Bulletin of Electrical Engineering and Informatics
Vol. 8, No. 4, December 2019, pp. 1224~1231
ISSN: 2302-9285, DOI: 10.11591/eei.v8i4.1623

Development of a quadruped mobile robot and its movement system using geometric-based inverse kinematics

Muhammad Aziz Muslim[1], Mochammad Rusli[2], Achnafian Rafif Zufaryansyah[3], B. S. K. K. Ibrahim[4]
[1,2,3]Electrical Engineering Department, Faculty of Engineering, Brawijaya University, Jl. MT. Haryono 167 Malang 65145, Indonesia
[4]School of Mechanical, Aerospace and Automotive, Faculty of Engineering, Environment and Computing Coventry University, Priory St, Coventry CV1 5FB, United Kingdom

Article Info

Article history:

Received Apr 30, 2019
Revised Jun 10, 2019
Accepted Jul 4, 2019

Keywords:

Geometric-based
Half rectified sine wave
Inverse kinematics
Quadruped mobile robot
Trot gait pattern

ABSTRACT

As the main testbed platform of Artificial Intelligence, the robot plays an essential role in creating an environment for industrial revolution 4.0. According to their bases, the robot can be categorized into a fixed based robot and a mobile robot. Current robotics research direction is interesting since people strive to create a mobile robot able to move in the land, water, and air. This paper presents development of a quadruped mobile robot and its movement system using geometric-based inverse kinematics. The study is related to the movement of a four-legged (quadruped) mobile robot with three Degrees of Freedom (3 DOF) for each leg. Because it has four legs, the movement of the robot can only be done through coordinating the movements of each leg. In this study, the trot gait pattern method is proposed to coordinate the movement of the robot's legs. The end-effector position of each leg is generated by a simple trajectory generator with half rectified sine wave pattern. Furthermore, to move each robot's leg, it is proposed to use geometric-based inverse kinematic. The experimental results showed that the proposed method succeeded in moving the mobile robot with precision. Movement errors in the translation direction are 1.83% with the average pose error of 1.33 degrees, means the mobile robot has good walking stability.

Corresponding Author:

Muhammad Aziz Muslim,
Electrical Engineering Department, Faculty of Engineering,
Brawijaya University,
Jl. MT Haryono 167, Malang 65145, Indonesia.
Email: muh_aziz@ub.ac.id

1. INTRODUCTION

As the main testbed platform of Artificial Intelligence, the robot plays an essential role in creating an environment for industrial revolution 4.0. According to their bases, the robot can be categorized into a fixed based robot and a mobile robot [1]. Fixed based robot is mainly used industry, in the form of robotic manipulator [2]. While mobile robot, due to its mobility, has broader application field. Such as in farming [3, 4], surveillance [5, 6], exploration [7, 8], and military [9, 10]. According to the environment in which they travel, the mobile robot can be categorized as an unmanned ground vehicle (UGV), unmanned aerial vehicle (UAV) and autonomous underwater vehicle (AUV). Furthermore, according to the device they used to move, UGV can be classified into a wheeled mobile robot [11] and legged mobile robot [12].

The first problem to be solved in a mobile robot is locomotion. It is about how the robot should move and how is the mechanism to move [1, 13]. The use of legs for robot mobility is inspired by the animal world. A mobile robot with six legs (hexapod) was reported as the first walking legged mobile robot, followed by the mobile robot with four legs (quadruped) around eight years later [14]. The hexapod robot has advantageous of good static stability [15], while a quadruped robot has better speed and mobility compared to the hexapod robot [16].

Since the robot has many legs, movement coordination through gait pattern is a must for smooth movement. Gait pattern is a repetitive pattern of each legs movement (translation or rotation) by the movement of the robot body so that the robot can move from one position to another position [14]. Simulation and experiment to get a gait pattern by Genetic Algorithm were given by [17]. Generation of gait pattern via central pattern generator (CPG) was proposed by [18, 19], and an adaptive approach of CPG was introduced by [20]. Integration of trot gait to CPG was presented by [21]; the combination of trot and walk gait was proposed by [22]. Analysis on the stability of generated trajectory by gait pattern was substantially discussed in [23, 24].

Gait pattern is a guideline to generate a trajectory for the leg tip of the mobile robot [25]. In this paper, we propose to use half rectified sine wave to generate trajectory guided by a simple trot gait. Since this trajectory must be followed by the tip of the robot's legs (end effector), it is necessary to employ an inverse kinematic method to provide joint angle given end effector trajectory. As inverse kinematic method, we propose to decompose the inverse kinematics geometrically into a more straightforward calculation.

2. RESEARCH METHOD

There are two purposes for this research. First is to build a legged mobile robot capable of exploring an indoor environment and the second is to design a control system for the movement. A mobile robot comprises of sensors, processor and locomotion system. Sensors provide information surrounding environment. This information proceeds by the processor and action are decided accordingly. For a mobile robot, the decision is about robot movement, provided by the locomotion system. Mobile robot realization consists of building stage and testing stage. The robot building steps consist of mechanical part building and electronic part building. Testing steps consist of mechanical functionality test and electrical functionality test (including sensor and actuator linearity test). The robot building will be reported in this section, while the testing step will be reported in section 3.

Mobile robot movement is designed by path planning and response of sensory information. According to the mobile robot movements method, there are two main categories, wheeled mobile robot and legged mobile robot. The legged mobile robot is classified according to the number of legs for movement and degrees of freedom for each leg. This research is focused on a four-legged mobile robot with three degrees of freedom (3 DOF) for each leg. The detail on robot movement design will be described in this section.

2.1. Robot mechanical design

Figure 1 depicts the mechanical design of the mobile robot base. Robot center represented by the white circled area in robot base. Servo motor positions are arranged uniformly so that the robot able to turn 90º or 180º without changing the position of the body, just by changing the movement direction. The horizontal distance among servos is 9.405 cm, and the distance among servos will be 13 cm if measured crossing the center. This servos arrangement is decided in order to give enough space for a 220 mAh Lithium-Polymer (Lipo) battery and to give free movement for each leg. Using this construction also enable a designer to add a spacer for strengthening robot structure.

Leg construction is shown in Figure 2. This leg is a 3 degree of freedom (3DOF) body comprises of 3 servo motors, namely coxa servo, femur servo, and tibia servo. These part names are originally the names an arthropod leg parts. From Figure 2, the length of the femur (length_femur) is 4 cm while the length of the tibia (length_tibia) is 5, 6 cm. Coxa servo rotational axis is intersecting with the rotational axis of femur servo, setting zero offsets for coxa servo. While rotational servo of tibia and femur are parallel to each other (as shown in Figure 2(a)), these mechanical setting will be essential parts for the derivation of geometric-based inverse kinematic. Angle measurement is defined in Figure 2(b). Femur and tibia angle are measures according to an axis connecting the rotational axis of femur and tibia. This definition will further simplify the calculation of inverse kinematics.

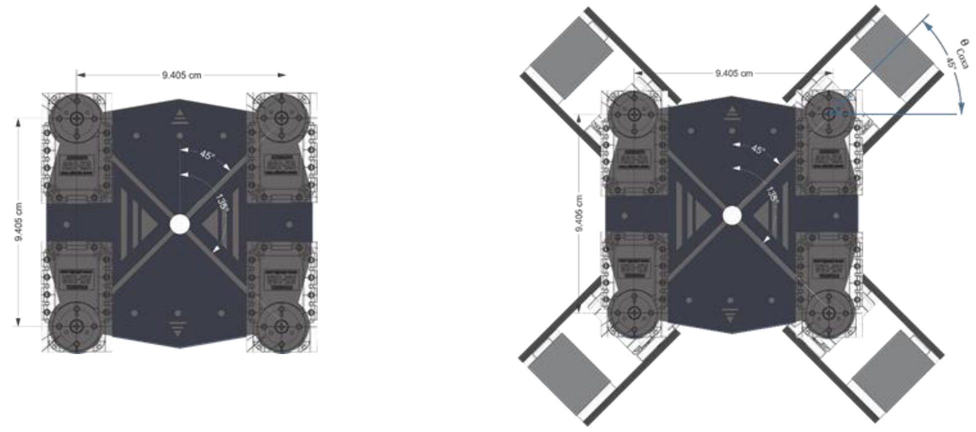


Figure 1. Mechanical design of the mobile robot base, (a) Base frame only, (b) Base frame with leg position

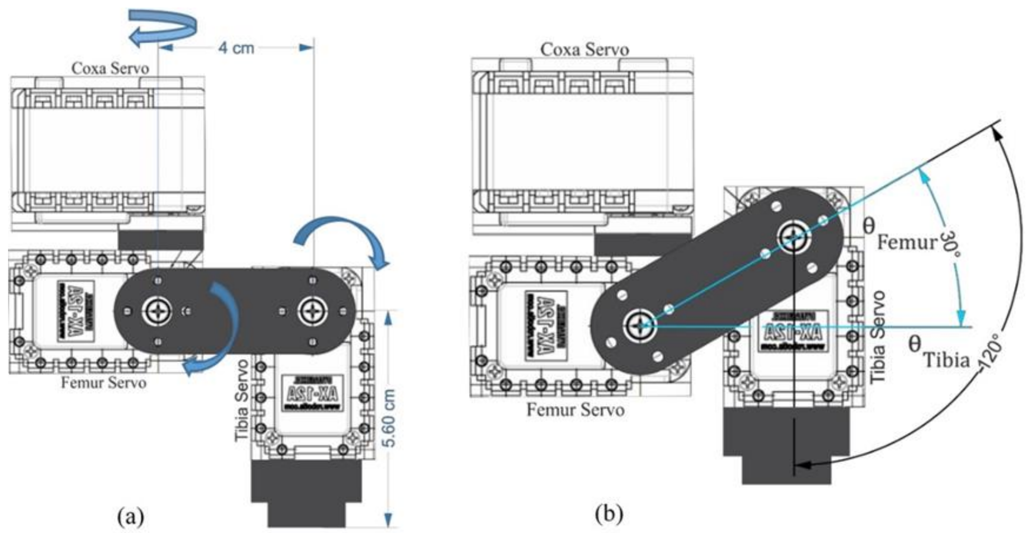
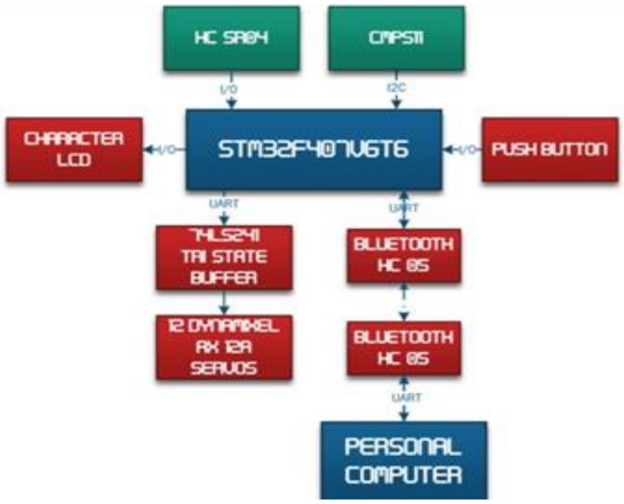


Figure 2. Mechanical configuration of robot leg, (a) Rotational direction, (b) Angle measurement of femur and tibia

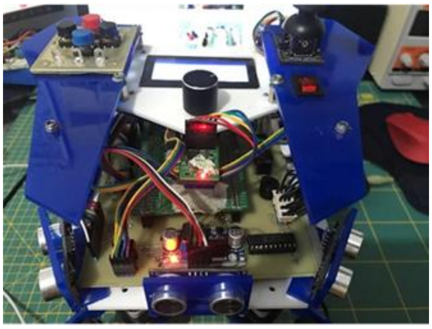
2.2. Robot electronics design

Figure 3 shows the electronics of the robot. As depicted in Figure 3(a), an STM32F407VGT6 is employed the main microcontroller for the system. The microcontroller is connected to the servos (12 units of Dynamixel AX 12A) via 74LS241 Tri-state buffer to ensure the servos received half-duplex signal needs for their movement. The microcontroller receives outside information from HC SR04 ultrasonic rangefinder sensor (provides distance to the object in front of the sensors) and CMPS11 attitude sensor (provides pitch, roll, and yaw orientation of the robot). The robot can be controlled via a push button or PC serial instruction via Bluetooth. Figure 3(b) shown the electronics part arranged in a single board and Figure 3(c) shows the assembled electronic parts.



(a)

(b)



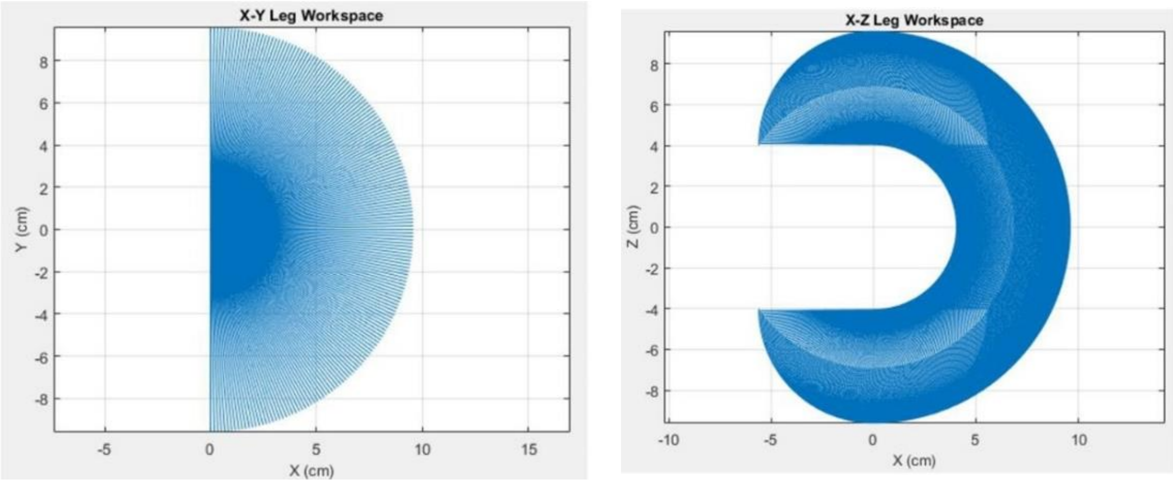
(c)

Figure 3. Electronic parts of the robot, (a) Diagram of the electronic system, (b) The electronic board, (c) Assembled electronic parts

2.3. Design of mobile robot movement

The legged mobile robot developed in this research has four legs with 3 degrees of freedom each. Hence it has 12 degrees of freedom (12 DOF). There are two problems to be solved for robot movement. First, how to coordinate legs for forwarding, backward, left and right movement. Second, given tibia tip position on how to determine coxa, femur and tibia angle. The answers for the first question lead to the generation of tibia tip trajectory, and the answer for the second question leads to the inverse kinematic formulation.

Constrain of robot movement is in its workspace. The workspace could be analyzed by moving the joints step by step for all possible angle combination. Workspace determination is particularly crucial for trajectory generation so that the algorithm only generate a reachable position of end effector (tibia tip position). The robot in this research reach a position in X-Y space by changing the angle of coxa joint and reach a position in X-Z space by changing femur and tibia angle. Figure 4 shows the workspace of these two spaces.



(a) (b)

Figure 4. Leg workspace in X-Y space and X-Z space

Legged-robot movement is performed according to a gait pattern. Gait pattern is a movement pattern of each leg which is coordinated with the body movement of the robot both translation and rotation which is done repetitively so that the robot's body can move from one place to another [14]. The gait pattern implemented in this study is trot gait. Trot gait is a movement pattern using two legs in the diagonal plane with each other to swing the leg (swing phase), while the remaining two legs are responsible for supporting the quadruped robot (support phase). Figure 5 illustrates the trot gait pattern used in this study. The distance traveled by each leg is identical between one leg and the other leg. In one movement cycle, each leg will experience one swing phase and one support phase with timings according to what can be seen in Figure 5. For smooth movement, a trajectory generator is added to trot gait pattern. Trajectory generator provides a smooth transition of end-effector trajectory from starting point to end point. We proposed to use half rectified sine wave for this purpose. Figure 6 illustrates the trajectory generated by half rectified sine wave combined with trot gait pattern.

The coordinates generated by the trajectory generator should be converted to angle movement commands for each joint. These angle movement commands are provided by inverse kinematics calculation. For simplicity, the inverse kinematics of 3 DOF robot leg decomposed into two sub-problems, inverse kinematics for coxa joint (1 DOF) and inverse kinematic for femur-tibia joint (2 DOF). Figure 7 depicts the kinematics of coxa joint. Without loss of generality, it is assumed that each leg is parallel with the center of the robot, hence α = 90°. Hence, the angle of the coxa joint (θ_{coxa}) is;

$$\theta_{coxa} = tan^{-1}\frac{Y}{X} \quad (1)$$

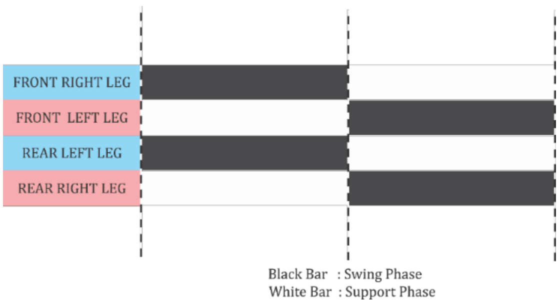


Figure 5. Trot gait pattern

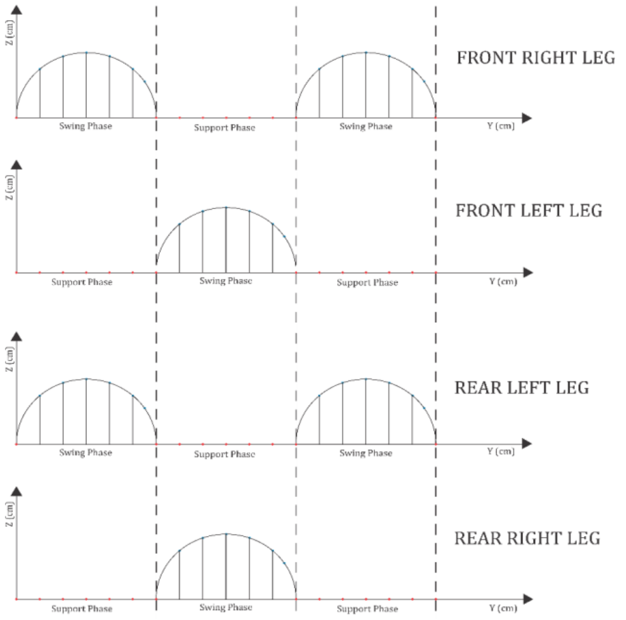


Figure 6. End-effector trajectory generated from the combination of trot gait and half rectified sine wave

Figure 8 shows the inverse kinematics for the femur-tibia joint (2 DOF). The femur length (length_femur) and tibia length (length_tibia) are constants. These constants will further simplify the angles calculation in (2) and (3). The inverse kinematic calculation in (1)-(3) in for right side legs, the solution for the left side legs can be generated accordingly by flipping the angle direction.

$$\theta_{tibia} = cos^{-1}(\frac{X^2+Z^2-length\_femur^2-length\_tibia^2}{2xlength\_femurxlength\_tibia}) \quad (2)$$

$$\theta_{femur} = tan^{-1}(\frac{X^2+Z^2-length\_femur^2-length\_tibia^2}{2xlength\_femurxlength\_tibia}) \quad (3)$$

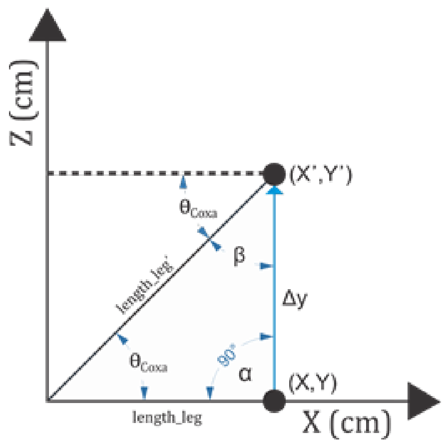


Figure 7. Kinematics problem of coxa joint

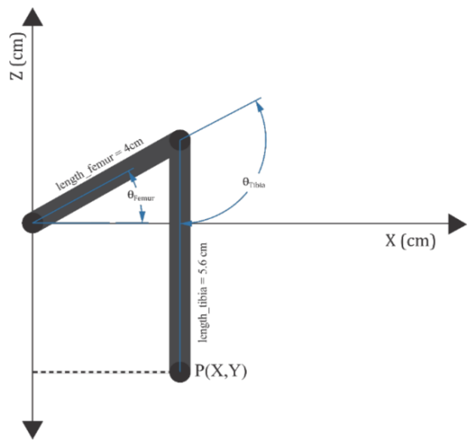


Figure 8. The kinematic problem of femur-tibia joint

2.4. Experimental design

In this study, the performance of the mobile robot movement using the proposed scheme will be tested. Without loss of generality, only forward movement (in the Y direction) will be considered. The movement of the mobile robot is considered reasonable if the robot's final position is as desired and the attitude of the robot remains in a state of equilibrium. Robot state of equilibrium is measured using a tilt sensor (CMPS11 sensor) which is returned pitch, roll, and yaw orientation of the robot. Figure 9 shows the experiment scenario for movement performance.

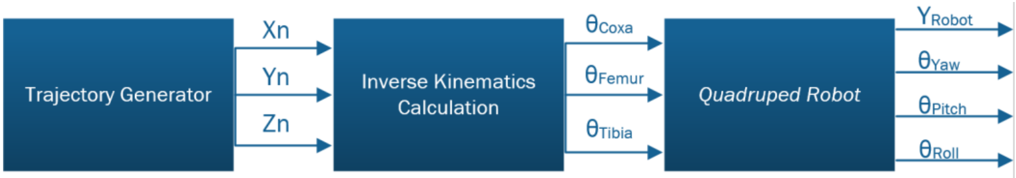


Figure 9. Experiment scenario for movement performance

3. RESULTS AND ANALYSIS

In this experiment, the mobile robot is moving in a lateral direction toward the wall at a certain distance. Table 1 shows the mobile robot performance of forwarding movement. Label "FM" in the first column means forward movement traveled by mobile robot toward the wall. The "Error.." in column 2 until 11 is the subtraction of lateral position (in Y-axis) to the set point (herein equals 0). While the last two columns are an average error for each distance toward the wall. Taking the average of the last column we got the average error rate is 1,83%, which is considerably small.

Next experiment is a concern with walking stability. It is hoped that the robot moves while maintaining its pose. A tilt sensor is used for this purpose. The sensor measured yaw, pitch and roll difference to the reference. Table 2 summarizes the experimental results. As in Table 1, Label "FM" in the first column means forward movement traveled by mobile robot toward the wall. From the table, it is understood that pose error also considerably small, just around 1.33 degrees. It could be concluded that walking stability is good.

Table 1. Performance of forward movement

FM	Error in each experiment (cm)										Avg	Avg
(cm)	1	2	3	4	5	6	7	8	9	10	(cm)	(%)
5	0.05	-0.12	-0.36	-0.16	0.05	-0.45	-0.21	0.12	-0.39	0.09	-0.14	2.75
10	-0.14	0.28	0.43	0.60	0.10	-0.02	0.29	0.70	-0.29	-0.43	0.15	1.53
15	0.22	-0.96	0.64	-0.05	0.07	0.60	-0.02	-0.31	-0.52	-0.72	-0.11	0.69
20	-0.39	0.33	-0.67	-0.86	-0.55	-0.95	-0.89	-0.22	0.67	0.21	-0.33	1.67
25	-0.93	-0.43	-0.10	-0.63	-0.12	-0.41	0.01	-0.52	-0.96	-0.16	-0.42	1.69
30	-0.67	-0.49	-0.72	-1.53	-0.22	-1.60	-0.93	-1.05	-0.43	-0.26	-0.79	2.63
Average												1.83

Table 2. Pose stability experiment results

FM (cm)	Yaw	Pitch	Roll	Average Error (deg)
5	2.8	-0.548	0	0.750667
10	5.2	-0.352	0.167	1.671556
15	3.9	-0.452	0	1.149333
20	0.2	-0.048	0	0.050667
25	5.6	-0.816	0.667	1.816889
30	7.8	-1.152	1	2.549333
Average				1.331407

4. CONCLUSION

This paper presents development of a quadruped mobile robot and its movement system using geometric-based inverse kinematics. The trot gait pattern method is proposed to coordinate the movement of the robot's legs, while the end-effector position of each leg is generated by a simple trajectory generator with half rectified sine wave pattern. Furthermore, to move each robot's leg, it is proposed to use geometric-based inverse kinematic. The experimental results showed that the proposed method succeeded in moving the mobile robot with precision. Movement errors in the translation direction are 1.83% with the average pose error of 1.33 degrees, means the mobile robot has good walking stability

REFERENCES

[1] R. Siegwart and I. R. Nourbakhsh, *Introduction to Autonomous Mobile Robots*. MIT Press, 2004.
[2] R. N. Jazar, *Theory of Applied Robotics*. Springer, 2007.
[3] A. Roshanianfard, T. Kamata, and N. Noguchi, "Performance evaluation of harvesting robot for heavy-weight crops," *IFAC-PapersOnLine*, vol. 51, no. 17, pp. 332–338, 2018.
[4] A. T. Braun, E. Colangelo, and T. Steckel, "Farming in the Era of Industrie 4.0," *Procedia CIRP*, vol. 72, pp. 979–984, 2018.
[5] J. Kim and S. N. Hong, "Adaptive buffer control for distributed autonomous robust routing in mobile surveillance robots," *Comput. Electr. Eng.*, vol. 43, pp. 306–316, 2015.
[6] P. S. Gohari, H. Mohammadi, and S. Taghvaei, "Using chaotic maps for 3D boundary surveillance by quadrotor robot," *Appl. Soft Comput. J.*, vol. 76, pp. 68–77, 2019.
[7] J. Vallvé and J. Andrade-Cetto, "Potential information fields for mobile robot exploration," *Rob. Auton. Syst.*, vol. 69, no. 1, pp. 68–79, 2015.
[8] C. J. H. Roth, "Mobile Robot Exploration Based On Three Dimension Cameras Acquisition," in *2nd IFAC Symposium on Telematics Applications*, 2010, pp. 116–121.
[9] S. S. Kim, S. Kim, H. Kang, and M. Oh, "A remote operating system of an unmanned military robot for indoor test environment," *2013 44th Int. Symp. Robot. ISR 2013*, pp. 1–4, 2013.
[10] S. Kr, C. Fancy, S. Vinothvikram, and K. Chittal, "Controlling Robots through Intelligent Mobiles for Military Purpose," *2017 Int. Conf. Energy, Commun. Data Anal. Soft Comput.*, pp. 2358–2363, 2017.
[11] G. Klančar, A. Zdešar, S. Blažič, and I. Škrjanc, *Wheeled Mobile Robotics*. Butterworth-Heinemann, 2017.
[12] M. Luo, M. P. Bowers, and M. B. Popovic, "17-Bioinspired Robotics," in *Biomechatronics*, Elsevier Inc., 2019, pp. 495–541.
[13] S. G. Tzafestas, *Introduction to Mobile Robot Control*. Elsevier Inc., 2014.
[14] P. G. de Santos, E. Garcia, and J. Estremera, *Quadrupedal Locomotion*. Springer Verlag-London, 2006.
[15] T. Braunl, *Embedded Robotics*, Third. Berlin Heidelberg: Springer-Verlag Berlin Heidelberg, 2008.
[16] J. P. Ostrowski, "Robotic Locomotion Systems, Unconventional," in *Encyclopedia of Physical Science and Technology*, 2004, pp. 263–273.
[17] T. Kato, K. Shiromi, M. Nagata, H. Nakashima, and K. Matsuo, "Gait Pattern Acquisition for Four-legged Mobile Robot by Genetic Algorithm," *IECON 2015 - 41st Annu. Conf. IEEE Ind. Electron. Soc.*, pp. 4854–4857, 2015.
[18] C. Liu, Y. Chen, J. Zhang, and Q. Chen, "CPG Driven Locomotion Control of Quadruped Robot," *2009 IEEE Int. Conf. Syst. Man Cybern.*, no. 60875057, pp. 2368–2373, 2009.
[19] F. Asadi, M. Khorram, and S. A. A. Moosavian, "CPG-Based Gait Transition of a Quadruped Robot," *2015 3rd RSI Int. Conf. Robot. Mechatronics*, pp. 210–215, 2015.
[20] Z. Pei, L. Song, B. Chen, and X. Guo, "Adaptive Control of a Quadruped Robot Based on Central Pattern Generators," *IEEE 10th Int. Conf. Ind. Informatics*, pp. 554–558, 2012.
[21] J. Zhang, F. Gao, X. Han, X. Chen, and X. Han, "Trot gait design and CPG method for a quadruped robot," *J. Bionic Eng.*, vol. 11, no. 1, pp. 18–25, 2014.
[22] Y. Xin, B. Liu, X. Rong, B. Li, and H. Wang, "Research on Smooth Trot-to-Walk Gait Transition Algorithm for Quadruped Robot," in *2017 Chinese Automation Congress (CAC)*, 2017, pp. 5967–5971.
[23] E. Jumantoro, A. H. Alasiry, and H. Hermawan, "Stability Optimization on Quadruped Robot using Trajectory Algorithm," pp. 93–98, 2017.
[24] Y. O. Aydin, J. M. Rieser, C. M. Hubicki, W. Savoie, and D. I. Goldman, "Physics approaches to natural locomotion: Every robot is an experiment," in *Robotic Systems and Autonomous Platforms*, Elsevier Ltd., 2019, pp. 109–127.
[25] H. Igarashi and M. Kakikura, "Adaptive Gait Control for a Quadruped Robot on 3D Path Planning," *IEEJ Trans. Electron. Inf. Syst.*, vol. 123, no. 10, pp. 1813–1821, 2004.