SIMULATION AND ANALYZES OF INVERSE-KINEMATIC MODEL
OF HUMANOID ROBOT HAND

Urgency of the research. Nowadays robotics and mechatronics come to be mainstream. With development in these areas also grow computing fastidiousness. Since there is significant focus on numerical modeling and algorithmization in kinematic and dynamic modeling.

Target setting. Suitable approach for numerical modeling is important from the view of time consumption as well as stability of computing.

Actual scientific researches and issues analysis. Designing and modeling of humanoid robots have high interest in the field of robotics. The hardware and mechanical design of robots is on significantly higher level in comparison with software of robots. So, modeling and control of robots is in the interest of researchers.

Uninvestigated parts of general matters defining. Comparison of methods for numerical modeling of inverse kinematics.

The research objective. Comparing four methods from the view of performance and stability.

The statement of basic materials. This paper investigates the area of kinematic modeling of humanoid robot hand and simulation in MATLAB.

Conclusions. The paper investigated inverse kinematic model approaches. There were analyzed pseudoinverse method, transpose of Jacobian method, damped least squares method as an optimization method. The results of the simulations show the advantages of optimization method. During the simulations it never fail in comparison with other tested methods.

Keywords: humanoid robot hand; inverse kinematics; Jacobian; simulation.

Introduction. Nowadays, people are in the contact with the robotic systems almost on daily base. The development in this area significantly arises. Service robots have their utilization in industrial companies, health services, military or like household robots [1]. They can be also used in medicine as prosthesis for people who lose their limbs.

This study focuses on kinematic modeling of robot hand. One of the first works in this research are [2] and [3]. Several researches are focused on modeling of human robot locomotion [4] and [5], some of them deal with modeling of robot hand [1][6][7]. This paper studies inverse kinematic models, simulate them and compare from the view of simulation speed and stability.

The paper is divided as follows. The second chapter deals with biomechanics of human hand describing the joints and bones. Based on biological human hand, the concept of robot hand is designed with corresponding DOF. Next chapter presents iteration methods for inverse kinematic modeling. The inverse kinematic model of robot hand is established and simulated in MATLAB. In the conclusion the methods are compared and the results are discussed.

Biomechanics. This section discusses about human hand. Fig. 1 shows particular bones and joints of a human finger. As can be seen in the Fig. 1, human hand consists of 14 phalanges, 5 splint bones as well as 8 wrist bones, see also Fig. 2.

Fig. 1. Finger of human hand
Hand is connected to forearm through carpal bones. For the purposes of kinematic model design it can be neglected. Metacarpal bones form a palm of hand by their arcuate shape and their motion is limited. Carpometacarpal, proximal interphalangeal and distal interphalangeal joints can be considered as revolute joints and metacarpophalangeal joint as ball-joint. A thumb is different from other fingers because it does not have second phalangeal bone and its metacarpophalangeal joint gives it significant opportunity of motion [14]. When the carpal bones are neglected the human hand has $24 + 6$ DOF, 24 for hand and 6 for placement in 3D space.

The range of motion of particular joints in the Tab. 1 are shown.

| Joint position       | Kind of joint | Motion                | Range     |
|----------------------|---------------|-----------------------|-----------|
| Wrist                | Elliptical    | Flexion, Duction      | 120°, 20° |
| Carpal – thumb       | Cylindrical   | Flexion               | 90°       |
| Metacarpal – thumb   | Saddle        | Duction, Opposition   | 50°, 60°  |
| Metacarpal – fingers | Spherical     | Flexion, Duction      | 90°, 30°  |
| Middle – thumb       | Cylindrical   | Flexion               | 20°       |
| Middle – fingers     | Cylindrical   | Flexion               | 100°      |
| Terminal – thumb     | Cylindrical   | Flexion               | 90°       |
| Terminal – fingers   | Cylindrical   | Flexion               | 80°       |

Mathematical model of humanoid robot hand. The aim of inverse kinematic model is to find generalized variables $\mathbf{q} = [q_1, q_2, \ldots, q_n]^T \in \mathbb{R}^n$, where $n$ is number of DOF. The end-effector coordinates is $\mathbf{x} \in \mathbb{R}^m$, where $m$ represents number of task. Considering inverse kinematic model, finding the solution is significantly more difficult task in comparison with direct kinematic model. Numerical solution arises from basic term

\[ \mathbf{x}_k = f(\mathbf{q}_k) \]

By iteration of following term can be solved inverse kinematic model

\[ \mathbf{q}_{k+1} = \mathbf{q}_k + \mathbf{J}^{-1}(\mathbf{x}_p - \mathbf{x}_k) \]

Where $\mathbf{x}_p$ is vector of desired position and $\mathbf{x}_k$ is vector of actual position. Considering $n$ number of DOF is higher than number of performed task $m$ we can speak about kinematically redundant mechanism. In this case we can you for example pseudoinverse arising from

\[ \Delta \mathbf{q} = \mathbf{J}_p \Delta \mathbf{x} \]

Since Jacobian is no symmetric matrix we can use following equation

\[ \mathbf{J}_p = \mathbf{J}^T(\mathbf{J}^T)^{-1} \]

Considering the case when $n < m$, Jacobian is expressed as

\[ \mathbf{J}_p = (\mathbf{J}^T)^{-1}\mathbf{J}^T \]
Next frequently used method for inverse kinematic is method based on transposed of Jacobian. This method was firstly used in the works [12] and [13]. The method is based on idea of replacing Jacobian inversion by transpose of Jacobian. It can be expressed as

\[ \Delta q = \delta J^T \Delta x \]

where \( \delta \) is scalar value defined by user.

Next considered method is damped least squares (DLS). DLS assume with finding such \( \Delta q \) that minimizes following equation

\[ \| J \Delta q - \Delta x \|^2 + \lambda \| \Delta q \|^2 \]

where \( \lambda \) is damping constant. By mathematical operations can be last mentioned term adjust as

\[ \Delta q = J^T (J^T + \lambda^2 I)^{-1} \Delta x \]

where \( I \) is unit matrix.

With three mentioned methods will be also considered method which lies in optimization process. For optimization method the function \( \text{fmincon} \) is used in software MATLAB. This function tries to find minimum of scalar function of variables. For simulation has to be set the set of initial guess of variables.

\[
\min f(x) \text{ for } \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ Ax \leq b \\ Aeqx = beq \\ lb \leq x \leq ub \end{cases}
\]

where \( x \) is vector of independent variables, \( lb \) is vector of lower boundary values, \( ub \) is vector upper boundary values, \( c(x) \) and \( ceq(x) \) are functions of \( x \) for conditions of equality and inequality, \( A \) and \( Aeq \) are matrices of parameters for conditions of linear equality and inequality, \( b \) and \( beq \) are vectors of parameters of right sides of conditions of linear equality and inequality, \( f(x) \) is objective function of independent variables \( x \), from which the extreme is searched [15]. Function \( \text{fmincon} \) is gradient-based method.

**Numerical simulations.** All mentioned methods in the previous chapter will be now simulated in order to find the best approach. The simulations in the software MATLAB are done. The parameters for simulations arise from biomechanics of human hand. So particular part of the simulated finger has following length: \( l_1 = 79.16 \text{ mm} \); \( l_2 = 67.5 \text{ mm} \); \( l_3 = 30.43 \text{ mm} \); \( l_4 = 15.81 \text{ mm} \). Tolerance of inverse kinematic solution is set to be 0.01 mm. The simulation are evaluated from the two aspects. The first is the time of simulation and the second is number of iteration necessary for finding of solution.

**Table 2**

| Method                        | Point [mm]     | Solution | Time [s] | Number of iterations |
|-------------------------------|----------------|----------|----------|----------------------|
| 1                             |                |          |          |                      |
| Damped least squares          | [80 150 45]    | found    | 1.858877 | 543                  |
|                               | [40 220 20]    | not found| >10      | –                    |
|                               | [80 140 80]    | found    | 1.795458 | 538                  |
|                               | [50 90 80]     | found    | 1.735288 | 509                  |
|                               | [30 200 -5]    | not found| >10      | –                    |
| Pseudoinversion of Jacobian   |                |          |          |                      |
|                               | [80 150 45]    | found    | 1.816513 | 542                  |
|                               | [40 220 20]    | not found| >10      | –                    |
|                               | [80 140 80]    | found    | 1.763199 | 538                  |
|                               | [50 90 80]     | found    | 1.665617 | 509                  |
|                               | [30 200 -5]    | not found| >10      | –                    |
As can be seen from the Tab. 2, there are some cases when the simulations fail. However, using optimization method the solution were found always. The advantage of this method is in non Jacobian based approach. In the following figures are some examples of optimization method for particular humanoid robot hand tasks.

*Fig. 3. Pushing of the button by finger*

*Fig. 4. Grasping task*

**Conclusions.** The paper investigated inverse kinematic model approaches. There were analyzed pseudoinverse method, transpose of Jacobian method, damped least squares method as well as optimization method. The results of the simulations show the advantages of optimization method. During the simulations it never fail in comparison with other tested methods.

**Acknowledgement.** The authors would like to thank to Slovak Grant Agency – project VEGA 1/0389/18 and VEGA 1/0872/16.
References

1. J. Hirt, K. Berns, K. Mianowski, Designing Arms and Hands for the Humanoid Robot ROMAN, in: Advanced Materials Research (2012), pp. 1233–1237.

2. I. A. Kapandji. The Physiology of the Joints (1970), Vol. 1. E&S Livingstone, Edinburgh and London, 2 editions.

3. K.S. Salisbury, B. Roth, Kinematics and force analysis of articulated mechanical hands, Journal of Mechanisms, Transmissions and Actuation in Design, 105, 1983, pp. 35–41.

4. S. Kagami, M. Mochimaru, Y. Ebara, N. Miyata, K. Nishiwaki, T. Kanade, and H. Inoue, Measurement and comparison of human and humanoid walking, in Proceedings of IEEE International Symposium on Computational Intelligence in Robotics and Automation, Vol. 2, 2003, pp. 918–922.

5. T. Ishida, Y. Kuroki, and J. Yamaguchi, Mechanical system of a small biped entertainment robot, in Proceedings of the 2004 IEEEERAS International Conference on Humanoid Robots (Humanoids), Los Angeles, California, USA, November 10 – 12, 2004, pp. 235–252.

6. A. Schmitz, M. Maggiali, L. Natale, G. Metta, Touch Sensor for Humanoid Hands, IEEE Symposium on Robot and Human Interactive Communication, 2010, pp. 691–697.

7. N. Fukaya, S. Toyama, T. Asfour, R. Dillmann, Design of the TUAT/Karlsruhe Humanoid Hand, International Conference on Intelligent Robots and Systems, 2000, pp. 1754–1759.

8. C. L. Taylor, R. J. Schwarz, The Anatomy and Mechanics of the Human Hand, Artificial Limbs (1955), Vol. 2, No. 2, pp. 22–35.

9. J. de Lope, T. Zarraonandia, R. González-Careaga, D. Maravall, Solving the Inverse Kinematics in Humanoid Robots: A Neural Approach, Lecture Notes in Computer Science (2003), Vol. 2687, pp. 177–184.

10. S. R. Buss, J.S. Kim, Selectively Damped Least Squares for Inverse Kinematics, Journal of Graphics Tools (2005), Vol. 10, Issue 3, pp. 37–49.

11. S. R. Buss, Introduction to Inverse Kinematics with Jacobian Transpose, PseudoInverse and Damped Least Squares methods, IEEE Journal of Robotics and Automation (2004), pp. 681–685.

12. Wolovich, W. A., Elliott, H., A Computational Technique for Inverse Kinematics, IEEE Conference on Decisions and Control (1984), pp. 1359–1363.

13. Balestrino, A., De Maria, G., Sciacicco, L., Robust Control of Robotic Manipulators, IFAC World Congress (1984), pp. 2435–2440.

14. Virgala, I., Kelemen, M., Varga, M., Kurylo, P. Analyzing, Modeling and Simulation of Humanoid Robot Hand Motion, Procedia Engineering (2014), Elsevier.

15. Virgala, I., Gmiterko, A., Kelemen, M., Varga, M. Inverse Kinematic Model of Humanoid Robot Hand, Applied mechanics and Materials (2014), pp. 75-82.
тимізації. Результати моделювання показують переваги методу оптимізації. Під час моделювання цей метод ніколи не відмовляє порівняно з іншими перевіреними методами.

Ключові слова: руха людинооподібних роботів; зворотна кінематика; якобіан; моделювання.

Рис.: 4. Табл.: 2. Бібл.: 15.

Martin Varga – PhD student, Technical University of Košice, Faculty of Mechanical Engineering, Institute of Automation, Mechatronics and Robotics, Department of Mechatronics (Park Komenského 8, 04200 Košice, Slovak Republic).
Мартин Варга – аспірант, Технічний університет Кошице (Park Komenského 8, 04200 Košice, Slovak Republic).
E-mail: martin.varga.2@tuke.sk

Filip Filakovský – PhD student, Technical University of Košice, Faculty of Mechanical Engineering, Institute of Automation, Mechatronics and Robotics, Department of Mechatronics (Park Komenského 8, 04200 Košice, Slovak Republic).
Філіп Філаковський – аспірант, Технічний університет Кошице (Park Komenského 8, 04200 Košice, Slovak Republic).
E-mail: filip.filakovsky@tuke.sk

Ivan Virgala – assoc. professor, Ph.D. of Technical Sciences, Technical University of Košice, Faculty of Mechanical Engineering, Institute of Automation, Mechatronics and Robotics, Department of Mechatronics (Park Komenského 8, 04200 Košice, Slovak Republic).
Іван Виргала – доцент, кандидат технічних наук, Технічний університет Кошице (Park Komenského 8, 04200 Košice, Slovak Republic).
E-mail: ivan.virgala@tuke.sk

Varga, M., Filakovský, F., Virgala, I. (2019). Simulation and analyzes of inverse-kinematic model of humanoid robot hand. Technical sciences and technologies, 3 (17), 117–122.