

UDC 681.518

DOI <https://doi.org/10.32782/2663-5941/2023.2.1/33>

Nevliudov I.Sh.

Kharkiv National University of Radio Electronics

Yevsieiev V.V.

Kharkiv National University of Radio Electronics

Demska N.P.

Kharkiv National University of Radio Electronics

Kostrova H.Yu.

Kharkiv National University of Radio Electronics

DEVELOPMENT AND IMPROVEMENT OF THE DESIGN OF A LIGHTWEIGHT MOBILE ROBOT MANIPULATOR USING GENERATIVE DESIGN

This paper is devoted to the study of the possibility of minimizing the mass of an on-board manipulator for a mobile robot without losing structural strength. The analysis of publications showed that the solution of this task will allow to increase the mass of the payload, therefore it will allow to significantly increase the time of autonomous operation. Which, accordingly, will allow solving more complex manipulation tasks in areas of increased danger or man-made disasters. To solve the task, the authors developed a kinematic scheme and a movement mechanism of a 5-axis mobile manipulator; performed an analysis and selected stepper motors as the drivers. The rationale for this choice is to increase the positioning accuracy of the gripping mechanism, which will allow for more accurate operations of moving objects. Using the Autodesk Fusion 360 design environment, 3D models of the structural elements of the mobile manipulator were developed, assembly was carried out, and weight and strength parameters were investigated. The total weight of the manipulator was 1060g, under the conditions that the material to preserve the strength parameters will be sheet metal with a thickness of 5mm. Using the approach to generative design, the authors improved all structural elements and conducted a series of simulations in the Simulation: Shape Optimization plugin. The results of the typological analysis of each link of the developed mobile manipulator showed the possibility of reducing the mass of each part by ~30-40%, depending on its design features, without losing strength parameters. As a result of improving the designs of the mobile manipulator using the generative design method, it was possible to reduce the total weight from 1060g to 601g, that is, the weight of the manipulator decreased by 41.5%. The authors hope that in the future, the conducted research will allow to reduce the consumption of materials and the time of manufacturing structural elements without loss of strength parameters when using additive technologies (3D printing by the FDM method), and therefore to increase the autonomous operation time of the mobile manipulative robot.

Key words: mobile robots, manipulators, kinematic scheme, design, generative design, modeling, Autodesk Fusion 360.

Formulation of the problem. The problem of research in the field of autonomous mobile manipulation robots is the need to develop and improve not only control algorithms, but also design features that will ensure effective autonomous functioning of robots in various conditions. To achieve this, it is necessary to reduce the mass of the robot, to increase the payload, but at the same time it is necessary to preserve the strong characteristics of the structures in order to perform the tasks [1].

Analysis of recent research and publications. The development and improvement of manipulator

structures for mobile robots has a number of advantages and is necessary to achieve the following goals [2-4]:

- increased robot mobility: Robots equipped with manipulators can perform more complex tasks, such as collecting, moving or manipulating objects inside and outside the building. An improved manipulator can provide greater mobility of the work, which will allow it to work in more diverse conditions and perform tasks that were previously unavailable.

- improved accuracy and efficiency: Manipulators designed with robustness and mobility requirements

in mind can provide greater accuracy and efficiency when performing tasks. This can be especially important for robots operating in complex and hazardous environments where precision and efficiency can be critical.

– reduction of production cost: Development and improvement of manipulator designs can help reduce the cost of manufacturing robots. An improved and more compact design can reduce the amount of required materials and components, which will reduce the cost of production.

– improved safety: Manipulators designed with robustness and mobility requirements in mind can be safer to use. The improved design can ensure more stable operation of the machine, reduce the probability of errors and increase the safety of others.

Shantanu Thakar analyzed the constructions of mobile manipulators, developed a classification, and developed a calculation methodology [5]. The authors suggest using classical approaches to designing structures and calculating the reliability of the manipulator, which leads to increased mass of the manipulator, which is negative for mobile robots, as it reduces the payload. Charles C. Kemp proposed a new manipulator design that, according to the author, reduces size, weight, and cost while supporting multiple tasks. The main structure consists of a two-wheeled mobile base with a differential drive, a lift and a telescopic boom configured to achieve Cartesian motion at the end of the manipulator [6]. Analyzing the publications, one can see that the authors propose to use the principle of a telescopic boom to simplify constructions. This makes it possible to reduce the total weight of the manipulator, while the authors do not conduct research on strength analysis, while controlling such a manipulator requires additional hardware modules, which increases the mass and reduces the payload of the mobile robot. Zhenshan Bing's research in the field of autonomous mobile manipulation is aimed at developing mobile robotic systems with manipulation capabilities that enable them to perform complex tasks in dynamic, unstructured, and field environments that require task-adapted design, control, and new application methods [7]. The authors propose to use biological and traditional methods of designing manipulation systems, which will allow to propose new approaches to the development of structures. But the proposed approaches have a theoretical and methodological basis for research, and not design recommendations for their use. Ferdinando Vitolo proposes a method of integrating mobile robots with manipulators for their use as collaborative robots [8]. As part of the

study, the authors developed a general mechatronic manipulator interface, while conducting the analysis, it is possible to see that the proposed solution is suitable for standard industrial manipulators, and cannot be applied to flexible mobile robots.

As you can see, research on the development of new designs of manipulators for mobile robots is an urgent task, which allows to increase the efficiency and autonomy of mobile robots by reducing the mass of the manipulator, without losing strength parameters.

The purpose of the article – development and improvement of structures of a lightweight manipulator of a mobile robot without losing its strength indicators using generative design.

Presenting main material. Generative design (GD) is an optimization method that uses algorithmic models to optimize material layout within a user-defined space for a given set of loads, conditions, and constraints. Topological optimization maximizes the performance and efficiency of the structure by removing excess material from areas that do not have significant loads [9].

GD shape optimization usually occurs at the end of the design process, when the desired part must be lighter or use fewer materials. Next, the designer detects certain preset parameters. Structural shape optimization first determines the minimum allowable design space required to optimize the shape of the product. Next, the software applies pressure to the project from various angles, checks its structural integrity and identifies unnecessary material. Design validation involves defining a threshold for the element's density field between a value between 0 and 1. A value of 0 cancels the material in the specified area of the structure, while a value of 1 defines the designated area as solid material. The designer can then remove all unnecessary material from the model and complete the topology optimization.

The calculation process consists of three main parts; input data, generative design algorithm and production data generation. The inputs to the generative design algorithm are available material, design goals, and rules. The generative design algorithm consists of material classification and a design cycle that repeats the following stages: search algorithm, shape search, and selection. The last step starts the next iteration of the design cycle. The result of the algorithm is a set of possible solutions. Data for production are generated for the selected solution [10-12].

The created kinematic chain (KC) of the future manipulator (Fig. 1) consists of 4 links and a working body (WB). The characteristics of the rotary axes of the manipulator robot are described in Table 1.

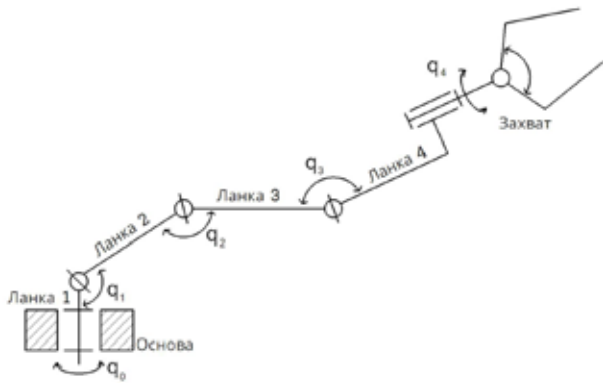


Fig. 1. Kinematic scheme and mechanisms of movement of the 5-axis designed manipulator

When forming the initial link, a diameter of 185 mm was chosen, and the thickness of the sheet metal was 5 mm (Fig. 2).

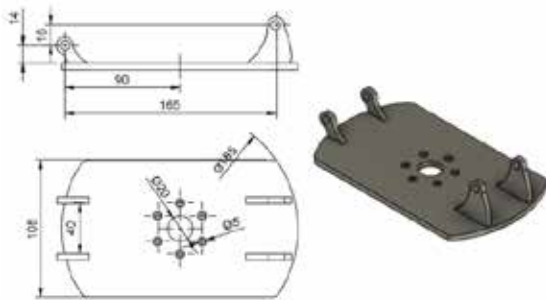


Fig. 2. Dimensions of the initial link

The schematic diagram (Fig. 3) shows the placement of manipulator objects and their attachment to the mobile platform.

The designed link is presented in fig. 4, its length along the attachment points is 420 mm, which fully meets the requirements.

In fig. 5 shows what the link and linear actuator will look like in the assembled state, fixed on the platform.

The next steps are the creation of two more links (3rd and 4th) and four auxiliary elements (Fig. 6, 7).

The design of the created manipulator distributes the load between two symmetrical (except for link 4) links and thus it is possible to achieve a greater potential load than is perceived.

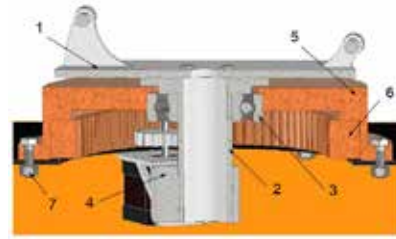


Fig. 3. Schematic diagram of the connection of the base and the initial link

1 – initial link; 2 – rotation shaft; 3 – bearing; 4 – engine with mount; 5 – base body; 6 – toothed insert; 7 – fixing the base

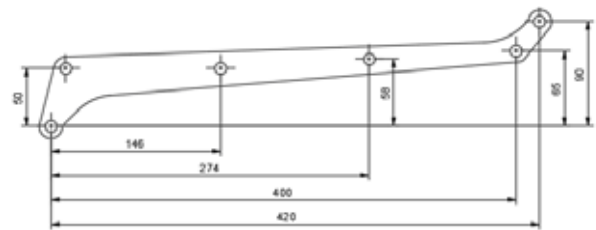


Fig. 4. Position and dimensions of the fastening holes of the 2nd link

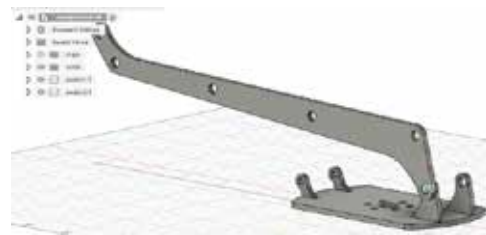


Fig. 5. Position and dimensions of the fastening holes of the 2nd link

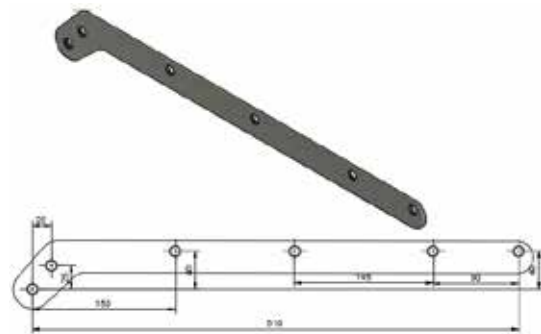


Fig. 6. Location and dimensions of the 3rd link mounting holes

Table 1

Characteristics of rotary axes of the manipulator robot

Rotary axis	Limits (degrees) – relative to the base position		Stepper motor (typical size, torque (N·m))	Torque at the output (N·m)
	Min.	Max.		
Axis q_0	-360	360	Nema 24, 3 N·m	20,25 N·m
Axis q_1	-110	110	Nema 24, 3 N·m	45 N·m
Axis q_2	-140	140	Nema 23, 1,2 N·m	12 N·m
Axis q_3	-360	360	Nema 17, 0.5 N·m	3.75 N·m
Axis q_4	-360	360	Nema 17, 0.5 N·m	3 N·m

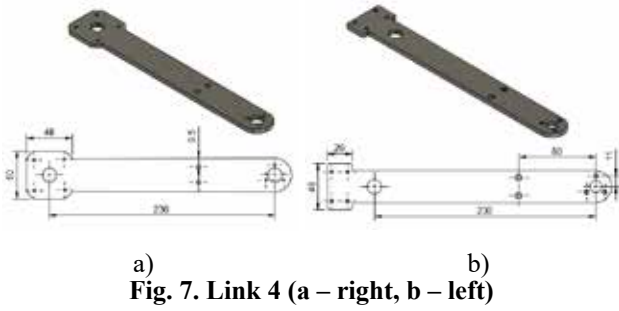


Fig. 7. Link 4 (a – right, b – left)

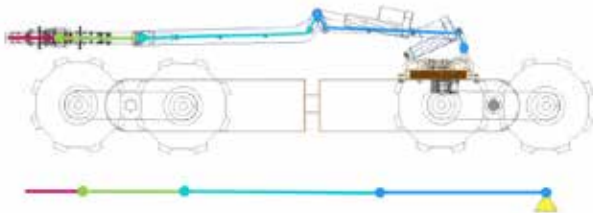


Fig. 8. The manipulator in an expanded form and a simplified diagram

In order to correctly load individual elements of the manipulator, you need to consider the option in an expanded form (Fig. 8).

Figure 10 shows that each link is clamped on one side, this is done with the expectation that there will be no random movements in the joints. All links have a load in the middle, this is the load from the mass of the link itself, there are certain deviations from the real points of attachment and centers of mass, but for the sake of simpler calculation, exactly half the length was chosen.

The total weight of the mechanism is 1.2 kg, the load on one link is 6 N. It is necessary to take into account the maximum weight of the object of transportation, the task is set so that the manipulator must be able to lift and transport an object weighing 10N. The total load on the link will be $(12N+10)*0.5=11N$. Let's do a simulation in the Autodesk Fusion 360 environment [13].

We can observe the load diagram of the right part with a weight of 15N and the margin factor. The entire part is of the same color and has a margin of strength of 15 (Fig. 10), which shows the ability of the link to withstand the load.

The load on all subsequent links will be cumulative. If the output link No. 4 perceived a load of 15N,

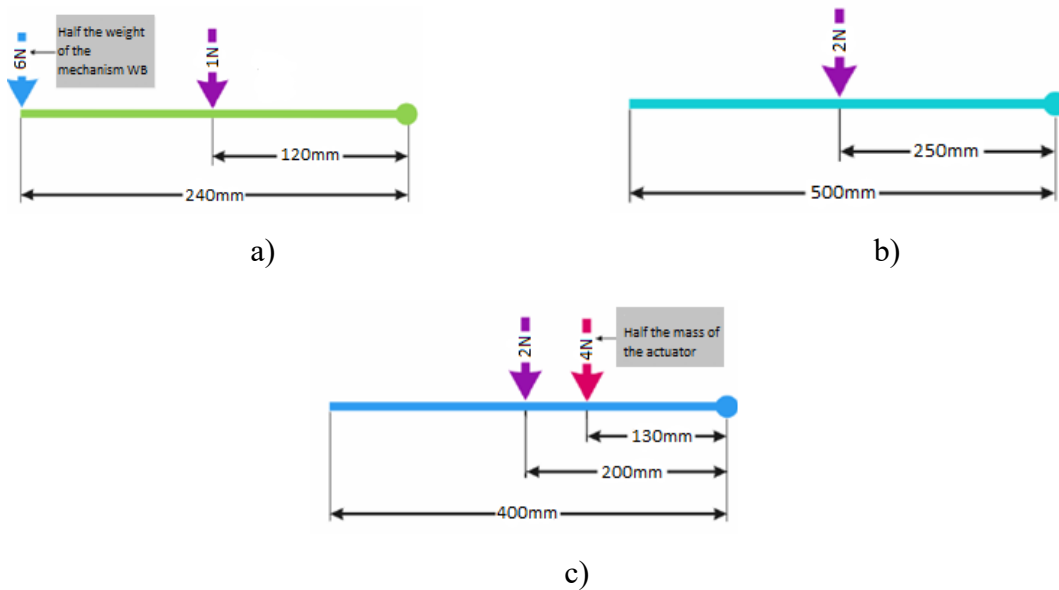


Fig. 9. Loads perceived by links independently of each other
a – load on the fourth link; b – load on the third link; c – load on the second link

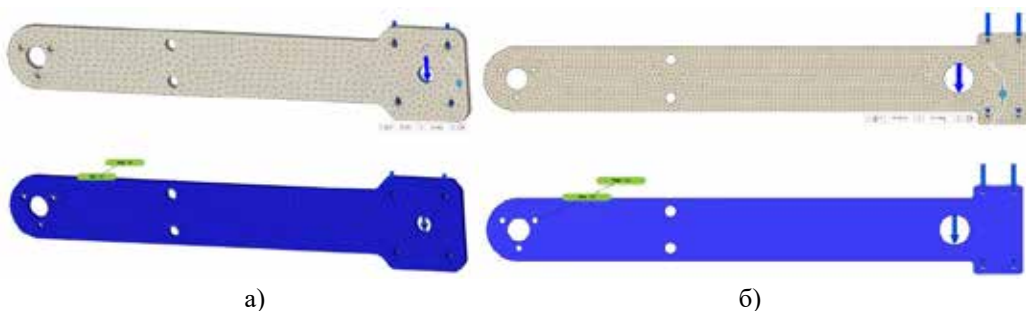


Fig. 10. Loaded link № 4 and simulation (a – right part, b – left)

then link No. 3 will perceive the total load of both links. That is, the load perceived by link №3 will be $11N+2N=13N$, for greater safety a load of $16N$ will be applied. The load simulation is shown in fig. 11.

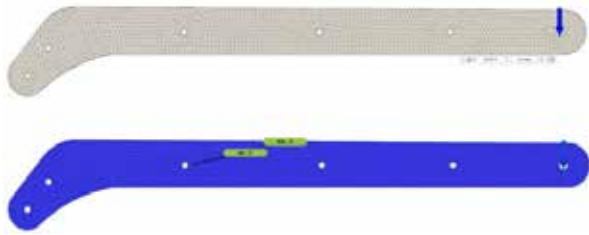


Fig. 11. Load of link №3 and simulation

In fig. 11 we can see that the part can easily withstand the load and has a high margin ratio.

The next detail is link №2 (Fig. 12), which must accept the total load from all previous links. It has an additional load caused by the weight of the linear actuator. The load for testing will be $16N+4N+2N=22N$, for safety we accept $25N$.

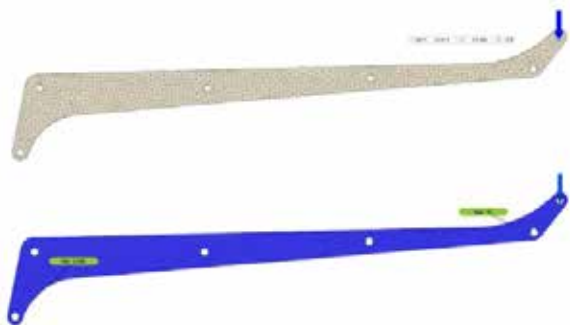


Fig. 12. Load of link №2 and simulation

We can observe that the link easily accepts the set load and has a weight reserve factor of at least 9 times.

The last link is link No. 1 (Fig. 13). It perceives the greatest load, so it is important to correctly load and conduct an analysis.



Fig. 13. Link №1 load and simulation

The main load is $25N$, it is distributed between two mounting lugs, but to ensure normal perception of the

load by the link, it was decided to check each of the mounting holes to the maximum possible, i.e. $30N$.

To reduce the mass of each of the links, it is necessary to analyze and optimize the form. To conduct the analysis, we will use the Simulation: Shape Optimization plug-in in the Autodesk Fusion 360 automated software control environment [13].

We set the loads identical to the previous experiments and observe the gradation shown in fig. 14.

In fig. 14c shows that the removed material that did not participate in the distribution of the load. If we look at the scale on the right, we can see that the load is fully absorbed by the part on only 40% of the volume, so there is an opportunity to change, modify the shape of the part and make it more rational in the use of resources.

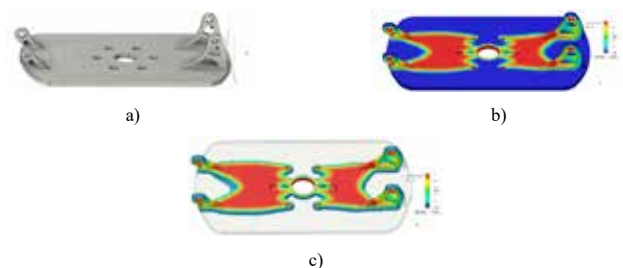


Fig. 14. Results of topological analysis of link №1
a – the initial view of the link; b – link load;
c – removed material

As a result of the optimization, the use of material was reduced by 45%, the weight changed from $266g$ to $120g$ (Fig. 15), and all strength indicators were preserved, the margin factor was 15.

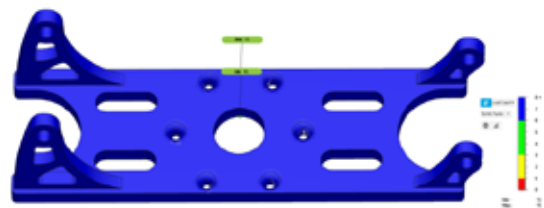


Fig. 15. Optimized link №1

Figure 16 shows the optimization process of link №2 and link №3. The result is a reduced weight of link №2 (Fig. 16 a, 3) from $82g$ to $57g$, that is, the weight is reduced by 31%, and link №3 (Fig. 16, 3) from $188g$ to $110g$, that is, the weight is reduced by 39%.

Figure 17 shows the optimization process of link №4. The result is a reduced weight of the right part of the link (Fig. 17 a, 3) from $77g$ to $52g$, that is, the weight is reduced by 33%, the left part of the link (Fig. 17 b, 3) from $77g$ to $47g$, that is, the weight is reduced by 39% and the shape of additional link 4 in Fig. 18 is optimized.

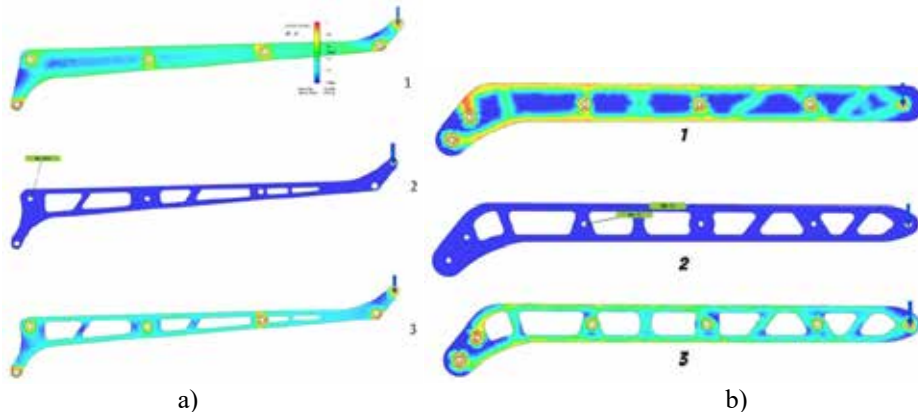


Fig. 16. Optimization of links (a – link №2, b – link №3)

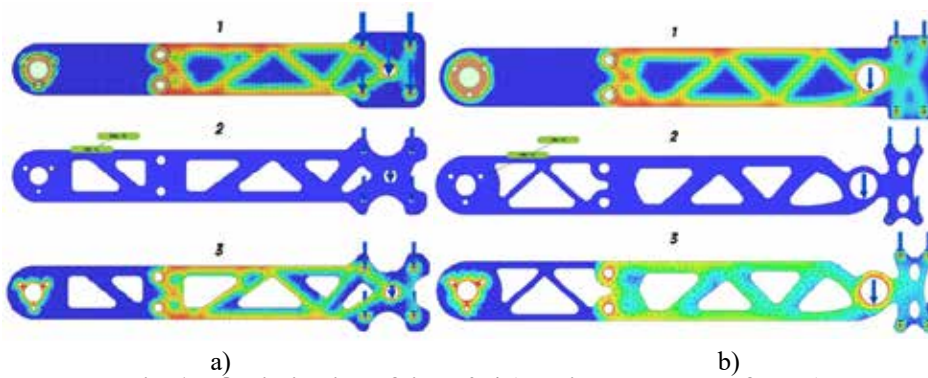


Fig. 17. Optimization of link № 4 (a – right part, b – left part)



Fig. 18. Optimization of the form of auxiliary link 4 (a – link before optimization, b – link after optimization)

The final design is a flat mechanism that rotates about a vertical axis with the help of a motor located at the base of the manipulator.

In fig. 19 shows the manipulator fixed on the platforms before optimization, the total weight of the links was 1060 g. After optimization, the design reduced its mass (Fig. 20), but retained the necessary strength.

Conclusions. To solve the task, the authors developed a kinematic scheme and a movement mechanism of a 5-axis mobile manipulator, performed an analysis and selected stepper motors as the drivers. The rationale for this choice is to increase the positioning accuracy of the gripping mechanism, which will allow for more accurate operations of moving objects. Using the Autodesk Fusion 360 design environment, 3D models of the structural elements of the mobile manipulator were developed, assembly was carried out, and weight and strength parameters were investigated. Using the

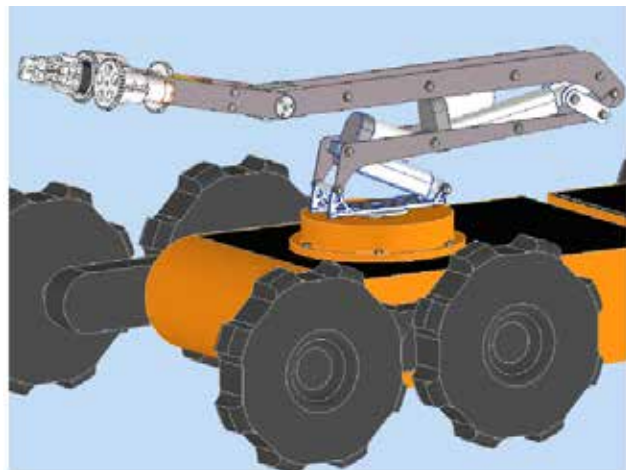


Fig. 19. Link optimization manipulator



Fig. 20. Manipulator after optimization of links

approach to generative design, the authors improved all structural elements and conducted a series of simulations in the Simulation: Shape Optimization plugin. The results of the typological analysis of each link of the developed mobile manipulator showed the possibility of reducing the mass of each part by ~30-40%, depending on its design features, without losing strength parameters. As a result of optimizing the shape of the links, significant changes in the shape and weight of the link manipulator were achieved. It

was possible to reduce the total weight of the MR links from 1060 g (Fig. 19) to 601 g (Fig. 20), that is, the total weight decreased by 41.5%. The authors hope that in the future, the conducted research will allow to reduce the consumption of materials and the time of manufacturing structural elements without loss of strength parameters when using additive technologies (3D printing by the FDM method), and therefore to increase the autonomous operation time of a mobile manipulative robot [14].

Bibliography:

1. Невлюдов І. Ш., Андрусевич А. О., Євсєєв В. В., Новоселов С. П., Демська Н. П. Проектування мобільних маніпуляційних роботів: Монографія. Х., 2022. 427 с.
2. Colucci, G., Baglieri, L., Botta, A., Cavallone, P., Quaglia, G. (2022). Optimal Positioning of Mobile Manipulators Using Closed Form Inverse Kinematics. In: Müller, A., Brandstötter, M. (eds) *Advances in Service and Industrial Robotics. RAAD 2022. Mechanisms and Machine Science*, vol 120. Springer, Cham. https://doi.org/10.1007/978-3-031-04870-8_22
3. Colucci, Giovanni, Andrea Botta, Luigi Tagliavini, Paride Cavallone, Lorenzo Baglieri, and Giuseppe Quaglia. 2022. "Kinematic Modeling and Motion Planning of the Mobile Manipulator Agri.Q for Precision Agriculture" *Machines* 10, no. 5: 321. <https://doi.org/10.3390/machines10050321>
4. A Small-Scale Manipulation Robot a Laboratory Layout Development / Yevsieiev V., Starodubcev N., Maksymova S., Stetsenko K. // *International independent scientific journal*, №47, P.18-28. 2023
5. Shantanu Thakar, Srivatsan Srinivasan, Sarah Al-Hussaini, Prahar M. Bhatt, Pradeep Rajendran, Yeo Jung Yoon, Neel Dhanaraj, Rishi K. Malhan, Matthias Schmid, Venkat N. Krovi, Satyandra K. Gupta. (2023). A Survey of Wheeled Mobile Manipulation: A Decision-Making Perspective. *J. Mechanisms Robotics*. Apr 2023, 15(2). P.25. <https://doi.org/10.1115/1.4054611>
6. Charles C. Kemp; Aaron Edsinger; Henry M. Clever; Blaine Matulevich. (2022). The Design of Stretch: A Compact, Lightweight Mobile Manipulator for Indoor Human Environments. In *International Conference on Robotics and Automation (ICRA)*. 23-27 May. Conference Location: Philadelphia, PA, USA. DOI: 10.1109/ICRA46639.2022.9811922
7. Zhenshan Bing, corresponding author, Fei Chen, Rui Li, Junpei Zhong, and Qiang Li. (2022). Editorial: Biological-Inspired Autonomous Mobile Manipulation: Challenges in Design, Control, and Real-World Applications. *Front Neurorobot.* 2022; 16. DOI: 10.3389/fnbot.2022.928465
8. Vitolo, Ferdinando, Andrea Rega, Castrese Di Marino, Agnese Pasquariello, Alessandro Zanella, and Stanislao Patalano. 2022. "Mobile Robots and Cobots Integration: A Preliminary Design of a Mechatronic Interface by Using MBSE Approach" *Applied Sciences* 12, no. 1: 419. <https://doi.org/10.3390/app12010419>
9. Barbieri, Loris, and Maurizio Muzzupappa. 2022. "Performance-Driven Engineering Design Approaches Based on Generative Design and Topology Optimization Tools: A Comparative Study" *Applied Sciences* 12, no. 4: 2106. <https://doi.org/10.3390/app12042106>
10. Vladyslav Yevsieiev, Nikolaj Starodubcev (2023). Development of a control algorithm for a small-sized mobile manipulation robot. *Scientific Collection «InterConf»*, (140), P. 648-651.
11. Yevsieiev V. (2023) Development of a program for modeling the control of a mobile manipulation robot in the unity environment / Yevsieiev V., Starodubcev N. // *Scientific Collection «InterConf»*, (141), P. 331-334.
12. Development of a 3D Model of a Manipulator for Mobile Robotic Platforms Based on Unigraphics NX / V. Yevsieiev, I. Nevliudov, N. Demska, Y. Valkivskiy // *Вчені записки Таврійського національного університету імені В. І. Вернадського. – Серія : Технічні науки. – 2022. – Т. 33(72), № 1. – С. 157–164.*
13. Fusion 360 | 3D CAD, CAM, CAE, & PCB Cloud-Based Software. Available: <https://www.autodesk.com/products/fusion-360/overview>
14. Attar, H., & et al.. (2022). Zoomorphic Mobile Robot Development for Vertical Movement Based on the Geometrical Family Caterpillar. *Computational Intelligence and Neuroscience*, 2022, Article ID 3046116, <https://doi.org/10.1155/2022/3046116>.

Невлюдов І.Ш., Євсєєв В.В., Демська Н.П., Кострова Г.Ю. РОЗРОБКА ТА УДОСКОНАЛЕННЯ КОНСТРУКЦІЙ ПОЛЕГШЕНОГО МАНІПУЛЯТОРА МОБІЛЬНОГО РОБОТА З ВИКОРИСТАННЯМ ГЕНЕРАТИВНОГО ДИЗАЙНА

Ця стаття присвячена дослідженню можливості мінімізувати масу бортового маніпулятора для мобільного робота без втрати конструктивної міцності. Аналіз публікацій показав, що розв'язання цього завдання дозволить збільшити масу корисного навантаження, отже це дозволить значно збільшити час автономної роботи. Що відповідно дозволить вирішувати більш складні маніпуляційні завдання у зонах підвищеної небезпеки чи техногенних катастроф. Для вирішення поставленого завдання автори розробили кінематичну схему та механізм переміщення 5-вісного мобільного маніпулятора, проведено аналіз та обрано у вигляді рушіїв – крокові двигуни. Обґрунтуванням даного вибору є підвищення точності позиціонування захватного механізму, що дозволить виконувати більш точні операції переміщення об'єктів. Використовуючи середовище проектування Autodesk Fusion 360 розроблено 3D моделі елементів конструкції мобільного маніпулятора, проведено складання та досліджено вагові та міцнісні параметри. Загальна вага маніпулятора склала 1060г, за умов що матеріалом для збереження параметрів міцності буде використовуватися листовий метал товщеної 5мм. Використовуючи підхід до генеративного дизайну, автори провели удосконалення всіх елементів конструкції та провели низку симуляцій у плагіні Simulation: Shape Optimization. Результати типологічного аналізу кожної ланки розробленого мобільного маніпулятора показав можливість зниження маси кожної деталі від ~30-40%, залежно від його конструктивних особливостей, без втрати параметрів міцності. Внаслідок удосконалення конструкції мобільного маніпулятора методом генеративного дизайну, дозволили скоротити загальну масу з 1060г до 601г, тобто маса маніпулятора зменшилася на 41,5%. Автори сподіваються, що проведені дослідження дозволять у майбутньому скоротити витрату матеріалів та час виготовлення конструкційних елементів без втрати міцнісних параметрів при використанні адитивних технологій (3D друк методом FDM), а отже збільшити час автономної роботи мобільного маніпуляційного робота.

Ключові слова: мобільне роботи, маніпулятори, кінематична схема, конструкція, генеративний дизайн, моделювання, Autodesk Fusion 360.