Integrated kinematics of DOBOT MG400 robot in Matlab and CAD simulation

Sylvester Bozherikov, Mina Tsoneva

***Abstract*—In this paper, a methodology for studying the kinematics of a DOBOT MG400 robot is proposed. The main points are related to the creation of a kinematic model using an analytical method for kinematic analysis and the construction of a block structure model in Matlab in order to implement the direct and inverse kinematics problem. A geometric model of the robot in a CAD environment has also been created for the purpose of simulation and comparison of the obtained numerical solutions in Matlab.**

***Keywords*— CAD, direct and inverse kinematics problem, geometric model, kinematics, kinematic model, , Matlab.**

I. INTRODUCTION

In recent years, robotic manipulators have become essential tools in industrial automation, precision, quality manufacturing and research applications and activities. The DOBOT MG400 robotic manipulator stands out as a compact and cost-effective solution, particularly suitable and oriented towards automation tasks and educational purposes. A basic requirement for the effective use and operation of such manipulators and systems is the understanding and knowledge of their kinematics and movement capabilities. This requires a comprehensive kinematic study - introduction of generalized coordinates and derivation of the mathematical apparatus for describing the movement of the mechanism.

This article offers a comprehensive methodology for kinematic analysis of the DOBOT MG400, combining analytical modeling through numerical implementation in MATLAB and CAD-based simulation. The goal is to create a reliable kinematic model, to simulate and validate its behavior based on the built three-dimensional model. In this way, we verify its correctness with multiple tools and approaches.

The process begins with the creation of a kinematic and structural diagram, the introduction of coordinate systems and generalized coordinates, and the derivation of kinematic dependencies for solving the direct and inverse kinematics of the robot. The direct kinematics problem calculates the position of a point on the executive unit given known generalized coordinates, while the inverse problem specifies the kinematic characteristics of the end-member motion – the laws of motion of the driving units are sought. [1]

In order to implement both tasks of the kinematics of the mechanism under consideration, a simulation based on the block structures of MATLAB has been developed. The analytical expressions are converted into MATLAB scripts and functions, which allows numerical evaluation under

different input data and conditions. Block diagrams representing the functional structure of the system have been built in Simulink. Customized subsystems for solving the direct and inverse kinematics have been added. Through this simulation, the validity and response of the model under different configurations can be analyzed in a time-efficient and visual manner.

A detailed geometric model of the DOBOT MG400 was created in a CAD environment (SolidWorks). This three-dimensional model reproduces the physical dimensions and structure of the robot joints, serving as both a reference model and a simulation source. The CAD model is used to perform motion simulations based on joint input data,

allowing for a visual comparison of the robot behavior with the numerical results obtained in MATLAB. This cross-validation ensures that the analytical and numerical models are consistent with the actual geometry and motion constraints of the physical system.

By integrating analytical modeling, MATLAB-based simulation, and CAD-based visualization, this methodology provides a robust and multifaceted approach to studying the kinematics of the DOBOT MG400. This work not only supports the development of control strategies and motion planning but also serves as a foundation for future research in this area, including dynamic modeling and the development and validation of real-time systems and control.

II. KINEMATIC MODEL OF THE DOBOT MG400

DOBOT MG400 is a manipulator with an anthropomorphic structure that resembles a human arm (*Fig. 1*). It has three degrees of freedom. These are one rotation around the vertical axis and two rotations around parallel horizontal axes.

Fig. 1. DOBOT MG400 robot construction [6]

2.1. KINEMATIC SCHEME

Fig. 2 shows the kinematic diagram of the robot's manipulation mechanism. It consists of ten links that are interconnected by rotational kinematic pairs of the Vth class. An **Oxyz** coordinate system is introduced. The degrees of freedom of the mechanism are:

- rotation of unit 1 around an axis Oz;

- rotation of link 3 around an axis parallel to the axis O′x′;
- the rotation of link 6 around an axis parallel to the axis O″x″.

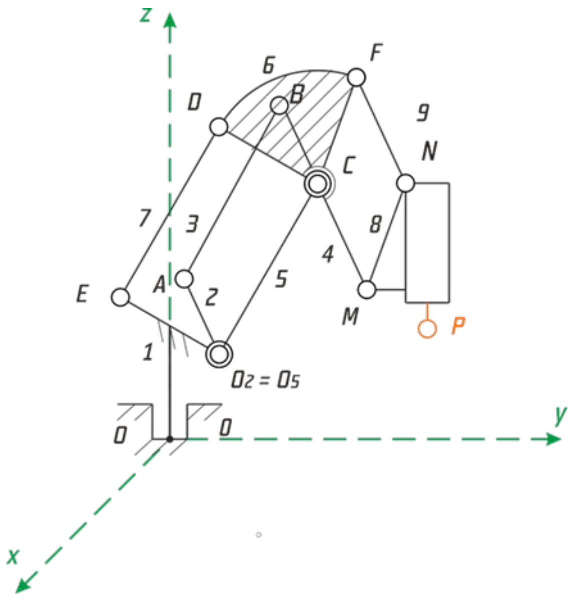


Fig. 2. Kinematic scheme of DOBOT MG400 robot

For the kinematic study of the mechanism, it is sufficient to create a kinematic model of the vertical kinematic chain, which has two drives. Link 1 is locked. The kinematic analysis was performed using the closed vector loop analytical method [2], [3]. The necessary and sufficient number of loops for determination of the kinematic parameters is **r-1**, where **r** corresponds to the number of closed loops in a given structure, provided that each kinematic pair is read twice. For the given mechanism, **r = 4** (*Fig. 3*).

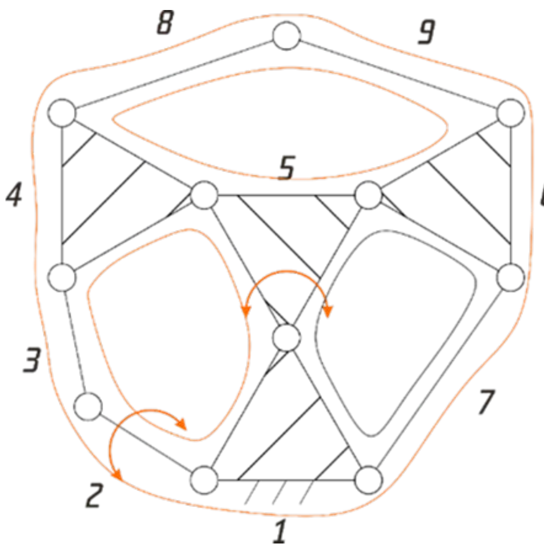


Fig. 3. Block diagram of DOBOT MG400 robot, r = 4

2.2. VECTOR CONTOURS

Fig. 4 shows the vector contours of the mechanism
- for kinematic chain 1-2-3-4-5;
- for kinematic chain 1-5-6-7;
- for kinematic chain 5-4-8-9-6.

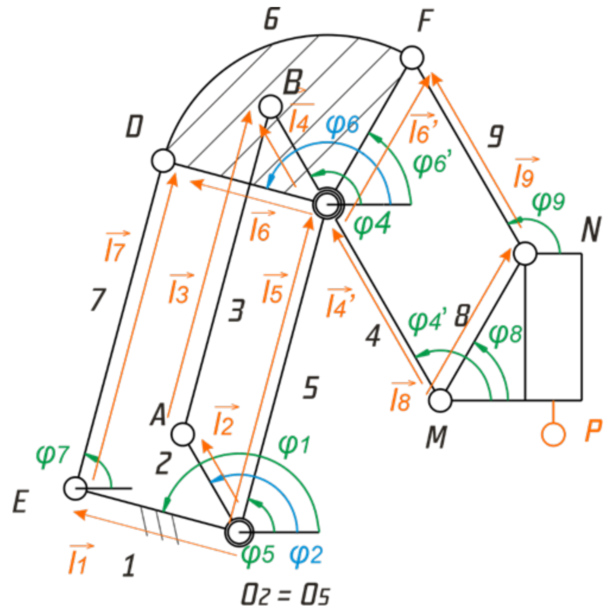


Fig. 4. Vector contours of the DOBOT MG400 robot

At any moment of the mechanism's movement, the contours are in the shape of a parallelogram. The movement is based on the parallelogram principle [4].

- *for kinematic chain 1-2-3-4-5;*

$$\vec{l_2} + \vec{l_3} = \vec{l_5} + \vec{l_4} \tag{1}$$

$$\begin{aligned} l_2.cos\varphi_2 + l_3.cos\varphi_3 &= l_5.cos\varphi_5 + l_4.cos\varphi_4 \\ l_2.sin\varphi_2 + l_3.sin\varphi_3 &= l_5.sin\varphi_5 + l_4.sin\varphi_4 \end{aligned} \tag{2}$$

where: $l_2 = l_4;\ l_3 = l_5;$
$\varphi_2 = \varphi_4 = f_1(t)$ – rotation angle of the initial link 2 (set value).
$\varphi_3 = \varphi_5 = f_2\ (t)$ – rotation angle of initial link 5 (set value).

- *for kinematic chain 1-5-6-7;*

$$\vec{l_1} + \vec{l_7} = \vec{l_5} + \vec{l_6} \tag{3}$$

$$\begin{aligned} l_1.cos\varphi_1 + l_7.cos\varphi_7 &= l_5.cos\varphi_5 + l_6.cos\varphi_6 \\ l_1.sin\varphi_1 + l_7.sin\varphi_7 &= l_5.sin\varphi_5 + l_6.sin\varphi_6 \end{aligned} \tag{4}$$

where: $l_1 = l_6;\ l_5 = l_7;$
$\varphi_1 = \varphi_6 = const.$ – angle of the robot structure;
$\varphi_7 = \varphi_5 = f_2\ (t)$ – set angle.

- *for kinematic chain 5-4-8-9-6;*

$$\vec{l_{4'}} + \vec{l_{6'}} = \vec{l_8} + \vec{l_9} \tag{5}$$

$$\begin{aligned} l_{4'}.cos\varphi_{4'} + l_{6'}.cos\varphi_{6'} &= l_8.cos\varphi_8 + l_9.cos\varphi_9 \\ l_{4'}.sin\varphi_{4'} + l_{6'}.sin\varphi_{6'} &= l_8.sin\varphi_8 + l_9.sin\varphi_9 \end{aligned} \tag{6}$$

where: $l_{4'} = l_9;\ l_{6'} = l_8;$
$\varphi_{4'} = \varphi_9$, a $\varphi_{4'} = \varphi_4 = \varphi_5 = f1\,(t);$

$\varphi_{6'} = \varphi_8$, a $\dot{\varphi_{6'}} = \varphi_6 - \alpha = \varphi_1 - \alpha = const. \Rightarrow \varphi_8 = const.$

Therefore, the direction of link 8 remains constant.

2.3. LAW OF MOTION OF POINT P BY THE EXECUTIVE UNIT

- *Vector equation*

The radius vector of point P (*Fig. 5*) is determined by the vector equation:

$$\overrightarrow{r_p} = \overrightarrow{l_5} + \overrightarrow{l_{4''}} + \overrightarrow{l_{8'}} \qquad (7)$$

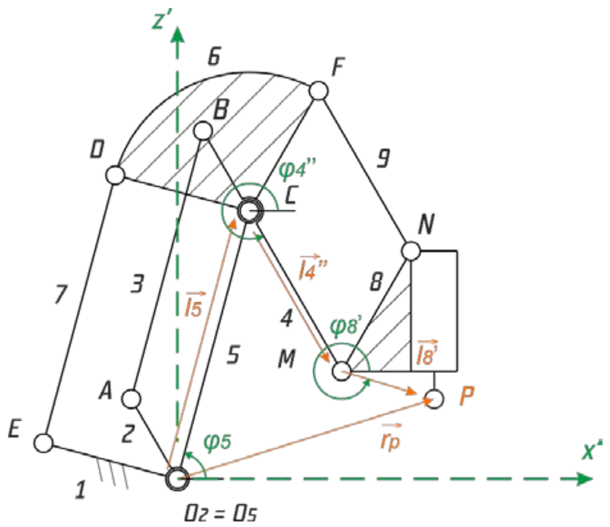


Fig. 5. Vector contour of point P of DOBOT MG400 robot

- *Projection equations*

$$x_p = l_5.cos\varphi_5 + l_{4''}.cos\varphi_{4''} + l_{8'}.cos\varphi_8$$
$$z_p = l_5.sin\varphi_5 + l_{4''}.sin\varphi_{4''} + l_{8'}.sin\varphi_8 \qquad (8)$$

where: $l_{4''} = l_{4'}$;
$\varphi_{4''} = 180^0 + \varphi_4 = 180^0 + \varphi_2$
$\varphi_{8'} = 360^0 - \beta - \varphi_8$
$= 360^0 + \varphi_1 - \beta - \alpha = \gamma = const.$
$\beta = \sphericalangle NMP,\ \alpha = \sphericalangle DCF$

Equation (8) takes the form:

$$x_p = l_5.cos\varphi_5 - l_{4'}.cos\varphi_2 + l_{8'}.cos\gamma$$
$$z_p = l_5.sin\varphi_5 - l_{4'}.sin\varphi_2 + l_8'.sin\gamma \qquad (9)$$

2.4. SPEED OF POINT P

$$V_p = \sqrt{V_{px^2} + V_{pz^2}} \qquad (10)$$

$$V_{px} = \dot{x}_p = -l_5.\dot{\varphi}_5.sin\varphi_5 + l_{4'}.\dot{\varphi}_2.sin\varphi_2$$
$$V_{pz} = \dot{z}_p = l_5.\dot{\varphi}_5.cos\varphi_5 - l_{4'}.\dot{\varphi}_2.cos\varphi_2 \qquad (11)$$

where: $\dot{\varphi}_2 = \omega_2$ – angular velocity of the initial unit 2;
$\dot{\varphi}_5 = \omega_5$ – angular velocity of the initial unit 5.

2.5. ACCELERATION OF POINT P

$$a_p = \sqrt{a_{px^2} + a_{pz^2}} \qquad (12)$$

where:

$$a_{px} = \ddot{x}_p = -l_5.\ddot{\varphi}_5.sin\varphi_5 - l_5.\dot{\varphi}_5^2.cos\varphi_5 + l_{4'}.\ddot{\varphi}_2.sin\varphi_2 + l_{4'}.\dot{\varphi}_2^2.sin\varphi_2$$
$$a_{pz} = \ddot{z}_p = l_5.\ddot{\varphi}_5.cos\varphi_5 - l_5.\dot{\varphi}_5^2.sin\varphi_5 - l_{4'}.\ddot{\varphi}_2.cos\varphi_2 + l_{4'}.\dot{\varphi}_2^2.sin\varphi_2 \qquad (13)$$

where: $\ddot{\varphi}_2 = \varepsilon_2$ – angular acceleration of the initial link 2;
$\ddot{\varphi}_5 = \varepsilon_5$ – angular acceleration of the initial link 5.

III. DIRECT KINEMATIC PROBLEM

To solve the direct kinematics problem, it is necessary to determine the position, velocity, and acceleration of point P from the actuator at given generalized coordinates $\Pi_2 = f_1(t)$ и $\Pi_5 = f_2(t)$.

Equations (9, 11, 13) are solved in the Matlab environment. *Fig. 6* shows the block structure for solving the direct kinematic problem, built in the Simulink toolbox.

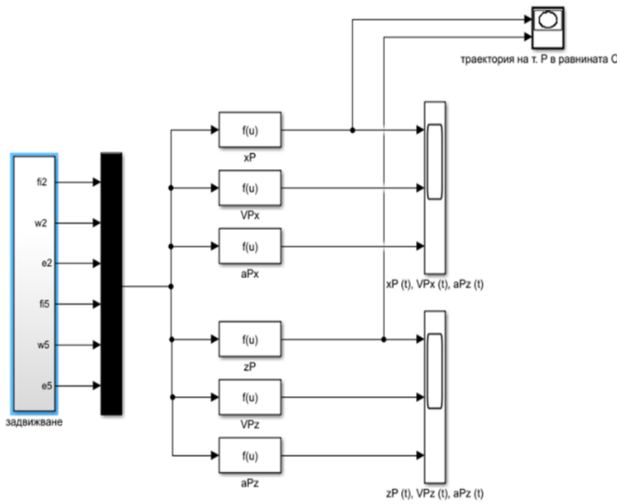


Fig. 6. Block structure for solving the direct problem of manipulator kinematics

A numerical solution was obtained for the input data:

$$l_2 = l_4 = 40\ mm;\ \ l_3 = l_5 = 175\ mm;$$
$$l_1 = l_6 = 45\ mm;\ l_5 = l_7 = 175\ mm;$$
$$l_{4'} = l_9 = 175\ mm;\ \ l_{6'} = l_8 = 45\ mm; \qquad (14)$$
$$\alpha = 82°;\ \beta = 103°$$

The limit positions of the manipulator are set by the angles:

$$\varphi_{20} = 80°, \varphi_{21} = 225° \quad \varphi_{50} = 15°, \varphi_{51} = 125° \tag{15}$$

Figures 7 and *8* show the results of the numerical solution of the direct problem of the manipulator kinematics in Matlab. The simulation duration is $t = 20s$.

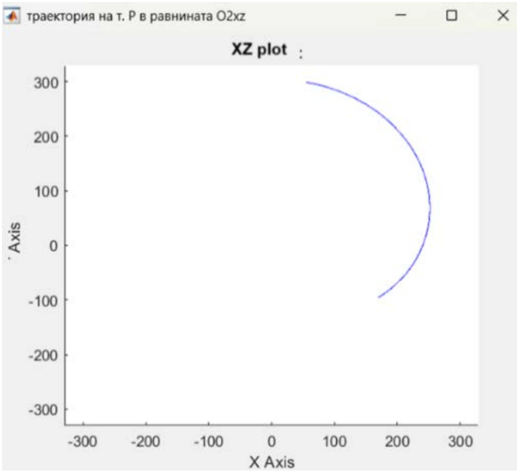
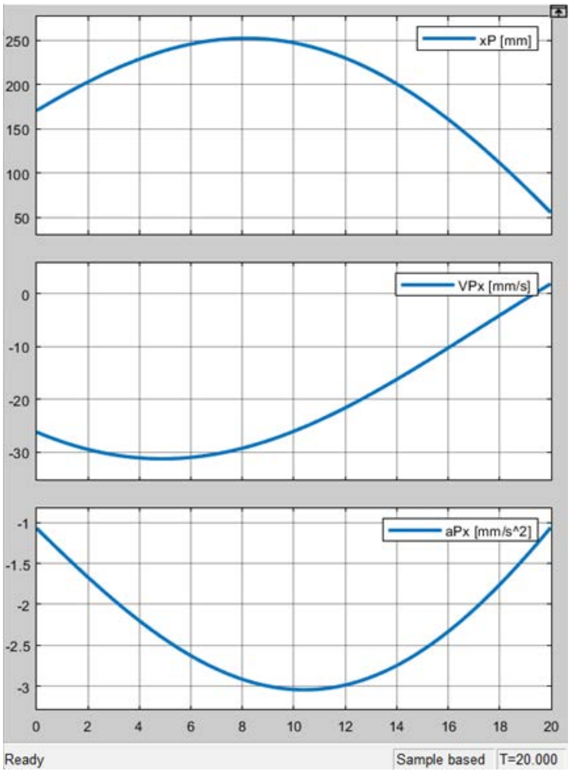
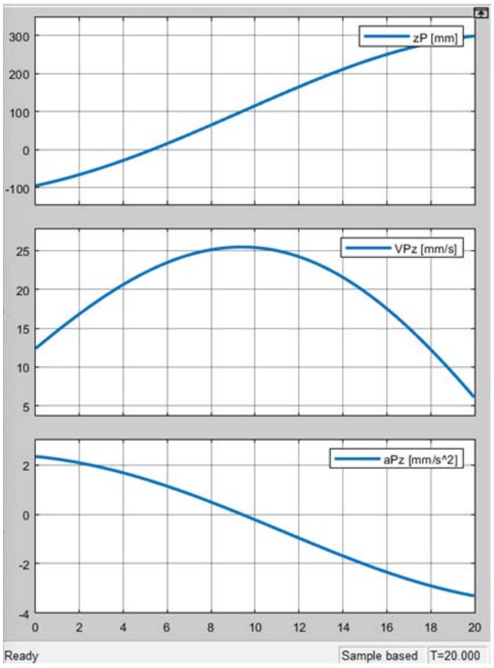


Fig.7. Trajectory of point P from the executive unit

Fig. 8.a and b shows the kinematic characteristics of point P with respect to the axes O_2x' and O_2z'z' of the introduced coordinate system $O_2x'z'$ (*Fig. 5*).



a) Movement, velocity and acceleration of point P along the O_2x'axis



b.) Displacement, velocity and acceleration of point P along the O_2z' axis

Fig. 8. The kinematic characteristics of point P at t=20s

IV. THREE DIMENSIONAL MODEL

To verify the reliability of the created kinematic model of a manipulator with an anthropomorphic structure, the real geometric structure of the DOBOT MG400 robot was built in a 3D CAD environment with geometric dimensions (13). *Fig. 9* shows the full constructive implementation of the model.

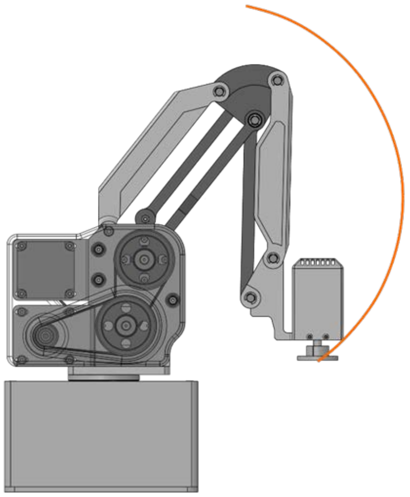
The built 3D model will be used in a kinematic study of the robot for accurate specification of certain important dimensions, for determining the initial position, for visualizing the solutions of the direct and inverse kinematics problem, for comparing the obtained results and correct realization of the trajectory, as well as for verifying the reliability of the mechano-mathematical models. [5]

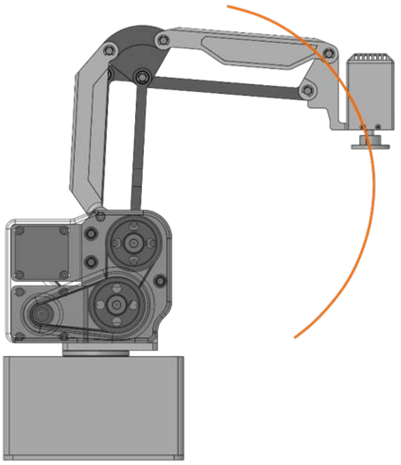
SolidWorks was chosen as the CAD environment for building and learning the model. The software provides the necessary tools for authentic construction of the selected model, through the possibility of parameterization and optimization of the individual nodes of the structure. Here, when parameterizing, it is important to pay attention to the connections and how this would affect the kinematics of the mechanism, although for the specific model we do not use this method.

All individual elements are built according to the design of the robot [6], respecting the results obtained from the kinematic study. A large part of the dimensions of the individual vectors and the positions of the main angles are adopted and mastered after building the 3D model.

Fig. 9. Realistic image (rendering) of a DOBOT MG400 robot

Fig. 10 shows the trajectory of the end element of the DOBOT MG400 robot at limit positions (14).





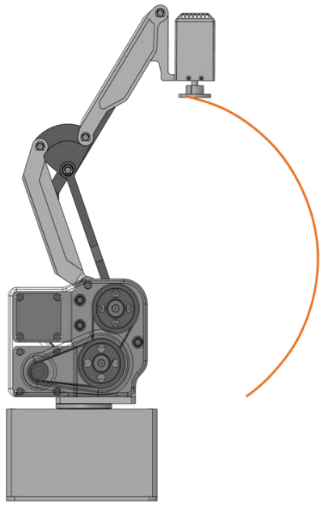


Fig. 10. Trajectory of the DOBOT MG400 robot with given data

The results completely coincide with those from the solution of the problem in MATLAB, which proves the reliability of the created kinematic model and the possibilities for implementation.

V. CONCLUSION

This paper presents an integrated methodology for kinematic analysis of the manipulation mechanism of the DOBOT MG400 robot, combining analytical modeling, MATLAB-based implementation, and CAD simulation.

A numerical solution to the direct kinematic problem is performed, which is visualized and simulated using the built detailed CAD model of the robot. The integration of CAD and MATLAB environments has proven effective in verifying the accuracy of the kinematic model and increasing its practical significance.

The proposed approach demonstrates a reliable and adaptive methodology for studying robotic manipulators. This offers a solid foundation for future work, including inverse kinematics, dynamic analysis, trajectory optimization, and implementation of real-time controlAppendix

Appendixes, if needed, appear before to write the acknowledgment.

REFERENCES

[1] Цонева М.; *Кинематика на манипулационни механизми на промишлени роботи в MATLAB* - издателсво на ТУ-София, 2024, ISBN 978-619-167-553-1.

[2] Михайлова Г., Цонева М.; *Относно кинаметиката на регионални подсистеми на промишлени роботи с три степени на свобода* - 2020, Механика на машините, бр. 124, стр. 22-27, ISSN 0861-9727.

[3] Yang B., Yang W.; *Modular approach to kinematic reliability analysis of industrial robots* - Reliability Engineering & System Safety, Volume 229, January 2023, 108841.

[4] Цонева М., Милев М., Топалова М.; *Геометричен модел на робот с паралелна кинематика* - 2023, Механика на машините, бр. 130, стр. 73-75, ISSN 0861-9727.

[5] Arrouk K. A., Bouzgarrou B. C., Gogu G.; *CAD-based unified graphical methodology for solving the main problems related to geometric and kinematic analysis of planar parallel robotic manipulators* - Robotics and Computer-Integrated Manufacturing, Volume 37, February 2016, Pages 302-321.

[6] https://www.dobot.nu/en/product/dobot-mg400/