

# Robot Engineering Implementation for Monitoring Small-Diameter Pipelines

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## Abstract

**Background/Objectives:** The developed NDT method requires measuring sensor motion along the pipe and around its circumference. This article focuses on determining the design a robotic device for sensor delivery and motion in pipelines.

**Methods/Statistical Analysis:** The review of the existing control systems, examined design concepts, advantages and disadvantages enabled to develop a robotic device considering the following:

- It shall consist of several modules interconnected by hinge joints
- Secure traction of the robotic device requires expanding modules in the pipe and determines the use of three tracking mechanisms for motion unit.
- The "braking" track shall be applied to ensure crossing of the inclined and vertical sections.

**Findings:** As a result of the research, design documentation of the robot motion unit was developed and its unit design was determined, we have obtained an engineering study of the robotic device motion unit, which consists of two motion modules and the motor control circuit stacked together via cardan joints. The motion module consists of a track and a folding mechanism. The authors have also justified the selected technical solutions verified by appropriate calculations the required parameters: motion drive calculation, thrust drive calculation, electric motor and advancing mechanism selection.

**Applications/Improvements:** This device provides solution for timely inspection of corrosion damage in subsurface pipelines of small-diameter heating networks (DN200, DN400) of housing and public utilities in places inaccessible for external inspection.

**Keywords:** Engineering Study, Motion Unit, Technical Implementation, Track

## 1. Introduction

Steel pipelines are essential for transporting gas, oil and petroleum products. In some countries, they are used as basic in municipal services for a long time. Over time, numerous destructions occur in pipelines, the majority of which are caused by aging, corrosion, cracks and mechanical damage that can lead to accidents. To avoid such situations diagnostic works should be carried out, in order to determine the residual life of the pipeline working parts for further conclusion about the possibility of

operating the pipe section or the need to replace it. The main problem with the In-Line Diagnostics (ILD) of heating systems is:

- The need for pipe surface preparation and cleaning from corrosion products and slurry sediments that reach considerable thickness, as sediments partially or completely clog hollow pipe, preventing the delivery of diagnostic equipment.

Existing methods cannot solve this problem, so we developed a NDT method for ILD which is based on measuring the pipe wall thickness using the variable

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magnetization of metal capable of monitoring heating main pipes through a layer of corrosion and slurry sediments, providing a clearance between the monitored item and the measuring sensor of the system up to 15 mm<sup>1</sup>.

To implement the developed method it is required to provide measuring sensor motion both along the pipe and around its circumference. In this connection there is a need to develop a robotic device for sensor delivery and motion in small-diameter (200 to 400 mm) pipelines of a complex configuration (with inclined vertical sections and horizontal elbows having 90° deflection angle and axis bending radius not less than 1.5 diameters of pipeline) in which there are corrosive and slurry sediments (not thicker than 15 mm) under conditions of low and high temperature (from -20 to 45 ° C) and humidity (up to 100%) with the presence of water (no more than 1/3 of pipeline rated diameter in mm (DN)).

To determine the robot design it is necessary to consider the most common existing design decisions.

## 2. Existing Robotic Complexes

In-line robots have a long history of development and can be classified by the displacement structure inside the pipeline into a few basic forms shown in Figure 1.

Most of these structures have been designed to solve specified tasks.

Push type robots (Figure 1a) are among most common. They are passively controlled and move inside pipelines by fluid pressure. Robots of this type are designed for the inspection of large-diameter pipelines.

A walking robot shown in Figure 1b has articulated legs producing complex movements.

Wheeled robot shown in Figure 1c is a mobile robot analog designed for hard-to-reach areas in outdoor operations.

Thrust-type robots shown in Figure 1d have a number of advantages when moving in the vertical pipeline

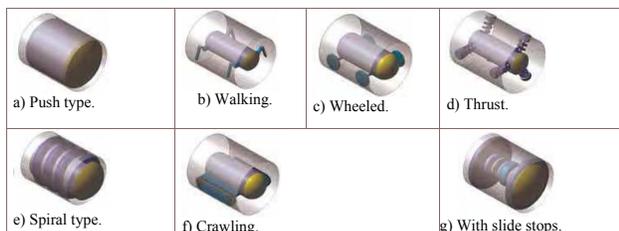


Figure 1. Classification of in-line robots.

sections. By means of a flexible mechanism robots of this type can pass horizontal and vertical bends.

Spiral-type robots (or spiral-type drives) is shown in Figure 1e move in the pipeline along a spiral by twisting.

Figure 1f shows design of a robot using a crawling chassis.

The type of robots with slide stops shown in Figure 1g is used in small-diameter pipelines.

Most in-line robotic designs apply drive mechanisms of one type or a combination of several drives. The main purpose of in-line robot is the implementation of capability to move along an assigned route and carry out inspection within this route. Existing robots usually successfully move along horizontal pipelines, but only a part of them can cope with a complicated pipeline configuration such as vertical sections and bends (elbows, L-shaped pipelines), etc. In addition, few of them can cross tees (T-shaped pipelines). To successfully navigate the developed in-line robot must be able to freely overcome the above-mentioned sections of pipeline design.

The in-line robot should have a small size to be able to move in small-diameter pipes. Small robot design often differs greatly from their macro-size counterparts.

As a result of the search for design solutions of robot mechanical units a number of companies was found which are engaged in the development and manufacture of robotic vehicles for industrial use for the purpose of visual in-line pipeline survey and a number of research institutions involved in the development and prototyping decisions for In-Line Diagnostics.

The search for design solutions of robot mechanical units for the measuring module delivery and motion in DN200 – DN 400 pipeline was carried out.

### 2.1 Explorer II Robotic Complex

The robotic complex for In-Line Diagnostics, Explorer II, was developed by researchers at the Carnegie Mellon University in collaboration with the Northeast Gas Association (NGA) and the National Energy Technology Laboratory (NETL). Design of the robot being a component of Explorer II robotic complex is shown in Figure 2.

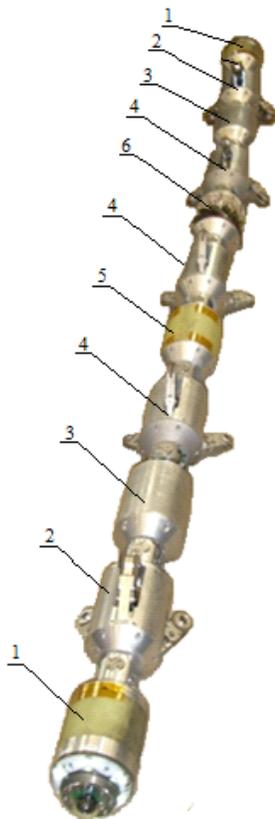
Explorer II module design intended for main gas pipeline inspection is presented in Figure 3.

This robot differs in an autonomous power system. The robot consists of several modules. Dome camera modules (1) are located in the robot front and tail parts and then towards the structure center – chassis modules (2) accumulator storage battery modules (3) and three



**Figure 2.** Robot being a component of Explorer II robototechnical complex.

- 1 – Dome camera module.
- 2 – Chassis module.
- 3 – Accumulator storage battery module.
- 4 – Support module.
- 5 – Exciting coil module.
- 6 – Pipeline wall loss measuring module.



**Figure 3.** Explorer II module architecture for main gas pipeline inspection.

support modules (4) with centering rollers. An excitation winding module (5) and a pipeline wall loss measuring module (6) are located between the support modules (4) in the direction from the front to the tail unit. Robot modules are connected by active joints, enabling them to rotate and pivot relative to each other.

As an option, support modules (4), accumulator storage battery modules (3) and pipeline wall loss measuring modules (6) can be added to the robot design.

Robot passing 90° bend is shown in Figure 4.

Dual wheels with carbide spikes positioned at an angle of 120° are used as drive wheels in robot chassis modules.

The advantages of Explorer II robotic complex include a modular design, which makes it possible to collect a robot from universal modules for specific tasks.

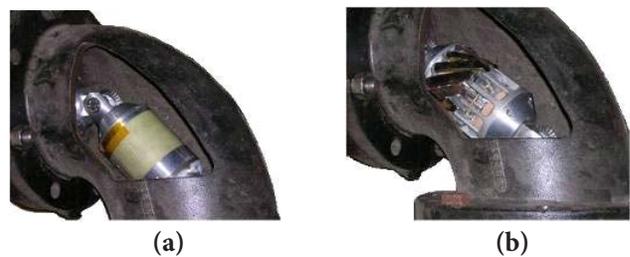
Having articulated joints can be attributed to the shortcomings as well, they are difficult-to-make in miniature sizes. A robot of this design is limited by a range of pipeline diameters.

Design solutions of Explorer II robotic complex may be considered for the use in the developed robot design.

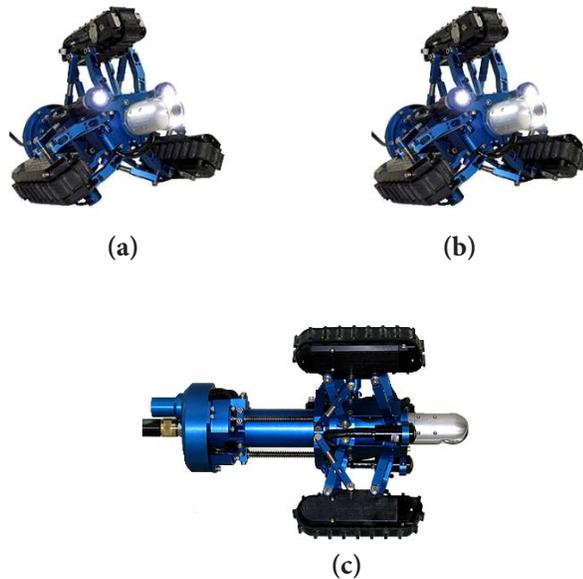
The robot can pass horizontal bends due to articulated joints of module units and the availability of support modules, as well as navigate through the vertical sections with sufficient force of pressing drive wheels. The diameter of the wheels allows a robot to cross a layer of corrosive and slurry sediments only up to 5 mm.

## 2.2. Versatrax Vertical Crawler Robotic Complex

Versatrax Vertical Crawler is a robotic complex from the Inuktun Company<sup>2</sup>. Being a component of Versatrax Vertical Crawler robotic complex a robot (see Figure 5) is moved by means of three Microtracks™, it has an expandable tripod chassis securely fixing robot in a pipeline.



**Figure 4.** Robot passing 90° bend with exciting coil module and pipeline wall loss measuring module. (a) Robot passing exciting coil module. (b) Robot passing measuring module.



**Figure 5.** Robot being a component of Versatrax Vertical Crawler robototechnical complex. (a) Unfolded tracks. (b) Folded tracks. (c) Side view.

Robot is self-centering, i.e. the axis of dome rotation and pivot and the axis of the laser range finder profilometer included in the robot design coincide with the pipeline axis. Versatrax Vertical Crawler robotic complex can monitor pipes with diameters in a range of from 300 to 457 mm in almost any orientation.

Independent control of each track allows robot easily passing a few bends and vertical pipe segments over distances up to 200 m. Auxiliary LED lighting is complemented with the high-quality video that is captured by the onboard camera, while sensors show the size of the pipe and the holding force of each track on-time.

Versatrax Vertical Crawler is made of marine grade aluminum and stainless steel and is durable and completely immersed in the underwater applications.

Robot can cross corrosive and slurry sediments and pass horizontal bends owing to crawling platform use. The presence of a third support point in the form the top track allows robot to move in pipeline vertical sections.

Design solutions of robot being a component of Versatrax Vertical Crawler robotic complex can be considered for the use in robot design.

Robot being a component of Versatrax Vertical Crawler robotic complex can pass vertical sections and bends due to top tracks.

Robot being a component of Versatrax Vertical Crawler robotic complex can cross corrosive and slurry

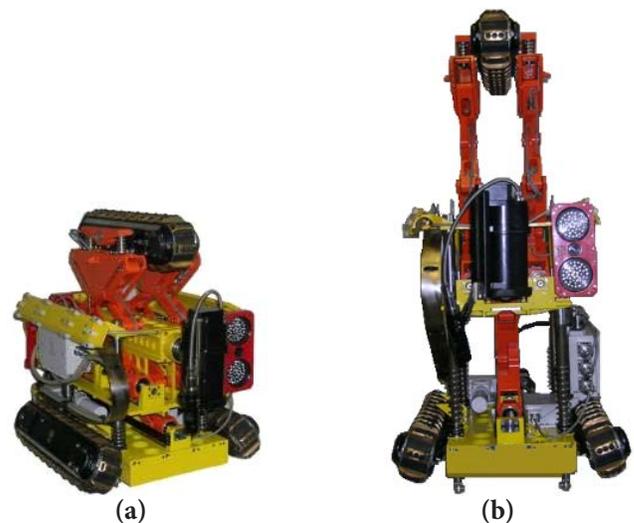
sediments and inclined pipeline sections owing to the use of the crawling platform that provides a good traction with the surface. Due to the difference in tracks rotation robot can pass horizontal bends.

### 2.3. Remotely-Operated Diagnostic System manufactured by CJSC Diakont

For example and comparison, consider the robot design intended to be used in large-diameter pipelines – it is explosion-proof vehicle (hereinafter – EPV) being a component of remotely-operated diagnostic system (hereinafter – RODS) produced by CJSC Diakont (Saint-Petersburg)<sup>3</sup>.

RODS is designed to monitor DN700-DN1400 pipelines. Moving inside the pipe, EPV with set diagnostic equipment measures wall thickness, reveals defects in the pipe body and carries out a visual control of the welds. Robot design enables to cross horizontal, vertical and inclined pipeline sections. Robot is made in explosion-proof sealed design. The physical configuration of the robot is shown in Figure 6.

EPV can move horizontally at a speed of 50 mm/s and vertically at a speed of 25 mm/s. When translating within the pipeline the protector surfaces of lower tracks are installed parallel to the pipeline surface. Before moving on pipeline inclines and vertical sections the upper track is lifted to thrust EPV. The upper track is equipped with a position sensor and track holder sensor. Track



**Figure 6.** Explosion-proof vehicle, a component of remotely-operated diagnostic system. (a) In the folded state. (b) In the unfolded state.

clamping force is also maintained during a power failure. To perform the monitoring an opportunity to fix the EPV in an upright position and forward movement lock and the final vertical sections are provided.

EPV has the ability to cross the rapids with the height up to 50 mm. To do this, retractable wheels are installed in EPV, which lift its front and back. Watching the movement of EPV within in-line space is performed by means of surveillance television equipment. The required level of illumination in the field of view is provided by built-in LED illuminator.

The EPV diagnostic equipment design includes a monitor camera unit and the Electromagnetic Acoustic module (hereinafter – the EMA module). The monitor camera unit is designed to receive a television color image of the test surface, suitable to detect surface defects and to measure their size.

The EMA module provides detection of metal loss on the pipe outer surface (solid, pitting corrosion, dents), the detection of internal flaws of the pipe body (layering effects), the measurement of the wall thickness of pipeline straight sections and measuring the reduction in metal wall thickness on the bend convex side caused by erosion damage and identification of Corrosive Stress Cracking (CSC).

### 2.3.1 Application

- Pipeline diagnostics at the gas compressor stations;
- Pipeline diagnostics at the oil terminals;
- Water supply diagnostics at the energy facilities;
- Diagnostic of heating mains.

### 2.3.2 Features

- Monitoring corroded pipes without surface preparation;
- In-Line motion and control of underground pipelines;
- Identification of hidden defects and leaks in the pipe body;
- Determining the pipeline corrosion condition.

Diameter of pipelines in which the above mentioned robot structures move, allows using tricycle crawling platform with tracks positioned at an angle of 120°. The use of such design solution allows robot to cross not only inclined, but vertical pipeline sections as well.

Design solutions of EPV being a component of RODS may be considered for use in the robot design.

EPV being a component of RODS can cross vertical sections and bends due to the upper track.

EPV being a component of RODS can cross corrosive and slurry sediments and pipeline sloping areas owing to the use of crawling platforms and protector with spikes that provide a good traction with the surface. Due to the difference in rotation of tracks EPV being a component of RODS can pass horizontal bends.

After a review of the existing monitoring systems and comparing their design solutions the following conclusions are drawn:

- To perform In-Line Diagnostics (thickness measurement) and due to the limited space in the small-diameter pipelines the robot should consist of several modules designed to accommodate all the necessary units and components;
- Modules are to be connected through articulated joints enabling to cross the twists and bends in the monitored pipelines;
- Motion units must be thrust in pipelines to provide the necessary traction with the pipe surface at crossing inclined and vertical sections;
- Modules must be resistant to low and high temperatures (from -20 to 45° C). Resistance to high humidity must be achieved by module design tightness;
- Three track mechanisms should be used as a motion device. Tracks provide secure coupling to the pipeline surface in conditions of possible contamination. If particularly dirty or with large corrosive sediments spiked protector should be used;
- It is required to use a track “breaking” along the motion path to increase the lines of the track protector traction with the pipeline surface while crossing the bend upwards (downwards) or sidewise with parallel arrangement of track walls as for the direction of the exit, i.e. it becomes either convex or concave, forming at least three lines of contact;
- Robot power and monitoring should be performed by a cable for possible emergency extraction at a failure.

Let us consider the robot motion unit in detail.

## 3. The Robot Motion Unit

While developing the robot motion unit its design has been determined and parameters of its drives and mechanisms have been calculated.

The motion unit is intended to create the required pulling force for robot motion to deliver the measuring module into pipeline, to move it in the course of monitoring along the vertical and horizontal pipeline sections and to ensure information exchange between the measuring module and control system. The robot comprises two identical motion units.

The physical configuration of motion unit is shown in Figure 7.

Motion unit comprises two motion modules (1) and the motor control circuit (2) stacked together via Cardan joints (3). Having two motion modules in motion unit structure enables increasing the robot total pulling force. Cardan joints allow passing bends with the rotation angle up to 90° with a radius of curvature on the axis of at least 1.5 times the pipeline diameter in vertical and horizontal planes.

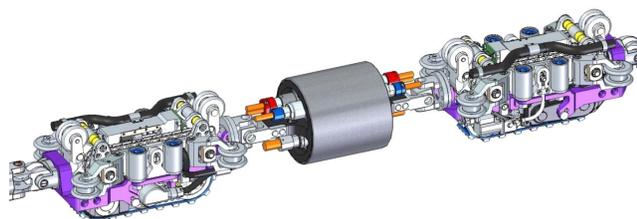
The physical configuration of motion module is shown in Figure 8.

The main elements of motion module are track (1) and folding mechanism (2).

Structurally, the track (see Figure 9) is a frame (1) with the drive assembly (2) mounted thereon, a relay roller (5) and track holder sensor (8). The drive assembly (2) consists of a motor (3) and a lead wheel (4). The motor (3) includes a motor, a reducer and encoder. The lead wheel (4) is designed as a toothed rim with the roller gear situated inside. The connection between the motor shaft and the Roller Screw Gear (RSG) is made by a flexible toothed belt. The protector having a toothed profile on its inner surface corresponding to the profile of the lead wheel toothed rim (4) is put on the lead wheel (4) and relay roller (6).

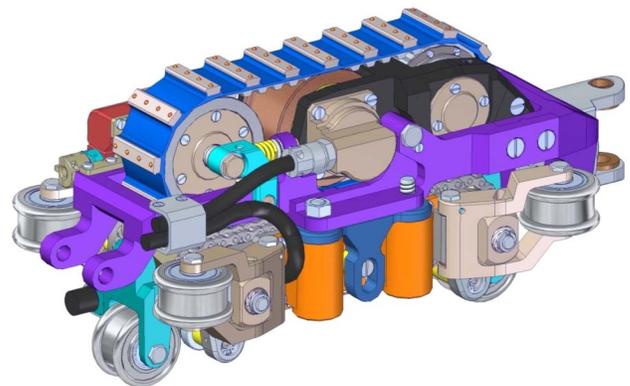
The required protector tension (6) is provided by relay roller motion (5) via a protector tension mechanism

1 2 1 3 3

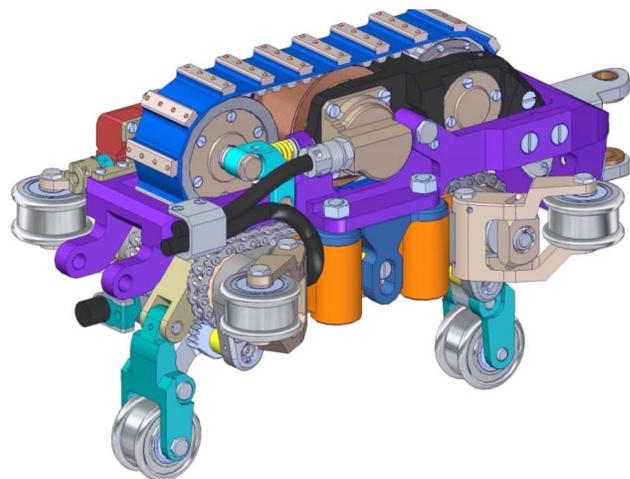


1 – Motion module.  
2 – Motor Control Circuit (MCC).  
3 – Cardan joint.

Figure 7. Physical configuration of motion unit.



(a)



(b)

1 – Track.	2 – Folding mechanism.	3 – Screw.
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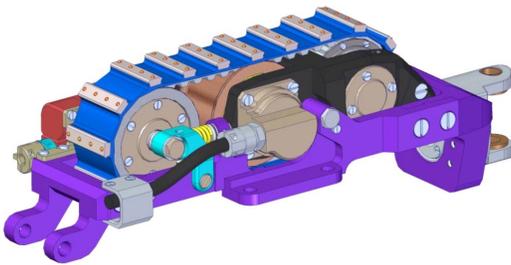
Figure 8. Physical configuration of motion unit. (a) Run-in position. (b) Operative position.

(7). The track holder sensor (8) supplies the management system with the information on thrusting efforts, i.e. efforts of track holder to the pipeline inner surface.

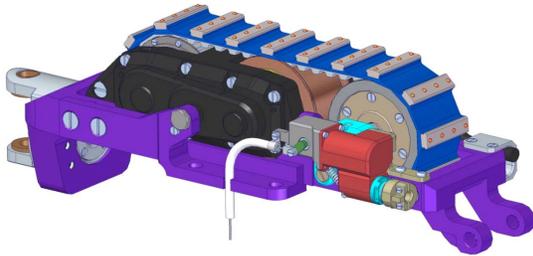
Folding mechanism design is shown in Figure 10.

Inside the frame (1) there is a motor (2), which rotates the screw of Ball Screw Unit (BSU) (4) with the electromagnetic coupling (3). The BSU screw is connected to the chain (5) with a lever. The BSU screw motion leads to motion of chain links (5) and rotation of lever mechanism (6) and (7) with wheel spacers (8) and (9) respectively. When folding wheel spacers (8) and (9) there is a decrease in efforts of track holder to the pipe and eventually, folding motion module to download it in the pipeline and the robot emergency extraction from a pipeline in an emergency case. Simultaneously with the reversal movement of lever mechanisms (6), (7) and wheel spacers (8), (9)

7 1 3 5



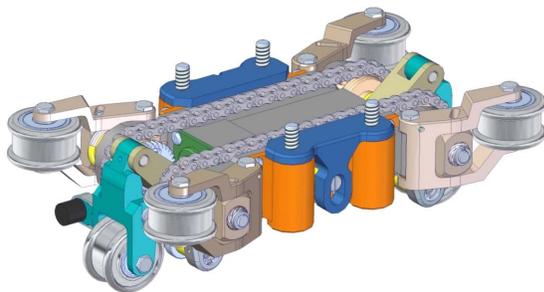
6 8 2 4



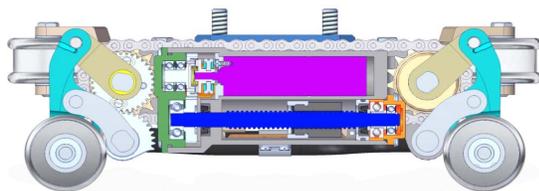
1 – Frame.	5 – Relay roller.
2 – Drive assembly.	6 – Protector.
3 – Engine.	7 – Protector tension device.
4 – Lead wheel.	8 – Track holder sensor.

Figure 9. Track design.

14 5 10 16 15 11 12 13



2 4 3 7 6 9 8 1



1 – Body frame.	8, 9 – Wheel spacers.
2 – Engine.	10, 11 – Lever mechanism.
3 – Electromagnetic coupling.	12, 13 – Side wheel.
4 – Ball Screw Assembly (BSA).	14 – Spring cartridge.
5 – Chain.	15 – Guard.
6, 7 – Lever mechanism.	16 – Screw.

Figure 10. Folding mechanism design.

from the same drive the lever mechanisms (10), (11) and side wheels (12), (13) rotate, providing support for motion module laterally. In their design the lever mechanisms (10), (11) have compression springs providing a constant pressure of the side wheels (12), (13) to the inner pipeline surface during advance of the motion module. When devoid of the power electromagnetic coupling (3) disengages the motor driving connection with the BSU, thus ensuring free rotation of the BSU shaft and folding lever mechanisms for the robot emergency eject out of the pipeline.

Amounting track on the folding mechanism is performed through two spring cartridges (14). The track is mounted on guard pads (15) with tightened screws in their back (16) and secured with nuts.

Inside the spring cartridge body (14) under each screw (16) there are cylindrical compression springs, ensuring the necessary pressing force of the track to the inner pipeline surface and the possibility of motion module movement into the pipeline having ovality, internal diameter change, sediments and contamination on the inner pipeline surface.

To provide the necessary thrust force in pipes of different diameters setting up spacers between the track and folding mechanism (see. Pos. 1 and 2, respectively, Figure 8), as well as replacement of lever mechanisms of wheel spacers and side wheels in accordance with Figure 11 is provided in module design.

## 4. Substantiation the Chosen Technical Solutions when Designing a Unit for Robot Motion along the Inner Pipeline Surface

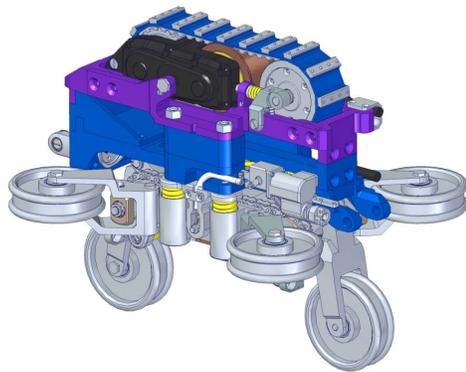
To assess robot motion unit working efficiency the selected technical decisions were substantiated and confirmed by the relevant calculations.

### 4.1. Motion Drive

To assess the drive working efficiency we will use the evaluation data:

Robot weight, kg, not more than	110.00
Maximum motion velocity, Vr, mm/s, not less than	50.00
The cable running meter weight, γK, kg	0.28

1 2 3 4 5 6 7 8 9 3



1 – Front beam.	4 – Spacer plate.	7 – Frame.
2 – Bracket.	5 – Tightening device.	8, 9 – Side lever.
3 – Vehicle lever.	6 – Bracket.	

Figure 11. Physical configuration of motion unit.

The lead drum diameter $D_d$ , mm	64.00
Gear ratio of roller gear $i_{RSG}$	252.00
The coefficient of performance (COP)	
RSG, $\eta_{RSG}$	0.70
The teeth number of tooth wheel $Z_1$	10.00
The teeth number of tooth wheel $Z_2$	122.00
Safety factor, $K_3$	2.00

### 4.1.1 Motion Drive Calculation

Motion Drive Calculation was carried out in accordance with the guide for designers and mechanical motorers.<sup>3</sup>

Kinematic scheme of motion drive is shown in Figure 12.

Rotation of the motor is transmitted through the tooth wheels  $Z_1, Z_2$  via a belt transmission to RSG, on the outer ring of which the track lead drum is mounted.

To select the motor let us calculate the torque extrapolated for the motor shaft of the maximum load on the track.

When moving in a horizontal pipe robot has to transport over a cable connection with a force at least equal the force, calculated by formula (4.1);

$$F_{DF} = P_C \cdot f_{CF}, \tag{4.1}$$

Where

$F_{DF}$  is the driving force in pipeline movement in the horizontal plane;

$f_{CF}$  is the coefficient of friction for cable against the pipe.

$P_C$  is the weight of the cable connection calculated by formula (4.1);

RSG

Engine

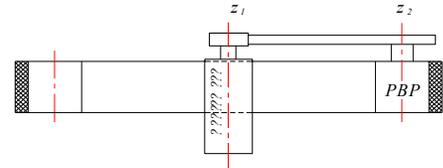


Figure 12. Kinematic scheme of motion drive.

$$P_C = \gamma_c \cdot l_c = 0.28 \cdot 400 = 112 \text{kg}, \tag{4.2}$$

Where  $\gamma_c$  is the weight of one meter of cable used in the design of the connecting cable,  $\gamma_c = 280 \text{ g}$ ;  $l_c$  is the length of the cable, used in the connecting cable design,  $l_c = 400 \text{ m}$ .

We find the driving force, substituting values in formula (4.1);

$$F_{DF} = 112.0 \cdot 0.3 = 33.6 \text{ kg}$$

If the trajectory of the robot movement in the pipeline includes vertical sections, the total driving force ( $F_{DF}$ ) should not be less than the force value calculated by formula (4.3);

$$F_{T\Sigma} = P_R + P_C + F_{DF}, \tag{4.3}$$

Where  $P_R$  is the robot weight,  $P_R = 110 \text{ kg}$ ;

$P_C$  is the weight of the cable, used in the cable connection design in the vertical section.

Since the robot movement in the pipeline may alternate up and down in inclined and vertical sections, then we take to calculate the worst-case scenario: when the robot transports the connecting cable along the horizontal pipeline section and 200 m – along the vertical one. At that the weight of two hundred meter cable connection in the vertical section  $P_{C200}$  is calculated by formula (4.4);

$$P_{C200} = \gamma_c \cdot 200 = 0.28 \cdot 200 = 56 \text{ kg}, \tag{4.4}$$

And the force for pulling the 200 m connecting cable at the horizontal section  $F_{DF200}$  is calculated by formula (4.5);

$$F_{DF200} = P_{C200} \cdot f_{DF} = 56 \cdot 0.3 = 16.8 \text{ kg} \tag{4.5}$$

Assuming  $F_{DF200} = 17$  kg, then the total required driving force makes:

$$F_{T\Sigma} = 110 + 56 + 17 = 183 \text{ kg}$$

Two motion units are components of the robot and composed two motion modules are components of motion unit, so the driving force of one motion module should not be less than the force value calculated by formula (4.6);

$$F_T = \frac{F_{T\Sigma}}{4} = \frac{183}{4} = 46 \text{ kg} \quad (4.6)$$

We accept on the safe side  $F_T = 60$  kg.

$$F_{T\Sigma} = 110 + 56 + 17 = 183 \text{ kg}$$

### 4.1.2 Motor Selection

The lead drum torque ( $M_D$ ) is calculated by formula (4.7);

$$M_D = F_T \cdot R_D. \quad (4.7)$$

Where  $R_D$  is the lead drum radius equal to 32 mm and taking into consideration tread thickness  $R_D = 40$ .

$$M_{B_D} = 60 \cdot 40 = 2400 \text{ kg} \cdot \text{mm} = 24 \text{ Nm}$$

The torque at the RSG output shaft (or at the tooth wheel  $Z_2$ ) is calculated by formula (4.8);

$$M_{RSG} = \frac{M_D}{i_{RSG} \cdot \eta_{RSG}}, \quad (4.8)$$

Where  $i_{RSG}$  is RSG gear ratio,  $i_{RSG} = 252$ ;

$\eta_{RSG}$  - RSG eff.  $\eta_{RSG} = 0.7$ .

$$M_{RSG} = \frac{24}{252 \cdot 0.7} = 0.136 \text{ Nm}$$

The torque extrapolated for the motor shaft ( $M_m$ ) is calculated by formula (4.9);

$$M_m = \frac{M_{RSG}}{i_z \cdot \eta_{1,2}} k_s, \quad (4.9)$$

Where  $i_{zp}$  - gear ratio of tooth wheels  $i_{zp} = \frac{z_2}{z_1}$ ;

$z_1$  is the teeth number on the motor shaft,  $z_1 = 10$ ;

$z_2$  is the teeth number on the motor shaft,  $z_2 = 22$ ;

$\eta_{1,2}$  is the belt drill efficiency  $z_1 - z_2$ ,  $\eta_{1,2} = 0.95$ ;

$k_s$  - storage coefficient,  $k_s = 2$ .

Having substituted the value in formula (9), we will find the torque extrapolated for the motor shaft:

$$M_m = \frac{0.136 \cdot 2}{2.2 \cdot 0.95} = 0.130 \text{ Nm.}$$

That is, the rated torque of the motor must be at least 130 mN m.

Define the desired speed of the motor shaft rotation  $n_e$  by formula (4.10) in terms of robot speed motion  $V_r = 50$  mm/s:

$$V_R = \frac{n_e}{i_{ZP} \cdot i_{RSU}} \cdot 2\pi \cdot R_D$$

$$\text{From which. } n_e = \frac{V_r \cdot i_{ZP} \cdot i_{RSU}}{2\pi \cdot R_D} \quad (4.10)$$

$$n_e = \frac{50 \cdot 2.2 \cdot 252}{2\pi \cdot 40} = 110.4 \text{ RPS} = 6624 \text{ RPM.}$$

That is, the rated speed of the motor rotation must be not less than 6650 RPM.

According to the calculated values of  $M_e$  and  $n_e$  chose EC-4 pole 30 motor in the Catalogue<sup>4</sup>.

## 4.2. Thrust Drive

Motion module weight, kg, no more than	10
Ball Screw Unit screw diameter (BSU), ds, mm	12
Pitch of BSU screw,	4
BSU static load rating, $C_0$ (H)	5700
BSU dynamic load rating, C (H)	3000
Teeth number of tooth wheel $Z_1$	37
Teeth number of tooth wheel $Z_2$	38
Teeth number of tooth wheel $Z_3$	33
Teeth number of tooth sector $Z_4$	33
Sprocket reference diameter $d_p$ , mm	45
Expandable roller lever length l, mm	33
Tooth gear efficiency, $\eta_{ig}$	0.97
Chain gear efficiency, $\eta_{cg}$	0.954 ÷ 0.98
BSU efficiency, $\eta_{BSU}$	0.94

### 4.2.1 Thrust Drive Calculation

Drive calculation is carried out in accordance with the textbook<sup>5</sup>.

The thrust drive kinematic scheme is shown in Figure 13.

The rotation of the motor through the gears  $Z_1$  and  $Z_2$  is transmitted to the BSU shaft. The BSU screw moving

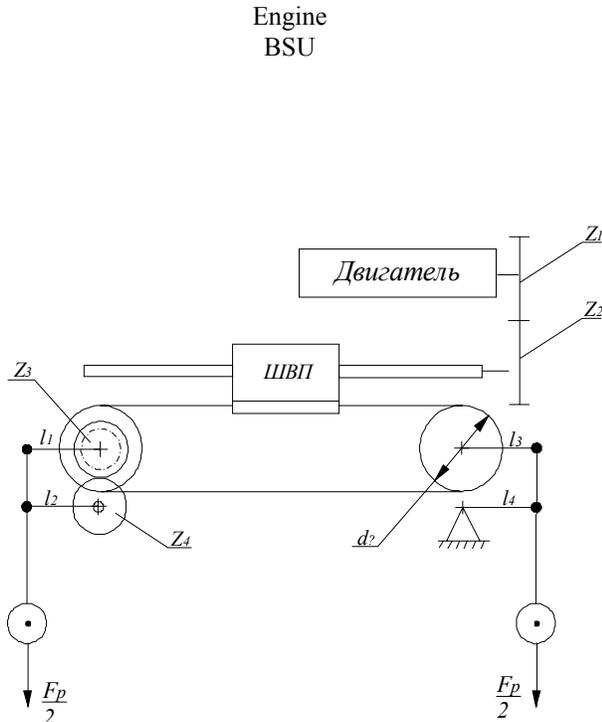


Figure 13. Kinematic scheme of thrust drive.

along the spiral entails the chain that drives two sprockets. Each sprocket is connected with a lever mechanism of wheel spacer. Lever mechanisms are parallelograms, one arm of which is connected with its sprocket of the chain drive. Levers  $l_1, l_4$  freely rotate on axes, lever  $l_2$  is connected with the sprocket axis by gears  $Z_3$  and  $Z_4$ , and lever  $l_3$  is fastened to the second sprocket axis and rotates together with it. The length of levers  $l_1 - l_4$  is the same.

When pulling force  $F_p = 80$  kg, thrust force  $F_T$  is calculated by formula (4.11);

$$F_T = \frac{F_p}{f}, \tag{4.11}$$

Where  $f$  is the coefficient of friction of rubber on steel,  $f = 0.5$ .

That is  $F_T = \frac{80}{0.5} = 160$  kg

### 4.2.2 Motor Selection

To select the motor you need to calculate the torque extrapolated for the motor shaft and the rotation speed of the motor shaft.

For the calculation consider the worst-case scenario: the axis of lever  $l_2$  is connected with the sprocket axis and tooth wheels  $Z_3$  and  $Z_4$  and the angle of lever inclination  $l_2$  is  $0^\circ$  (Figure 14).

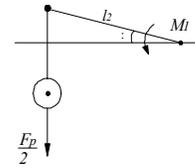


Figure 14. Configuration for determining torque required to generate one wheel thrust force.

The torque required to create a thrust force of one wheel  $M_1$ , is calculated by formula (4.12);

$$M_1 = \frac{F_T}{2} \cdot l_2 \cdot \cos\alpha \tag{4.12}$$

The maximum value of this torque when  $\alpha = 0^\circ$ .

Then  $M_1 = \frac{F_T}{2} \cdot l_2$ .

The torque extrapolated for the sprocket axis and chain gear  $M_2$ , is calculated by formula (4.13);

$$M_2 = \frac{M_1}{i_{3,4} \cdot \eta_{tg}} \tag{4.13}$$

Where  $i_{3,4}$  is the gear ratio of tooth gear  $Z_3, Z_4$ , is determined by formula (4.14);

$$i_{3,4} = \frac{Z_4}{Z_3} = \frac{33}{33} = 1 \tag{4.14}$$

$\eta_{tg}$  is the tooth gear efficiency,  $\eta_{tg} = 0.97$ , then,

$$M_2 = \frac{M_1}{i_{3,4} \cdot \eta_{tg}} = \frac{F_T \cdot l_2}{2 \cdot i_{3,4} \cdot \eta_{tg}} = \frac{160 \cdot 33}{2 \cdot 1 \cdot 0.97} = 2722 \text{ kg}\cdot\text{mm} = 27.2 \text{ N}\cdot\text{m}.$$

The force to be created by the BSU screw to rotate the two sprockets  $F_{BSU}$ , is determined by formula (4.15);

$$F_{BSU} = \frac{2 \cdot M_2 \cdot 2}{d_g \cdot \eta_{CG}} \tag{4.15}$$

Where  $d_g$  is the sprocket reference diameter,  $d_g = 45$  mm;  $\eta_{CG}$  is the chain gear efficiency,  $\eta_{CG} = 0.96$ ;

Then  $F_{BSU} = \frac{2 \cdot 27.2 \cdot 2 \cdot 1000}{45 \cdot 0.96} = 1890$  N.

The torque extrapolated for the sprocket axis for the motor shaft, is determined by formula (4.16);

$$M_e = \frac{F_{BSU} \cdot P}{2000 \cdot \pi \cdot \eta_{BSU} \cdot \eta_{CG} \cdot i_{1,2}} \tag{4.16}$$

Where  $P$  is BSU pitch screw,  $P = 4$  mm;

$\eta_{BSU}$  is the BSU efficiency,  $\eta_{BSU} = 0.94$ ;  
 $\eta_{tg}$  is the tooth gear efficiency  $Z_1, Z_2, \eta_{tg} = 0.97$ ;  
 $i_{1,2}$  is the gear ratio of the tooth gear  $Z_1, Z_2, i_{1,2} = \frac{Z_2}{Z_1} = \frac{38}{37}$ .

Then  $M_e = \frac{1890 \cdot 4 \cdot 37}{2000 \cdot 3.14 \cdot 0.94 \cdot 0.97 \cdot 38} = 1.28 \text{ N.m.}$

Define the desired speed of the motor shaft. The initial data will include a range of expandable rollers motion  $\Delta h = 50 \text{ mm}$  and motion time  $t = 30 \text{ s}$  (see Figure 15);

Sprocket angle of bend  $\alpha$  and corresponding to the expandable roller motion at  $\Delta h = 50 \text{ mm}$ , is determined by the design parameters of the lever mechanism,  $\alpha = 96^\circ$ . BSU screw motion  $\Delta l$  is then determined by formula (4.17);

$$\Delta l = \frac{\alpha \cdot \pi d_g}{360^\circ}, \tag{4.17}$$

Where  $\alpha$  – sprocket angle of bend,  $\alpha = 96^\circ$ ;

$d_g$  is the sprocket reference diameter,  $d_g = 41 \text{ mm}$ .

Insert values in formula (4.17). We receive:

$$\Delta l = \frac{96 \cdot \pi \cdot 45}{360^\circ} = 38 \text{ mm.}$$

At the BSU pitch screw  $p = 4 \text{ mm}$  for the screw motion  $\Delta l = 38 \text{ mm}$  during  $t = 25 \text{ sec}$ , is the speed of its rotation  $n_{BSU}$  is determined by formula (4.18);

$$n_{BSU} = \frac{\Delta l}{p \cdot t} \tag{4.18}$$

Inserting values into formula (4.18), we receive:

$$n_{BSU} = \frac{38}{4 \cdot 25} = 0.2 \text{ RPS} = 12 \text{ RPM.}$$

The rotation speed of the motor output shaft is determined by formula (4.19);

$$n_e = n_{BSU} \cdot \frac{Z_2}{Z_1} \tag{4.19}$$

Then  $n_e = 12 \cdot \frac{38}{37} = 12.3 \text{ RPM. RPM.}$

According to calculated values  $M_e = 1.28 \text{ N.m}$  and  $n_e = 12.3 \text{ RPM}$  in the catalogue<sup>4</sup> we will choose the A-max 26 motor with the GP26A reduction gear box.

## 5. Conclusion

To detect defects in the heating pipe mains appliances information measuring systems are used which are based on different nondestructive monitoring methods. However, almost all of them have significant drawbacks: they require a large amount of preparatory work which consumes time to perform monitoring, do not provide non-contact object monitoring, they have a strong dependence of the sensitivity and accuracy of the pipe material properties and the location of defects. Therefore, a new method of NDT for ILD was developed which allows carrying out pipe thickness gauging without surface preparation – through the layer and corrosive and slurry sediments with high productivity, while providing sufficient clearance between the surface of the object under monitoring and system measuring module

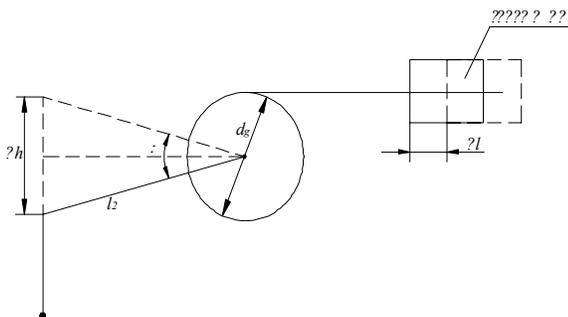
To perform the developed method it is necessary to ensure measuring module motion inside the pipe. The result is that there is a need to develop a device for the robot delivery and motion.

To determine the robot design the existing systems for ILD were reviewed, their design solutions, pros and cons were considered and the robot motion unit was worked out on the basis of the findings.

In the process of work a sketch design documentation of the robot motion unit was developed, this unit design was determined, the parameters of its drives and mechanisms were calculated.

## 6. Acknowledgment

The research is carried out in compliance with ARAD “Applied research on creation of a new non-contact magnetic method for nondestructive testing of pipelines with alternating magnetization of metal and advanced development of an experimental prototype of an in-line robotic system based on this method providing solu-



**Figure 15.** Configuration for determining relationship between BSU screw travel and expandable roller travel.

tion to the timely inspection of corrosion damage in subsurface pipelines of small-diameter heating networks (DN200, DN400) without pipeline break in the energy and utilities area”, Unique identifier of Applied Research and Advanced Developments RFMEFI58114X0004 in the ITMO University.

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