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BRISTLED PIPE ROBOT WITH ADJUSTABLE BRISTLES

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Abstract: The bristled pipe robot moving in the pipe on the principle of friction difference is intended for locomotion in the pipe using the friction difference between the bristles and the pipe's inner wall. The robot consists of an electromagnetic linear actuator, on the frame of which the rear bristle block is attached and on its extension rod, the front bristle block is placed. The bristle blocks contain three bristle carriers and clamps. The bristles are the contact elements between the robot and the pipe's inner wall. The geometry of the bristles can be adjusted using the adjusting elements. The bristles are mounted on the robot so that the span of their free ends is greater than the inner diameter of the pipe, thus creating the desired normal and frictional force between the pipe wall and the bristle ends. The bristles are mounted at a mounting angle concerning the robot axis, thus creating a difference in friction between the pipe wall and the bristles as they move back and forth, resulting in a forward movement of the robot.

1 Introduction

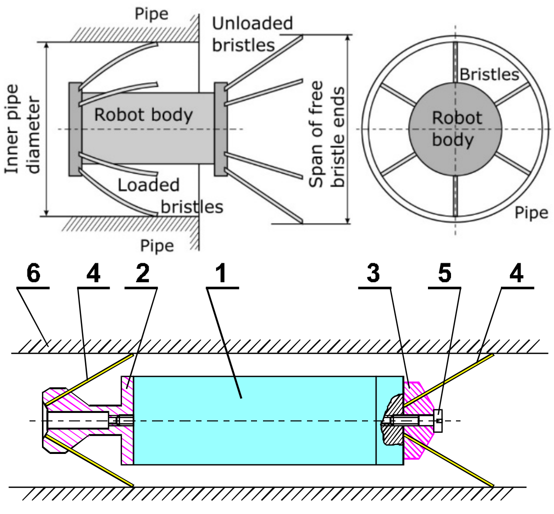
If we imagine a vehicle moving on a solid surface, most of us imagine a kind of "monster" with wheels. However, it is not just the wheels that move the world, and in some situations, the wheels cannot cope, and what we often see on snowy and icy roads will happen. Therefore, unconventional types of contact elements between the moving means and the surface are increasingly used. The vast majority of them are inspired by biological patterns. All we need is a look at the fascinating movement of a spider, caterpillar or cockroach, etc.

Pipe robot move in the pipeline, and their task is mostly inspection work, repair of the pipeline or installation of cables in the pipeline, or other special tasks. With the decreasing inner diameter of the pipe, wheel slippage becomes a serious problem, especially in the case of dirty pipes.

Instead of wheels, it is possible to use, e.g. bristles. Then we are talking about a bristled in-pipe robot (fig. 1). This article deals with the application of bristles in the role of supporting elements for pipe robot. Bristles are bending springs that are embedded at one end. Bristles are often used in common practice, e.g. for sealing the bearing spaces of rotating parts, which are exposed to extreme conditions (high pressure and temperature, the presence of aggressive substances, etc.) [1-21].

2 Robot motion analysis

In the case of the solved in-pipe robot, the bristles are mounted on two modules around the circumference while they are positioned diagonally (obliquely) with respect to the axis of the robot and the pipe. A suitable actuator is to achieve a cyclic change in the distance between these bristle modules and, due to the existence of a friction difference between the bristle and the inner pipe wall as the bristle moves back and forth, the entire robot moves. The choice of the use of diagonal bristles (fig. 1) results from the experience in solving pipe robot within the solved research tasks. The problem is to design the bristles so that the movement of the robot is as efficient as possible.



1 - actuator; 2 - front bristle block; 3 - rear bristle block; 4 - bristles; 5 - screw for fixing the bristle block; 6 - pipe

Figure 1 The principle of locomotion of a pipe robot

To derive the mean speed of the V_S robot, it is possible to use the extended Hamiltonian principle for steady oscillation of the actuator. A representation of Hamilton's principle is that the robot moves to minimize the overall work done by the robot. This work includes W_{IW} work done on the inner wall of the pipeline and external W_E work. If we assume that the actuator will perform harmonic movements, then the speed of movement of the bristle end in the direction of the robot's movement is approximately described by (1), (2):

$$v_1 = v_s + v_b(\omega)\cos(\omega t) \qquad (1)$$

$$v_2 = v_s - v_b(\omega)\cos(\omega t) \qquad (2)$$

Where:

ω - angular velocity of the actuator,

v_S - steady speed actuator.

The speeds v_1 and v_2 represent the bristle ends of the front and rear bristle blocks.

The total work done by robot W is determined by (3):

$$W = W_E + W_{IW} \qquad (3)$$

Where the work done by the front bristle block on the inner wall of the robot is (4):

$$W_{IW1} = \int_{-\frac{T}{4}}^{t_1} N_0\mu_2 v_2 dt - \int_{t_1}^{t_2} N_0\mu_1 v_1 dt + \int_{t_2}^{\frac{T}{4}} N_0\mu_2 v_1 dt \qquad (4)$$

And the work done by the robot's rear bristle block on the inner wall is (5):

$$W_{IW2} = \int_{-\frac{T}{4}}^{\frac{T}{4}} N_0\mu_2 v_2 dt \qquad (5)$$

The external work of the robot is defined by the relationship (6):

$$W_E = \frac{F \cdot v_s T}{2} \qquad (6)$$

Where F is the traction force that can be derived from this relationship.

The steady speed of the robot can then be derived in the form of (7):

$$v_s = \frac{\pi\left[2(\mu_1 - \mu_2) - \frac{F}{N_0}\right]}{4(\mu_1 + \mu_2)} \cdot v_b \qquad (7)$$

The pipe robot is designed for movement inside the pipeline for the purpose of inspection or repair of damaged pipeline or for the purpose of transporting cables or other equipment inside the pipeline. Existing solutions usually use the wheeled principle of movement in the pipeline, but this principle of motion is ineffective if the inner wall of the pipeline is covered with dirt and deposits. The subject of this work is a robot that allows movement in the pipeline by means of bristles, which are contact elements with the wall of the pipeline and allow movement even along the dirty wall of the pipeline.

3 The principle of the robot's function

The robot is designed to move inside the pipeline. The contact elements of the robot are three bristles placed evenly around the perimeter of the robot in two blocks - front and rear block. The bristles are attached to the robot so that the span of their free ends is larger than the inner diameter of the pipe, and thus when the robot is inserted into the pipe, the bristles are deformed and a normal contact force and frictional force is created between the robot and the inner wall of the pipe (fig. 1). The bristles are held at a mounting angle with respect to the axis of the robot, so that when the bristles move, there is a difference in frictional force. This means that the friction force between the bristle and the pipe wall is less when moving in the direction of the bristle bevel than when moving in the direction against the bristle bevel (fig. 1, 2).

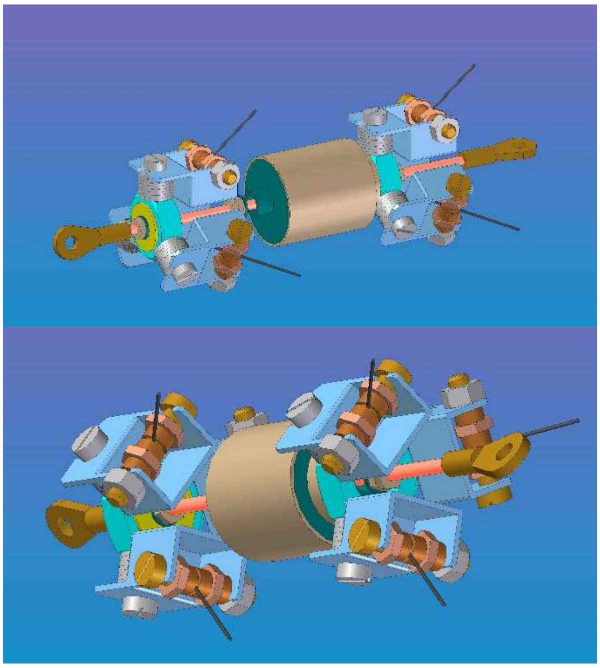


Figure 2 Pipe robot arrangement with adjustable bristles

The rear bristle block is attached to the frame of the linear electromagnetic actuator coil. The front bristle block is attached to the extension rod of the linear electromagnetic actuator. Activation of the linear electromagnetic actuator cyclically extends and retracts the extension rod, thus creating a change in the relative position of the front and rear bristle blocks. The difference in the frictional force of the bristles will cause the robot to move forward (fig. 2).

The essence of the robot is that the friction difference between the bristles and the inner wall of the pipe is used to create a movement of the robot in the pipe.

The advantage of this piping robot solution is that it allows movement even in piping that is dirty and contains deposits.

Another advantage is that the robot allows to adjust the geometry of the bristles - the length of the bristle attachment, the mounting angle of the bristles and the distance of the bristle attachment from the axis of the robot. By optimally adjusting the geometry of the bristles, it is possible to achieve that the return movement of the bristles is minimal and thus it is possible to achieve the phenomenon of self-locking of the return movement of the robot, thus increasing the efficiency of the robot movement in the pipeline (fig. 3).

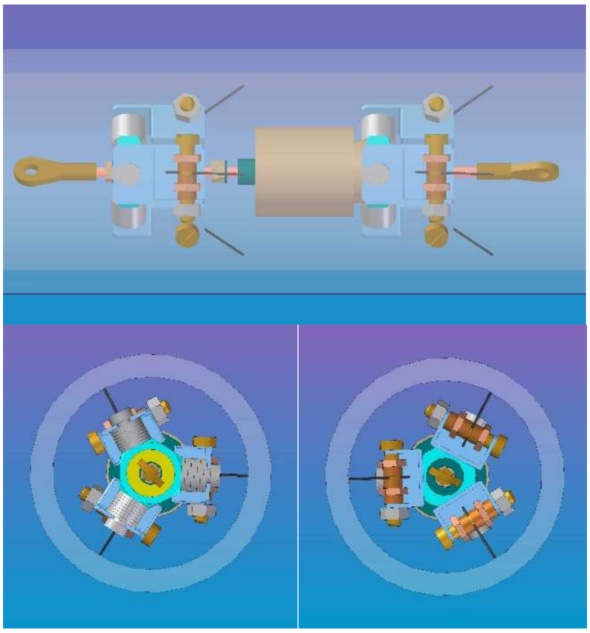


Figure 3 Pipe robot in the pipeline

4 Realisation of a pipeline robot

The robot comprises an electromagnetic linear actuator (1) for creating a linear reciprocating motion (fig. 4). A rear bristle block (3) is attached to the frame of the linear electromagnetic actuator (1).

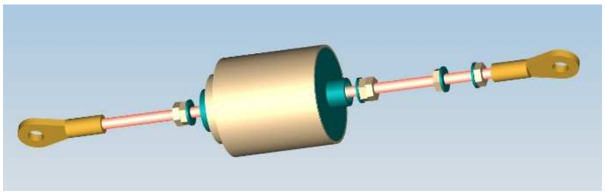


Figure 4 Electromagnetic linear actuator

The front bristle block (2) is attached to the extension rod (9) of the electromagnetic linear actuator (1) (fig. 5). The front bristle block (2) and the rear bristle block (3) are identical.

The bristle block (2, 3) comprises three bristle carriers (4), in which bristle clamps (6) with inserted bristles (5) are inserted. The bristle clamp (6) allows you to adjust the length of the free end of the bristle (5) and the mounting angle of the bristle (5). The carriers (4) are fastened with screws (7) for fastening the bristle carrier to the bristle block (2, 3) (fig. 6, 7).

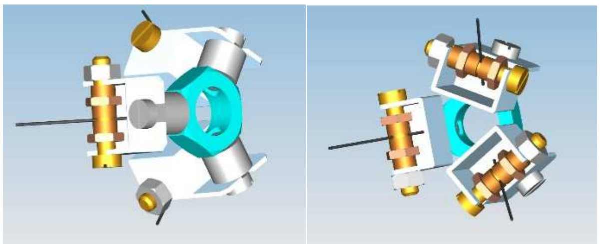


Figure 5 Bristle block

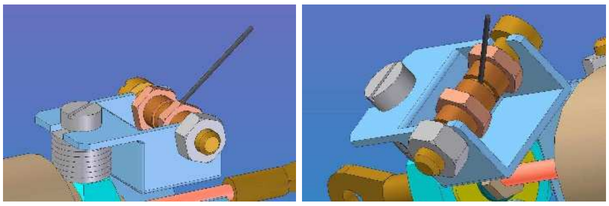
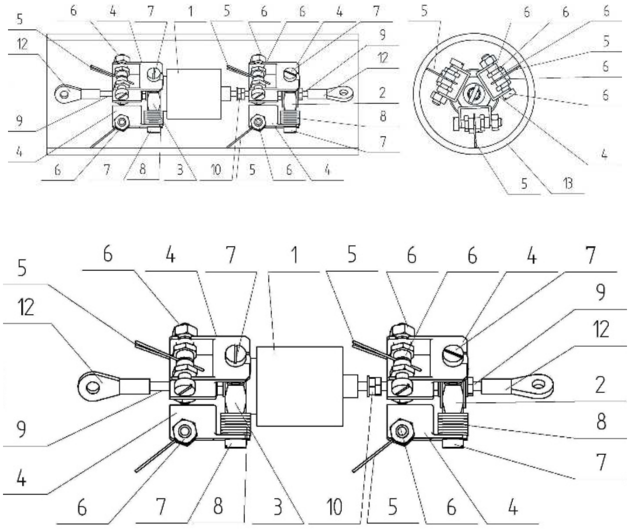


Figure 6 Bristle geometry adjustment mechanism



1 - Electromagnetic linear actuator; 2 - Front bristle block; 3 - Rear bristle block; 4 - Bristle carrier; 5 - Bristles; 6 - Bristle clamp; 7 - Screw for attaching the bristle carrier to the bristle block; 8 - Spacers for adjusting the distance of the bristle from the robot axis; 9 - Linear actuator extension rod; 10 - Actuator stroke adjustment nut; 11 - Nuts for securing the front bristle block to the actuator extension rod; 12 - Actuator hanging eye; 13 - Piping

Figure 7 Pipe robot components

Under each bristle carrier (4), spacers (8) are inserted to adjust the distance of the bristle (5) from the axis of the robot. To adjust the stroke of the linear electromagnetic actuator (1), nuts (10) for adjusting the stroke of the actuator are arranged on the extension rod (9) of the actuator. The front bristle block (2) is attached to the extension rod (9) of the linear electromagnetic actuator by means of nuts (11) for holding the front block. The robot moves in the pipe (13) by cyclically changing the stroke of the actuator, using the difference of friction between the bristles (5) and the wall of the pipe (13). On the extension rod (9) of the electromagnetic linear actuator (1), suspension eyes (12) are attached for attaching the guide wire (fig. 7, 8).

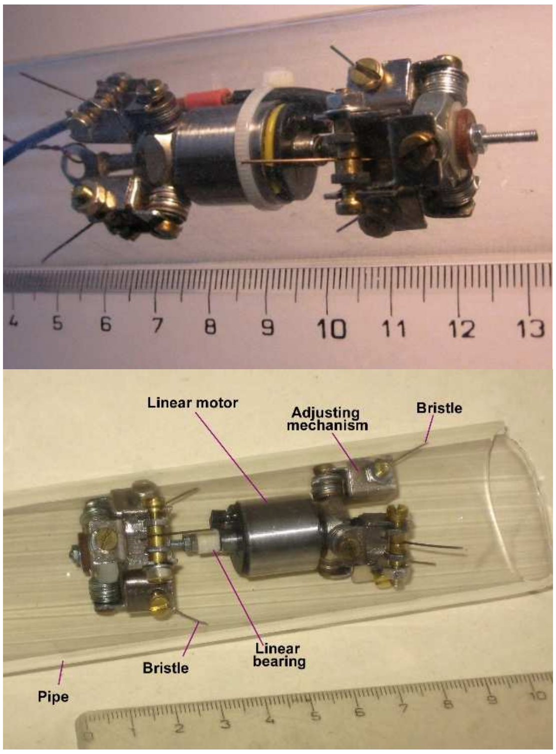


Figure 8 Pipe robot prototype

The overall dimensions of the prototype (fig. 8) are 25 mm in diameter and 80 mm in length. The robot was tested for pipes with an inner diameter of 35 mm. In this pipeline, the robot reached a maximum speed of 50 mm / min. But this is still the subject of further research in the future to find the optimal geometry to achieve the maximum speed and traction of the robot.

5 Conclusion

The application of bristles in the role of supporting elements for a pipe robot brings with it a number of advantages in the form of elimination of slippage on the contaminated inner surface of the pipe and better adaptation due to geometric deviations in the size and shape of the pipe. Their application is especially important for pipes with a small inner diameter (less than 25 mm). This work was focused on the design of a mechatronic system for a specified purpose, and other works are known from practice, where a similar methodology is followed [22-33].

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References

[1] AOSCHIMA, S., TSUJIMURI, T., YABUTA, T.: *'Design and analysis of a midget mobile robot using piezo vibration for mobility in a thin tube '*, In Proc. of

the International Conference on Advanced Mechatronics, Tokyo, pp. 659-663, 1989.

[2] SUZUMORI, K., MIYAGAWA, T., KIMURA, M., HASEGAWA, Y.: Micro Inspection Robot for 1-in Pipes, *IEEE/ASME Transactions on Mechatronics*, Vol. 4, No. 3, September 1999, pp. 286-292, 1999.

[3] HIROSE, S., OHNO, H., MITSUI, T. and SUYAMA, K.: '*Design of In-Pipe Inspection Vehicles for φ25, φ50, φ150 Pipes* ', In Proceedings of the 1999 IEEE International Conference on Robotics and Automation, Detroit, Michigan, May 1999, pp. 2309-2314, 1999.

[4] JUN, Ch., TAO, Ch., ZONGQUAN, D.: '*Design method of Modular Units for Articulated in-Pipe Robot Inspecting System* ', 2011 IEEE Second International Conference on Digital Manufacturing & Automation, pp. 389-392, 2011.

[5] BERTETTO, AM., RUGGIU, M.: '*In-pipe inch-worm pneumatic flexible robot* '. In Proc. of IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Vol. 2. Italy; pp. 1226-31, 2001.

[6] QIAO, J., SHANG, J., GOLDENBERG, A.: Development of inchworm in-pipe robot based on self-locking mechanism. *IEEE/ASME Transactions on Mechatronics*, Digital Object Identifier 10, 1109/TMECH, 2012.

[7] BYUNGKYU, K., MOON GU, L., YOUNG PYO, L., YONG In, K., GEUN Ho, L.: An earthworm-like micro robot using shape memory alloy actuator, *Sensors and Actuators A*, Vol. 125, pp. 429-437, 2006.

[8] KUWADA, A., TSUJINO, K., SUZUMORI, K., KANDA, T.: '*Intelligent Actuators Realizing Snake-like Small Robot for Pipe Inspection* ', In Proc. of International Symposium on Micro-Nano Mechatronics and Human Science, 2006, Nagoya, pp. 1-6, 2006.

[9] NEUBAUER, W.: Locomotion with articulated legs in pipes or dusts, *robot. Autonomous Syst.*, Vol. 11, No. 3-4, pp. 163-169, 1993.

[10] YUM, Y.J., HWANG, H.S., KELEMEN, M., MAXIM, V., FRANKOVSKÝ, P.: In-pipe micromachine locomotion via the inertial stepping principle, *Journal of Mechanical Science and Technology*, Vol. 28, No. 8, pp. 3237-3247. 2014.

[11] DEGANI, A., FENG, S., CHOSET, H., MASON, M.T.: '*Minimalistic, Dynamic, Tube Climbing Robot*', Proc. of 2010 IEEE Int. Conf. on Robotics and Automation Anchorage Convention District, May 3-8, 2010, Anchorage, Alaska, USA, pp. 1100-1101, 2010.

[12] GMITERKO, A., DOVICA, M., KELEMEN, M., FEDÁK, V., MLÝNKOVA, Z.: '*In-Pipe Bristled Micromachine*', In Proc. of 7th Int. Workshop on Advances Motion Control July 3-2. 2002, Maribor, pp. 467-472, 2002.

[13] GMITERKO, A., DOVICA, M., KELEMEN, M., FEDÁK, V., MLÝNKOVA, Z.: 'In-Pipe Bristled Micromachine', In Proc. of 7th Int. Workshop on Advances Motion Control July 3-2. 2002, Maribor, pp. 467-472, 2002.

[14] YAGUCHI, H., IZUMIKAWA, T.: Performance of cableless magnetic in-piping actuator capable of high-speed movement by means of inertial force, *Advances in Mechanical Engineering*, Vol. 2011, ID 485138 (2011), pp. 1-9, 2011.

[15] IZUMIKAWA, T., YAGUCHI, H.: Novel Cableless Magnetic Actuator Capable of High-speed Locomotion in a Thin Pipe by Combination of Mechanical Vibration and Electromagnetic Force, *Procedia Engineering*, Vol. 29, pp. 144-149, 2012.

[16] MAŤAŠOVSKÁ, T., KELEMEN, M.: '*Wheeled in-pipe micromachine - Fenaus*', In Mechatronics, Robotics and Biomechanics 2003, Brno VUT, 2003, pp. 71-72. 2003.

[17] BOCKO, J., KELEMEN, M., KELEMENOVÁ, T., JEZNÝ, J.: Wheeled locomotion inside pipe, *Bulletin of Applied Mechanics*, Vol. 5, No. 18, pp. 34-36. 2009.

[18] ČEREVKA, T.: '*Design pressure arm of the pipe robot for locomotion in the pipe with inside diameter over 100mm*', In Winter Workshop of Applied Mechanics 2007: Prague, Czech Republic, February 16, 2007, Prague: CTU, 4 p. 2007.

[19] RUSNÁK, J., ČEREVKA, T.: Real time measurement of the force generetad in deformed spiral spring, *Acta Mechanica Slovaca*, Vol. 12, No. 3-B, pp. 677-690, 2008.

[20] GMITERKO, A., KELEMEN, M., KELEMENOVÁ, T., MIKOVÁ, Ľ.: Adaptable Mechatronic Locomotion System, *Acta Mechanica Slovaca*. Vol. 14, No. 4, pp. 102-109. 2010.

[21] VACKOVÁ, M. et all: '*Intelligent In-pipe Machine Adjustable to Inner Pipe Diameter* ', In SAMI 2012: 10th IEEE Jubilee International Symposium on Applied Machine Intelligence and Informatics: proceedings: Herľany, Slovakia, January 26-28, 2012, Budapest: IEEE, 2011, pp. 507-513, 2012.

[22] DUCHOŇ, F., HUBINSKÝ, P., HANZEL, J., BABINEC, A., TÖLGYESSY, M.: Intelligent Vehicles as the Robotic Applications, *Procedia Engineering*, Vol. 48, 2012, pp. 105-114. 2012.

[23] KONIAR, D., HARGAŠ, L., ŠTOFAN, S.: Segmentation of Motion Regions for Biomechanical Systems, *Procedia Engineering*, Vol. 48, 2012, pp. 304-311, 2012.

[24] VITKO, A., JURIŠICA, L., KĽÚČIK, M., MURÁR, R., DUCHOŇ, F.: Embedding Intelligence into a Mobile Robot, *AT&P Journal Plus*, Vol. 2008, No. 1, Mobile robotic systems, pp. 42-44, 2008.

[25] BOŽEK, P.: Robot path optimization for spot welding applications in automotive industry, *Tehnicki vjesnik / Technical Gazette*, Sep/Oct 2013, Vol. 20, No. 5, pp. 913-917, 2013.

[26] PÁSZTÓ, P., HUBINSKÝ, P.: Mobile robot navigation based on circle recognition, *Journal of*

Electrical Engineering, Vol. 64, No. 2, pp. 84-91, 2013.

[27] ABRAMOV, I.V., NIKITIN, Y.R., ABRAMOV, A.I., SOSNOVICH, E.V., BOŽEK, P.: Control and Diagnostic Model of Brushless DC Motor, *Journal of Electrical Engineering*, Vol. 65, No. 5, pp. 277-282, 2014.

[28] KARAVAEV, Y.L., KILIN, A.A.: Nonholonomic dynamics and control of a spherical robot with an internal omniwheel platform: Theory and experiments, *Proceedings of the Steklov Institute of Mathematics*, Vol. 295, No. 1, pp. 158-167, 2016.

[29] VIRGALA, I., MIKOVÁ, Ľ., KELEMEN, M., HRONCOVÁ, D.: Snake-like robots, *Acta Mechatronica*, Vol. 3, No. 4, pp. 7-10, 2018.

[30] MIKOVÁ, Ľ., VIRGALA, I., KELEMEN, M.: Embedded systems, *Acta Mechatronica*, Vol. 3, No. 2, pp. 1-5, 2018.

[31] KELEMENOVÁ, T., FRANKOVSKÝ, P., VIRGALA, I., MIKOVÁ, Ľ., KELEMEN, M., DOMINIK, L.: Educational models for mechatronic courses, *Acta Mechatronica*, Vol. 1, No. 4, pp. 1-6, 2016.

[32] LIPTÁK, T., KELEMEN, M., GMITERKO, A., VIRGALA, I., HRONCOVÁ, D.: The control of holonomic system, *Acta Mechatronica*, Vol. 1, No. 2, pp. 15-20, 2016.

[33] KURYŁO, P., PIVARČIOVÁ, E., CYGANIUK, J., FRANKOVSKÝ, P.: Machine vision system measuring the trajectory of upper limb motion applying the Matlab software, *Measurement Science Review*, Journal of Institute of Measurement Science of Slovak Academy of Sciences, Vol. 19, No. 1, pp. 1-8, 2019.

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