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Design, Simulation and Fabrication of Quadrupedal Robot Integrated using Five-Jointed Legs with Suspension Spring

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Abstract: ***In this paper, a complete description of the design process for a four-legged locomotion robot or also known as quadrupedal robot will be presented. The quadrupedal robot is purposely designed as the Messenger Robot 2 (MR2) to participate in Robocon 2019. To overcome the challenges in Robocon 2019, each leg of the quadrupedal robot is designed with five joints integrated with a compression spring at the foot for suspension. The quadrupedal robot consists of a total sixteen standard servomotors where groups of four servos actuate leg joints of the quadrupedal robot. Furthermore, there are an additional three servomotors, where one servomotor is a joint at each front leg to allow the robot to rotate its orientation, and the last servo for an extension mechanism system. Finally, the simulation and experimental results demonstrated that the quadrupedal robot achieves a stable walking motion with the fastest locomotion of two legs contacting the ground at half walking cycle. In the future, the legged mechanism of the quadrupedal robot will be further improved and optimized toward the generalization of the dynamic legged locomotion in other challenging terrains.***

Keywords: Quadrupedal robot, five-jointed leg, simulation, Robocon.

I. INTRODUCTION

Robotic technologies have been advancing at a fast pace, simulation software have been developed that allows easier and faster design of new robots. Generally, a robot with two-legs is called a bipedal robot while a four- legged robot is called a quadrupedal robot. Some robots have combined legs and wheels and are considered as hybrids locomotion robots. Many researchers have also worked on design and development of quadrupedal robots.

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In the development of legged locomotion robots, Boston Dynamics is a company well known for developing the bipedal humanoid robot called Atlas [1] and various designs of quadrupedal robots such as BigDog, Spot and SpotMini [2].

The quadrupedal robots developed by Boston Dynamics are capable to perform complex movements and adapt to rough open terrain. SpotMini consists of two motors and a linear actuator to actuate each leg. Moreover, ANYbotics is another company which developed a quadrupedal robot called ANYmal [3], with three motors to actuate each leg and having a different leg structure compared with SpotMini. Massachusetts Institute of Technology (MIT) is well-known for construction of quadrupedal robots mimicking the movement of a cheetah. Wensing et al. published a paper on the leg structure and force analysis of the MIT Cheetah 2 that is capable to jump over obstacles while running [4, 5]. Seok et al. developed an energy efficient MIT Cheetah robot [6]. Bosworth et al. constructed the MIT Super Mini Cheetah which is a small and low-cost quadrupedal robot with weight of 10 kg [7]. MIT Cheetah 3 developed by Bledt et al. has similar movement as Spot but it is able to gallop at a speed of 3m/s, climb staircases without the usage of external sensors, and walking forward on three legs only [8]. Wang et al. proposed a cheetah robot under the neural mechanism controlling the leg muscles for a smoother movement [9]. Furthermore, Zhang et al. proposed a simple quadrupedal robot design by simplifying the quadrupedal mammal’s body into a four joint configuration style and mimicking a cat’s movement [10]. The joint configuration style is very simple and has been repeatedly implemented in many quadrupedal robots for high mobility. Ishihara and Kuroi designed a quadrupedal robot with jack-like legs for high capacity loads without active energy consumption and it has the locomotion of a lizard [11]. The implementation of jack-like legs sacrifices speed for high load capacity. Sugiyama et al. developed a large size quadrupedal robot prototype for maintenance and inspection of nuclear power plant facilities [12].

After analysing the movement of developed quadrupedal robots, two types of locomotion with constant movement were derived: the fastest locomotion for a quadrupedal robot to constantly walk is by having two legs contacting the ground to propel forward in half a walking cycle while the other locomotion will have at least three legs contacting the ground while walking which provide better stability and greater weight capacity for the robot.

In Robocon 2019, two robots are required for the competition namely Messenger Robot 1 (MR1) and Messenger Robot 2 (MR2). MR1 will be carrying an object called *Gerege* and pass it to MR2 after moving around obstacles. MR2 must have four legs with no wheel and all four legs must contact and leave the ground in one walking cycle.

MR2 will have four challenges during the competition which are walking over a 100 mm high step, walking over two ropes placed 0.8m apart, walking up a 14 degree slope, and lift the *Gerege* to a position that is 1 metre above the ground. This paper presents the design of quadrupedal robot with five joints in each leg by implementing sixteen units of RDS3128 servomotors with four servomotors to actuate a leg, and three units of MG995 servomotors with one servomotor at each front leg to allow the robot to rotate its orientation and one servomotor for the extension mechanism system. An approach of motion control strategy was used to control the leg to propel the body forward in a linear motion without external sensors and derivation of the mathematical equations will be discussed. There are two designs of the leg where simulation was performed with the first leg design and then the second leg design was implemented to overcome the technical issues with the first design during testing.

II. MECHANICAL DESIGN

Leg Design

The first leg design as shown in Figure 1 was inspired by the MIT Super Mini Cheetah [6]. Part C of the leg was longer for easier construction of the foot and having a longer leg to walk further in one walking cycle. Part A and B were constructed with 0.195m × 0.0254m × 0.003m aluminium flat bar, part D with 0.2171m × 0.0254m × 0.003m aluminium flat bar while part C was constructed with 0.2625m × 0.0254m × 0.0127m aluminium hollow bar and a 0.01m long 2 inches diameter acrylonitrile butadiene styrene (ABS) pipe as foot. Servomotors were used to control the hip joints. The five joints leg achieved the state of equilibrium when the total moment of part A and B is equal to the total moment of part C and D. Therefore, the maximum weight capacity of a leg is equal to the stall motor torque divided by the length of part C in addition with stall motor torque divided by the length of part D.

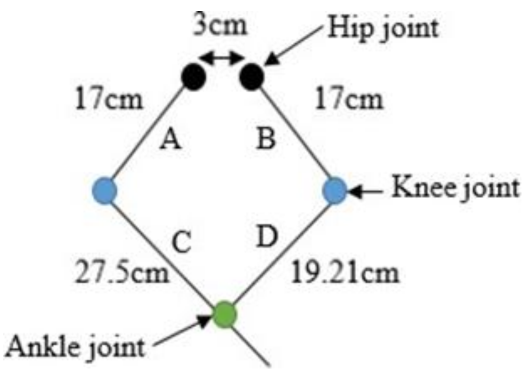

Fig. 1 First leg design

The leg design in Figure 1 was further simplified by making all structural links to have the same length as shown in Figure 2 to derive the formula to control the leg to move in linear motion. By setting the lengths of all linkages on the leg to be equal ($L_a \approx L_b \approx L_c \approx L_d$) and the angles θ_1, θ_2, θ_3 and θ_4 equal to 45 degrees, the height of the leg, h_{stand} when standing is approximately equal to 1.4142L of one part of the leg shown in Eq. (1). The angles θ_1 and θ_2 are the angle of the motors to control the hip joints. In order for the foot of the leg to move in linear motion, the leg must maintain the same height as it stands and the angle θ_1 will be directly controlled while the angle θ_2 will vary according to the angle θ_1 through a formula which relates angle θ_2 in terms of angle θ_1.

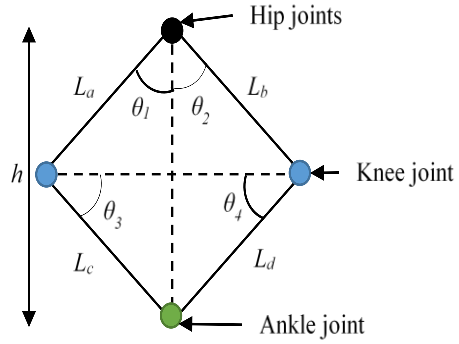

Fig. 2 Simplified standing leg design

$$h_{stand} = L \cos 45° + L \cos 45° = 1.4142L \quad (1)$$

Figure 3 shows the simplified leg design from Figure 2 after moving the foot backward where the angle θ_1 increased while the angle θ_2 remains at 45 degrees to relate the angles θ_3 with θ_2 shown in Eq.(2). The derivation of the formula to determine the height of the leg based on the angles θ_1 and θ_2 is shown in Eq. (3) to Eq. (5) using trigonometry and forward kinematics.

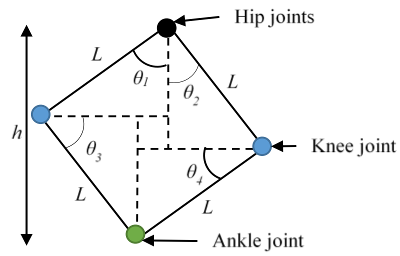

Fig. 3 Simplified moved leg design

$$\theta_3 = 90° - \theta_2 \quad (2)$$

$$h = L\cos \theta_1 + L\cos\theta_3 \quad (3)$$

$$h = L\cos \theta_1 + L\sin (90°-\theta_2) \quad (4)$$

$$h = L\cos \theta_1 + L\cos\theta_2 \quad (5)$$

The leg must remain at the same height as it stands. Hence, h_{stand} is substituted into Eq.(5) as shown in Eq.(6). Eq.(7) shows the formula to determine the angle θ_2 in terms of θ_1.

$$1.4142L = L\cos\theta_1 + L\cos\theta_2 \quad (6)$$

$$\theta_2 = \text{acos}(1.4142 - \cos\theta_1) \quad (7)$$

The possible values of cos θ_1 are 0 to 1 but in Eq.(7), the values are limited to 0.4142 to 1.

Hence, the angles $\theta_1$and $\theta_2$are limited to 0 to 65.53 degrees when applying Eq.(7) to move the leg in a linear motion at a constant height. The leg moves backward when the angle $\theta_1$is greater than the angle $\theta_2$and vice versa. Moreover, the maximum leg height that can be achieved is when both the angles $\theta_1$and $\theta_2$are 0 degree. This concludes the first iteration of the leg design. The second leg design is shown in Figure 4. It was an improvement of the first leg design after encountering issues during testing of the robot. Part C of the leg was shortened to reduce workload on the motor and reduce current consumption to overcome servomotor overheating issues. Additionally, compression springs were added to the foot base to act as a suspension to assist in balancing. The foot base was also made flatter and wider to improve stability.

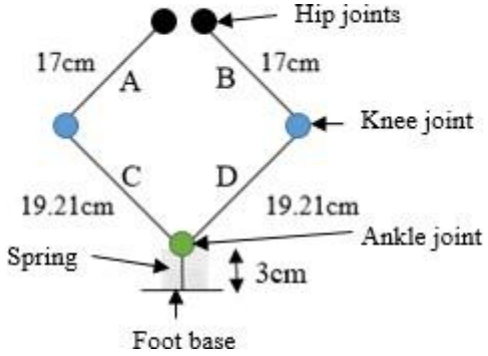

Fig. 4 Second leg design

Extension Mechanism

The extension mechanism was to allow the robot to lift the Gerege with the holder without tilting more than 45 degrees. The mechanism used a servomotor to extend by rotation due to its light weight and high torque. Figure 5 shows the extension mechanism before extension while Figure 6 shows the extension mechanism after extension. The Gerege was able to be lifted 1 meter above the ground when both the extension mechanism was extended and the legs were at maximum standing position.

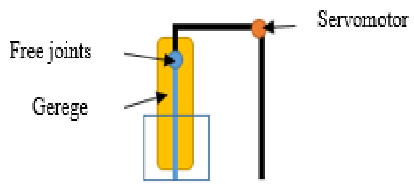

Fig. 5 Extension mechanism to lift Gerege, before extension

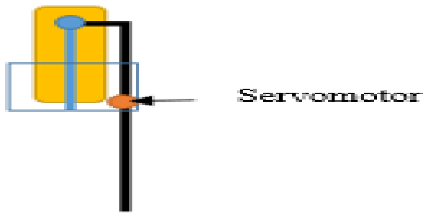

Fig. 6 Extension mechanism to lift Gerege, after extension

Electrical Design

Sixteen units of RDS3128 servomotors were used to actuate the four legs of the developed quadrupedal robot. For each leg, two servomotors actuate part A and another two servomotors actuate part B respectively to double the torque working on one part of the leg. In this design, the RDS3128 servomotors were chosen because they are lighter than high torque direct current (DC) geared motors. Besides, the usage of eight servomotors with torque at least double the torque of RDS3128 servomotor has higher total current consumption and cost. Moreover, one MG995 servomotor was used for the extension mechanism and two MG995 servomotors where one servomotor at each front leg to rotate its orientation. The specifications of both servomotors are shown in Table 1.

Table. 1 Specifications of Servomotors used on the walking robot

Servomotor	RDS3128	MG995
Stall torque (kg-cm)	25.0 @ 7.2V, 28.0 @ 8.4V	9.4 @ 4.8V, 11 @ 6.0V
Stall current (A)	3.2 @ 7.2V, 3.5 @ 8.4V	1.2
No-load speed (rpm)	100 @ 7.2V, 111 @ 8.4V	50 @ 4.8V, 62.5 @ 6.0V
Operational voltage (V)	6.0 – 8.4	4.8 – 7.2

The robot is powered with a single 22.2V 2600mAh Li-Po rechargeable battery, with eight XL4005 step-down voltage regulator modules each having a maximum output current of 5A supplying power to sixteen RDS3128 servomotors at 7.2V, an additional XL4005 voltage regulator module supplying power to the three MG995 servomotors, and an Arduino Mega 2560 microcontroller at 7.2V. Two RDS3128 servomotors is powered with a XL4005 module limiting each servo motor current consumption to 2A by the cables for overheating prevention so the servomotor capped torque, $T_m$is 15.625 kg-cm. The maximum weight capacity of the first leg, $W_{1,max}$ was designed as shown in Eq.(8). For first leg, the number of servomotors in part A and part B at the hip joints are N_a= 2 and N_b= 2 respectively, which has 4 servomotors in total. The maximum weight capacity of the second leg, $W_{2,max}$was simplified as shown in Eq.(9) since the L_c and L_d are equal. Hence, the number of servomotors of second leg, *Na* are 4. The minimum number of legs contacting the ground at a time are N_l= 2 during the half walking cycle so 2 legs will be lifting the weight of the robot while walking. By using Eq.(8) and Eq. (9), the value of $W_{1,max}$ and $W_{2,max}$ can be calculated as 5.526 kg and 6.507 kg respectively.

$$W_{1,max} = (Tm/Lc \times N_a + Tm/Ld \times N_b) \times N_l \quad (8)$$

$$W_{2,max} = (Tm/Lc \times 2N_a) \times N_l \quad (9)$$

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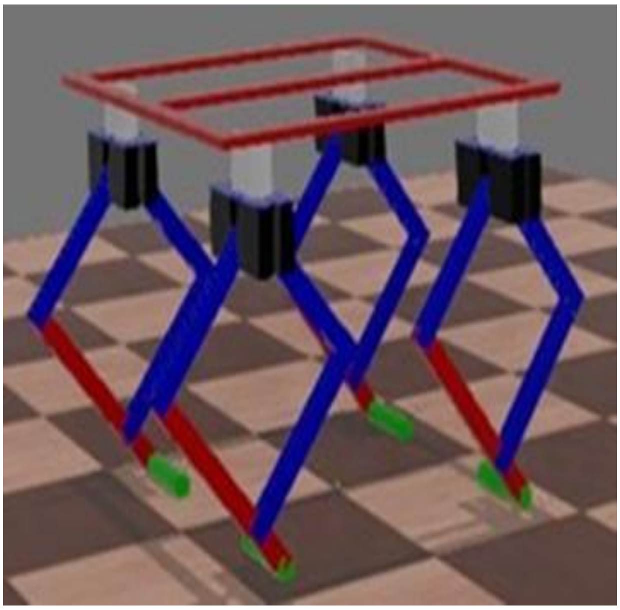
The Arduino Mega 2560 microcontroller board was chosen because of the number of input and output (I/O) pins required and it can be easily programmed using C++ programming language via the Arduino IDE. Three pulse-width modulation (PWM) pins were used to control the three MG995 servomotors while a PCA9685 16- channels servo driver was used to control the sixteen RDS3128 servomotors. The PWM frequency of the servo driver was set to 60Hz to control analogue servo such as the RDS3128 servomotors and controlled with pulse- width from 150µs to 600µs. However, the RDS3128 servomotor only responded to pulse-width from 150µs to 550µs so it can be rotated to angular position of 0 to 160 degrees but it was acceptable since it will not rotate exceeding 90 degrees.

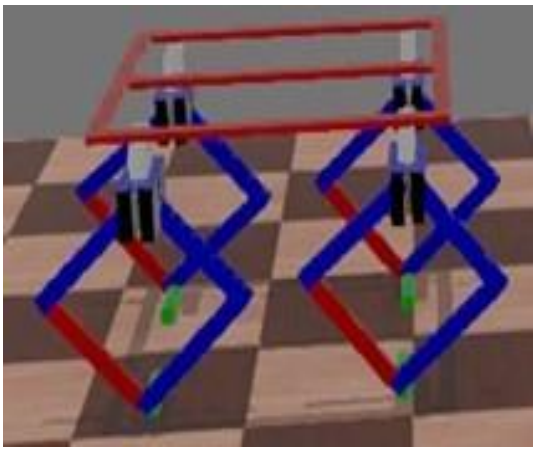
III. SIMULATION

The simulation software called 'Webots' was used to simulate the movement of the robot and ensure the specifications of the motors are sufficient to actuate the robot. The robot model with the first leg design was simulated in Webots and a screenshot is shown in Figure 7a. The simulation software was unable to simulate the actual mass of the robot due to the design constraints. The actual mass of the simulated robot was 3 kg but the simulated robot mass in the simulation was 6.652 kg so the simulation differed from the actual results in terms of physics.

Moreover, the robot model with the second leg design dimension and without the feet was simulated in Webots and a screenshot as shown in Figure 7b. The feet were not simulated due to the feet were complicated and lacking information on the specification of the springs to simulate them. The simulated robot was able to walk forward at a speed of 0.11m/s which is faster than the simulated robot in Figure 7a by 0.01m/s. There is a slight difference between theses designs because the motor in second leg design can achieve higher loaded speed due to lower load acting on the motor. The robot model with shorter legs was unable to be precisely simulated in Webots simulation software because Webots requires greater weight as the legs were shortened in order to simulate the robot which will result in the simulated robot having at least double the actual robot's weight. The simulation will obtain the dissimilar result between simulated robot and actual robot due to the large weight difference.



(a) Simulated quadrupedal robot with first leg design



(b) Simulated quadrupedal robot with second leg design excluding feet with spring

Fig. 7 The quadrupedal robot model was simulated in Webots simulation software

In simulation, maximum motor torque was set to be 28 kg-cm. The maximum mass that the robot was able to withstand without motor stress was 7kg. Figure 8 shows the simulated walking quadrupedal robot using the fastest locomotion of walking with 2 legs at half walking cycle from point A to B. The robot began the first half walking cycle by lifting the front left leg and back right leg up, then the front right leg and back left leg propel the body forward by moving the feet backward. Next step is moving the front left leg and back right leg back to standing position. The next half of the walking cycle repeats the first step but with the front right leg and back left leg, then propel the body forward with the front left leg and back right leg. The final step of the walking cycle is moving the front right leg and back left leg back to standing position. The simulated robot able to walk at a speed of 0.1m/s. Figure 9 shows the robot turning left as it walked forward with the front legs turned to the left in the simulation.

Figure 10 shows the robot turning right the same way as it turned left but with the front legs turned right in the simulation.

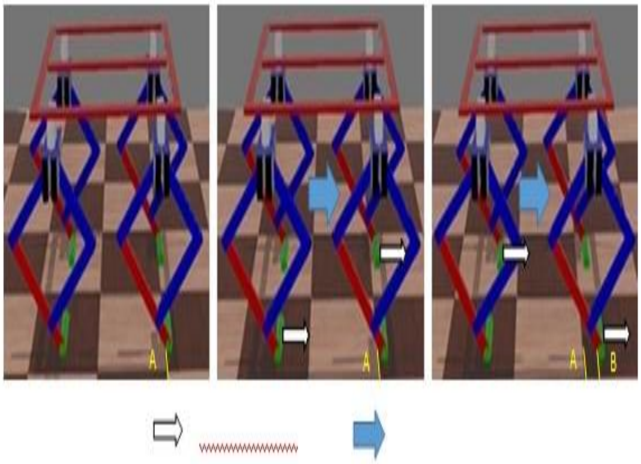


Fig. 8 Simulated walking quadrupedal robot Sequences simulate from left to right

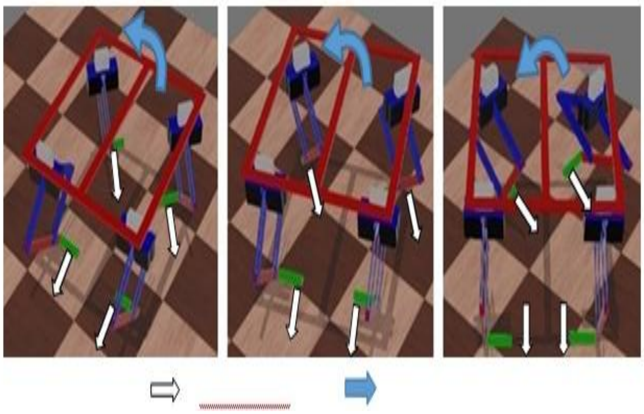


Fig. 9 Simulated quadrupedal robot turning left Sequences simulate from left to right

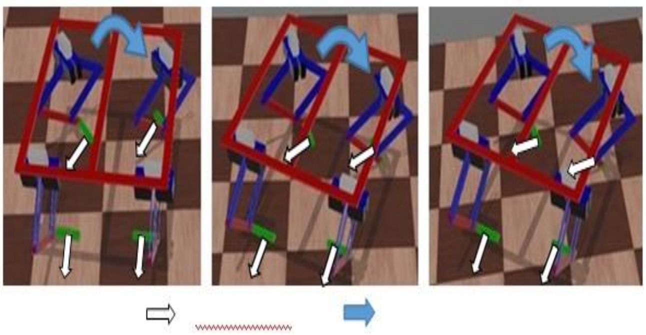


Fig. 10 Simulated quadrupedal robot turning right Sequences simulate from left to right

IV. RESULTS AND DISCUSSIONS

The prototype robot was constructed with the first leg design and it had a mass of 4.7kg. No-load movement was tested and worked as per simulation. However when placed on the ground with full load, it had difficulty to stand on four legs as it was slanted to the back and the back leg showing recoil movement. As the robot was showing difficulty in standing, it fell down as it began to walk. This issue was due to the centre of gravity of the robot was behind the centre of the feet contact area so more weight was shifted to the back legs and the servomotors of the back legs were unable to handle the weight. Additionally, some servomotors having constant current consumption resulting in overheating issues due to servomotors were working against each other from misaligned angular position which can be overcame by performing alignment by adding offset. Current to the servos were measured and it was discovered that the voltage regulators were unable to supply the required current for two RDS3128 servomotors to achieve the maximum torque.

The robot was modified by replacing the leg with the second leg design as shown in Figure 11. The robot had a dimension of 0.795m × 0.540m × 0.780m and a mass of 5.7kg. The suspension springs provided balance to robot and reduce active current consumption of the servomotors while the robot was standing. The robot was tested to walk forward but it was walking towards the left side at a speed of 0.01m/s.

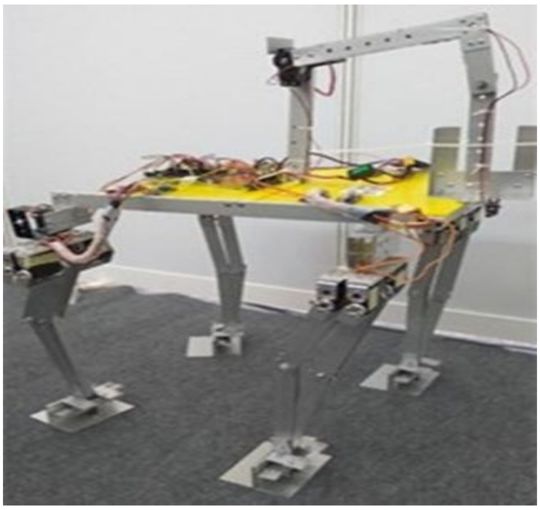


Fig. 11 Quadrupedal robot with second leg design and extension mechanism system

The robot was walking slanted to the left because of the components on the body shifted the centre of gravity more towards the left so more work needed to be done by the servomotors on the left legs which slowed down the servomotors on the left leg. The simulation walking speed and the real walking speed differ due to the behaviour of the simulated motors were different from the actual motors when running at loaded speed. The robot walking direction can be adjusted to walking straight by turning the front legs as it walks. However, one of the servomotors at back left leg broke down after a few walking tests because the weight was not distributed evenly to each servomotor.

As the weight distribution was not even to all legs resulting higher torque requirement for a few servomotors so the legs were shortened by 0.09 m for each part A, B, C, and D of each leg shown in Figure 4. The robot was replaced with shorter legs and the extension mechanism systems removed as shown in Figure 12. The robot has a dimension of 0.60m × 0.54m × 0.57m and a mass of 5.2 kg.

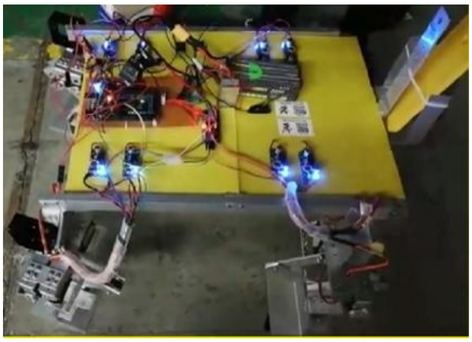


Fig. 12 Quadrupedal robot with shorter legs and without extension mechanism system

The robot was tested to walk forward by 4m on cement ground and carpet with 3 servomotors actuating the back left leg as one servomotor was broke down during previous testing. At first, the robot was walking slightly towards the left so the front legs were adjusted towards the right to allow the robot to walk straight by countering the left direction movement but it walked slightly towards the right. However, the robot walking direction differ when walking on carpet, it walked slightly to the left at start and then it walked slightly to the right at 2m. The results showed that the friction between the feet base and the ground will affect the robot's walking direction so the robot requires a position detection system to constantly correct its walking direction to walk straight.

The relation between the angles $\theta_2$and $\theta_1$as shown in Eq.(10) was used by replacing Eq.(7) when moving the legs backward to propel the body forward. The usage of Eq.(10) would result in the presence of changes in the vertical movement of the legs while the robot was walking forward but the legs were short so the changes in the vertical movement were small that can be ignored.

$$\theta_2 = \theta_1 - 22.5° \quad (10)$$

The robot had a walking speed of 0.04m/s. The walking speed of the robot with shorter legs was faster although it walked with smaller steps because the servomotors were running at faster loaded speed which allowed the robot to finish one walking cycle faster than when it had longer legs. The servomotors did not overheat after walking for 4m although having 1 servomotor lesser to actuate the legs.

V. CONCLUSIONS

This research is focused on the studies of the movement and constraint of the quadrupedal robot with five joints legs. The results also show that the locomotion of walking on two legs for quadrupedal robot at half walking cycle requires the robot to be able to achieve balance while walking on two legs in order to walk straight. In addition, combining two motors to work together to double the torque requires synchronisation of both motors and equal work distribution. Webots software has limitation in simulating small and thin objects. The real experimental result on robotic may differ from virtual simulation result as human error during the fabrication of robot. However, the mechanical component tolerance are still controllable and acceptable. For future improvement, the legged mechanism of the quadrupedal robot will be further developed and optimized toward the generalization of the dynamic legged locomotion in other challenging terrains.

ACKNOWLEDGEMENTS

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REFERENCES

1. S. Kuindersma, R. Deits, M. Fallon, A. Valenzuela, H. Dai, F. Permenter, T. Koolen, P. Marion and R. Ted rake. Optimization-based locomotion planning, estimation, and control design for the Atlas humanoid robot. Autonomous Robots, 2016; 40(3): 429-455.
2. E. Ackerman. Boston Dynamics' SpotMini is all electric, agile, and has a capable face-Arm. Retrieved from https://spectrum.ieee.org/automaton/robotics/home-robots/boston-dynamics-spotmini; 23 Jun 2016.
3. M. Hutter, C. Gehring, D. Jud, A. Lauber, C.D Bellicoso, V. Tsounis, J. Hwangbo, K. Bodie, P. Fankhauser, M. Bloesch, and R. Diethelm. Anymal-a highly mobile and dynamic quadrupedal robot. In: 2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),Daejeon, South Korea, pp. 38–44; 2016.
4. P.M. Wensing, A. Wang, S. Seok, D. Otten, J. Lang, and S. Kim. Proprioceptive actuator design in the MIT cheetah: Impact mitigation and high-bandwidth physical interaction for dynamic legged robots.IEEE Transactions on Robotics, 2017; 33(3): 509–522.
5. H.W. Park, P.M. Wensing, and S. Kim. High-speed bounding with the MIT Cheetah 2: Control design and experiments. The International Journal of Robotics Research, 2017; 36(2): 167-192.
6. S. Seok, A. Wang, M.Y.M Chuah, D.J Hyun, J. Lee, D.M. Otten, J.H. Lang, and S. Kim. Design principles for energy-efficient legged locomotion and implementation on the MIT Cheetah robot.IEEE/ASME Transaction on Mechatronics, 2015; 20(3): 1117–1129.
7. W. Bosworth, S. Kim, and N. Hogan. The MIT super mini cheetah: A small, low-cost quadrupedal robot for dynamic locomotion. In: 2015 IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR), Indiana, USA, pp. 1–8; 2016.
8. G. Bledt, M. J. Powell, B. Katz, J. Di Carlo, P. M. Wensing, and S. Kim. MIT Cheetah 3: Design and Control of a Robust, Dynamic Quadruped Robot. In: 2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, pp. 2245–2252; 2018.
9. X. Wang, M. Li, W. Guo, P. Wang, and L. Sun. Design and development of a cheetah robot under the neural mechanism controlling the leg's muscles. In: 2012 IEEE/RSJ International Conference on Intelligent Robots and Systems, Algarve, Portugal, pp. 2749–2755; 2012.
10. Z. Xiuli, Z. Haojun, L. Peng, and L. Guangming. Designing a Quadrupedal Robot Mimicking Cat Locomotion. In: 2006 IEEE International Conference on Systems, Man and Cybernetics, Taipei, Taiwan, pp. 4471–4474; 2006.
11. H. Ishihara, and K. Kuroi. A Four-Leg Locomotion Robot for Heavy Load Transportation. In: 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, pp. 5731–5736; 2006.
12. S. Sugiyama, K. Tanaka, N. Numata, Y. Nakano, M. Fujie, K. Kamejima, and H. Maki. Quadrupedal Locomotion Subsystem of Prototype Advanced Robot for Nuclear Power Plant Facilities. In: Fifth International Conference on Advanced Robotics 'Robots in Unstructured Environments, Pisa, Italy, pp. 326–333; 1991.