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DEVELOPMENT OF A 3D MODEL OF A MANIPULATOR FOR MOBILE ROBOTIC PLATFORMS BASED ON UNIGRAPHICS NX

The article discusses the issues of modernization of the mobile robot Festo Robotino, due to the integration of the MR-999E manipulator system into it. This solution will significantly expand the functionality of the mobile robot Festo Robotino and will allow for new research related to the development of new methods and models for making decisions on moving objects. Based on the study, it was revealed that the existing MR-999E manipulator system has a number of disadvantages, one of which is the insufficient compression force of the gripper to move the test objects, which does not allow it to be widely implemented as a mobile manipulation platform. To eliminate these shortcomings, the authors carried out research, on the basis of which a kinematic diagram of the gripping module was developed. To check the correctness of the decisions made and the obtained calculations in the CAD Unigraphics NX system, 3D models of all the main elements of the mobile manipulator were developed, the dimensions of the teeth with an involute profile were calculated, which made it possible to increase the positioning accuracy of the links in space to solve the problem of spatial assembly of structures with the required accuracy. Based on the developed 3D models, the authors have designed a detailed 3D model of the manipulator assembly, in the CAD Unigraphics NX system, as well as using numerical engineering analysis, based on the finite element method, calculations were carried out to determine the required gripping force of the improved gripping mechanism. The developed 3D models are made using additive 3D printing technologies. This made it possible to manufacture a prototype of the gripping mechanism and experimentally confirm the possibility of integrating it with the Festo Robotino mobile robot in order to expand its functionality.

Key words: *mobile robots, Festo Robotino, mobile manipulators, 3D models, modeling.*

Formulation of the problem. Modern mobile robots are widely used in solving various problems in all spheres of human activity. However, at the present stage of development, in connection with the intensive development of high-precision production, the complexity of automatic manipulations of the robot also increases, which now exceeds the complexity of the implementation of its mobility not only in solving production and research problems, but also in critical technologies, which requires the improvement of the manipulation functions of robotic systems. Such systems, with advanced manipulation capabilities, can be used for mine clearance, movement or disposal (detonation) of ammunition, in the conditions of man-made inventories, in areas dangerous to human life, as well as for scientific purposes to study the use of artificial intelligence.

The object of the study is one of the representatives of mobile robotic platforms – Robotino, developed by one of the leaders of modern robotics, Festo Didactic. This robot has high maneuverability due to the use of three roller wheels of the “omni wheel” type, an odometry subsystem, an array of infrared sensors, a wireless communication subsystem, a control system using a single-board industrial computer of the PC / 104 + format, which makes it possible to implement intelligent control systems with using computer vision systems.

PExpanding the functionality of Festo Robotino, using a lightweight manipulation complex based on the MR-999E, will increase the range of applications, significantly improve it and make it possible to conduct research in the field of artificial intelligence and decision-making systems, is a topical research.

Analysis of recent studies and publications. Robotic systems have found wide application in all spheres of human activity, from the simplest household ones to the use in cyber-physical production systems within the framework of the Industry 4.0 concept. [1–3]. D. Drozdov presents a practical example based on the Festo EnAS platform, supplemented by a mobile logistics robot and a camera for automated visual product control [4]. However, it is worth noting that the mobile robot used has only a computer vision system, while it cannot perform manipulative actions when a product defect is found to be detected. In his work, Květoslav Belda shows the application of the mobile robot Robotino from Festo as a solution for batch processing of handling operations over long distances, in contrast to conventional conveyor belts using group control, within the framework of the concept of autonomous automatic cyber-physical factories [5]. At the same time, the author does not describe the structural and functional structure of the loading implementation based on Robotino. In the works of V. Pachouri, P.M. Pathak the workspace of the multi-section bionic manipulator Robotino-XT is presented [6]. The authors pay attention to the development of various strategies to compensate for the loss of working space in the event of a single bellows failure, resulting in a possible pressure leak. Unfortunately, the use of the bionic robot arm Robotino-XT is not possible with the Festo Robotino. Ruqayah R. Al-Dahhan simulated a Festo Robotino in the Robotino®.Matlab system, using the capability of a fuzzy logic controller (FLC), to implement a safe Robotino® target search without any human intervention [7]. Real-time experiments have shown that using three infrared sensors and one ultrasonic sensor, Robotino® can detect and avoid any obstacles that might be found along its route. This gave the authors a reason to assert that the Festo Robotino mobile robot can perform complex route building in a dynamic environment and its modernization using a manipulation system will not only expand its functionality, but also allow it to be implemented as a mobile manipulation platform.

Setting objectives. The aim of this work is to develop and improve the 3D model of the MR-999E manipulator system for its integration with Festo Robotino. To achieve the goal, it is necessary to ensure the solution of the following tasks: develop a kinematic diagram of the gripping mechanism; make calculations of the required gripping force to increase the gripping force; determine the parameters and calculate the construction of a gear wheel using an involute profile; develop 3D models of structural elements to create a detailed 3D model of the assembly of a mobile robotic arm; simulate the gripping force based on the finite element method.

The practical value of these studies lies in the improvement of a mobile manipulator with a gripper to integrate it with the Festo Robotino mobile platform. This will allow Festo Robotino to be improved by expanding its functionality for research and development.

Presentation of the main material of the study. When developing multi-purpose mobile robots with advanced manipulation capabilities, great attention is paid to gripping mechanisms (GM). Interchangeable gripper designs are classically used for objects of various shapes. The choice of kinematics and structural features of the ZM is determined by the shape and mass of the object. The grab must hold the selected object and at the same time not damage it.

To carry out research on the modernization of the Festo Robotino mobile robot by integrating a manipulator into its design, the following restrictions must be taken into account [8]: the manipulator must have a minimum weight and have a modular design with the ability to be quickly installed and removed. Therefore, this will impose restrictions on the weight of the object that can be moved. Based on the fact that Festo Robotino was developed for laboratory research, colored cubes were chosen to implement the task in the form of a test object, which will allow in the future during experiments to use a computer vision system (CV) to identify and recognize the color of the object. Based on this, the following kinematic diagram of a tick-borne ZM with a rack and pinion transmission mechanism was developed, consisting of the following elements: two jaws; a gear wheel rigidly connected with the fingers and turning with a gear rack; electric motor gear. Figure 1 shows the kinematic diagram of the developed universal gripper designed to grip various objects weighing no more than 0.2 kg, which will be the basis for creating a 3-dimensional model.

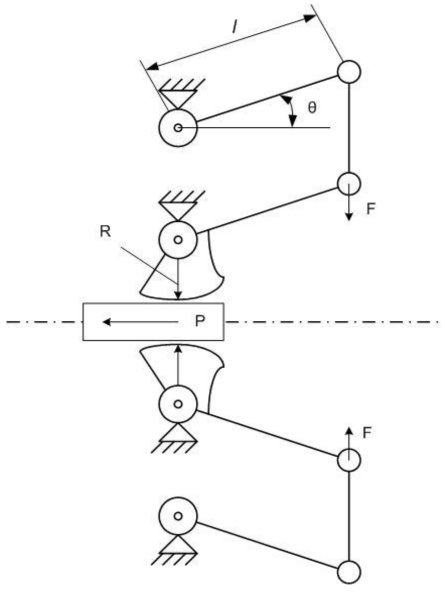


Figure 1. Kinematic diagram of the ZM

The ZM works as follows: when the electric drive gear rotates, a toothed rack is set in motion, turning the gear wheels, this causes the jaws to converge, as a result of which the object is captured. When the gears are turned backwards, the jaws are unclenched and the object is released.

When designing the most versatile ZM robots, it is necessary to take into account the specific type of part and group of parts, their shape and forces arising in the ZM. An important criterion in this case is the accuracy of holding the part and the permissible force on the jaws. Based on this, a large number of different grips have been developed, which differ in kinematic diagram and other design parameters.The ZM force must correspond to one of the values of the Ra10 series within the range of 1 – 8000 N [9]. The gripper must provide a wide range of movement. We take the developed kinematic diagram (Fig. 1) as the basis for the development of the ZM and the subsequent calculation of the acting forces.

Based on the kinematic model and the existing ZM, modification will be made by increasing the gripping force. At this stage, the calculation of the required gripping force was made using the example of a clamp-type gripper, using the method of analysis of the acting forces, for a part weighing 0.2 kg with two types of movements.

With vertical linear movement:

$$F = G\frac{K}{\mu}\left(1 + \frac{a_B}{g}\right), \tag{1}$$

where $\propto$ –friction coefficient; a_B – acceleration of vertical movement; K – safety factor ($K = 1,5 - 2,0$); g – acceleration of gravity.

$$F = 0,2\frac{1,5}{0,13}\left(\frac{0,6}{9,8}\right) = 2,438H\ .$$

With horizontal linear movement

$$F = G\left(\frac{K}{\mu} + \frac{a_Г}{g}tga\right), \tag{2}$$

where $a_г$ – acceleration of horizontal movement; a – jaw angle;

$$F = 0,2\left(\frac{1,5}{0,13} + \frac{0,47}{9,8}\right) = 2,3H\ .$$

Let us calculate the force that the power drive must develop to securely fix a part weighing 0.2 kg, according to the developed kinematic diagram (Fig. 1).

Calculation of the drive force P is made from the ratio between the required holding force F (the highest value is taken), the length of the levers l, the angle of their movement θ and the radius of the gear train R. The calculation of the drive force is made according to the formula:

$$P = F2l\cos\theta \ /\ R\ . \tag{3}$$

Substituting the value, we get:

$$P = 4,8H\ .$$

To modify the ZM in order to increase the gripping force and the possibility of holding and moving a part weighing 0.2 kg, it is necessary to install an electric drive developing a force equal to 4.8 N. The results obtained make it possible to choose an electric motor and a gearbox.

The next step will be the development of a 3D model of the parts of the mobile manipulator with the selected ZM. To solve this problem, the CAD Unigraphics NX solid modeling environment was chosen [10], which allows obtaining 3D models of parts and carrying out a detailed assembly of the improved manipulator. Parts are constructed using standard rotation and indentation / extrusion methods. One of the difficult elements is the design of a gear for 3D printing and chemical surface treatment to obtain accurate tooth parameters. Since the construction of a gear is an accurate process, therefore, all construction will be based on the values calculated by the handler. Construction in CAD Unigraphics NX will be broken down into the following stages: creation of the main control variables and dependencies; construction of the main diameters of the gearwheel, limiting the gearwheel; construction of the tooth profile as a curve according to the law in accordance with the parametric shape of the involute given below; deposition of the width of the tooth and the construction of its axis of symmetry; reflection of the involute relative to the constructed axis of tooth symmetry; the construction of all z teeth of the cogwheel.

The dimensions of the teeth with an involute profile determine the parameters characterizing the position of any point of the involute [11]. An involute is a sweep of the base circle in the form of the trajectory of a point on a straight line rolling without sliding along this circle.

The initial data for the calculation of both the involute and the gear wheel are the following parameters: m – modulus is the part of the pitch circle diameter per tooth, modulus is a standard value and is determined from reference books, z – number of teeth of the wheel, α – the profile angle of the original contour. The angle is a standard value and equal to 20 ° [11], as well as the diameter of the pitch circle d, root diameter concavity df and the circle diameter of the vertices da.

For a parametrically given curve, the involute equation has the form:

$$x = (d\_main\ /\ 2)(\cos(t) + t\sin(t))\ , \tag{4}$$

$$y = (d\_main\ /\ 2)(\sin(t) - t\cos(t))\ , \tag{5}$$

where t – the angle of the evolute; d_main – the diameter of the base circle (evolute).

The calculation of all parameters of the gearwheel will be carried out according to the formulas below:

Pitch circle diameter:

$$d = m \cdot z\,, \qquad (6)$$

where m – tooth module;
z – number of teeth.

Diameter of the circle of the vertices:

$$da = d + 2 \cdot m\,, \qquad (7)$$

where d – pitch circle diameter;
m – tooth module.

Root diameter concavity:

$$df = d - 2.5 \cdot m\,, \qquad (8)$$

where d – pitch circle diameter;
m – tooth module;

Base circle diameter:

$$d\_main = d \cdot \cos(20)\,, \qquad (9)$$

where d – pitch circle diameter.

Based on the calculations, taking into account the printing error on a 3D printer, to determine the parametric dependencies of the gear wheel, we will use the following parameters in the CAD Unigraphics NX editor, presented in Table 1.

Based on the selected parameters (Table 1), we will construct the base circles *d_main, d, da, df* of gear wheel, which is shown in Figure 2.

Completion of the sketch and the transition to the creation of the involute is performed by the command "Insert-Curves-Curve by Law". A given expression is selected as a function of the law.

Then the variables (t, xt, yt, zt) are specified, on the basis of which the construction of the involute curve is carried out (Fig. 3).

According to the values of the parameter $t = 0,...,1$ Unigraphics NX creates a curve according to the law in space. Because the parameter $zt = 0$, our curve is located on the plane.

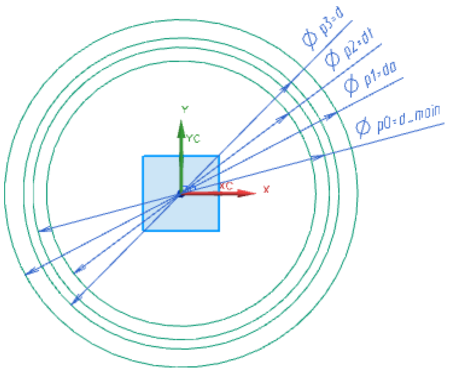


Figure 2. Circles of construction of a gear wheel

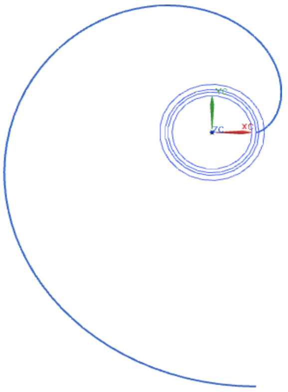


Figure 3. Involute in the construction plane

The construction of the tooth along the created line, which limits the concavity and tops of the tooth, is its lateral surface.

Tooth thickness is calculated by the formula:

$$s = m \cdot \pi / 2 \qquad (10)$$

where m – tooth module.

The length of the created arc s is equal to the thickness of the tooth, relative to which the line of symmetry of the tooth is built, is defined as a segment between the center of the circle and the middle of the arc, which is the basis for the mirror construction of the involute (Fig. 4).

Table 1

Parameter table for constructing a cogwheel

Name	Formula	Value	Unit
alpha	20	20	градусы
d	$m \cdot z$	45	mm
d_main	$d \cdot \cos(alpha)$	42,286	mm
da	$d + 2 \cdot m$	47	mm
df	$d - 2.5 \cdot m$	42,5	mm
m	1	1	
s	$m \cdot \pi / 2$	1,570796327	mm
t	0	0	mm
xt	$(d\_main / 2)(\cos(t) + t\sin(t))$	21,143083	
yt	$(d\_main / 2)(\sin(t) - t\cos(t))$	0	
z	*45*	45	

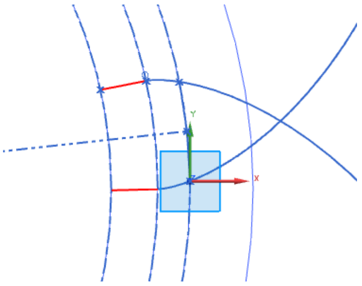


Figure 4. Construction of an involute side profile of a gear

The creation of a 3D model is based on the drawing of the contour of the gear (Fig. 5). Since the gear contour has self-intersections, the gear and tooth bodies are modeled separately from each other.

The construction of the tooth according to the given curves is shown in fig. 6. When selecting a curve, the system offers a selection of segments between the intersection points. As soon as the contour closes – NX offers to extrude a rigid body.

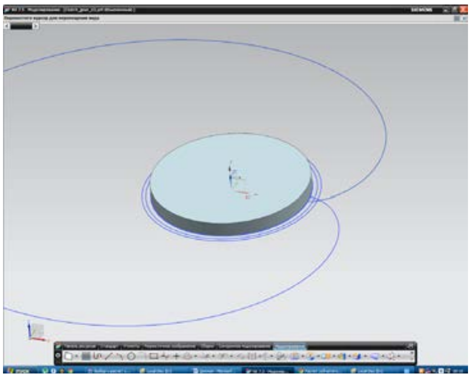


Figure 5. Development of a 3D model of the gear base

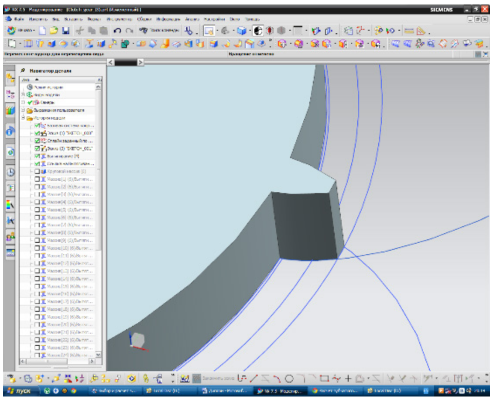
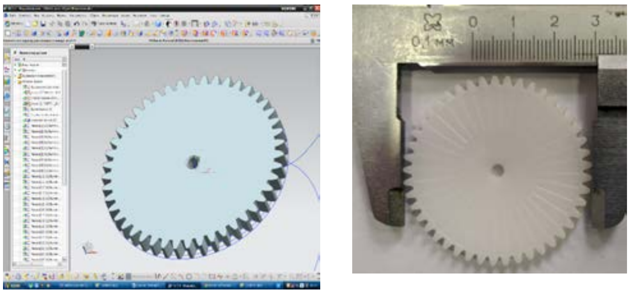


Figure 6. Construction of a gear tooth

For building z gear teeth, we will use the command "Insert-Associative Copy-Array Element". As a base element for a circular array, select the construction element that corresponds to the constructed tooth. As the number of teeth, we indicate the variable z – the number of teeth of the gear, and as the angle between the elements – $360 / z$.

A way to set the center of the circular array and the axis relative to which the elements are rotated is specified. Following the prompts, as a result, we get a 3D model of the gear (Fig. 7, a). In fig. 7b, the same wheel was obtained using 3D printing.



a) b)

Figure 7. 3D model of the gear and printed model on a 3D printer

There are many methods, approaches and sequences for modeling parts and assemblies, which the designer chooses at his own discretion. The basis for the construction of each element is a drawing, according to which 3D modeling of the element was performed (Fig. 8).

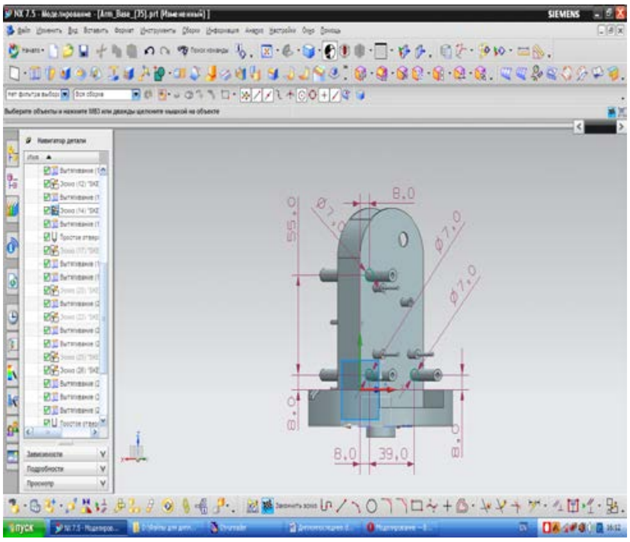


Figure 8. Development of a 3D model of the first link of the mobile manipulator

When developing every detail of the mobile manipulator, the parallel modeling method was used. The main concept of this method is to check all given dimensions by creating an assembly of elements in parallel, the ability to track in real time inaccuracies in the modeling of individual elements and instantly eliminate them. Figure 9 shows a fragment of the development of the ZM, in accordance with the proposed kinematic scheme (Fig. 1). To simplify the development of a detailed 3D model of the assembly, it was decided to neglect the development of the gearbox, and present it as a simplified part with attachment points and with a shaft on a gear to control the gear. This reduces design time and human effort.

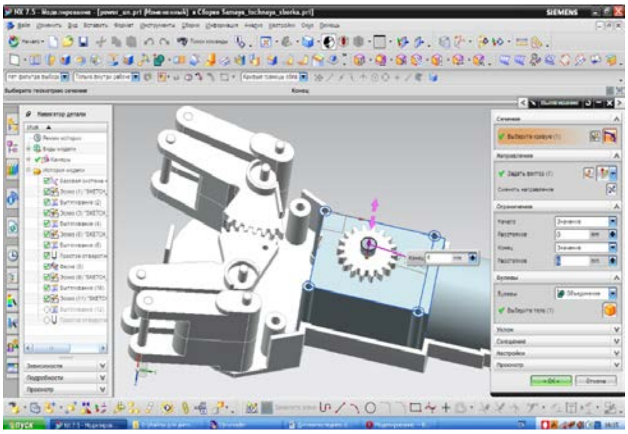


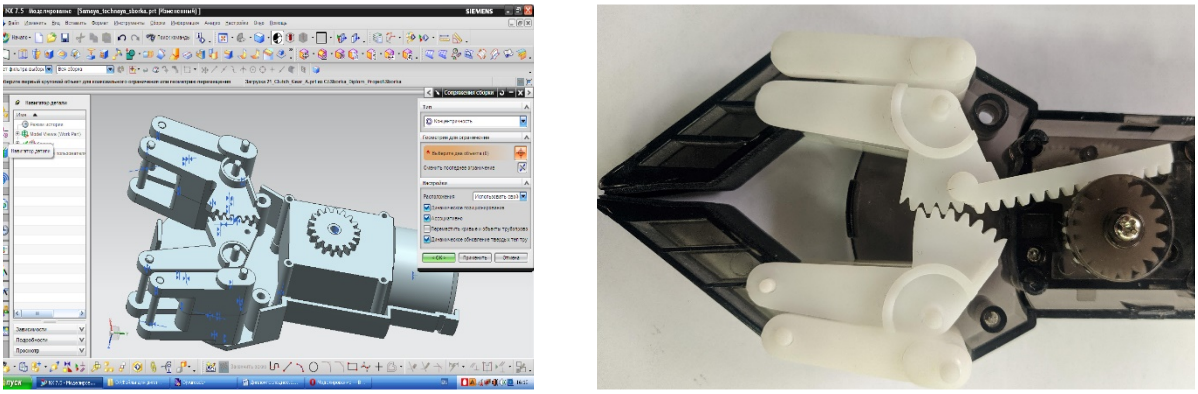
Figure 9. Fragment of editing the assembly element of the SM

The design is carried out according to a certain hierarchy given by the design of the robot, starting from the grip and ending with the base. This hierarchy formed the basis of the assembly of the robot.

Assembly of three-dimensional models into a single whole product is carried out in a special editor "NX Assembly". To assemble all the elements into a single product model, it is necessary to mate the links between each element of the assembly. It is necessary to set mates of concentricity of tangent alignment and fixation in accordance with the type of node (Fig. 10). The assembly of the ZM model developed in CAD Unigraphics NX is shown in fig. 10, a, the manufactured prototype is shown in Fig. 10, b.

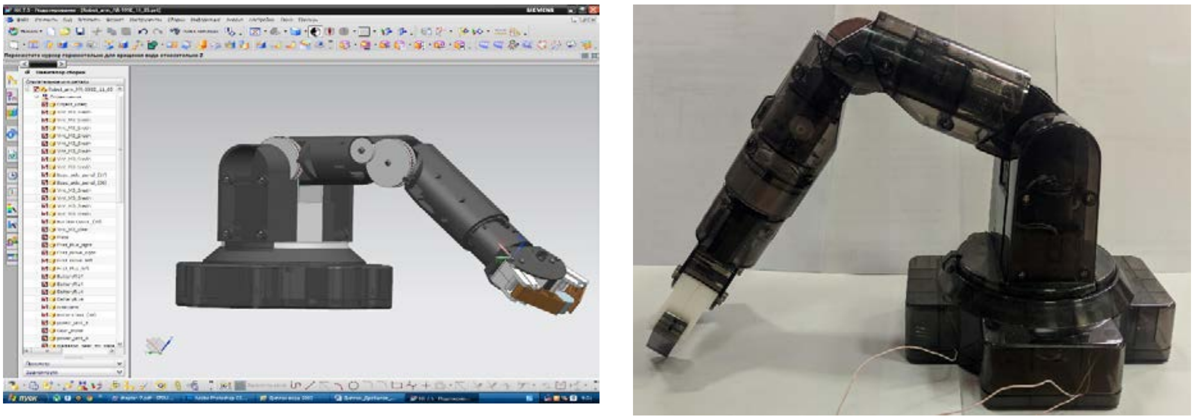
By setting the correct ratios between assembly elements, it is possible to set kinematic relationships and precise engineering analysis of individual joints or the whole product. After modeling all the elements and the assembly operation, we have a finished 3-dimensional model (Fig. 11, a) and a manufactured prototype (Fig. 11, b).

To verify the correctness of the decisions made in the course of calculations and development of a 3D model of a mobile manipulator, it is necessary to simulate the gripping force. The Unigraphics NX – Advanced Simulation system is a set of basic principles and concepts of numerical engineering analysis based on the finite element method (FEM).



a) b)

Figure 10. Assembling the ZM model with interfacing and a prototype



a) b)

Figure 11. 3D model of the assembly of the manipulator and prototype

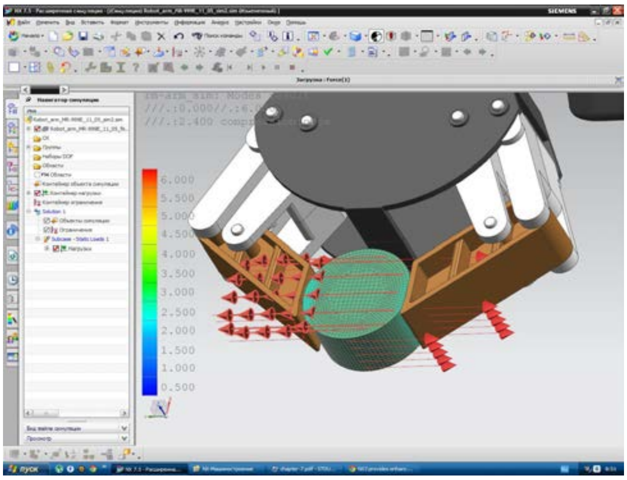


Figure 12. Modeling the grip force

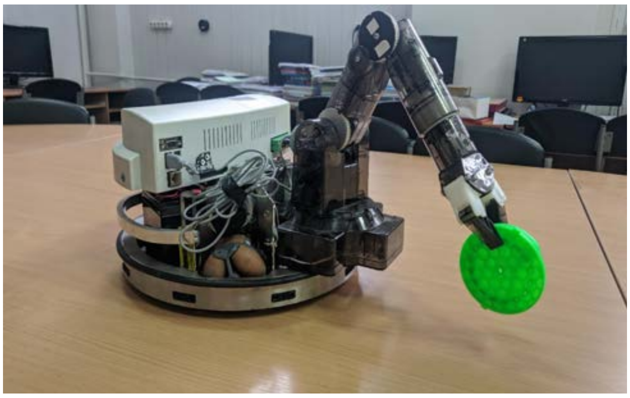


Figure 13. Upgraded robot Festo Robotino with an integrated manipulator

The result of this simulation was the determination of the value of the compression force, which, with a minimum error, corresponds to the calculations and is equal to 2.4 N (Fig. 12). The performed mathematical and engineering calculation of Unigraphics NX provides the maximum risk reduction when performing a modification in order to increase the gripping force of the SM, which allows you to start 3D printing and upgrading the Festo Robotino mobile robot.

In fig. 13 shows a modernized robot Festo Robotino with a manipulator integrated into the control system.

Conclusions. The article studies the modernization of the Festo Robotino robotic platform through integration with the MR-999E manipulator system. This solution made it possible to expand the functionality of the mobile robot, which will increase its manipulation capabilities and allow research in the field of artificial intelligence and decision making in assembly operations. Also, this improvement will allow testing control systems for mobile manipulation systems in solving the problems of recognition and identification of objects for their safe movement. Based on the tasks set, the authors carried out calculations to improve the gripping mechanism and movement mechanisms. A detailed 3D model of the manipulator system in CAD Unigraphics NX and tested it using grip force simulation was developed. Using 3D printing technology, advanced parts were printed with the MR-999E manipulator system. In the future, it is planned to research and develop intelligent control systems using the new handling functions of the Festo Robotino mobile robot.

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РОЗРОБКА 3D МОДЕЛІ МАНІПУЛЯТОРА ДЛЯ МОБІЛЬНИХ РОБОТОТЕХНІЧНИХ ПЛАТФОРМ НА БАЗІ UNIGRAPHICS NX

У статті розглядаються питання модернізації мобільного робота Festo Robotino за рахунок інтеграції у нього маніпуляторної системи MR-999E. Таке рішення дозволить суттєво розширити функціональні можливості мобільного робота Festo Robotino та дозволити проводити нові дослідження, пов'язані з розробкою нових методів і моделей прийняття рішень щодо переміщення об'єктів. На основі проведеного дослідження було виявлено, що існуюча маніпуляторна система MR-999E має ряд недоліків, одним з яких є недостатнє зусилля стиснення схвату для переміщення тестових об'єктів, що не дозволяє широко його реалізувати в якості мобільної маніпуляційної платформи. Для усунення цих недоліків авторами проведено дослідження, на основі яких була розроблена кінематична схема захватного модуля. Для перевірки правильності прийнятих рішень та отриманих розрахунків у системі CAD Unigraphics NX було розроблено 3D моделі всіх основних елементів мобільного маніпулятора, проведено розрахунки розмірів зубів з евольвентним профілем, що дозволило підвищити точність позиціонування ланок у просторі для вирішення задачі просторового складання конструкцій із необхідною точності. Ґрунтуючись на розроблених 3D моделях, авторами спроектована деталізована 3D модель складання маніпулятора, у системі CAD Unigraphics NX, а також за допомогою чисельного інженерного аналізу, на базі методу кінцевих елементів, проведено розрахунки для визначення необхідної сили схоплення вдосконаленого захватного механізму. Розроблені 3D моделі реалізовані за допомогою адитивних технологій 3D друку. Це дозволило виготовити прототип захватного механізму та експериментально підтвердити можливість його інтеграції з мобільним роботом Festo Robotino з метою розширення його функціональних можливостей.

Ключові слова: *мобільні роботи, Festo Robotino, мобільні маніпулятори, 3D моделі, моделювання.*