tests of the utilized tracks are included. Performed tests proved conformity of the design with stated requirements, therefore a prototype will be manufactured basing on the project.

Keywords: mobile robot, pipe and duct inspection, kinematic model, dynamic model, vision system

MOBILNE ROBOTY DO INSPKCJI RUROCIĄGÓW

Streszczenie

W artykule opisano projekt gąsienicowego robota inspekcyjnego do rurociągów z elastycznym systemem pozycjonowania gąsienic. Opisany robot przeznaczony jest do pracy w rurociągach o przekroju prostokątnym i kołowym i średnicy ponad 200 mm. W artykule przedstawiono kompletny proces projektowy, mający na celu utworzenie modelu trójwymiarowego w środowisku CAD/CAE. Opisane zostały również modele matematyczne robota w zakresie kinematyki i dynamiki ruchu, niezbędne do utworzenia algorytmów sterowania. Dołączono również opis badań laboratoryjnych gąsienic. Przeprowadzone testy potwierdzają poprawność projektu, który będzie służył do stworzenia prototypu robota.

Słowa kluczowe: robot mobilny, inspekcja rurociągów, kinematyka, dynamika, system wizyjny.

INTRODUCTION

Pipeline inspection is a popular application field of mobile robots. Since the access to a particular segment of a pipeline is usually limited, various in-pipe inspection mobile robots are utilized. This paper presents a design of a tracked mobile robot, that can adapt to various working environments. The robot platform is based on two track modules with integrated motors, mounted on a positioning structure, consisting of three drives per track. The robot can adapt to operate in pipes and ducts with round and rectangular cross-section, oriented horizontally and vertically or work on flat surfaces. Operation in liquid environment was also taken into consideration.

There already exist many other designs of mobile pipe inspection robots, but the majority of them possess low level of adaptivity to the operating environment, mainly due to geometric limitations. Choi and Roh [4] focus on design of wheeled inspection robots suitable for ø200 and ø85-109 mm round pipes, that are based on modular structure that feature segments with wheeled legs on pantograph mechanisms for diameter. Another concept is presented by Horodnica et al. [8]. They designed four robot architectures, utilizing rotor, equipped with three pairs of tilted wheels that move on helical trajectories, propelling the robot forwards in axial direction. The robots have different sizes for 170, 70 and 40 mm round pipes and allow only small changes of diameter. A snake-like 13-segment robot designed by Kuwada et al. [12] may operate in 40-170 mm pipes. The structure equipped with camera propels by clinging to pipe walls and is able to pass bends, T-shapes and changes of diameter. However, maintaining steady camera position for proper inspection may be problematic. Tadakuma et al. [14] proposed a platform with cylindrical track drive: Omni-Track that increases the contact area with pipes of different diameters and allows forward and backward motion along with side motion, realized by roll mechanism. A three-track vertical configuration for constant pipe diameter was described by the authors.

Robots for operation in ventilation ducts are mainly designed with focus on cleaning tasks. Wang and Zhang [16] propose a tracked platform with guiding wheel that can host interchangeable brushes, intended for cleaning of horizontal ducts.

Market research for inspection robots revealed several solutions. Inuktun produces a wide range of tracked inspection robots. Versatrax models are available in three different sizes for minimal pipe diameters: 100, 150 and 300 mm [10]. Their main components are individually operated tracks of different sizes. Manually adjustable chassis allows adapting of the robot to sewer and storm drains, air ducts, tanks, oil and gas pipelines, pulp and paper industry. Versatrax Vertical is a three-track version for vertical, dry pipe inspection [9]. iPEK produces wheeled inspection vehicles, ROVVER for pipes with diameter 100-300, 150-760 and 230-1520 mm [11]. These robots have modular design, with replaceable wheels, suitable for horizontal pipes and operation up to 10 m underwater. Solo robot by RedZone is a tracked, wireless, autonomous robot that can be used in horizontal pipes ranging from 200-300 mm diameter [13]. CUES offer tracked inspection robots for pipes with diameter from 150 to 760 mm. Their main feature is narrow track made of large segments. [5].

As we may observe, numerous solutions for inspection robots are available. Wheels provide the least rolling resistance and are energy efficient, however small contact surface may not be sufficient for some uneven surfaces. Crawling motion has speed limitations and especially upper limit of pipe or duct dimension is a major drawback. As presented by the market research, numerous solutions utilizing track drive have been developed. Tracks provide proper obstacle passing capabilities and considerably large contact is advantageous in terms of friction. The presented tracked robots, do not possess online track positioning and are designed for specific purposes. This paper presents a design of a versatile tracked mobile robot with an adaptive track positioning system intended for video inspection.

1. MECHANICAL STRUCTURE

Similarly to most of the analyzed robot structures, it was decided to utilize two tracks. That configuration will ensure proper robot stability and maneuverability, assuming that the robot will consist of one segment. For this project, Inuktun Microtrac track modules with dimensions 60x50x170 mm will be utilized. They are designed specifically for pipe inspection, with focus on small inspection platforms. For creating the virtual prototype of the inspection robot, Autodesk Inventor Professional 2012 was used.

Track positioning system consists of two independently rotating rings, with a centre of rotation in the axis of the robot body. To each of these rings, an arm is attached on a rotary joint. These arms are similarly mounted to both sides of each track. This configuration allows various orientations of track with respect to the robot body. Each track unit is adjusted by three drives. Two drives allow rotation of rings in the robot body axis and the third drive positions one arm with respect to the track. Drives selected for the rotating rings are digital servomotors Hitec HS-7950TH that possess high holding torque, compact size and integrated position controller. The rotating rings are connected with robot outer and inner arms. The general view of the robot is presented in the Fig. 1. Drive controllers and power electronics are located inside the robot body as depicted in Fig. 2.

In total, the robot has 8 drives: 2 tracks and 6 track positioning servomotors and consists of over 230 components, among which over 60 have to be manufactured. The total weight of the robot is 6.9 kg, where the weight of one stainless steel track is 2 kg. The total weight does not include camera, lighting and cables. Components such as robot body, arms, ring spacers, cups and track mounts. The robot is capable of operation in liquid environment such as water, sewage or oil. In order to meet this requirement, connections are sealed and cables are routed with usage of waterproof connectors.

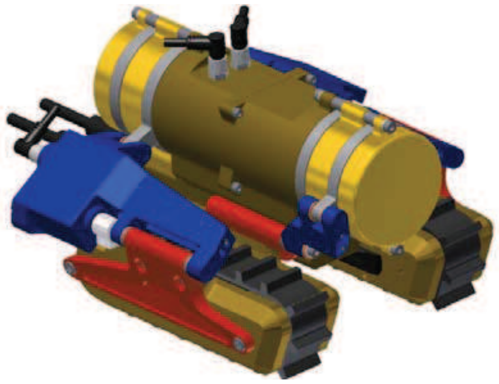


Fig. 1. Robot model - general view

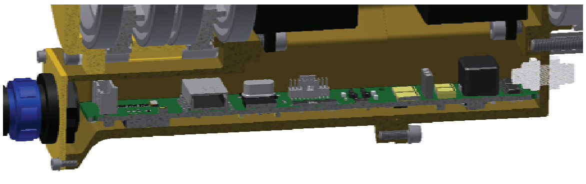


Fig. 2. Controller compartment

2. KINEMATIC MODEL OF THE ROBOT

Description of a crawler track motion in real conditions with uneven ground and changeable parameters is very complex. The detailed mathematical description of the movement of individual crawler track points is so compound that it is necessary to apply simplified models. It is possible to model elastomer tracks with treads (Fig. 3 a) as a non-stretch tape wound about determined shape by the drive wheel, tensioning wheel and undeformable ground (Fig. 3 b) [1, 6, 15, 17]. For the kinematic model, a horizontal orientation of two tracks was utilized, basing on formulation used for tank robot presented in [7].

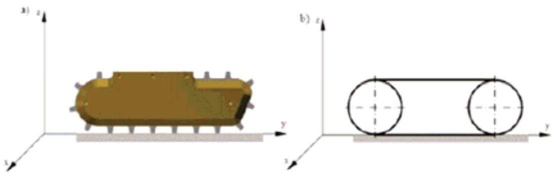


Fig. 3. a) CAD Model, b) Simplified Model

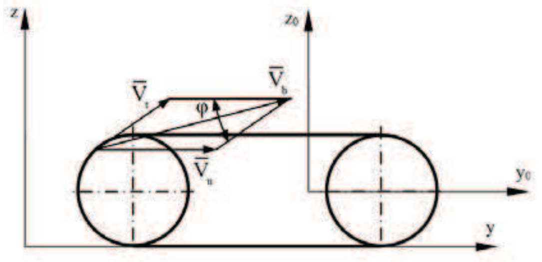


Fig. 4. Simplified model of the crawler track

For the description of motion points on the crawler track circumference (Fig. 4) two systems of coordinates were selected. Axes y and z form a reference frame associated with the ground, whereas axes y_0, z_0 are attached to a movable coordinate system associated with the vehicle [1, 2, 3, 6]. The motion of any crawler track point is a composition of two motions: relative motion of the moving frame y_0, z_0 and transportation motion relative to the reference frame y, z. The absolute velocity of any point on the crawler track circumference is equal to the resultant of transportation velocity and relative velocity.

$$V_{by} = V_u + V_t \cos\varphi, \tag{1}$$

$$V_{bz} = V_t \sin\varphi, \tag{2}$$

$$V_b = \sqrt{V_{by}^2 + V_{bz}^2} = \sqrt{V_u^2 + V_t^2 + 2V_u V_t \cos\varphi} \tag{3}$$

where: V_u –transportation velocity

V_t – relative velocity of any point on the crawler track circumference

V_b – absolute velocity of the point on crawler track circumference

φ – angle between vectors V_t and V_u

In case when $\varphi = \pi$, that is when points on the crawler track circumference contact the ground, the absolute velocity is a sum of transportation and relative velocities.

When the track load-bearing segment is in contact with the ground, then the effect of slip occurs [1, 2, 3]. The slip phenomenon is affected by properties of the ground, driving force, type and placement of track treads. The driving force appearing in the robot track driving modules, exerts shear stresses on the ground. It is possible to determine the relationship between the driving force and factors that influence the slip by:

$$P_n = 10^6 b \int_0^L \tau_x dx. \tag{4}$$

where: P_n – driving force

b – width of the crawler track

L – length of the load-bearing segment of the crawler track

τ_x – shear stresses in the soft ground

Assuming that the course of parallel deformations to the ground is linear, it is possible to express these deformations by:

$$\Delta l_x = x s_b, \tag{5}$$

where: s_b – slip

x – distance of the point, for which the slip is calculated from the point of crawler track contact with the ground; the greatest slip appears for x = L.

Therefore, it is possible to express the slip by:

$$s_b = \frac{\Delta l_x}{x} = \frac{\Delta l_{max}}{L}, \tag{6}$$

The velocity of point C, placed in the axis of symmetry of the crawler, assumed to be the center of gravity, [1, 2, 3, 6, 17] may be expressed as:

$$V_c = \frac{r d_1 (1 - s_1) + r d_2 (1 - s_2)}{2}, \tag{7}$$

When slip is neglected:

$$V_c = \frac{r\dot{\alpha}_1 + r\dot{\alpha}_2}{2}, \tag{8}$$

Velocity components of the point C:

$$\dot{x}_c = V_c \cos\beta, \tag{9}$$

$$\dot{y}_c = V_c \sin\beta, \tag{10}$$

After taking into account the relation (7) the equation of simple kinematic task was obtained:

$$\dot{x}_c = \frac{r\dot{\alpha}_1(1-s_1) + r\dot{\alpha}_2(1-s_2)}{2}\cos\beta, \tag{11}$$

$$\dot{x}_c = \frac{r\dot{\alpha}_1(1-s_1) + r\dot{\alpha}_2(1-s_2)}{2}\cos\beta, \tag{12}$$

$$\beta = \frac{r\dot{\alpha}_2(1-s_1) - r\dot{\alpha}_1(1-s_2)}{H}, \tag{13}$$

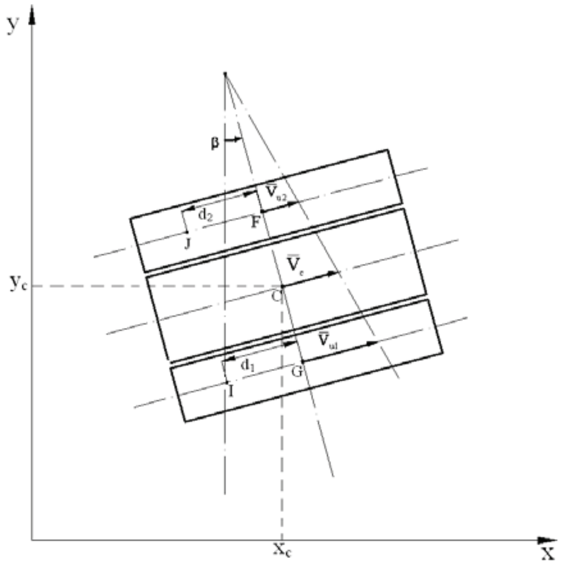


Fig. 5. Diagram of the robot frame turn for the angle

3. DYNAMICS OF THE INSPECTION ROBOT

In the dynamic model of the robot, the kinematic description is expanded, but still considering the same characteristic points on the structure (Fig. 6).

The dynamic description of the robot [1, 2, 3, 6, 15, 17] is based on energetic method based on Lagrange equations. In order to avoid modeling problems connected with decoupling Lagrange multipliers, Maggi equations were used. The final form of the dynamic motion equations based on Maggi formalism have been presented as follows:

$$\left(\frac{r}{2}[\dot{\alpha}_1(1-s_1) + \dot{\alpha}_2(1-s_2)]\cos\gamma\right)(m_R + 2m)\frac{1}{2}r(1-s_1)\cos\gamma + \left(\frac{r}{2}[\dot{\alpha}_1(1-s_1) + \dot{\alpha}_2(1-s_2)]\sin\gamma\right)(m_R + 2m)\frac{1}{2}r(1-s_1)\sin\gamma + I_y\ddot{\alpha}_1 = M_{s1}\eta t + (-0.5F_u - 0.5F_D - 0.5G\sin\gamma + 0.5F_W\sin\gamma - 0.5W_{t1})r(1-s_1),$$

$$\left(\frac{r}{2}[\dot{\alpha}_1(1-s_1) + \dot{\alpha}_2(1-s_2)]\cos\gamma\right)(m_R + 2m)\frac{1}{2}r(1-s_2)\cos\gamma + \left(\frac{r}{2}[\dot{\alpha}_1(1-s_1) + \dot{\alpha}_2(1-s_2)]\sin\gamma\right)(m_R + 2m)\frac{1}{2}r(1-s_2)\sin\gamma + I_y\ddot{\alpha}_2 = M_{s2}\eta t + (-0.5F_u - 0.5F_D - 0.5G\sin\gamma + 0.5F_W\sin\gamma - 0.5W_{t2})r(1-s_2).$$

where: α_1 - angle of rotation of wheel 1 , α_2 - angle of rotation of wheel 2, m_R - frame mass, m - track mass, W_t - the force of resistance of the rolling track, F_u - pulling force, F_W - hydrostatic force, F_D - hydrostatic resistance force, I_y - inertia moment for the robot frame, s_1 - slip for wheel 1, s_2 - slip for wheel 2, G - gravity force, η - efficiency.

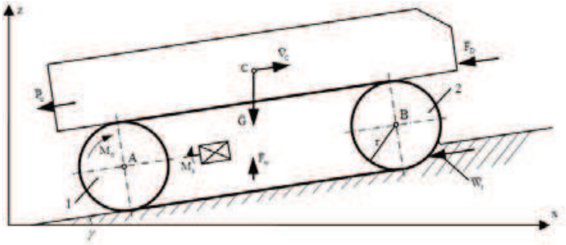


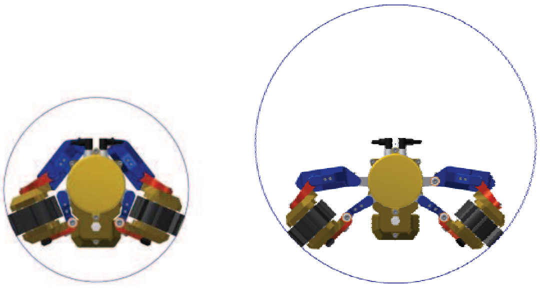
Fig. 6. The Dynamic model of the robot

The dynamic motion equations correspond to the robot moving on the horizontal surface. In case of operation with other track alignments, it is necessary to take into consideration the projections of forces and moments acting on a particular track.

4. OPERATION ENVIRONMENTS

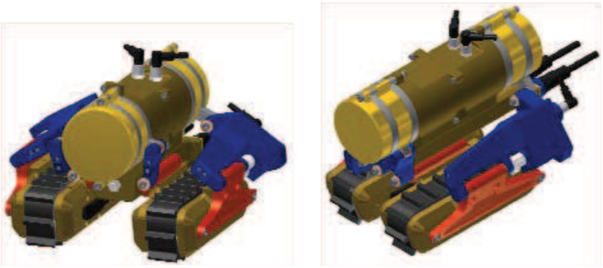
According to project requirements, the robot is capable of positioning its driving mechanism in various ways, to accommodate to working environment. For the most compact alignment, the robot will be able to operate in pipes with diameter above 210 mm (Fig. 7. a). In the Fig. 7. b), we may observe the robot with alignment for operation in a 330 mm diameter pipe. The upper limit of pipe diameter is determined by the capabilities of the vision system.

For pipes and ducts with rectangular cross-section, there are two different configurations. The first one, presented in the Fig. 8. a) is the configuration, when tracks are horizontally aligned, giving the robot the highest stability and lowest height, whereas in the Fig. 8. b) tracks positioned the closest to each other are depicted, making the robot capable of operation in narrower and higher ducts, or positioning the camera higher above the ground for greater field of view.



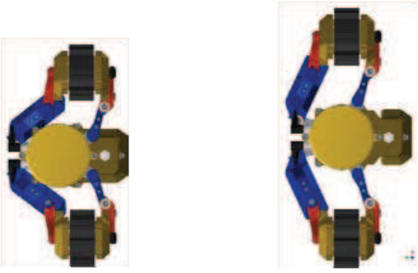
a) b)

Fig. 7. Operation in round pipes:
a) ø206 mm, b) ø330 mm



a) b)

Fig. 8. Operation in rectangular ducts:
a) wide,
b) narrow



a) b)

Fig. 9. Track parallel extension:
a)minimum,
b) maximum

Parallel extension of tracks is also possible for the robot structure. It may be utilized to operate in pipes or ducts with rectangular or circular cross section that are oriented in any direction, basing on friction force with respect to the walls. Possible minimum and maximum extensions (230 mm to 270 mm) are presented in Fig. 9.

5. TESTING OF INUKTUN MICROTRACS IN REAL ENVIRONMENT

In case of motion of such mobile platforms as the described robot, there appear problems with precise determination of position and orientation due to deformations of track treads and working surface. In order to reduce this unwanted influence, a previously described mathematical model was proposed. In the model it was assumed that that the track treads deform and the surface is undeformable.

The testing procedure was conducted in a laboratory with usage of horizontal pneumatic table with vibration isolation, Phantom v9.1 camera with 2 megapixel resolution. The vision system was equipped with TEMA Automotive software, dedicated to motion analysis, that feature automatic tracking and processing tools. The object of investigation consisted of two Inuktun Microtrac units mounted to a test frame with dimensions and weight corresponding to designed robot. Markers were placed on each track tread and on the track body. During motion, displacements in axes x and y were obtained for particular treads with respect to the marker situated in the lower left corner of the table (Fig. 10). In the we may observe plots of tread marker position in Y axis. Basing on the region of plot when the investigated tread is in contact with the table (lower plot), deformation that will be introduced in the was calculated to be $\Delta l = 0.02$ mm for this kind of motion.

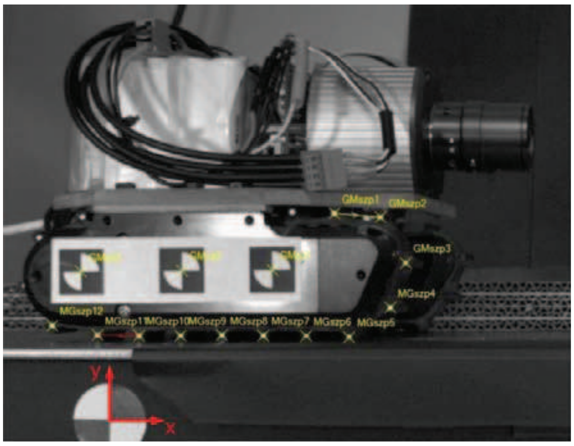


Fig. 10. Track deformation test - markers

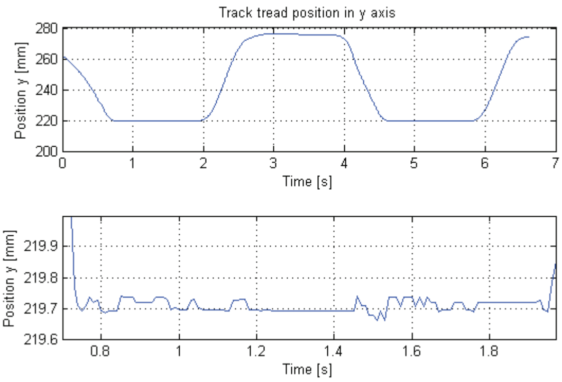


Fig. 11. Track tread position in y axis

6. CONCLUSIONS

This project covers a design process of a pipe inspection robot, using CAD/CAE tools. By reviewing over 20 solutions, market need for a tracked inspection robot with flexible positioning mechanism was identified. A 3D model of a versatile mobile inspection robotic platform was created and simulated. Basing on the conducted laboratory tests, determination of track tread deformation was crucial to correctly formulate the dynamic equations of motion, used for precise estimation of position and orientation of the robot.

7. FURTHER WORK

Experiments with track modules should be performed on different pipe and duct surfaces to provide values of coefficient of friction that will allow estimation of proper loading for positioning drives.

An efficient control system that would allow easy positioning and utilization of all opportunities of the structure must be created. A prototype should be created and equipped with a CCTV camera and lighting to conduct further tests in real operating environment. An algorithmic determination of track treads deformation need to be developed, basing on particular operating surfaces to optimize positioning in work environment.

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