

Design and Kinematic Analysis of Quadrupedal Cat-Like Robot

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Abstract—Robotics technology is one of the most important technologies in determining the progress of civilization in the world. Since the invention of mobile robot technology, the development of robotics has occurred in almost every sector of life, such as the military, manufacturing, industry, health, and others. On a mobile robot, there are two classifications of mechanisms used, namely the legged mechanism and the wheel mechanism. Of the two mechanisms, legged robots have advantages over wheel robots, because leg robots can pass through all the terrains to be traversed. In the legged robots, quadruped robots are easier to manufacture and control than a two-legged (biped) robot, and a six-legged robot (hexapod). Therefore, this study seeks to develop a Quadrupedal Robot inspired by the structure and movement of a cat. In this first phase of research, the robot was manufactured with a total weight of 1293 g and dimensions of 43 cm long, 20.5 cm wide, and 22 cm high. The equation of motion uses the geometry equation to model and determine the position of the end-effector (leg-tip) and perform a kinematic simulation with the toolbox in Matlab. The result of 2D forward kinematics is highly nonlinear that it is difficult to solve by analytical solutions. Symbolic toolbox and ‘solve’ command under Matlab software is utilized to obtain the joint angle inputs. The acquired angles are then used as input on the Simulink block to be embedded on the microcontroller, and the actuator on the robot, before the prototype is carried out in a straight walking test. From the results of walk test, the robot can successfully walk without falling. The robot can walk without orientation feedback control.

Keywords—cat-like robot, legged robot, kinematics, design

I. INTRODUCTION

Robotics technology is one of the most important technologies in determining the progress of civilization in the world. Robotics technology can increase the productivity of a job. With a robot, work that was previously difficult and dangerous to do can now be done more easily and safely. For example, exploring deep into the bowels of the earth, into the oceans, space exploration, and so forth. With such conditions, the development of robotics technology runs quite rapidly from time to time. Since the invention of mobile robot technology, the development of robotics has occurred in almost every sector of life, such as the military, defense, manufacturing, industry, health, and other sectors of life, so that several terms such as humanoid or human-like robots and animaloid robots or animal-like robots have become familiar terms in our modern life.

One type of robots is a mobile robot, a mobile robot that has a characteristic construction is to have an actuator to move the entire robot body so that the robot can move positions from one point to another [1]. In mobile robots, there are two classification mechanisms used, namely the leg mechanism and the wheel mechanism. Of the two mechanisms, legged robots are superior to wheeled robots, because legged robots can pass through any terrain that will be traversed [2]. Furthermore, in the legged robots, especially quadruped robots are easier to manufacture and control than biped robots and hexapods [3]. Therefore, this study seeks to develop a quadrupedal robot that is inspired by the structure and movement of a cat by combining the control system on a standard servo as an actuator controlled by an Arduino microcontroller.

The development of legged robots especially four-legged robots has increased rapidly especially regarding the development of gait generation. Researchers have developed and applied a central pattern generator (CPG) as a gait strategy on hexapod robots [4-5], quadrupeds robots [6-8] and salamander robots [9-12]. This gait generation method has promising results for the legged robot to walk similarly to the biological system but it needs more complex modeling and control methods.

In this study, a cat-like robot will be designed using SolidWorkS CAD software. Two DOF leg structure of the robot will be designed and analyzed in order to determine the joint angle inputs for the first and the second servomotor angle command. After determining the correlation between joint angle input and the tip leg of the cat robot, the forward kinematics is solved using the Symbolic Math Toolbox under Matlab software environment. The solved equation for forward kinematics is utilized for the gait generation of the cat-like robot.

II. MECHANICAL AND ELECTRICAL DESIGN

In the process of selecting a quadruped cat-like robot design concept, it is necessary to consider several aspects including weight, durability, the difficulty of manufacturing, and assembly. The weight of the quadruped cat-like robot greatly affects the actuator that will be used as a robot drive when walking, therefore a lightweight but strong structure is required to support the load on the robot so that it is easy to operate.

The material used on the robot body is acrylic. It was chosen with the consideration that acrylic material is stronger than plywood material, considering the body will support all the electrical systems of the robot. Plywood is chosen for the leg structure because the leg is the part that carries out the movement of the robot. The number of components needed is quite a lot and therefore a lightweight but still strong material is needed as the foundation of the robot. For the servo motor holder, aluminum material is chosen. Compared to PLA material, aluminum is stronger and the material has a longer service life, besides that the level of precision is also higher compared to materials printed using 3D printers. The type of chosen aluminum holder is the standard type of universal servo.

At this stage, the theoretical considerations of the weighting assessment resulting from the development stage of the selected design concept are transformed into physical shapes and dimensions in the drawing. The main concern at this stage is the process of manufacturing quadruped robot robots that are easily manufactured, fast, and at minimal cost without compromising the needs of the research mission. Visualization of the selected quadruped cat-like robot design in this study was carried out using the SolidWorks software as shown in Fig. 1.



Fig. 1. 3D design of the cat-like robot.

In quadruped cat-like robot, there are two main components, namely the servo motor and the Arduino microcontroller. Each component has a different power source because if the actuator and microcontroller have the same source, it can interfere with the stability of the circuit. The eight servo motors placed at the robot's leg have a power source of 11.1 V which is reduced to 6 V using DC step-down and connected to the Arduino ATmega 2560 as a microcontroller. Then the microcontroller has a 7.4 V source which is stepped down by UBEC 8A-V1.

In this study, the TowerPro MG995 servomotor was chosen as the robot actuator. This is because this type of servo has a standard size and uses metal gear material with a large enough torque. To control the quadruped cat-like robot that is able to drive the whole robot system, a small microcontroller is needed but able to run complex commands. In this research, RobotDyn Mega 2560 Pro is used which is relatively smaller in size compared to Arduino MEGA.

The consideration of battery selection in this study is only based on the current required by the robot components. Therefore, three LG HE4 18650 Li-ion Batteries 2500mAh 3.6V were selected in this study and arranged in series. These three batteries provide enough electricity to be consumed by eight servo motors and one microcontroller. The components of the cat-like robot are presented in Fig. 2.

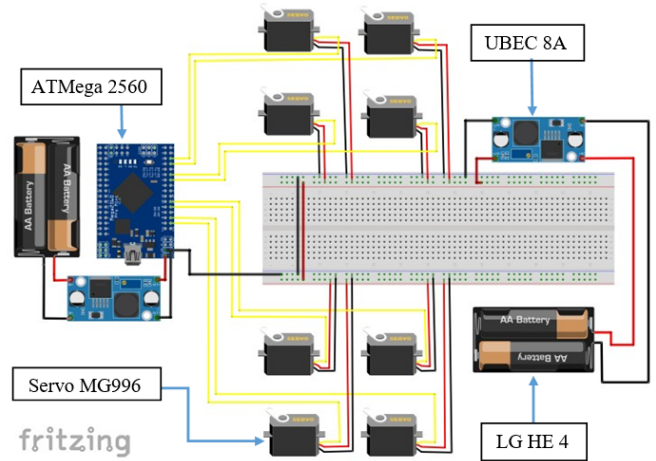


Fig. 2. Mechatronics components of the cat-like robot.

III. TWO DOF LEG KINEMATICS

In this research, forward kinematics is used to model the relationship between motor angle position input and leg-tip position and orientation as shown in Fig. 3. The determination of kinematic progress can be done in several ways, one of them with geometric [13]. Based on the equation used in this study, it can be written in equation (1) to equation (6). The mathematical modeling of the chosen four-legged cat robot can be adjusted to the shape of the robot's leg. Because one of the links in the robot is a passive link (link 4), the values of θ_2 and θ'_3 are the same. In accordance with equation (1) and equation (2), it can be simplified according to the shape conditions of the robot to be as follows.

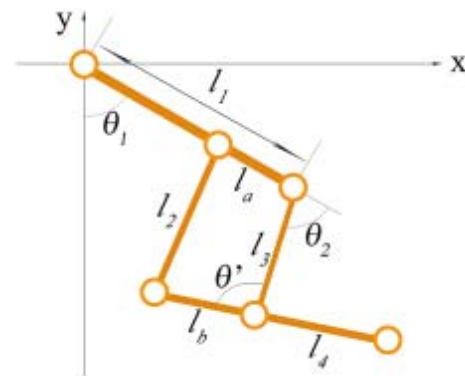


Fig. 3. Proposed mechanism of two DOF cat robot leg

$$x = l_1(\sin \theta_1 - \sin(\theta_2 - \theta_1)) + l_4 \sin \theta_1 \quad (1)$$

$$y = -l_1(\cos \theta_1 + \cos(\theta_2 - \theta_1)) - l_4 \sin \theta_1 \quad (2)$$

Equations (1) and (2) can be written further by using the sine rules as in equations (3) and (4) below

$$\cos(a) - \cos(b) = -2 \sin\left(\frac{a+b}{2}\right) \sin\left(\frac{a-b}{2}\right) \quad (3)$$

$$\sin(a) - \sin(b) = 2 \cos\left(\frac{a+b}{2}\right) \sin\left(\frac{a-b}{2}\right) \quad (4)$$

Then the final results of equations (3) and (4) as written in equations (5) and (6)

$$x = l_1 \times 2 \cos \frac{\theta_2}{2} \sin\left(\frac{2\theta_1 - \theta_2}{2}\right) + l_4 \sin \theta_1 \quad (5)$$

$$y = l_1 \times 2 \sin \frac{\theta_2}{2} \sin\left(\frac{2\theta_1 - \theta_2}{2}\right) - l_4 \sin \theta_1 \quad (6)$$

Where:

- l_1 : Length of the first link (mm)
- l_2 : Length of the second link (mm)
- l_3 : Length of the third link (mm)
- l_4 : Length of the fourth link (mm)
- θ_1 : First actuator angle
- θ_2 : Second actuator angle
- $l_2 = l_3$
- $\theta' = \theta_2$

Equations (5) and (6) can be solved using MATLAB software. The solutions of equations (5) and (6) can be performed using the Symbolic Math Toolbox and the built-in function "solve" in Matlab. After giving the initial position of the robot's ankle in x and y coordinates, the solve function is used to find solutions to equations (5) and (6) so that the angular values θ_1 and θ_2 are obtained. The joint angle inputs obtained from the results of this process will be used as input to the Simulink block to be processed so that the results of this data can be embedded in the microcontroller used to provide the command angle on the servomotor. In this calculation process, the calculation is performed at each shift of the position of the key point one to the next key point according to the gait cycle trajectory that is made as an end-effector (leg-tip) movement pattern from the robot's foot to walk straight.

The orientation and configuration of the parameters of the leg can be summarized in Table I. The value of the link length of each leg and the magnitude of each joint contained in the leg are given to calculate the input angles of θ_1 and θ_2 . Based on the calculations on forward kinematics, the end-effector position of the leg is at coordinates $x = 8.21$ mm, and $y = -174.23$ mm as shown in Fig. 4. The flowchart for solving the equation (5) and (6) is summarized in Fig. 5. The acquired and utilized trajectory for front-right of the robot is depicted in Fig. 6.

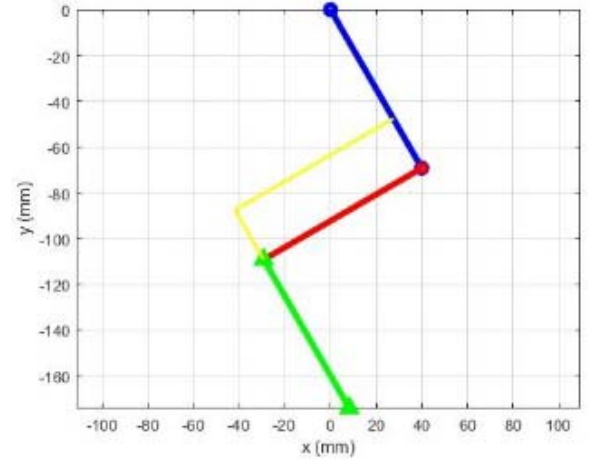


Fig. 4. The initial position of the DOF cat robot leg

TABLE I. INITIAL POSITION OF THE LEG

Link	Length (mm)	Link angle (deg)
l_1	80	30
l_2	80	90
l_3	80	90
l_4	75	90

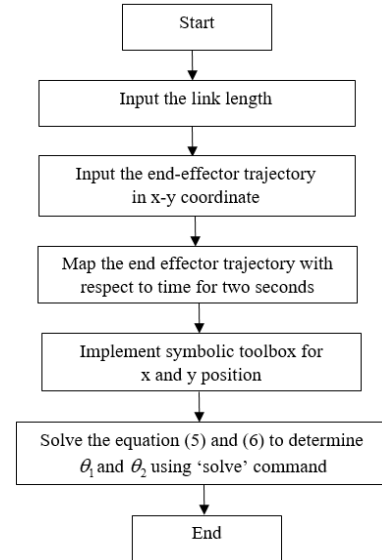


Fig. 5. The initial position of the DOF cat robot leg

IV. EXPERIMENTAL RESULTS

The robot was successfully manufactured with a total weight of 1293 g and dimensions of 43 cm long, 20.5 cm wide, 22 cm high. The acquired joint angle inputs from equation (5) and (6) are embedded into the Arduino microcontroller. The microcontroller board is placed on the upper body of the cat-like robot. The result of the final prototype of the proposed robot is shown in Fig. 7.

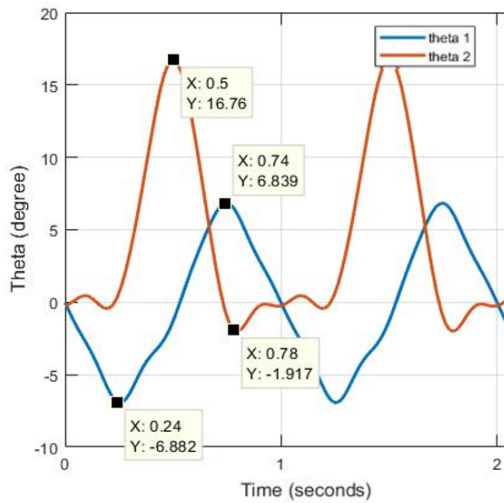


Fig. 6. One period trajectory of the joint angles inputs for front-right leg

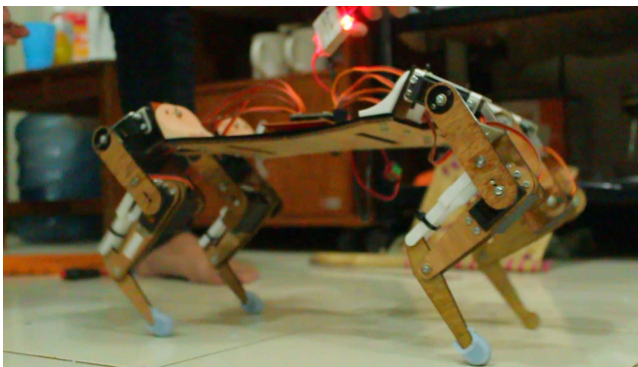


Fig. 7. The result of the proposed cat-like robot

The acquired joint angles obtained from equation (5) and (6) are implemented in the Simulink block diagram as signal inputs. The blocks are embedded into the Arduino microcontroller using Simulink Support Package for Arduino Hardware. The block runs with sample time of 0.02 seconds.

Although the cat-like robot can walk in a straight trajectory, there is still a deviation that is relatively smaller than the straight-line trajectory. In addition, there is also a slight deviation in the angular commands at some joints of the robot legs when in the testing process because the structure of the robot legs is less rigid and the limitations of servo motor movement are used. This leads the movement of walking cat-like robot can not run straight in accordance with the straight-line trajectory. The straight walk of the cat-like robot is presented in Fig. 8.

Three 185650 lithium-ion batteries are placed outside of the robot's body. If the battery is placed on the robot's body, the robot will have difficulty in walking. Based on the walking test, the proposed cat-like robot can successfully walk without difficulty and falling on the ground. The robot can walk without implementing the orientation stability control system.



Fig. 8. Sequence images of the walking cat-like robot

V. CONCLUSION AND FUTURE RESEARCH

In this study, the prototype of a cat-like robot has been built with two DOF legged mechanism. The forward kinematics of the leg is modeled using the geometric approach. For determining the joint angle inputs of θ_1 and θ_2 , inverse kinematics is performed using Matlab symbolic toolbox and 'solve' function. The obtained joint angle inputs of the leg-tip are embedded as the trajectory command in the microcontroller.

Based on the experiment for the walking test, the robot can walk in a straight trajectory although there is still a small deviation from the straight-line trajectory. This can occur because there is a slip between the leg-tip of the robot and tile. The deviation also comes from the less rigid of the leg structure which leads the joint angle input error.

In future research, the gait generation will be optimized for the gait strategy of the cat-like robot. The trajectory of the leg will be developed using Fourier series. The utilized servo motor will be replaced with higher torque servo motors. The leg structure of the robot will be manufactured more rigid, in order to reduce the deviation from the straight-line trajectory movements.

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REFERENCES

- [1] Machado, J. T., & Silva, M. F. "An overview of legged robots". In International symposium on mathematical methods in engineering. MME Press Ankara Turkey. 2006.
- [2] Zielinska, T., & Heng, J. "Mechanism and Machine Theory", Mechanical design of multifunctional quadruped., 38(5), pp. 463-478. 2003.
- [3] Silva, M. F., & Tenreiro Machado, J. A.. "A historical perspective of legged robots". Journal of Vibration and Control, 13(9-10), 1447-1486, 2007.
- [4] Rostro-Gonzalez, H., Cerna-Garcia, P.A., Trejo-Caballero, G., Garcia-Capulin, C.H., Ibarra-Manzano, M.A., Avina-Cervantes, J.G. and Torres-Huitzil, C., "A CPG system based on spiking neurons for hexapod robot locomotion". Neurocomputing, 170, pp.47-54, 2015.
- [5] Barron-Zambrano, J.H., Torres-Huitzil, C. and Girau, B. "Perception-driven adaptive CPG-based locomotion for hexapod robots". Neurocomputing, 170, pp.63-78, 2015.
- [6] Wang, M., Tang, Z., Chen, B. and Zhang, J. "Locomotion control for quadruped robot based on Central Pattern Generators". In Control Conference (CCC), 2016 35th Chinese pp. 6335-6339.
- [7] Feng, Huashan, and Runxiao Wang. "Construction of central pattern generator for quadruped locomotion control." In 2008 IEEE/ASME International Conference on Advanced Intelligent Mechatronics, pp. 979-984. IEEE, 2008.
- [8] Tran, Duc Trong, Ig Mo Koo, Yoon Haeng Lee, Hyungpil Moon, Sangdeok Park, Ja Choon Koo, and Hyouk Ryeol Choi. "Central pattern generator based reflexive control of quadruped walking robots using a recurrent neural network." Robotics and Autonomous Systems 62, no. 10 (2014): 1497-1516.
- [9] K. Karakasiliotis and A. J. Ijspeert, "Analysis of the terrestrial locomotion of a salamander robot," 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems, St. Louis, MO, 2009, pp. 5015-5020.
- [10] Horvat, T. , K. Karakasiliotis, K. Melo, L. Fleury, R. Thandiackal and A. J. Ijspeert. "Inverse kinematics and reflex based controller for body-limb coordination of a salamander-like robot walking on uneven terrain". IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Hamburg, 2015, pp. 195-201
- [11] Ijspeert, Auke Jan, Jean-Marie Cabelguen, "Gait Transition from Swimming to Walking: Investigation of Salamander Locomotion Control Using Nonlinear Oscillators," In: Kimura, Hiroshi, Kazuo Tsuchiya, Akio Ishiguro, Hartmut Witte. (eds.) Adaptive Motion of Animals and Machine, 2005, pp. 177-186
- [12] Munadi, M., Ariyanto, M., Pambudi, K.A., Setiawan, J.D., "Development of 18 DOF salamander robot using CPG based locomotion for straight forward walk", International Review of Mechanical Engineering, 13(1) pp. 70-77, 2019
- [13] Zhao, D., Xu, J., Wu, D., Chen, K., & Li, C.. "Gait definition and successive gait-transition method based on energy consumption for a quadruped". Chinese Journal of Mechanical Engineering, 25(1), pp 29-37, 2012.