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Adaptable Mechatronic Locomotion System

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KEY WORDS
Mechatronics, Locomotion, Actuator, Adaptable

ABSTRACT
Wheeled in-pipe locomotion is very favourite principle of locomotion used inside pipe. However, there are several problems in these systems like slipping or deadlocking on inner pipe wall. The construction of the system provides adaptation of the wheels position i.e. adaptation of the normal force of the wheels against to the inner pipe wall. This property is important, because of geometric deviations on inner pipe wall. Information about the actual normal force of wheels against the inner pipe wall is used for regulation of their value. When normal force is too small then slipping occurs, but if normal force is too large then deadlocking occurs. A designed system is able to adapt to pipe with inner diameter in range of 100mm to 200mm.

INTRODUCTION
This in-pipe machine is designed to locomote inside the pipe for inspection tasks, cable drawing, pipe wall maintenance etc. In-pipe machine can locomote inside horizontal and vertical pipes, also inside the curved pipe parts as for example elbow, reduction of diameter, double branch joint etc. These facts are very important for overall design of such systems.

This paper deals with conception design of the wheeled in-pipe machine which is able to locomote inside pipe with inner diameter in a range of 100 - 200 mm. Traditional conceptions tend to wheels slipping or self-blocking. Consequently, our conception is able to compensate these mechanical weaknesses. In addition, our construction has improved ability to locomote inside the pipe. Also energy balance and performance parameters are improved [1].

DESIGN OF THE LOCOMOTION MACHINE ARRANGEMENT
It is important to arrange the machine construction as small as possible. The design with very large pipe cross-section covering and very long body dimension could be a problem for ability to crossing the in-pipe obstacles. The main disadvantage of the wheeled construction is tending to slipping and self-blocking of the wheels caused with changed in-pipe geometry. Very small normal force of the wheels against the inner pipe wall causes the wheels slipping. But, very large normal force of the wheels against the inner pipe wall causes the wheels self-blocking. So, it is necessary to change normal force of wheels against the inner pipe wall in dependence of the actual status inside the pipe. Only mechatronic conception design allows solving of this problem.

One of the possible ways of the wheeled in-pipe machines is placement of the traction and stabilization wheels to the arms regularly placed around the machine body (Fig. 1). Imperfections of the inner pipe wall are very critical factor for design of this type of locomotion device. These imperfections are caused with production process and with using of the pipe. Inner pipe wall geometry can be also changed with dirties and sediments, technological processes (welding, gluing etc.)

Design of the three arms arrangement regularly placed around the machine body (Fig. 1) provides self-centring and equal normal force of every wheel to the inner pipe wall. This phenomenon is clearly from force analysis. This equal force distribution is secured also in case of changed inner pipe wall geometry and existence of the inner pipe deviations and sediments. Important condition is that, the angle between arms is equal to 120° (Fig. 1).

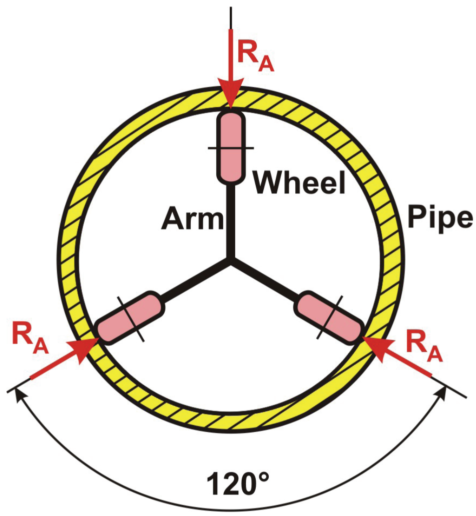

Fig. 1 *Design of machine arrangement*

DESIGN OF THE WHEEL ARM OF THE IN-PIPE MACHINE
Ability to locomote inside the changed inner pipe diameter is the main problem in process of wheel arm design. We assume the change of the inner diameter in a range 100 ÷ 200 mm. The machine has

to locomote also in every position (vertical, horizontal). Our wheel arm design is shown on Fig. 2 [1].

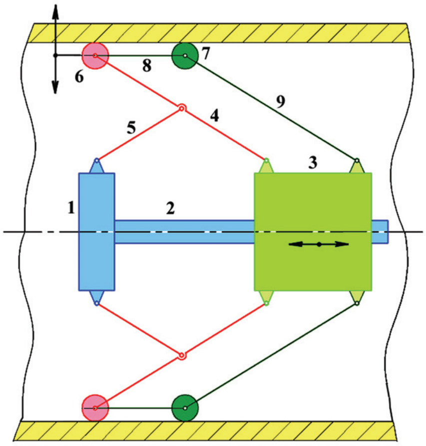

Fig. 2 *Machine arm arrangement [1]*

The basic part (fig. 2) is the machine body (1), which is connected with guiding rod (2). Carrier (3) is moving on guiding rod (2). Wheel holder (4, 5, 9) are connected to the machine body (1) and carrier (3) via plane joints. Wheel holder (4) holds driven wheel (6) and wheel holder (9) holds stabilization wheel (7). Stabilization wheel provides the better stabilization of machine locomotion inside pipe. Connecting part (8) is placed between these wheels (6, 7).

Parts (3, 4, 8, 9) compose the parallelogram mechanism. This mechanism can be as source of the problems in described situation of locomotion inside the pipe. For this reason carrier (3) has to be divided (Fig. 3) into the part (3) and part (10). These parts will be connected via spring (11). This configuration allows assuring of connection of the every wheel with inner pipe wall. This divided carrier with spring allows the passive compensation of the pipe deviations. Active adapting to change of inner pipe diameter is able to realize via change of the carrier position (3) from the machine body (1). This position change is can be obtained through the position servomechanism in combination with screw mechanism [1].

Dimensions of the wheels and machine body are the first parameters for dimension identification of wheel holder. The length of the wheel holder (4) and (9) has to be equal. Figure 4 shown only wheel holders (4) and (5) for simple illustration of the situation. Parameters a, b, c (Fig. 4) have to be designed in accordance with condition $\alpha_{r1} = \alpha_{r2}$. This condition is executed when .

The change of the position (Fig. 4) of the centre of gravity of the machine is minimum, when trajectory of the point D (for changing of the adjusting dimension L) is identical with axis o_k perpendicular to the axis of machine body. This case is secured only when a=b=c. [1]

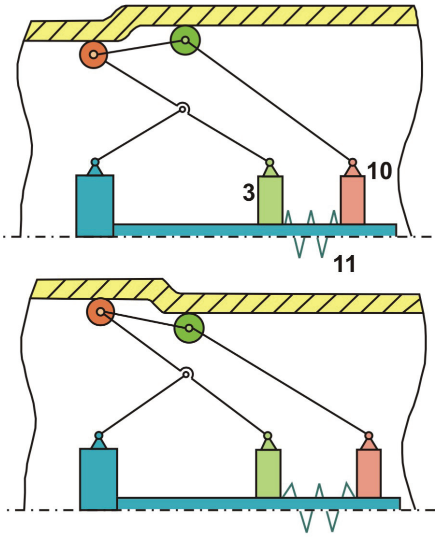

Fig. 3 *Adaptation to the change of the inner pipe surface geometry [1]*

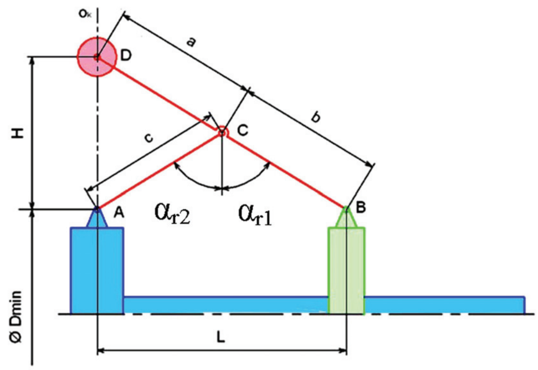

Fig. 4 *Design of the mechanism dimensions*

ACTUATOR AND TRANSMISSION MECHANISM

Every driven wheel (6) is driven via independent actuator (16) (Fig. 5).

Therefore, every arm has own actuator (together three actuators). Position servo mechanism has been chosen as actuator. The main reason for this selection is performance in small dimensions and easy controlling of it.

The placement of this actuator (16) has been proposed nearest to the driven wheel (Fig. 5). Actuator is placed between the wheel holders (4, 5) because of elimination of the parts collision in process of adaptation to changed inner diameter of the pipe (Fig. 6). GWS PARC L servo with bevel gears has been chosen on the base of performance calculations.

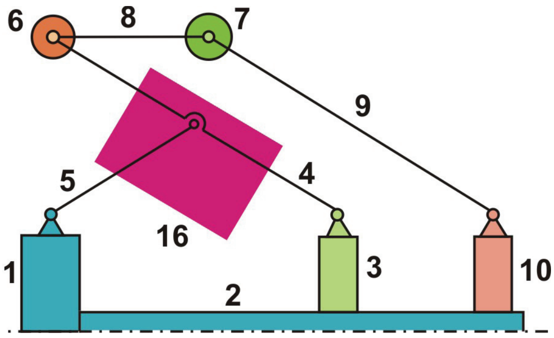

Fig. 5 *Servomechanism placement [1]*

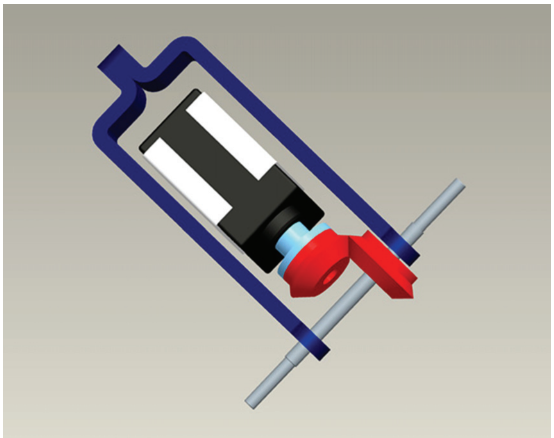

Fig. 6 *The placement of the servomechanisms and bevel gears*

PROPOSITION OF GEOMETRY OF THE WHEEL PLACEMENT

Conception of double wheel arrangement has been chosen because of better locomotion stability. Distance between these wheels is defined as mid wheel distance L (Fig. 7).

Distance of the upper wheel radius from the machine body centre (Fig. 7) can be derived in this form (equation 1):

$$H_X = \sqrt{(R-r)^2 - \left(\frac{L}{2}\right)^2} \qquad (1)$$

where:

R – radius of the inner pipe wall,
r – radius of the fillet of the wheel tire (Fig. 8),
L – mid wheel distance,
h_x – distance of the wheels from the highest point of the inner pipe wall.

Distance h_x can be described with the equation 2:

$$h_X = R - (H_X + r) \qquad (2)$$

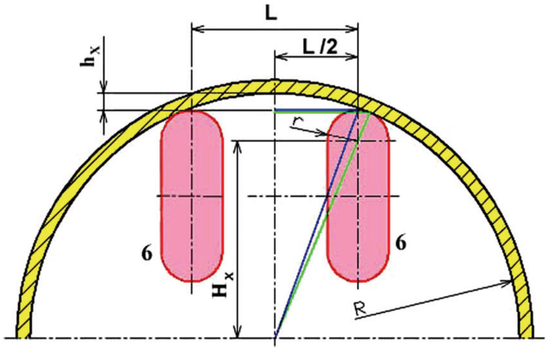

Fig. 7 *The contact of driven wheels with inner pipe surface [1]*

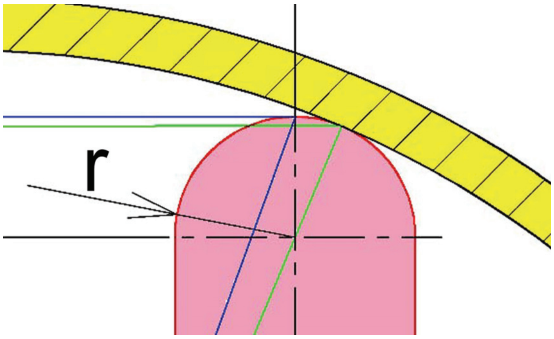

Fig. 8 *Detail of the wheel contact with pipe wall [1]*

After substitution of the equation 1 into the equation 2, we can obtain the h_x in the next form (equation 3):

$$h_X = R - \left[\sqrt{(R-r)^2 - \left(\frac{L}{2}\right)^2} + r\right] \qquad (3)$$

After that it is possible to determine high of stroke H (Fig. 4) with (equation 4)

$$H = H_X + r - \frac{D_{\min}}{2} \qquad (4)$$

Where:

D_{min} is diameter of the machine body

On the base of geometry analysis we can say that, if inner pipe diameter will reduce than distance h_x will enlarge.

If we use our values of variables it is possible to show dependence of the stroke H on the adjusting distance L (Fig. 9).

This dependence is non-linear. As you see, the stroke H is very sensitive on change of adjusting distance L in the range 60 to 70 mm. Maybe, this could be a problem in controlling process.

The range of the stroke H is limited through the geometry. The limit values of the stroke H is defined for minimal inner pipe diameter (100 mm) and for maximal inner pipe diameter (200 mm). Consequently, minimal stroke is 13,45 mm and maximal stroke is 66,5 mm.

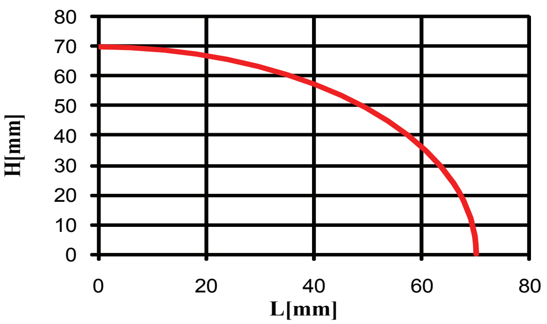

Fig. 9 *Dependence of the arm stroke H on the adjusting distance L (distance between points A, B (Fig. 4) [1]*

From the Fig. 4 it is possible to obtain the equation 5 for adjusting distance L

$$L = \sqrt{4a^2 - H^2} \tag{5}$$

Adjusting distance will be in the range from 21,8 mm to 68,7 mm for our assumptions and variables. Every arm (Fig. 5) is consisting of pair of parts (4, 5, 8 and 9). Final design is shown on figure 10.

PROPOSITION OF THE OPENING AND CLOSING OF THE MACHINE ARMS

Opening and closing of the arms is provided via displacement of the part (3a) (fig. 11). Displacement of the part (3a) could be secured through the screw mechanism placed in axis of the machine. Screw rod (2a) is at the both ends fixed in bearings. Screw rod (2a) is connected with part (3a) through thread (it is female screw). So, part (3a) and screw rod (2a) compose the screw mechanism. Rotating of the screw rod (2a) causes the displacement of the part (3a) and it means that arms of the machine will open or close.

Part (3b) has no thread (there is only simple hole) because of possibility to adaptation to change of inner pipe diameter near the driven wheels (6) and near the stabilization wheels (7).

Guiding of the parts (3a) and (3b) is provided through three guiding rods (circular cross-section) (2b).

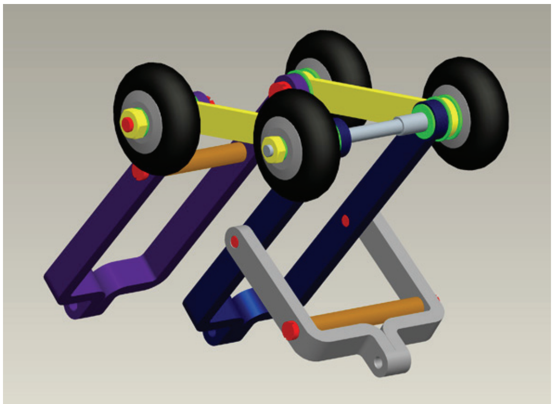

Fig. 10 *Final design of the arm [1]*

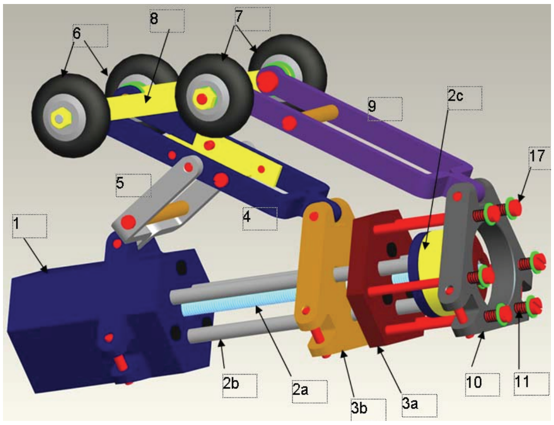

Fig. 11 *Opening and closing of the machine [1]*

Guiding rods (2b) is fixed in machine body (1) and end part (2c) (Fig. 11). End part (2c) is able to move through the part (10). This proposition causes shortening of the overall machine length. Part (10) is used for pressing of the stabilization wheels (7) to the inner pipe wall. This is the reason that part (10) is not fixed to the part (3a). Part (10) is able to move on six

guiding rods (17). The pressing of the stabilization wheels is provided through the springs (11).
Wheel holders are connected to the part (1), (3b) and (10) through the joint pins.
Part (3b) can free-run on guiding rods (2b). The spring (12) is placed between part (3a) and (3b) (fig. 12). This spring is deformation part used for normal force measurement between driven wheels and inner pipe wall. The change of the normal force is caused via change of the inner pipe diameter and it will make spring deformation. Consequently, it is necessary to measure spring deformation through the distance sensor.
Spring deformation is measured through the hall sensor (13) (placed on part 3a) and permanent magnet (14) (placed on part 3b). The microcomputer will evaluate the change of distance between the part (3a) and (3b). After that, microcomputer can affect to actuator for opening and closing of the arms. This is a way how to control normal force between the driven wheels and inner pipe wall [2, 3].

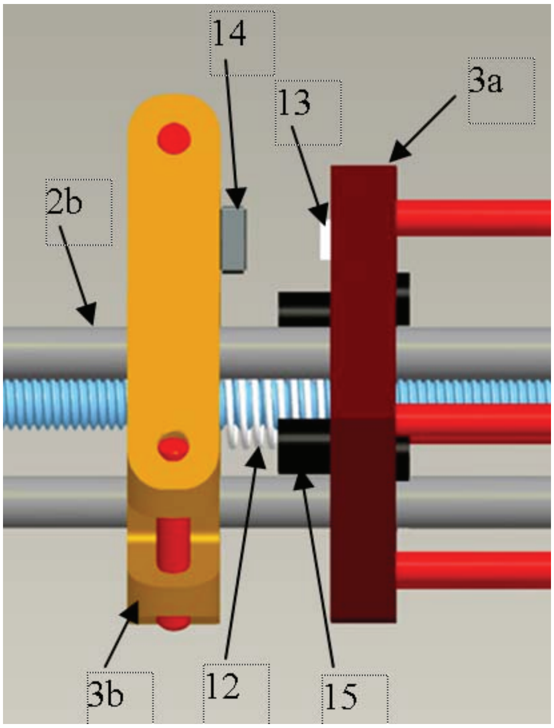

Fig. 12 *Spring deformation measurement [2]*

Actuator has to rotate with screw rod (2a) in suitable direction for controlling of the arm opening and closing. This is a way how to react to the changed conditions inside the pipe. Final design of the adaptable in-pipe machine is shown on figure 13 and 14.

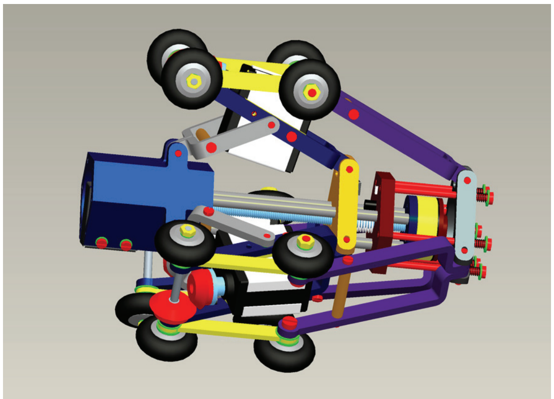

Fig. 13 *Model of the adaptable in-pipe machin [1]*

MAIN TECHNICAL PARAMETERS OF THE IN-PIPE MACHINE

- *Overall machine weight: 0,628 kg*

Basic dimensions:

- *Opening of the arms (range of the inner pipe diameters): min.:98 mm; max.: 204mm*
- *Length (for 100 mm pipe): 186 mm*
- *Length (for 200 mm pipe): 134mm*
- *Theoretical maximum locomotion speed in horizontal pipe 0,082m.s^{-1}*

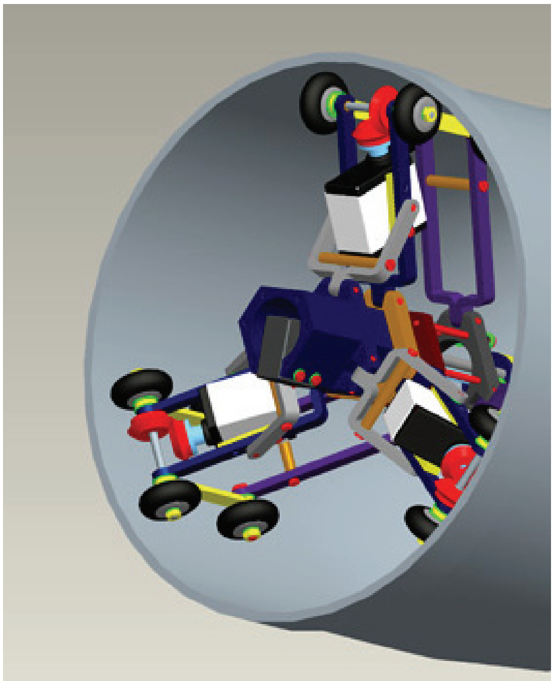

Fig. 14 *Model of the adaptable in-pipe machine inside the pipe [1]*

CONCLUSION

Simulations realized on 3D model (Fig. 14) have confirmed that designed conception is suitable for locomotion inside pipe with diameter change or inner pipe wall deviations.

The designed system is able to hold mention value of normal force through the suitable chosen controlling algorithm. This concept will eliminate the weakness like slipping and self-blocking of wheels inside pipe.

This mechatronic concept is one of the possible solutions for elimination of above mentioned weakness. It provides to obtain better designed in-pipe machine performance and other properties than in-pipe machine used before [4, 5].

The controlling of the value of the normal force also causes the improving of the energy balance and decreasing of looses.

The overall in-pipe machine will consist of several these modules (Fig. 13) arranged one after another. These modules will connected through the suitable controlled joints. This articulated structure looks like snake will be able to locomote inside curved pipes like elbow, reduction of diameter, double branch joint etc.

ACKONWLEDGEMENTS

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