Mathematical Model of a Robot-spider for Group Control Synthesis: Derivation and Validation

Viktor V. Kravchenko [1], Artem A. Efremov [2], Anton A. Zhilenkov [3], Vladimir N. Kozlov [4*],
Grycshenko Kristina [5], Popov Anton [6], Psarev Mark [7], Serebryakov Mikhail [8]
[1, 2, 4] Department of IT, Peter the Great St. Petersburg Polytechnic University, Polytechnicheskaya 29, St. Petersburg, Russia
[3, 5, 6, 7, 8] Department of SFS, St. Petersburg State Marine Technical University, Leninsky Prospect, 101, St. Petersburg, Russia
Email: [1] kravchenko.vv@spbstu.ru, [2] artemefremov@spbstu.ru, [3] zhilenkovanton@gmail.com, [4] sergiiblack@mail.ru,
[5] grycshenko@smtu.ru, [6] popovanton@smtu.ru, [7] psarev@smtu.ru, [8] dop3fun@gmail.com
*Corresponding Author

***Abstract*—A six-legged spider robot is a complex object from the point of view of the problem of synthesizing a system for controlling its movement. To synthesize an advanced control system for such a robot, which must solve non-trivial problems of overcoming obstacles, functioning under conditions of external disturbances, etc., we first solve the problem of synthesizing an information model of the object, on the basis of which its control system will subsequently be built.The paper compares two methods for synthesizing the information model of a six-legged spider-robot. In the first method, an information model is automatically synthesized from a CAD model of a spider-robot in a MATLAB-based graphical programming environment Simulink. In the second method, the information model is synthesized in the environment of dynamic modeling of technical systems SimInTech on the basis of a system of differential equations in the Cauchy form. Control loops and external influences are added to the information models synthesized in each of the modeling environments. The study showed that each of the resulting models has both its own individual advantages and disadvantages. They are mainly related to taking into account the mutual influence of various blocks of models on each other. It is shown that, in the end, the two models complement each other and make it possible to obtain an advanced basis for further synthesis of the motion control system.The results obtained in this work make it possible to use information models as a basis for the development of a control system for a physical model of a six-legged spider-robot, printed on a 3D printer and assembled on the basis of the Arduino hardware platform.**

Keywords—Automatic Control; Hexapod; Complex System; Motion Control; Walking Robot; Interaction Forces; Degrees of Freedom; Information Model; Programming; Simulink; Arduino.

I. INTRODUCTION

This work investigates the problem of group control of such a complex mechanical object as a walking robot with many legs. Specifically, an example with a six-legged spider robot is considered. This research is part of a larger effort to develop a walking robot for autonomous underwater operations. Since the bottom usually has a complex surface, and the nature of the soil complicates the task of moving along it due to its mobility and looseness, the task of autonomous movement control by moving multiple robot manipulators becomes extremely difficult. The same may apply to the movement of such a robot in the air.

In this work, research is continued in the field of synthesis of control of a group of autonomous walking robots. Our task was to compare the mathematical model synthesized in [1] with the automatically synthesized model of the spider-robot, as well as, if possible, to refine the previously obtained mathematical model.

Automatic synthesis of an information model by internal means of a program based on a 3D model does not always allow influencing the final result of synthesis, which leads to the concept of a black box, in which it is impossible to change some of the fundamental foundations of the model. Building a model based on a mathematical model entails overly complicating the design of the model, in which the fundamentals are set manually. Joint consideration of two information models will allow us to supplement and clarify our data on the object under study.

The paper compares and tests the mathematical model of a spider-robot simple mented in the dynamic modeling environment of technical systems SimInTech [2] and an information model of a spider-robot automatically synthesized in MATLAB-based graphical programming environment Simulink.

The article includes a description of the design of a six-legged spider robot, followed by a description of its mathematical model. Next, based on the mathematical model, a description of the physical model and a description of the computational experiment are derived. In conclusion, a comparative analysis of the results obtained and a conclusion about the quality and effectiveness of each of the considered methods is made.

II. METHOD

The method used in this study will be discussed in detail further in three sections. In the section on designing a spider robot, we describe its structure and review the main models presented today in the world scientific literature. The next section provides a description of the mathematical models of the spider robot, including a description of the specific parameters of the designed models. Then, all presented models are linked to a specific prototype created in our laboratory.

The section following this describes the results of computational experiments obtained on synthesized models. This approach allows not only to compare the quality of each model, but also to analyze the results obtained by checking them on the physical model of a particular robot.

III. DESIGNING A SPIDER-ROBOT

A spider-robot is a multi-legged (usually four, six, or eight legs) walking robot with limbs consisting of one or more links.

Designing a spider-robot information model is challenging due to the large number of degrees of freedom. The more limbs and links, the more nonlinear equations describing the system and the more complex the resulting mathematical model. Difficulties associated with the derivation of a mathematical model of a spider-robot force researchers to look for alternative methods for synthesizing information models.

In [3], researchers simulate a robot with eight legs, which uses an eccentric cylindri36 cal cam mechanism for movement, powered by only two actuators. In [4], the authors, using the SimMechanics tools, synthesize the informational model of the crab. In [5] in SimMechanics the fast motion of a multi-legged dynamic model is simulated.

There are works devoted to the study of individual limbs of a spider-robot. In [6] the adhesion of the limb to the surface is studied; in [7], [8], [9] and [10] they model a limb based on data obtained from living spiders; in [11], researchers use a spring-loaded inverted pendulum model as a limb mechanism, which allowed them to imitate walking, 43 running and jumping; and in [12] the results of the development of the limb of the arachnid monkey are given. The articles [13] and [14] provide solutions to the inverse kinematic problem. A detailed analysis of the spider limb using the results is given in article [15].

There are works devoted to the study of motion algorithms. In [5], the authors studied the movements of a real spider to determine a suitable movement pattern. In [16] and [17], using neural networks of a robot-spider, they teach how to adapt to different types of surfaces. In [18] and [19], a method for moving a spider-robot in tunnels is given. In works [20], [21] and [22] the problem of finding a set of admissible coordinates of extremities, ensuring the stability of a spider-robot, is solved. Physical models of spider-robots capable of working in extreme conditions are described in [23], [24] and [25]. In [26], a robot with hinged limbs is described, which allows servicing complex pipe-wire systems. In [27], the authors present the design of a robot capable of moving in a wide range of two-dimensional tunnels. In [28], a "smart" spider-robot is presented, capable of wireless monitoring of the environment.

IV. CREATING MODELS

It is necessary to synthesize and test information models of a six-legged spiderrobot with three-link limbs (see Fig. 1) in two environments for dynamic modeling of technical systems: Simulink and SimInTech. A spider-robot is described by a vector of phase coordinates [25-34]:

$$q = (\xi\ \eta\ \zeta\ \psi\ \theta\ \gamma\ \dots \varphi_{i1}\ \ \varphi_{i2}\ \varphi_{i3}\ \dots)^T \qquad (1)$$

where $i = \{1 - 6\}, \xi, \eta$ and ζ – coordinates of the center of mass O spider-robot body, ψ, θ 61 and γ – angles of rotation of the body relative to its center of mass O, φ_{i1} – the angle of 62 rotation of the i-th limb relative to the body ($i1$), φ_{i2} and φ_{i3} – angles of position of its joints ($i2$ and $i3$);

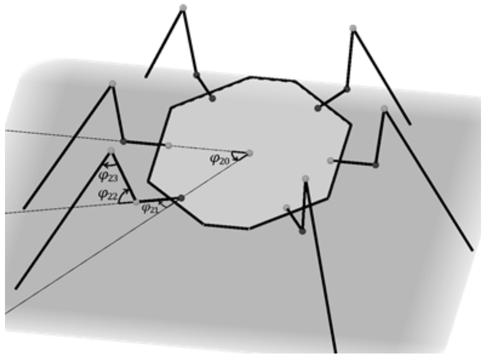

Fig. 1. Spider-robot schematic

The model in the Simulink environment is synthesized on the basis of the CADmodel of the spider-robot [1], imported from the CAD environment (see Fig. 2).

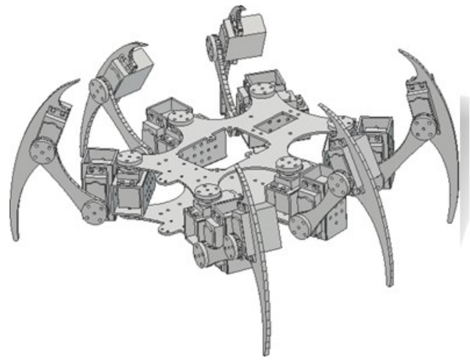

Fig. 2. 3D model of a spider-robot

This information model of a spider-robot consists of blocks describing the me chanical elements of the spider-robot (body and individual links of each limb) and 69 the connections between them. General parameters of the model (mass, dimensions, moments of inertia, etc.) and the world in which it is located (the force of gravity). The physical parameters of the spider-robot model, automatically calculated by CAD tools, are given in Table I and Table II.

TABLE I. BODY AND LIMB PARAMETERS

Parameter1	Body	Joint 1	Joint 2	Joint 3
m, kg	0.0942	0.0848	0.0105	0.0383
l, cm	-	3.0000	7.6200	11.0300
I, kg·mm^2	486.8409	52.6469	12.3215	27.0795

[1] m – weight, l – the length of the articulation of the limb, I – moment of inertia.

TABLE II. PARAMETERS OF THE LOCATION OF ATTACHMENTS OF LIMBS TO THE BODY

Parameter1	Limb					
	1. AR2	2. AL	3. MR	4. ML	5. RR	6. RL
$\varphi i0$, rad	π/3	2π/3	0	π	5π/3	4π/3
$li0$, mm	101	101	70	70	101	101

[1] φ_{i0} – angle from the positive semiaxis O_x, on which the attachment point of the i-th limb is located, i.e. first hinge, l_{i0} – distance from the point O to the attachment point of the i-th limb.

[2]AR – anterior right, AL – anterior left, MR – middle right,

ML – middle left, RR – rear right, RL – rear left.

To control the position of the joints of the limbs, a control loop implemented on PID controllers is added to the information model synthesized in Simulink (see Fig. 3 and Fig. 4). The parameters of the PID controllers were selected using the built-in Simulink tools [35-39].

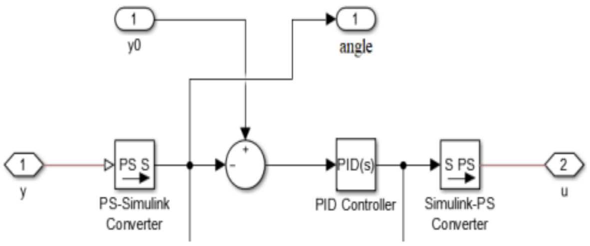

Fig. 3. Limb joint control unit, where y is the signal of the current angle of rotation of the joint, $y0$ is the task signal

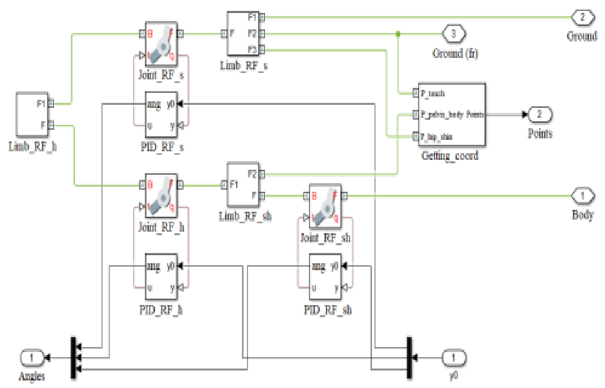

Fig. 4. The limb of the spider-robot, implemented in the Simulink environment

The interaction of the spider-robot model with the floor is realized by adding for each limb a force that is activated upon contact of the limb with a surface acting in the opposite direction of movement of the limb (see Fig. 5) and the frictional force of sliding of the limb with a given dependence [40-43]:

$$\vec{F} = -k\vec{v}$$

where k – constant depending on the characteristics of the contacting bodies, v – limb speed.

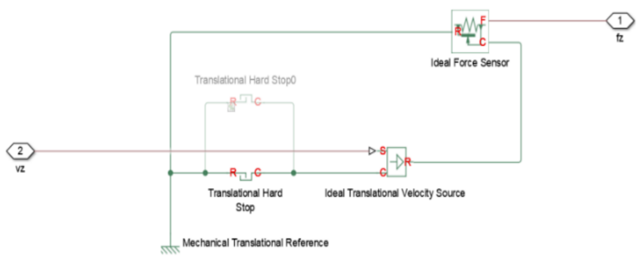

Fig. 5. Block for imitation of floor hardness

The model in the SimInTech environment was built on the basis of the previously obtained mathematical model [1]:

$$\dot{v} = Hv + Fu = C$$

where $v = q^{\cdot}$ – generalized velocity vector, u – control vector (moments of rotation applied to the joints of the limbs), $H_{24\times24}$, $F_{24\times18}$ and $C_{24\times1}$ – functional matrices of the system. The physical characteristics of SimInTech are taken from a model synthesized in the Simulink environment. In Fig. 6 is a diagram of the model.

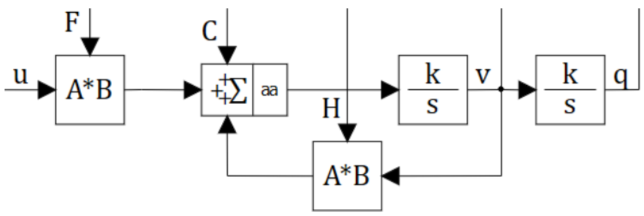

Fig. 6. Informational model of a spider-robot made in the SimInTech environment

The control loop of the hinges is implemented in the same way as in the Simulink model (see Fig. 7).

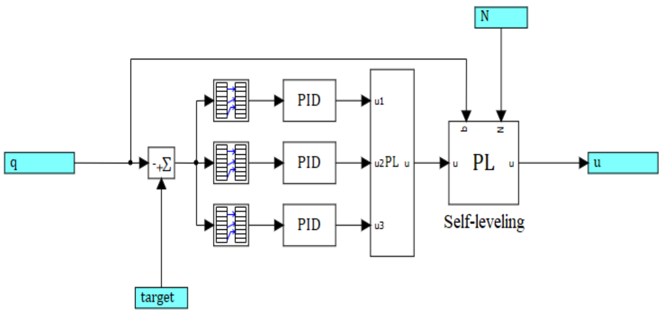

Fig. 7. Block function for calculating the moments of rotation

Interaction with the floor is set using a force applied to the coordinates of the body ξ and η, directed against the rotation of any of the coordinates $\phi i1$ ($\forall i \in [1,6]$) provided that the limb is supporting. It is worth noting that an important part of calculating the force of interaction with the floor is the correct distribution of the load on the limbs of the spider-robot. A variant of the solution to this problem is shown by us in [1, 44-46]. After analyzing the Simulink model for each hinge of the limbs of the spider-robot, friction is specified, which is expressed as a moment opposite to the control moment:

$$m = -k_{fr}N^{ij},$$

where $k_{fr} \in R$ – rolling friction coefficient, N^{ij} – support reaction force acting on the j-th joint of the i-th limb

To visualize the operation of the model, an interface was developed (see Fig. 8), which schematically shows the position of the body and limbs in space, and also contains controls for the model [47-50].

V. SPIDER ROBOT PHYSICS MODEL

As a prototype of the physical model of the spider-robot, the model of the spider robot [29] was used. Parts of the body and limbs were 3D printed. The control controller is based on the Arduino Due. The physical model of a spider-robot is shown in the Fig. 9.

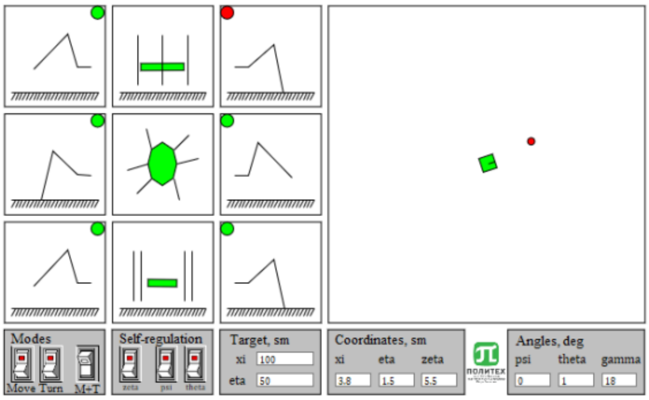

Fig. 8. Schematic visualization of the work of the information model of a spider-robot, made inthe SimInTech environment

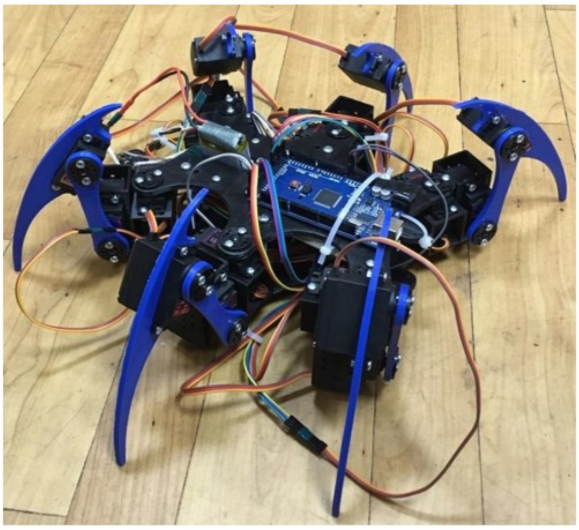

Fig. 9. A physical model of a spider-robot

The physical model of a spider-robot is powered by a 7.2-volt battery and can stand and move in a plane O_{xy}.

VI. Computational Experiment

As testing of both models, the programmed movement of the spider-robot from point A to point B. The spider-robot performed a turn at point A and moved in a straight line towards point B [51-55]. The movement of the spider-robot ended when the model moved to the delta – neighborhood of point B.

The main results of the experiment:

1. The spider-robot reached the delta neighborhood of point B in 130 s,
2. Time spent on turning – 35 s,
3. Time spent on movement – 95 s,
4. The Simulink model turned a little to the right, therefore, at the stage of movement, it became necessary to constantly correct the direction and switch to the "Rotate" subroutine.

The graphs for switching control commands and movement of the spider-robot are shown in Fig. 10, Fig. 11 and Fig. 12.

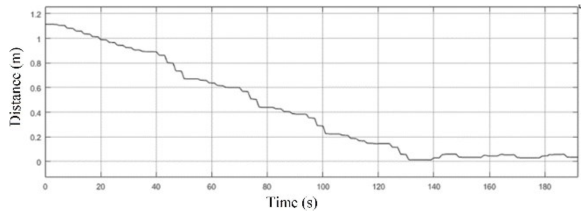

Fig. 10. Schedule of switching control commands, where "1" – forward movement, "2" – alignment, "3" – turn, "4" – standard position

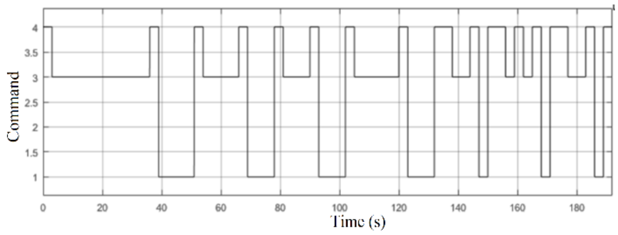

Fig. 11. Distance to target point B versus time

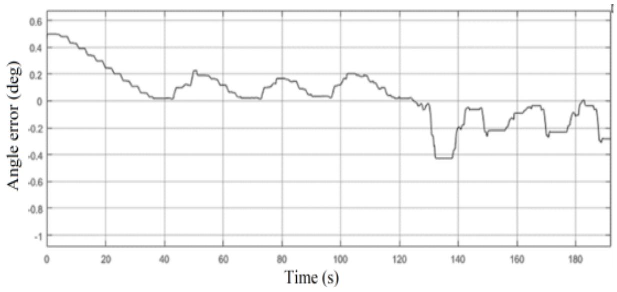

Fig. 12. Graph of the difference between the current angle of rotation and the target versus time

Spider robot model in SimInTech

The main results of the experiment [56-65]:

1. The spider-robot reached the delta neighborhood of point B in 71 s,
2. Time taken to turn – 27 s,
3. Time spent on movement – 43 s,
4. Turning in place and moving forward are performed uniformly, which indicates the correctness of the original mathematical model and a successful selection of the parameters of the regulators.

The graphs for switching control commands and movement of the spider-robot are shown in Fig. 13, Fig. 14 and Fig. 15.

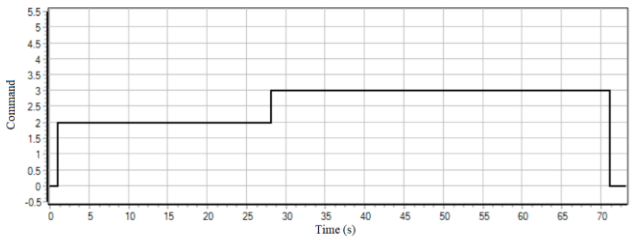

Fig. 13. Schedule of switching control commands, where "0" – standard position, "1" – turn left, "2" – turn right, "3" – move forward, "4" – move back, "5" – move along an arc

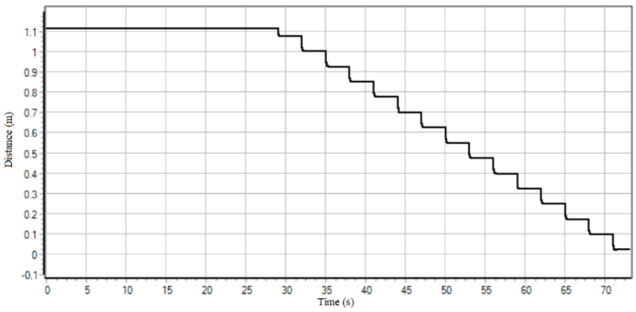

Fig. 14. Distance to target point B plot

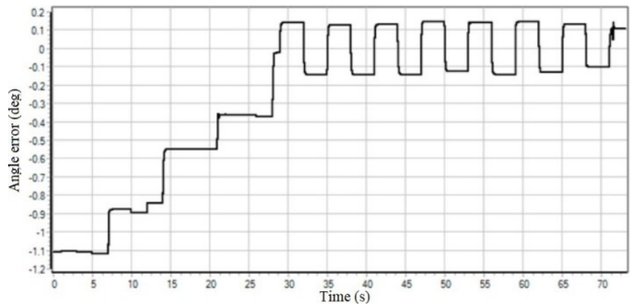

Fig. 15. Plot the difference between the current steering angle and the target

VII. Results and Discussion

The main criteria for assessing the quality of the resulting information model were the quality of the representation of transient processes in each of the models, the complexity of the resulting model, the degree of accuracy in modeling the mutual influence of various blocks of the model on each other. Considering these criteria both information models show similar modeling results but they have key differences. Simulink model gives smoother transient response (Figure 11). This is because Simulink automatically adds interaction forces between the individual blocks of the model. In the SimInTech model, these interactions are absent, but they can be taken into account by complicating the original mathematical model [51, 66-70].

Spider robot information models are synthesized in Simulink and SimInTech environments. In the first case, the basic information model was a 3D CAD model of a spider-robot. In the second case, the previously derived mathematical model of a spider-robot. Comparison of the simulation results gave similar results and demonstrated the applicability of these models for further research.

Information models complemented each other perfectly. The physical parameters, as well as the initial settings of the regulators from the model synthesized in the Simulink environment, were used in the SimInTech information model. Analysis of the Simulink model made it possible to refine the mathematical model and make the model in SimInTech better. The programmed control worked out in each of the information models is implemented in the physical model of the spider-robot [71-80].

VIII. Conclusions

The conducted research shows that the shortcomings of each of the information models we obtained can be compensated for by the joint use of both models together. The synthesis of an automatic group control system for the limbs of a multi-legged walking robot based on such a joint model promises to provide a new level of efficiency and control accuracy.

The simultaneous use of two information models in different ways interact with the environment, allows a more detailed study of the behavior of the spider-robot.

This will allow us to synthesize an effective robot control system. In particular, this approach will be significant when controlling a robot in difficult conditions - on surfaces with complex geometry, the presence of drifts, unsteady surfaces, and external disturbances.

Since in the future we are interested in solving the problem of managing a group of robots that make up a multi-agent system, the refined information model will be used to synthesize more complex control systems.

The data obtained in the work will be distributed to a group of walking spider-robots.

In particular, the presented results will be used in the design of a multi-agent system of walking robots for searching and moving objects on the seabed and land.

Funding: The research is partially funded by the Ministry of Science and Higher Education of the Russian Federation as part of the World-class Research Center program: Advanced Digital Technologies (contract No. 075-15-2022-312 dated 20 April 2022).

References

[1] M. I. Uddin, M. S. Alamgir, J. Chakrabarty, M. I. Hossain, and M. A. Abdulla Samy, "Multitasking Spider Hexapod Robot," *2019 IEEE International Conference on Robotics, Automation, Artificial-intelligence and Internet-of-Things (RAAICON)*, pp. 135-140, 2019, doi: 10.1109/RAAICON48939.2019.58.

[2] S. P. Khabarov and M. L. Shilkina, "Fundamentals of modeling of technical systems. SimInTech Environment: a tutorial," *Lan Publishing House*, 2019.

[3] R. Thennarasu, K. Thiruppathi, and S. Raghuraman, "Modeling and simulation of spider robot with an eccentric cylindrical cam mechanism," *2016 International Conference on Robotics: Current Trends and Future Challenges (RCTFC)*, pp. 1-4, 2016, doi: 10.1109/RCTFC.2016.7893403.

[4] R. Rynkevic, M. F. Silva, and M. A. Marques, "Biomechanical modeling and simulation of the spider crab (maja brachydactyla)," *2013 IEEE 3rd Portuguese Meeting in Bioengineering (ENBENG)*, pp. 1-6, 2013, doi: 10.1109/ENBENG.2013.6518429.

[5] S. N. Álvarez, M. C. Rojas, and H. Leon-Rodriguez, "Walking robot bio-inspired by insect's locomotion for carbon dioxide diagnostic indexed in the air," *ICINCO 2018 - Proceedings of the 15th International Conference on Informatics in Control, Automation and Robotics*, vol. 2, pp. 490–496, 2018.

[6] A. Gasparetto, R. Vidoni, and T. Seidl, "Passive control of attachment in legged space robots," *Applied Bionics and Biomechanics*, vol. 7, no. 1, pp. 69-81, 2010.

[7] A. R. Mojdehi, M. Alitavoli, and A. Darvizeh, "Kinematic Simulation of Spider's Walking by Image Processing," *2009 Second International Conference on Information and Computing Science*, pp. 3-6, 2009, doi: 10.1109/ICIC.2009.108.

[8] A. R. Mojdehi, M. Alitavoli, A. Darvizeh, H. Rajabi, and H. Larijani, "Modeling And Simulation Of Spider's Walking," *International Journal of Design & Nature and Ecodynamics*, vol. 6, no. 2, pp. 83-96, 2011.

[9] L. Zentner, "Modelling and application of the hydraulic spider leg mechanism," *Spider Ecophysiology*, pp. 451–462, 2013.

[10] H. Faraji, R. Tachella, and R. L. Hatton, "Aiming and vaulting: Spider inspired leaping for jumping robots," *2016 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 2082-2087, 2016, doi: 10.1109/ICRA.2016.7487357.

[11] S. Soyguder and H. Alli, "Kinematic and dynamic analysis of a hexapod walking–running–bounding gaits robot and control actions," *Computers & Electrical Engineering*, vol. 38, no. 2, pp. 444-458, 2012.

[12] C. -T. Kuo, W. -Y. Li, Y. -H. Wang, and P. -C. Lin, "Dynamic modeling analysis of a spider monkey robot," *2017 International Conference on Advanced Robotics and Intelligent Systems (ARIS)*, pp. 99-99, 2017, doi: 10.1109/ARIS.2017.8297197.

[13] M. Ghayour and A. Zareei, "Inverse kinematic analysis of a hexapod spider-like mobile robot," *Advanced Materials Research*, vol. 403, pp. 5061-5067, 2012.

[14] Z. Yang, M. Yuan, X. Shi, Z. Yang, and M. Li, "Mechanism Design and Kinematics Analysis of Spider-like Octopod Robot," in *Journal of Physics: Conference Series*, vol. 1314, no. 1, p. 012109, 2019.

[15] S. Landkammer, F. Winter, D. Schneider, and R. Hornfeck, "Biomimetic spider leg joints: a review from biomechanical research to compliant robotic actuators," *Robotics*, vol. 5, no. 3, p. 15, 2016.

[16] T. Ohnishi and T. Asakura, "Spider-robot 8-leg cooperative walking velocity control strategy based on environmental information," *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing*, vol. 47, no. 4, pp. 1101-1107, 2004.

[17] T. Ohnishi and T. Asakura, "On walking behavior strategy for spider-robot based on environmental information," *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 3406-3411 vol. 4, 2004, doi: 10.1109/IROS.2004.1389943.

[18] A. Shapiro, E. Rimon, and S. Shoval, "Immobilization based control of spider robots in tunnels environment," *21st IEEE Convention of the Electrical and Electronic Engineers in Israel. Proceedings*, pp. 149-153, 2000, doi: 10.1109/EEEI.2000.924347.

[19] E. Rimon, S. Shoval, and A. Shapiro, "Design of a quadruped robot for motion with quasistatic force constraints," *Autonomous Robots*, vol. 10, pp. 279-296, 2001.

[20] J. D. Boissonnat, O. Devillers, L. Donati, and F. P. Preparata, "Stable placements for spider robots," in *Proceedings of the eighth annual symposium on Computational geometry*, pp. 242-250, 1992.

[21] J. -D. Boissonnat, O. Devillers, and S. Lazard, "From spider robots to half disk robots," Proceedings of the 1994 IEEE International Conference on Robotics and Automation, vol. 2, pp. 953-958, 1994, doi: 10.1109/ROBOT.1994.351230.

[22] J. D. Boissonnat, O. Devillers, and S. Lazard, "Motion planning of legged robots," *SIAM Journal on Computing*, vol. 30, no. 1, pp. 218-246, 2000.

[23] D. Rogers, "Incy Wincy spider," *Engineering*, vol. 249, pp. 42–47, 2008.

[24] Y. Qu, P. Durdevic, and Z. Yang, "Smart-spider: Autonomous self-driven in-line robot for versatile pipeline inspection," *Ifac-papersonline*, vol. 51, no. 8, pp. 251-256, 2018.

[25] R. Saranya and K. R. Kashwan, "Octapod spider-gait-walking robot implementation using nano processor," *2016 International Conference on Advances in Human Machine Interaction (HMI)*, pp. 1-4, 2016, doi: 10.1109/HMI.2016.7449192.

[26] W. Neubauer, "A spider-like robot that climbs vertically in ducts or pipes," *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS'94)*, vol. 2, pp. 1178-1185, 1994, doi: 10.1109/IROS.1994.407465.

[27] S. Shoval, E. Rimon, and A. Shapiro, "Design of a spider-like robot for motion with quasi-static force constraints," *Proceedings 1999 IEEE International Conference on Robotics and Automation*, vol. 2, pp. 1377-1383, 1999, doi: 10.1109/ROBOT.1999.772553.

[28] R. Teymourzadeh, R. N. Mahal, N. K. Shen, and K. W. Chan, "Adaptive intelligent spider robot," *2013 IEEE Conference on Systems, Process & Control (ICSPC)*, pp. 310-315, 2013, doi: 10.1109/SPC.2013.6735153.

[29] J. Chotai and K. Narwekar, "Modelling and position control of brushed DC motor," *2017 International Conference on Advances in Computing, Communication and Control (ICAC3)*, pp. 1-5, 2017, doi: 10.1109/ICAC3.2017.8318792.

[30] P. Kumar, S. Chatterjee, D. Shah, U. K. Saha, and S. Chatterjee, "On comparison of tuning method of FOPID controller for controlling field controlled DC servo motor," *Cogent Engineering*, vol. 4, no. 1, Jul. 2017.

[31] A. S. Shekhawat and Y. Rohilla, "Design and Control of Two-wheeled Self-Balancing Robot using Arduino," *2020 International Conference on Smart Electronics and Communication (ICOSEC)*, pp. 1025-1030, 2020, doi: 10.1109/ICOSEC49089.2020.9215421.

[32] S. Shekhar, P. K. Saha, and P. R. Thakura, "Optimal PID Tuning of BLDC Drive using LQR Technique," *2019 IEEE International Conference on Intelligent Systems and Green Technology (ICISGT)*, pp. 57-574, 2019, doi: 10.1109/ICISGT44072.2019.00028.

[33] C. F. Hsu, C. T. Su, W. F. Kao, and B. K. Lee, "Vision-Based Line-Following Control of a Two-Wheel Self-Balancing Robot," in *Proceedings - International Conference on Machine Learning and Cybernetics*, vol. 1, pp. 319–324, 2018.

[34] A. K. Mishra, V. K. Tiwari, R. Kumar, and T. Verma, "Speed control of dc motor using artificial bee colony optimization technique," *2013 International Conference on Control, Automation, Robotics and Embedded Systems (CARE)*, pp. 1-6, 2013, doi: 10.1109/CARE.2013.6733772.

[35] A. Rodríguez-Molina, M. G. Villarreal-Cervantes, and M. Aldape-Pérez, "An adaptive control study for a DC motor using metaheuristic algorithms," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 13114–13120, 2017.

[36] A. Rodríguez-Molina, M. G. Villarreal-Cervantes, J. Álvarez-Gallegos, and M. Aldape-Pérez, "Bio-inspired adaptive control strategy for the highly efficient speed regulation of the DC motor under parametric uncertainty," *Appl. Soft Comput*. J., vol. 75, pp. 29–45, 2019.

[37] D. Potnuru, K. Alice Mary, and C. Sai Babu, "Experimental implementation of flower pollination algorithm for speed controller of a BLDC motor," *Ain Shams Eng. J.*, vol. 10, no. 2, pp. 287–295, 2019.

[38] A. T. El-Deen, A. A. H. Mahmoud, and A. R. El-Sawi, "Optimal PID tuning for DC motor speed controller based on genetic algorithm," *Int. Rev. Autom. Control*, vol. 8, no. 1, pp. 80–85, 2015.

[39] Z. -L. Gaing, "A particle swarm optimization approach for optimum design of PID controller in AVR system," in *IEEE Transactions on Energy Conversion*, vol. 19, no. 2, pp. 384-391, 2004, doi: 10.1109/TEC.2003.821821.

[40] L. Syafaah, Widianto, I. Pakaya, D. Suhardi, and M. Irfan, "PID designs using DE and PSO algorithms for damping oscillations in a DC motor speed," *2017 4th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI)*, pp. 1-5, 2017, doi: 10.1109/EECSI.2017.8239138.

[41] B. Hekimoğlu, "Optimal tuning of fractional order PID controller for DC motor speed control via chaotic atom search optimization algorithm," *IEEE Access*, vol. 7, pp. 38100–38114, 2019.

[42] A. G. Guggisberg, P. J. Koch, F. C. Hummel, and C. M. Buetefisch, "Brain networks and their relevance for stroke rehabilitation," in *Clinical Neurophysiology*, vol. 130, no. 7, pp. 1098–1124, 2019.

[43] C. M. Stinear, M. C. Smith, and W. D. Byblow, "Prediction tools for stroke rehabilitation," *Stroke*, vol. 50, no. 11, pp. 3314-3322, 2019.

[44] S. K. Lui and M. H. Nguyen, "Elderly Stroke Rehabilitation: Overcoming the Complications and Its Associated Challenges," in *Current Gerontology and Geriatrics Research*, vol. 2018, 2018.

[45] Y. Chen, K. T. Abel, J. T. Janecek, Y. Chen, K. Zheng, and S. C. Cramer, "Home-based technologies for stroke rehabilitation: A systematic review," *International journal of medical informatics*, vol. 123, pp. 11-22, 2019.

[46] A. Lloyd, K. Bannigan, T. Sugavanam, and J. Freeman, "Experiences of stroke survivors, their families and unpaid carers in goal setting within stroke rehabilitation: a systematic review of qualitative evidence," *JBI Evidence Synthesis*, vol. 16, no. 6, pp. 1418-1453, 2018.

[47] P. L. Kolominsky-Rabas and P. U. Heuschmann, "Incidence, etiology and long-term prognosis of stroke," *Fortschritte der Neurologie-psychiatrie*, vol. 70, no. 12, pp. 657-662, 2002.

[48] A. V. L. De Araújo, J. F. D. O. Neiva, C. B. D. M. Monteiro, and F. H. Magalhães, "Efficacy of Virtual Reality Rehabilitation after Spinal Cord Injury: A Systematic Review," in *BioMed Research International*, vol. 2019, 2019.

[49] M. Mekki, A. D. Delgado, A. Fry, D. Putrino, and V. Huang, “Robotic Rehabilitation and Spinal Cord Injury: a Narrative Review,” in *Neurotherapeutics*, vol. 15, no. 3, pp. 604–617, 2018.

[50] L. Weber, N. H. Voldsgaard, N. J. Holm, L. H. Schou, F. Biering-Sørensen, and T. Møller, “Exploring the contextual transition from spinal cord injury rehabilitation to the home environment: a qualitative study,” *Spinal Cord*, vol. 59, no. 3, pp. 336–346, 2021.

[51] F. Biering-Sørensen, “International Spinal Cord Injury Data Sets in clinical practice and research,” *Archives of Physical Medicine and Rehabilitation*, vol. 103, no. 12, 2022.

[52] M. I. Uddin, M. S. Alamgir, J. Chakrabarty, M. I. Hossain, and M. A. Abdulla Samy, "Multitasking Spider Hexapod Robot," *2019 IEEE International Conference on Robotics, Automation, Artificial-intelligence and Internet-of-Things (RAAICON)*, pp. 135-140, 2019, doi: 10.1109/RAAICON48939.2019.58.

[53] J. B. Han, K. M. Yang, D. H. Kim, and K. H. Seo, "A Modeling and Simulation based on the Multibody Dynamics for an Autonomous Agricultural Robot," *2019 7th International Conference on Control, Mechatronics and Automation (ICCMA)*, pp. 137-143, 2019, doi: 10.1109/ICCMA46720.2019.8988607.

[54] L. Zhang et al., "Topology Optimization of Biped Robot Based on Rigid-flexible Coupling Dynamics," *2022 7th International Conference on Automation, Control and Robotics Engineering (CACRE)*, pp. 14-19, 2022, doi: 10.1109/CACRE54574.2022.9834177.

[55] J. -H. Park, T. -Y. Uhm, G. -D. Bae, and Y. -H. Choi, "Stability Evaluation of Outdoor Unmanned Security Robot in Terrain Information," *2018 18th International Conference on Control, Automation and Systems (ICCAS)*, pp. 955-957, 2018.

[56] D. Jian, J. Haibo, L. Kun, Y. Kaihong, and Y. Wang, "Flocking control of flying robots considering model's dynamics processes," *2017 36th Chinese Control Conference (CCC)*, pp. 817-821, 2017, doi: 10.23919/ChiCC.2017.8027445.

[57] J. Guo, K. Zhang, S. Guo, C. Li, and X. Yang, "Design of a New Type of Tri-habitat Robot," *2019 IEEE International Conference on Mechatronics and Automation (ICMA)*, pp. 1508-1513, 2019, doi: 10.1109/ICMA.2019.8816501.

[58] M. S. Yasar and T. Iqbal, "Robots That Can Anticipate and Learn in Human-Robot Teams," *2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI)*, pp. 1185-1187, 2022, doi: 10.1109/HRI53351.2022.9889369.

[59] C. Li *et al*., "Design and analysis of a spherical robot based on reaction wheel stabilization," *2022 19th International Conference on Ubiquitous Robots (UR)*, pp. 143-148, 2022, doi: 10.1109/UR55393.2022.9826266.

[60] X. Li, H. -X. Sun, L. -J. Liao, and J. -Z. Song, "Modeling and Simulation Research of Kane Dynamics Method for the 5-DOF Modular Industrial Robot," *2016 International Conference on Information System and Artificial Intelligence (ISAI)*, pp. 124-128, 2016, doi: 10.1109/ISAI.2016.0035.

[61] K. A. Alattas, J. Mostafaee, A. K. Alanazi, S. Mobayen, M. T. Vu, A. Zhilenkov, and H. M. Abo-Dief, "Nonsingular terminal sliding mode control based on adaptive barrier function for n th-order perturbed nonlinear systems," *Mathematics*, vol. 10, no. 1, p. 43, 2021.

[62] K. A. Alattas, J. Mostafaee, A. Sambas, A. K. Alanazi, S. Mobayen, M. T. Vu, and A. Zhilenkov, "Nonsingular integral-type dynamic finite-time synchronization for hyper-chaotic systems," *Mathematics*, vol. 10, no. 1, p. 115, 2021.

[63] A. Rezaie, S. Mobayen, M. R. Ghaemi, A. Fekih and A. Zhilenkov, "Design of a Fixed-Time Stabilizer for Uncertain Chaotic Systems Subject to External Disturbances," *Mathematics*, vol. 11, no. 15, p. 3273, 2023.

[64] M.-W. Tian, S.-R. Yan, A. Mohammadzadeh, J. Tavoosi, S. Mobayen, R. Safdar, W. Assawinchaichote, M. T. Vu, and A. Zhilenkov, "Stability of interval type-3 fuzzy controllers for autonomous vehicles," *Mathematics*, vol. 9, no. 21, p. 2742, 2021.

[65] S.-R. Yan, K. A. Alattas, M. Bakouri, A. K. Alanazi, A. Mohammadzadeh, S. Mobayen, A. Zhilenkov, and W. Guo, "Generalized Type-2 Fuzzy Control for Type-I Diabetes: Analytical Robust System," *Mathematics*, vol. 10, no. 5, p. 690, 2022.

[66] S. G. Chernyi, A. S. Bordug, L. N. Kozachenko, P. A. Erofeev, and V. A. Zhukov, "The Reliability Assessment of Functioning of Autonomous Power System of Drilling Rigs," *2020 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus)*, pp. 259-263, 2020, doi: 10.1109/EIConRus49466.2020.9039117.

[67] B. A. Avdeev, A. V. Vyngra, S. G. Chernyi, A. A. Zhilenkov, and S. S. Sokolov, "Evaluation and Procedure for Estimation of Interharmonics on the Example of Non-Sinusoidal Current of an Induction Motor With Variable Periodic Load," in *IEEE Access*, vol. 9, pp. 158412-158419, 2021, doi: 10.1109/ACCESS.2021.3130442.

[68] C. -L. Lee and C. -C. Peng, "Analytic Time Domain Specifications PID Controller Design for a Class of 2nd Order Linear Systems: A Genetic Algorithm Method," in *IEEE Access*, vol. 9, pp. 99266-99275, 2021, doi: 10.1109/ACCESS.2021.3093427.

[69] D. Baidya, S. Dhopte, and M. Bhattacharjee, "Sensing System Assisted Novel PID Controller for Efficient Speed Control of DC Motors in Electric Vehicles," in *IEEE Sensors Letters*, vol. 7, no. 1, pp. 1-4, 2023, doi: 10.1109/LSENS.2023.3234400.

[70] M. H. S. Bomfim, E. J. Lima II, N. S. Monteiro, and A. L. A. Dias, "A Novel Hybrid (PID + MRAC) Adaptive Controller for an Air Levitation System," in *IEEE Latin America Transactions*, vol. 19, no. 8, pp. 1400-1409, 2021, doi: 10.1109/TLA.2021.9475871.

[71] L. Shen and H. Xiao, "Delay-dependent robust stability analysis of power systems with PID controller," in *Chinese Journal of Electrical Engineering*, vol. 5, no. 2, pp. 79-86, 2019, doi: 10.23919/CJEE.2019.000014.

[72] M. Gheisarnejad and M. H. Khooban, "An Intelligent Non-Integer PID Controller-Based Deep Reinforcement Learning: Implementation and Experimental Results," in *IEEE Transactions on Industrial Electronics*, vol. 68, no. 4, pp. 3609-3618, 2021, doi: 10.1109/TIE.2020.2979561.

[73] Z. Qi, Q. Shi, and H. Zhang, "Tuning of Digital PID Controllers Using Particle Swarm Optimization Algorithm for a CAN-Based DC Motor Subject to Stochastic Delays," in *IEEE Transactions on Industrial Electronics*, vol. 67, no. 7, pp. 5637-5646, 2020, doi: 10.1109/TIE.2019.2934030.

[74] P. Teppa Garran and G. Garcia, "Design of an Optimal PID Controller for a Coupled Tanks System employing ADRC," in *IEEE Latin America Transactions*, vol. 15, no. 2, pp. 189-196, 2017, doi: 10.1109/TLA.2017.7854611.

[75] Y. Yuan, H. Lv, and Q. Zhang, "DNA Strand Displacement Reactions to Accomplish a Two-Degree-of-Freedom PID Controller and Its Application in Subtraction Gate," in *IEEE Transactions on NanoBioscience*, vol. 20, no. 4, pp. 554-564, 2021, doi: 10.1109/TNB.2021.3091685.

[76] J. Z. Shi, "A Fractional Order General Type-2 Fuzzy PID Controller Design Algorithm," in *IEEE Access*, vol. 8, pp. 52151-52172, 2020, doi: 10.1109/ACCESS.2020.2980686.

[77] V. Emelianov *et al.*, “Application of artificial intelligence technologies in metallographic analysis for Quality Assessment in the shipbuilding industry,” *Heliyon*, vol. 8, no. 8, 2022, doi: 10.1016/j.heliyon.2022.e10002.

[78] Y. K. Cherivirala and D. D. Wentzloff, "A Capacitor-Less Digital LDO Regulator With Synthesizable PID Controller Achieving 99.75% Efficiency and 93.3-ps Response Time in 65 nm," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 70, no. 5, pp. 1769-1773, 2023, doi: 10.1109/TCSII.2023.3257686.

[79] Q. Ma and S. Xu, "Consensusability of First-Order Multiagent Systems Under Distributed PID Controller With Time Delay," in *IEEE Transactions on Neural Networks and Learning Systems*, vol. 33, no. 12, pp. 7908-7912, 2022, doi: 10.1109/TNNLS.2021.3084366.

[80] Z. Ren, T. Zhang, X. Liu, and J. Lin, "A Novel Neuro PID Controller of Remotely Operated Robotic Manipulators," in *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 70, no. 6, pp. 2131-2135, 2023, doi: 10.1109/TCSII.2022.3229668.