Mechanisms and Machine Science

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Advances in Asian Mechanism and Machine Science

Proceedings of IFToMM Asian MMS 2024

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Mechanisms and Machine Science 167

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Preface

The first conference on Asian Mechanism and Machine Science, in short Asian MMS, started in Taipei in 2010 as an initiative of IFToMM, the International Federation for the Promotion of Mechanism and Machine Science (MMS), as a specific forum for Asiatic communities to promote better relations and disseminations of MMS activities in Asia. Then, following events were held successfully in Tokyo in 2012, in Tianjin in 2014, in Guangzhou in 2016, in Bengaluru in 2018, and in Hanoi in 2021 in mixed teleconference and presential modes because of the COVID-19 pandemic. This year, the Asian MMS is organized in Kazakhstan by a very active IFToMM member organization. Once again, the conference has attracted a large number of researchers coming mainly but not only from Asia in a wide range of topics, within the spirit of collaboration of the IFToMM mission. This seventh event of Asian MMS is organized in Almaty during 28–30 August 2024 with a program for paper presentations thanks to the great effort of local organizers from U. Joldasbekov Institute of Mechanics and Engineering. The Asian MMS, although primarily intended for Asian countries, serves as a global platform for participants to exchange ideas and present their research work in the several fields of MMS in order to exchange and share new and innovative ideas. The papers in this proceedings volume were accepted after a peer review process and then they are presented in sessions of the conference which covers different topics on History and Education in MMS, Mechanism Design and Theory, Computational Methods, Machine and Robot Design, Gearing and Transmissions, Actuators and Sensors, Dynamics and Control of Multibody Systems, Vibration Techniques, Reliability, Biomechanics, Micro and Nano Systems, Experimental Methods in Mechanics, and Space Engineering and Technology . We have received 78 papers, of which 58 full papers were accepted after the review for presenting and being included in this proceedings volume together with four keynote contributions. The majority of the papers are from Kazakhstan, but submissions came also from other IFToMM communities such as China-Beijing, China-Taipei, India, Japan, Russia, Turkey, and even with collaboration from non-Asiatic countries. We express our grateful thanks to the members of International Scientific Committee for Asian MMS, for the support and promoting activities, namely Marco Ceccarelli (Italy) (Chair), Gondi Kondaiah Ananthasuresh (India), Yusuke Sugahara (Japan), Weizhong Guo (China-Beijing), Yu-Hsun Chen (China-Taipei), Khang Nguyen Van (Vietnam), Erkin Gezgin (Turkey), Jomartov Assylbek (Kazakhstan). We would like to express our sincere gratitude to the reviewers, who contributed to the review process with their experience and expertise in due time with a speedy but rigorous review process. The authors of the papers are also acknowledged for having finalized the papers submission after careful revision according to the review comments. We believe that the published papers can be of interest and stimulus for readers for their future activity also with the aim to contribute with their results to the next events of the Asian MMS. We would like to thank all the team members of the organizing committee at the U. Joldasbekov Institute of Mechanics and Engineering in Almaty, who helped with the conference organization and preparation of these proceedings. We would like to send our also appreciation to the Springer-Nature team for their support and patience in publishing this book in time for Asian MMS conference.

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Contents

Definition and Visualization of Distributed Dynamic Loads of Manipulators

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Abstract. In this paper, an approach to 3D modeling of spatial manipulators using the Maple 2023 is proposed. Algorithms and program codes have been developed in order to obtain 3D computer models of manipulators controlled by generalized coordinates. Implementation of developed algorithms and program codes made it possible to create 3D computer models of manipulators with the accurate images of links and their cross sections, kinematic pairs, grips and loads, with various structures and degrees of freedom and which are clearly visible in three-dimensional space.

When manipulators move, from own masses of links the distributed dynamic loads of a complex nature arise in the links. Such dynamic loads cause the problems: for example, due to large dynamic loads or due to large deformation of the links, the manipulator may fail, etc. Therefore, analytical approaches have been developed to determine the patterns of dynamic loads distribution along the longitudinal axes of manipulator links. Algorithms and program codes have been developed for constructing diagrams of distributed dynamic loads in mutually perpendicular planes formed by the main axes of the cross sections of the links and the axes passing along the links. Through this it is possible to see changes in the direction and magnitude of distributed dynamic loads in all cross sections of the links for the full working process of the manipulator. This enables to consider the found dynamic loads in strength and stiffness calculations of manipulator links, which are important in design of new innovative manipulators.

Keywords: Manipulators · Computer 3D Modeling · Maple 2023 · Kinematics · Dynamic Loads · Dynamic Loads Diagrams

1 Introduction

In recent years, 3D computer modeling of robotic systems has been widely used for research and educational purposes, since it is one of the most promising and effective areas of research on spatial manipulators. With the increasing complexity of the designed

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robotic manipulators, their analytical study becomes more difficult, and the creation of experimental samples becomes more expensive. 3D computer modeling of robotic manipulators is often the most appropriate research method, or even in some cases may be the only available method.

Currently, there are CAD, CAM and CAE systems capable of creating 3D models of spatial manipulators, such as SimMechanics, Autodesk Inventor, SolidWorks, CadMech, Adams and others.

A robotic OLP system called RobSim, based on SolidWorks Microsoft Visual Studio 2010 was developed [1]. RobSim is designed as an additional tool for the widely used SolidWorks CAD software. Integrating of SolidWorks and Matlab/Simulink in the Matlab/Simulink, performed through the implementation of CAD models created earlier in the SolidWorks program was described [2]. A computer model of a three-bar vertically walking robot in the Matlab was developed, which shows in general terms the principle of operation of such robots [3]. The simulation of the motion of a vertically walking robot was carried out using the SimMechanics library of Simulink in the Matlab.

SolidWorks is a CAD software system with great performance in 3D modeling, visualization and simulation with a rich API containing hundreds of functions. Unfortunately, there are no existing add-ons or toolkits in SolidWorks to control the created 3D models of robotic manipulators. The strength of parallel manipulators with statically determinate and indeterminate structures was investigated, taking into account dynamic loads [4–6].

One difficulty of analyzing the stress-strain state of manipulator links is due to the fact that the manipulator under study is in motion and at the same time distributed dynamic loads of a complex nature arise from the mass of the links in each cross section of the links. These dynamic loads change their magnitude, direction and depend on the kinematic characteristics of the links. Since the manipulator is moving, it is not known in which cross section of the link and at which position of the manipulator the maximum value of any internal force or deformation occurs. Therefore, it is necessary to study the stress-strain state of the manipulator for a full working cycle. It is also necessary to visualize the stress-strain state of all links during the full operating cycle of the manipulator so that all types of dynamic loads, internal forces and deformations are clearly visible in all cross sections of the links. This permits the designer to analyze the stress-strain state of each link and make the right decision when calculating the strength and stiffness of manipulator links.

1.1 Algorithm for 3D Modeling of Manipulators in the Maple'23

The Maple 2023 software includes three–dimensional primitives of the plottools package allowing design engineers to build three-dimensional shapes and surfaces – cones, cylinders, parallelepipeds, cubes, polyhedra, etc. With the help of these primitives, links, racks, grips and kinematic pairs of manipulators are built. The obtained three-dimensional parts in the Maple 2023 can be moved in the direction of three axes of space and rotated along these three axes. Using the obtained links, kinematic pairs, grips, racks a 3D model of the manipulator can be assembled. Further, all the elements of the manipulator are combined into one system by introducing basic joints (kinematic pairs) from the grip to the rack, with the construction of a complete visual moving model of a manipulator controlled by generalized coordinates. In the Maple 2023, it is possible to join links rigidly or allowing relative motion to each other. Therefore, the designer can build manipulators of the necessary structure and degree of freedom. Using the mentioned algorithms, program codes for building 3D models of manipulators, the movement of which is controlled by generalized coordinates, have been developed in the Maple 2023. The implementation of the developed algorithms and program codes made it possible to create 3D computer models of manipulators with clear images of links and their cross sections, kinematic pairs, grips and loads, with various structures and degrees of freedom, well-viewed from all sides of the space (see Fig. 1, 2). Using this algorithm, the designer can build 3D computer models of manipulators with any desired structure and with different degrees of freedom.

By setting certain patterns to the generalized coordinates of the obtained manipulators, their movement in space can be seen.

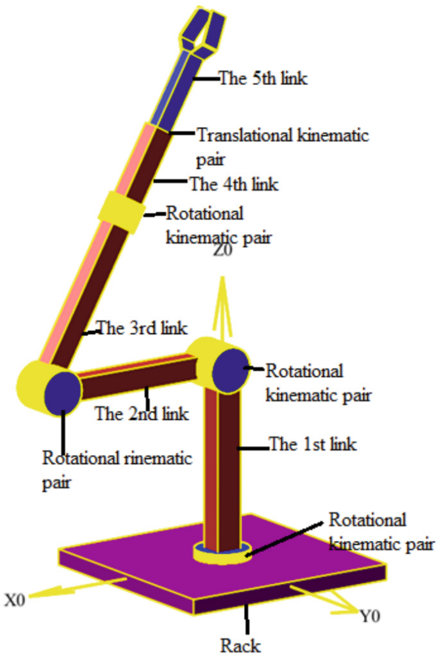

Fig. 1. A six-bar manipulator with five degrees of freedom (RRRRT), with four rotational and one translational kinematic pairs.

Kinematic Characteristics of Manipulator

In this paper, the Denavit-Hartenberg convention is used to determine the position and directions of the manipulator links in space, which first used homogeneous 4×4 transformation matrices to describe the spatial geometry of the manipulator.

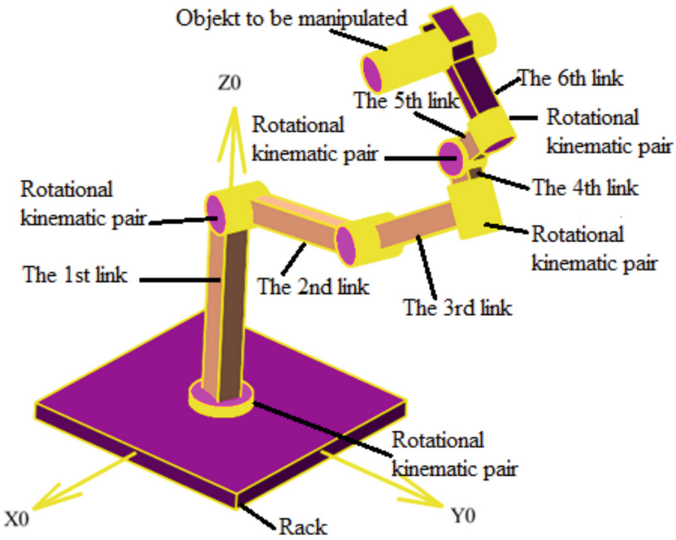

Fig. 2. A seven-bar spatial manipulator with six degrees of freedom (RRRRRR) and with six rotational kinematic pairs.

The vectors of angular velocities, angular accelerations and linear velocities, linear accelerations of the points of the manipulator links are determined relative to the Denavit-Hartenberg coordinate systems associated with the links using the recurrent Newton-Euler equations. The components of these vectors make it possible to determine all types of dynamic loads and establish patterns of their distribution.

Dynamic loads arising from the mass of the links during the motion of the manipulator

In this paper, it is assumed that the cross section of the links is constant and the mass is distributed along the axis of the link, from this condition the patterns of distribution of dynamic loads along the axis of the link are determined.

With a constant cross-section of the manipulator links, the intensity of the distribution of gravity forces relative to the base coordinate system in any cross section of the i-th link is determined by the following vector (unit of measurement $\left(\frac{N}{m}\right)$:

$$\overrightarrow{f_i} = \left[0, 0, -\gamma_i s_i\right]^T, \tag{1}$$

where γi – the specific weight of material of i-th link (N/m^3);

si – the cross-sectional area of the i-th link(m^2).

In the coordinate system $O_i\ X_i Y_i Z_i$, rigidly connected with the i-th link, the intensity of the laws of gravity distribution is determined by the following vector along the coordinate axes:

$$\overrightarrow{R_0^i f_i} = R_0^i * \overrightarrow{f_i}, \tag{2}$$

where $R^i{}_0$ – the matrix that defines the directions of the axes of the coordinate system $O_0\ X_0 Y_0 Z_0$ relative to the coordinate system $O_i X_i Y_i Z_i$.

While the manipulator moves at points $\overrightarrow{P}_i^i = [x_i\ y_i\ z_i]^T$, rigidly connected to a link in the coordinate system $O_i X_i Y_i Z_i$, linear accelerations appear relative to this coordinate system, which can be determined using the following equation:

$$\overrightarrow{R_0^i a_{pi}} = R_0^i * \overrightarrow{a}_i + \left(R_0^i * \overrightarrow{\omega}_i\right) \times \left[\left(R_0^i * \overrightarrow{\omega}_i\right) \times \left(R_0^i * \overrightarrow{P}_i^i\right)\right] + \left(\left(R_0^i * \overrightarrow{\varepsilon}_i\right) \times \left(R_0^i * \overrightarrow{P}_i^i\right)\right). \tag{3}$$

From the accelerations of points located on the axis of the link, inertial forces arise, distributed along the axes of the manipulator links. If we assume that the cross sections of the link are constant, then the mass of the link per unit length (cross-sectional mass or intensity of mass distribution along the axis of the link) is equal to $\frac{\gamma_i s_i}{g}\left(\frac{H*c^2}{M^2}\right)$. In order to determine the intensity of inertia forces arising from linear accelerations at the points of the coordinate system axes $O_i X_i Y_i Z_i$, rigidly connected with i-th link, a mass intensity inertia matrix will be constructed, which will look like this:

$$m_i = \begin{pmatrix} \frac{\gamma_i s_i}{g} & 0 & 0 \\ 0 & \frac{\gamma_i s_i}{g} & 0 \\ 0 & 0 & \frac{\gamma_i s_i}{g} \end{pmatrix} \tag{4}$$

Then the intensity of the inertia forces in the cross sections of the *i*-link is determined by the following expression (unit of measurement $\left(\frac{N}{m}\right)$):

$$\overrightarrow{q}_i = -m_i * \overrightarrow{R_0^i a_{pi}} \tag{5}$$

The vector of distribution of the intensity of dynamic loads arising from the intensity of the distribution of dead weight of the cross sections of the links and from the intensity of the distribution of inertia forces arising from linear accelerations of the cross sections is determined by the following equation:

$$\overrightarrow{F}_i = \overrightarrow{R_0^i f_i} + \overrightarrow{q}_i \tag{6}$$

In order to determine the intensity of the distribution of moments of inertia arising from angular velocities and accelerations, the intensity of the axial moments of inertia in the cross sections of the link will be found. Fig. 3 shows an image of the cross-section of the link, as if the quadrilateral were a thin plate.

If the axes Xi, Yi, Zi of the cross sections of the *i*-th link are directed in this way in the cross section, then the moments of axial inertia relative to the axes are determined by the following expressions (unit of measurement $N * s^2$):

$$I_{xi} = \frac{\gamma_i s_i c_i^2}{12g},\ I_{yi} = \frac{\gamma_i s_i h_i^2}{12g},\ I_{zi} = \frac{\gamma_i s_i (c_i^2 + h_i^2)}{12g} \tag{7}$$

where hi, ci - the lengths of the sides of the cross section of the *i*-th link,

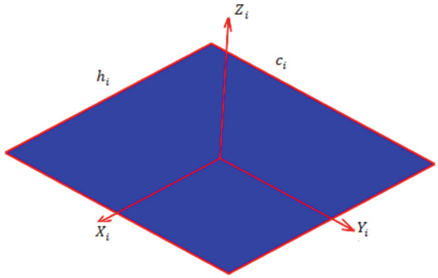

Fig. 3. The image of the cross section of the link, as if the quadrilateral were a thin plate.

si = hi * ci- the cross-sectional area of the *i*-th link.

The intensity matrix of the moments of inertia of the cross section of the *i*-th link:

$$\mathrm{I_i} = \begin{pmatrix} \mathrm{I_{xi}} & 0 & 0 \\ 0 & \mathrm{I_{yi}} & 0 \\ 0 & 0 & \mathrm{I_{zi}} \end{pmatrix} \tag{8}$$

The intensities of the moments of inertia arising in the cross sections of the *i*-th link are determined using the following ratio (unit of measurement *N*)

$$\overrightarrow{\mathrm{M}}_{\mathrm{i}} = -\left(\mathrm{I_i} * \left(\mathrm{R_0^i} \times \overrightarrow{\varepsilon}_{\mathrm{i}}\right) + \left(\mathrm{R_0^i} * \overrightarrow{\omega}_{\mathrm{i}}\right) \times \left(\mathrm{I_i} * \left(\mathrm{R_0^i} * \overrightarrow{\omega}_{\mathrm{i}}\right)\right)\right) \tag{9}$$

Using the above algorithms, program codes have been developed for constructing visual diagrams of distributed dynamic loads on the links of the manipulator.

Determination of dynamic loads occurring in the links of the RRRRT manipulator and the construction of their visual diagrams

The laws of motion of the generalized coordinates of the manipulator are specified as follows: $\theta_1 = \dot{\theta}_1 * t$, $\dot{\theta}_1 = \pi$, $\ddot{\theta}_1 = 0$, the unit of time is the second, defined by the relation $t = \frac{i}{k}$, где i = 0…36 – considered positions of the manipulator, k = 36 – total number of positions; $\theta_2 = \dot{\theta}_2 * t$, $\dot{\theta}_2 = \pi$, $\ddot{\theta}_2 = 0$; $\theta_3 = -\frac{\pi}{2} * \dot{\theta}_3 * t$, $\dot{\theta}_3 = \frac{2\pi}{3}$, $\ddot{\theta}_3 = 0$; $\theta_4 = \dot{\theta}_4 * t$, $\dot{\theta}_4 = \pi$, $\ddot{\theta}_4 = 0$; $d_5 = \dot{d}_5 * t$, $\dot{d}_5 = 0.35$, $\ddot{d}_5 = 0$.

Cross-sectional areas of the manipulator links (unit of measurement m^2): $s_1 = 0.012$, $s_2 = 0.008$, $s_3 = 0.008$, $s_4 = 0.008$, $s_5 = 0.0048$.

Specific gravity of materials of manipulator links (units of measurement $\frac{\mathrm{N}}{\mathrm{m}^3}$):$\gamma_1 = \gamma_2 = \gamma_3 = \gamma_4 = \gamma_5 = 78 * 10^3$.

Dimensions of cross sections of manipulator links (units of measurement m): $c_1 = 0.12, h_1 = 0.1$; $c_2 = 0.1, h_2 = 0.08$; $c_3 = 0.1, h_3 = 0.08$; $c_4 = 0.1, h_4 = 0.08$; $c_5 = 0.06, h_5 = 0.04$:

The implementation of the developed algorithms and program codes made it possible to construct distribution diagrams of all dynamic loads in all links, in mutually perpendicular planes formed by the main axes of the cross sections of the links and the axes passing along the links of the manipulator. The results are shown in Fig. 4, 5, 6, 7.

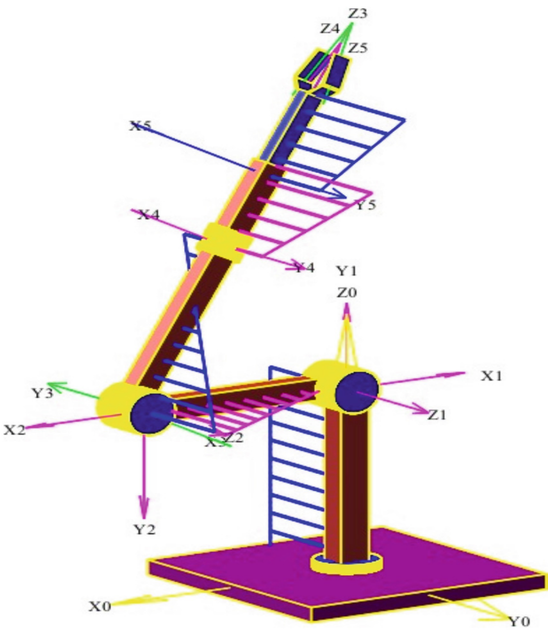

Fig. 4. The patterns of distribution of longitudinally distributed dynamic loads arising from the own weight of the links of the RRRRT manipulator.

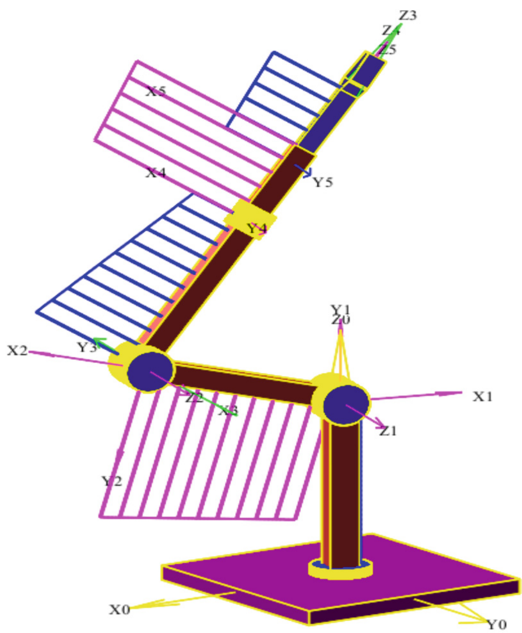

Fig. 5. The regularities of the distribution of transversely vertically distributed dynamic loads arising from the own weight of the links of the RRRRT manipulator.

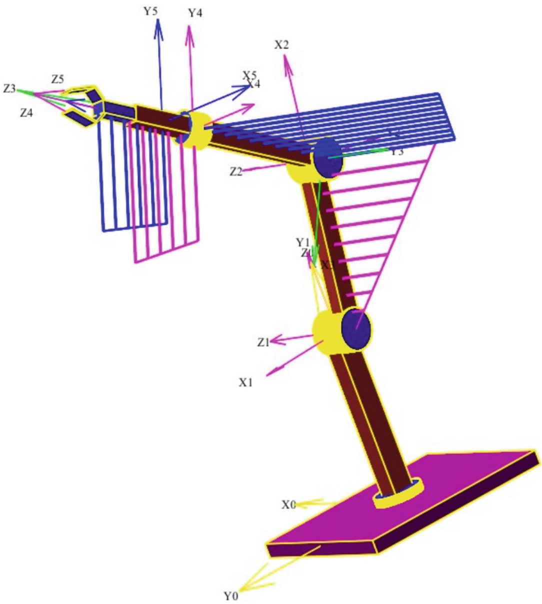

Fig. 6. The diagrams of horizontally distributed dynamic loads arising from the own weight of the links of the RRRRT manipulator.

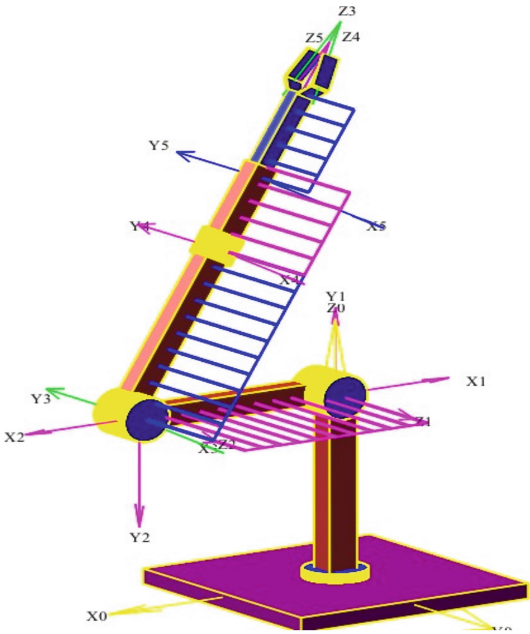

Fig. 7. The diagrams of distributed dynamic moments arising from the own weight of the links and rotation of the links around their axis links of the RRRRT manipulator.

2 Conclusion

The algorithms and program codes have been developed and implemented in the proposed work, with the help of which 3D computer models of manipulators are built in the Maple 2023, controlled by generalized coordinates. This paper also develops analytical approaches for determining patterns of distribution of dynamic loads along the longitudinal axes of manipulator links. The algorithms and program codes have been developed and visual diagrams of distributed dynamic loads on the manipulator links have been constructed. Using the results obtained in the work, it is possible to analytically derive and visualize the dynamic stress-strain state for one full cycle of the work process, constructing diagrams of internal forces and displacements in the cross sections of the manipulator links. The results obtained also allowing to select the optimal shapes of the cross sections of the links and find their linear dimensions. The development of new analytical methods for calculating the strength and stiffness of manipulators can be used to create new innovative robotic manipulators that solve new scientific and industrial problems.

References

1. Wu, H., Deng, H., Yang, C., Guan, Y., Zhang, H., Li, H.: A robotic off-line programming system based on SolidWorks. In: Proceedings of the 2015 IEEE Conference on Robotics and Biomimetics, pp. 1711–1716. IEEE (2015)
2. Cekus, D., Posiadała, B., Waryś, P.: Integration of modeling in SolidWorks and Matlab/Simulink environments. In: Archive of Mechanical Engineering, vol. 61, pp. 57–74. Polish Academy of Sciences (2014)
3. Kalinichenko, S., Konovalov, K., Sevostyanov, N., Sevostyanov, I.: Simulation in MATLAB of a vertical walking three-link robot. In: AIP Conference Proceedings, vol. 2195. AIP Publishing (2019)
4. Utenov, M., Baigunchekov, Z., Zhilkibayeva, S., Utenov, N.: Computational method of determination of internal efforts in links of mechanisms and robot manipulators with statically definable structures considering the distributed dynamically loadings. In: Proceedings of ECCOMAS Congress 2016, vol. IV, pp. 8627–8639 (2016)
5. Utenov, M., Zhilkibayeva, S., Utenov, N.: Animation of motion of mechanisms and robot manipulators in the Maple system with the construction of diagrams of internal forces on the links. In: ACM International Conference Proceedings Series of the 2nd International Conference on Robotics, Control and Automation 2017, pp. 30–34. ACM Digital Library (2017)
6. Utenov, M., Sobh, T., Baigunchekov, Z., Zhilkibayeva, S., Patel, S.: Analytical method for determination of internal forces of mechanisms and manipulators. MDPI Robot. **7**(3), 53 (2018)