Cascaded PID Trajectory Tracking Control for Quadruped Robotic Leg

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***Abstract*—This paper presents a cascaded Proportional Integral Derivative (PID) trajectory tracking controller to control the foot's tip of a quadruped robotic leg. The proposed robotic leg is designed and developed using electric Quasi-Direct Drive (QDD) actuators with high efficiency and torque density. Both the forward and inverse kinematics of the robotic leg are introduced to generate the desired path with the associated velocity of the foot's tip. Furthermore, the cascaded PID trajectory tracking controller is developed as a low-level controller to control the position and angular velocity of each leg's joint. Both the numerical simulation and experimental results showed that the proposed controller succeeded in tracking the desired trajectory with high accuracy and robustness of two different types of trajectories.**

***Keywords*— trajectory tracking control, quadruped robots, cascaded PID controller**

I. INTRODUCTION

Quadruped robots have been gaining importance in recent years by enhancing the robot design in terms of actuation technique, sensory system, advanced control algorithms, and design optimization to introduce agile quadrupedal robots such as the Massachusetts Institute of Technology (MIT) Cheetah [1], ANYmal [2], and Mini-HyQ [3]. Recently, legged robots can be used in many applications as it can offer an alternative and excellent solution to the mobility problems. Scientists are inspired by what legged animals can do where it can go almost everywhere and move dynamically with high mobility and agility to overcome challenging obstacles.

Quadruped robots have recently provided great progress in dynamic locomotion capabilities by utilizing different actuation and control approaches. For instance, using hydraulic actuators which can provide high joint forces, was fortunate in some quadruped platforms such as IIT's HyQ [4] and Boston Dynamics' Big Dog [5]. On the other hand, Series Elastic Actuators (SEA) provide higher impact mitigation properties and better force control capacity. SEA is suitable for high speed legged locomotion as demonstrated in ANYmal quadruped robot [2]. Another actuating approach is using a custom-designed proprioceptive actuator to acquire impact mitigation properties and high force control capabilities.

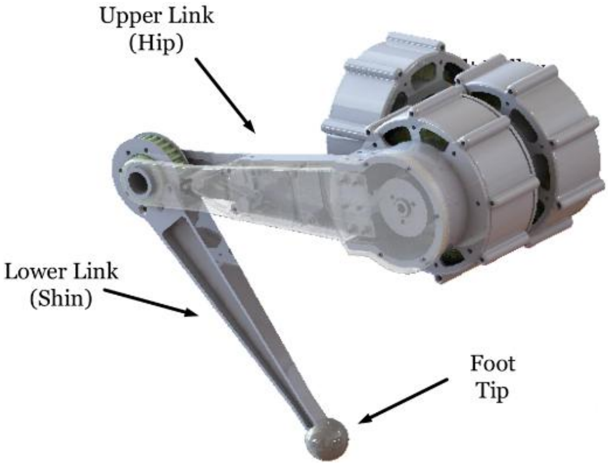

Figure 1. The proposed robotic leg with three Quasi-Direct Drive (QDD) actuators.

This approach was used in developing the MIT Cheetah II [6], in which the robot was able to successfully perform jumping over obstacles and bounding at high speeds of up to 6 m/s [7].

A noticeable limitation in the field of quadruped robot is to implement a robust control algorithm. It is required to support the robot's body weight, control its attitude, place the robot's feet in a certain trajectory and provide locomotion while keeping the robot balanced during the planned trajectory. Position control strategies can be employed through precise kinematic modeling and trajectory tracking. It requires detailed knowledge about the internal states of the robot and the surrounding environment. Position control can be integrated with impedance control during the swing phase to ensure flexible interaction between the leg and the ground to reduce the impact [8].

A different control approach named Model Predictive Control (MPC) is considered as a powerful approach for controlling robotic systems. Therefore, it can be used as motion control for complex nonlinear dynamic systems such as quadruped locomotion [9]. Another approach is Zero Moment Point (ZMP) control is considered as an

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approach to maintaining the balance of a quadruped robot by keeping its Center of Mass (COM) directly above a support region that can be previously determined [10].

While the Proportional Integral Derivative (PID) controllers are also widely used to control machines in various industrial applications. In robotic systems, a typical PID controller independently controls the motion of each joint, whereas model-based controllers are used to improve the performance of the PID controllers as they are based on the system dynamics as feedback.

Various control approaches were used in different quadruped robots. Yasuhiro Fukuoka used a PID controller for the leg's joints to simulate a virtual spring–damper system [11], while the neural model consists of a Central Pattern Generator (CPG) and some reflexes. The CPG receives data from sensors and then modifies the active phase period, the desired angle, and the gains of each joint. While the MIT cheetah quadruped platform has a control approach that uses a gait-pattern generator to calculate each leg's foot trajectory, the desired speed, duration of swing, and stance phases for each leg. The desired leg trajectory serves as an equilibrium point for the leg impedance controller which controls leg's mechanical behavior to mimic it as a spring-damper system positioned between the hip and the foot.

Boston Dynamics' quadruped robot BigDog has a control system that coordinates between the robot's kinematics and ground reaction forces at the feet. For adapting to the terrain changes, it uses sensor information from joints to determine the feet status by calculating the load on each leg [5]. While Victor Barasuol proposed a novel reactive controller framework to cope with terrain irregularities, trajectory tracking problems, and state estimation problems [12]. It uses a module to generate an elliptic feet trajectory and another module for stability control of the whole robot. Barasuol also proposed a CPG-based trajectory generation method for adapting smoothly to terrain irregularities. CPG is becoming a popular model for the locomotion control of quadruped robots [13].

Sangbae Kim presented an implementation of MPC to calculate the ground reaction forces for MIT Cheetah III. The robot was able to perform different gaits including walking, trotting, flying-trotting, bounding, pacing, and galloping with a maximum speed of up to 3 m/s. The controller introduced excellent results because the model was able to capture all the vital details of locomotion, especially the ground reaction forces [14]. Hutter proposed a novel technique for quadruped robot training neural-network policies and terrain-aware locomotion. This technique combines model-based motion planning method and reinforcement learning to estimate the terrain-aware locomotion and improve locomotion accordingly [15].

In this paper, a fully designed and developed QDD actuation approach is used for developing a single quadruped robotic leg with the required control and sensing systems for investigating the robotic leg performance with different trajectories and different loads. Furthermore, a cascaded PID trajectory tracking controller is presented to control the foot's tip of the quadruped robotic leg. First the forward and inverse kinematics models of the robotic leg is introduced for generating the desired foot's tip positions and the associated joints' angles. Then, trajectory tracking control is proposed as a low-level controller to control the position, velocity, and torque for each joint. Finally, experimental results show the effectiveness of the proposed controller framework in tracking the desired path of the foot's tip.

II. Robotic Leg Design

In this section, an overview of the robotic leg system will be introduced, followed by the mechanical and electrical design with the actuation and sensory system.

A. Mechanical Design and Actuation

Selecting a suitable actuation technique is a very challenging process as quadruped locomotion requires a lot of conflicting characteristics such as high force, high speed, and high torque density properties. Direct Drive (DD) actuators have high effective torque with no backlash and high efficiency but at the cost of low torque and high speed properties [16]. Another approach is using SEA which provides precise force control, better impact absorption, and high torque density [17]. SEA have high mechanical complexity, control difficulty and cost. SEA are used in quadruped platforms such as StarlETH [18].

Using proprioceptive QDD robotic actuators with a relatively low reduction ratio gearbox integrated with a Brushless Direct Current (BLDC) motor allows for high efficiency and high torque density actuator [19]. QDD actuators are used without a dedicated force sensor since the torque values of any joint can be measured using motor phase current [20].

Most innovative electric-derived quadruped actuators use custom-designed electric motors and gears, which makes the total cost very high. In this paper, an off-the-shelf electric BLDC motor is used as a base for building an inexpensive QDD actuator which offers features such as impact resistance, high torque density, and robust force control through internal torque control without sensory feedback.

Quadruped legs have great importance in the legged locomotion performance, the most important parameters are having a low mass, low inertia, and maximum range of motion. In this design approach, changing the knee actuator position from its natural place at the knee and moving it up to the hip allows for a low inertia leg. The design approach is based on most of the modern quadrupeds that exist in the robotics field, such as Boston Dynamics Spot [21], Unitree Robotics quadruped robots Laikago [22], vision 60 of Ghost Robotics [23], and the MIT Cheetah III [24].

The leg parts are CNC machined from Aluminum Alloy 7075, which is chosen for its lightweight and high-strength properties. The upper link of the leg consists of two identical parts and the lower link is machined as one piece. The leg's total mass is approximately 1:5 Kg without actuation joints. For transmitting the torque to the knee joint, a system of two pulleys and a high shock absorbing characteristics timing belt is used. The range of motion is ±135° for the Knee Flexion/ Extension (KFE) joint from the fully extended lower part of the leg, the Hip Abduction/Adduction (HAA) joint allows for a motion range of 90°, and the Hip Flexion/Extension (HFE) joint allows for a range up to 345°, these wide ranges provide agility and different motion capabilities for the quadruped robot as shown in Fig. 1.

B. *Electric Design and Sensing*

The main electrical configuration of the robotic leg consists of a PC, a motor controller (ODrive v3.6), two position sensors (AS5047P), a 24-volt power supply, and an emergency switch as shown in Fig. 2. The high-performance motor controller consists of a microcontroller with two voltage and current feedback sensors and two motor drivers. The motor controller can control the two BLDC motors simultaneously and capable of controlling the actuators' position, velocity, and torque. Moreover, the motor controller can read the motors' positions using an external encoder for arbitrarily precise motions and is powered by a 24-volt dedicated power supply. A personal computer is used to communicate with the motor controller through serial communication. The PC is used as a high-level trajectory tracking controller. The position sensor is a magnetic rotary position sensor used for high speed angle measurement. The magnetic position sensor is placed concentrically with a diametric magnet allowing for position tracking.

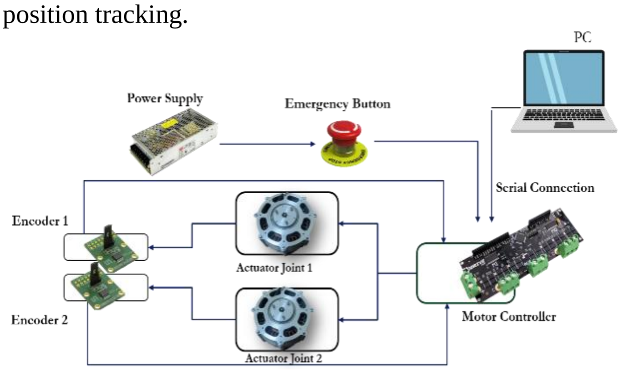


Figure 2. Electric diagram circuit and sensory system.

III. ROBOTIC LEG KINEMATICS

Quadruped's body is mathematically represented as a rigid box where its four robotic legs are mostly symmetrically distributed and structured. The robotic leg consists of rigid links and rotary joints, where the rigid links are connected through the rotary joints. The kinematic modeling and analysis are necessary for modeling and controlling quadruped robots. Where it studies all the possible motions of the robot, regardless of the forces and moments that generate these motions. Kinematics is classified into two types; forward kinematics and inverse kinematics [25]. It is sufficient to study the kinematics of a single robotic leg since the quadruped robot has four similar legs.

A. *Forward Kinematics*

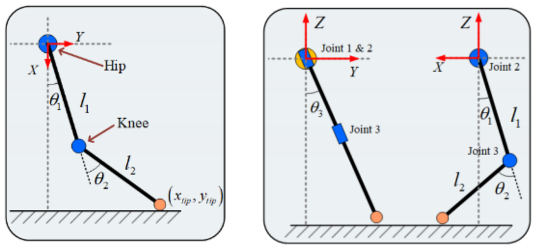
The basic requirement is to find all the possible positions that a quadruped foot can achieve. Forward kinematic analysis is used as a pre-calculation for inverse kinematic analysis. In 3D space with X-Y-Z frame of reference, the HAA joint is perpendicular to the HFE joint, which is connected to the thigh with length (l_1) through the KFE joint. The angle between the thigh and the X-axis is called (θ_1), while the angle between the shin and the thigh extension is called (θ_2). Fig. 3a and Fig. 3b show the forward kinematic model for a 3-Degree of Freedom (DOF) and a 2-DOF robotic Leg respectively. The robotic leg forward kinematics in space can be defined as follows:

$$x_{tip} = l_1 \sin\theta_1 + l_2 \sin(\theta_2 - \theta_1)$$
$$y_{tip} = (l_1 \cos\theta_1 + l_2 \cos(\theta_2 - \theta_1)) \sin\theta_3 \quad (1)$$
$$z_{tip} = (l_1 \cos\theta_1 + l_2 \cos(\theta_2 - \theta_1)) \cos\theta_3$$

While the forward kinematics in 2D plane is written as:

$$x_{tip} = l_1 \cos\theta_1 + l_2 \cos(\theta_1 + \theta_2)$$
$$y_{tip} = l_1 \sin\theta_1 + l_2 \sin(\theta_1 + \theta_2) \quad (2)$$

The analytic algebraic approach is used for solving the forward kinematics using Denavit-Hartenberg (DH) notation for describing the legged robots [26]. The relationship between two coordinate frames has four parameters; two rotations and two displacements respectively. The algebraic solution is obtained by defining these four parameters for each leg. The path that forms the hip joint to the tip was described using the matrix transformations, by multiplying all the transform matrices. The final matrix describes the kinematic model, where (θi) is the joint angle, (αi) is the link twist, (ai) is the link length, and (di) is the link offset. Table I describes the DH Parameters of the proposed robotic leg.



(a) 3D Kinematics. (b) 2D Kinematics.

Figure 3. Free-body diagram of the 3-DOF and 2-DOF legs.

TABLE I. THE FOUR DH PARAMETERS.

	θ_i	α_{i-1}	a_{i-1}	d_i
Link 1	θ_1	0	l_1	0
Link 2	θ_2	0	l_2	0

The 4 DH parameters (θi, αi-1, ai-1, and di) are associated with each link, where θi is rotation about the z-axis, or called the joint angle and it equals zero if the joint (i) is a prism. While (di) is the distance on the Z-axis or

called the joint offset which equals zero, and it can be a variable if the joint (i) is prismatic. The parameter (ai-1) is the length of each link, and (αi-1) is the angle between two successive Z-axes or called the twist angle which equals zero. The homogeneous transformation A represents the pose of the foot tip of the robotic leg, and by using the DH parameters, the foot pose can be written as a sequence of elementary homogeneous transformations as in (3).

By expanding and multiplying all the transformations, the 3×3 homogeneous transformation matrix is representing the pose of the leg's foot tip as follows:

$$A = R(\theta_1)\, T_x(L_1)\, R(\theta_2)\, T_x(L_2) \tag{3}$$

$$\begin{bmatrix} c(\theta_1+\theta_2) & -s(\theta_1+\theta_2) & l_2 c(\theta_1+\theta_2)+l_1 c\theta_1 \\ [s(\theta_1+\theta_2) & c(\theta_1+\theta_2) & l_2 s(\theta_1+\theta_2)+l_1 s\theta_1] \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Where *c* (.) and *s* (.) denote *cos* (.) and *sin* (.) respectively. Solving for the developed 2DOF quadruped robotic leg in (X-Y) coordinates results in the same solution from the geometric approach as derived in (2).

B. Inverse Kinematic

The inverse kinematics approach is to find the angles of the robotic leg's joints that map the desired position of the foot's tip. By using the geometric inverse kinematic approach in the following equations with simplifying them using trigonometric, we can get the values of the required joint angles for a 3-DOF robotic leg. These angles are the HAA angle, HFE angle, and KFE which are denoted as θ_1, θ_2 and θ_3 respectively as follows:

$$\theta_1 = D + E \tag{5}$$

$$\theta_2 = \arccos\left[\frac{C^2 + L_1^2 - L_2^2}{2L_1L_2}\right] - \pi \tag{6}$$

$$\theta_3 = -atan2(Y,Z) + \pi \tag{7}$$

Where:

$$\begin{aligned} B &= -\sqrt{z_{tip}^2 + y_{tip}^2} \\ C &= \sqrt{x_{tip}^2 + B^2} \\ D &= atan2\left(x_{tip},B\right) \\ &\arccos\left(\frac{C^2 + l_1^2 - l_2^2}{2Cl_1}\right) \end{aligned} \tag{8}$$

For a 2-DOF robotic leg, using (2), the solution of inverse kinematics can be computed geometrically as follows, then the angles of joints can be calculated as follows:

$$\begin{aligned} \theta_2 &= \pm cos^{-1}\left(\frac{x_{tip}^2 + y_{tip}^2 - l_1^2 - l_2^2}{2l_1l_2}\right) \\ \theta_1 &= \tan^{-1}\left(\frac{y_{tip}}{x_{tip}}\right) \mp \tan^{-1}\left(\frac{l_2\sin\theta_2}{l_1 + l_2\cos\theta_2}\right) \end{aligned} \tag{9}$$

By using (2) which represents the foot pose in 2D, and considering the angles of joints are function of time as follows:

$$\begin{aligned} \theta_1 &= \theta_1(t) \\ \theta_2 &= \theta_2(t) \end{aligned} \tag{10}$$

The linear relationship between the quadruped leg foot velocity (v) or the spatial velocity, and the joint angles rate of change ($\dot{\theta}$) can be calculated as follow:

$$\begin{aligned} v &= J(\theta)\dot{\theta} \\ \begin{bmatrix} \dot{x}_{tip} \\ \dot{y}_{tip} \end{bmatrix} &= J(\theta)\begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \end{bmatrix} \end{aligned} \tag{11}$$

Where (*J*) is the Jacobian matrix which can be calculated as follows:

$$J(\theta) = \begin{bmatrix} -l_1 s\theta_1 - l_2 s(\theta_1+\theta_2) & -l_2 s(\theta_1+\theta_2) \\ l_1 c\theta_1 + l_2 c(\theta_1+\theta_2) & l_2 c(\theta_1+\theta_2) \end{bmatrix} \tag{12}$$

From (11) and (12), the foot tip spatial velocity can be estimated as:

$$\begin{aligned} \dot{x}_{tip} &= -l_1\dot{\theta}_1\sin\theta_1 - l_2\left(\dot{\theta}_1+\dot{\theta}_2\right)\sin(\theta_1+\theta_2) \\ \dot{y}_{tip} &= l_1\dot{\theta}_1\cos\theta_1 + l_2\left(\dot{\theta}_1+\dot{\theta}_2\right)\cos(\theta_1+\theta_2) \end{aligned} \tag{13}$$

Therefore, the angular velocity of the joints $\theta^{\cdot}$ can be calculated as follows:

$$\dot{\theta} = J(\theta)^{-1}v \tag{14}$$

IV. Trajectory Tracking Control

Proper foot trajectory tracking is a vital aspect to have efficient locomotion of the quadruped robot. First, the desired trajectory has to be sampled with multiple points, and the foot's tip should follow the desired points' path with a specific velocity. The trajectory might be a smooth polynomial interpolation of these points, some examples of these paths are cubic and Bernstein polynomials trajectories [27]. Multiple foot trajectories are studied along with their description equations, and distinct characteristics, some examples of these trajectories are cycloidal, Fourier-Series trajectory, elliptical, and a combination between cubic polynomial and straight line.

The trajectory tracking control consists of two levels; the high-level controller, and the low-level controller.

- In the high-level controller, inverse kinematics is used to generate the desired angles for each joint with the associated velocity and torque. Then, the desired joints' angles are sent to the low-level controller to control the position, velocity, and torque for each joint.
- The low-level controller is a cascaded PID controller as shown in Fig. 4 where the desired joints' angles are sent directly into the position PID controller. Then, the output is the velocity command associated with the desired joints' angular velocities as a feed-forward to the velocity PID controller.

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Finally, the output from the velocity PID controller is the torque command associated with the desired torque as a feed-forward to the torque PID controller. As a result, the appropriate position, velocity, and torque will be achieved by the driver of the motor.

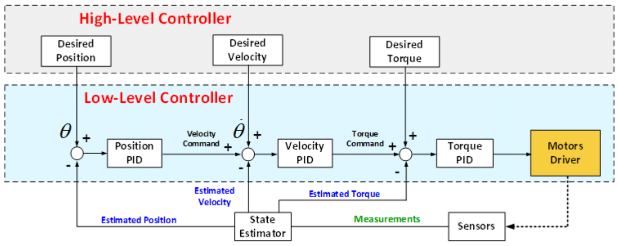


Figure 4. The PID control diagram for robotic leg trajectory tracking.

V. Numerical and Experimental Results

This section demonstrates the performance of the cascaded PID controller as described in section IV using numerical simulations and experiments. Where, two different trajectories are considered to assess the robotic leg performance: the full circle and a combination between cubic polynomial (swing phase) and straight line (stance phase). The proposed trajectories are verified in both simulation and experiments. The results are compared with the reference trajectories.

A. Simulation Results

For the quadruped robot to perform a certain task such as different gaits of locomotion, the task is transformed into a path planning problem aiming to generate a set of points from the start to the goal. From that path the trajectories can be generated to schedule or follow the desired reference path including information about the pose, the speed, and the acceleration. Then, the low level control capabilities are used to perform the trajectory tracking. Numerical simulation is performed using MATLAB to generate and execute the required motion trajectories. The robotic leg model is represented in 2D as two links which are connected together by joints allowing rotational motion. The two links are considered as a kinematic chain with the foot tip as an end-effector. After assigning the robotic leg variables such as the links' angles, the desired trajectories are provided along with boundary conditions, trajectory Cartesian points, and sampling rate. MATLAB software is also used to guarantee that these trajectories are within the allowable workspace of the leg's foot as shown in Fig. 5.

The first trajectory represents a full circle with a diameter of 200 mm. The second trajectory consists of an energy efficient combination of two phases, a cubic polynomial for the swing phase and a straight line for the stance phase. The step length is 400 mm, and the step height is 100 mm. The results demonstrate the simulation of different trajectories tracking.

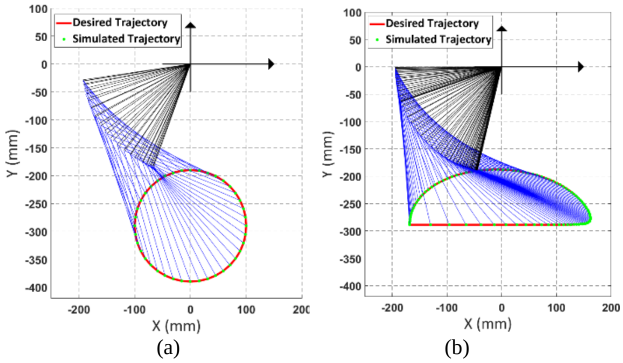
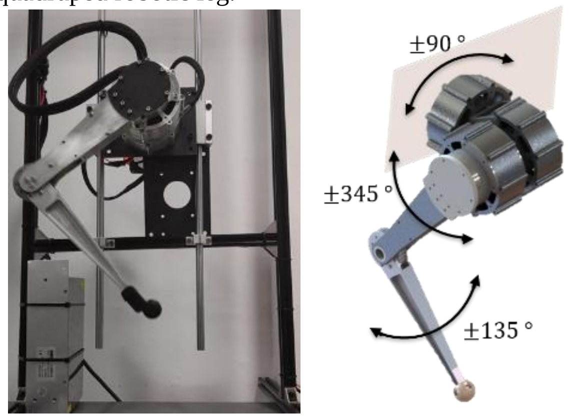


Figure 5. The simulation results of tracking: (a) Full circle trajectory (b) A combination between cubic polynomial and straight-line trajectory

Fig. 5a shows the full circle trajectory, where the proposed cascaded PID controller succeeded to track the desired circular trajectory. Also, Fig. 5b shows that the controller is able to track the combination trajectory between cubic polynomial and a straight line which confirm the robustness of the proposed controller to track different trajectories.

B. Experimental Results

To evaluate the performance of the proposed robotic leg and the controller framework, a 2-DOF robotic leg prototype is developed, and attached to a stand with vertical linear sliding as shown in Fig. 6a. The ranges of the robotic leg joints are demonstrated in Fig. 6b, where the KFE has a ±135 °range of motion from fully extended, and the HAA joint allows for a ±90 ° from the initial position, and the HFE joint can provide up to ±345 °. Table II shows the characteristics of the developed 2-DOF quadruped robotic leg.



(a) The developed test rig (b) The robotic leg joints' ranges

Figure 6. The robotic leg test rig and the ranges of the joints

The test rig is used for performing various trajectories tracking experiments. For the full circle trajectory, the desired circle's diameter used in this experiment is 200 mm, which is used as an input for the high-level controller.

Fig. 7 shows the experimental results, where Fig. 7a shows the desired and actual angles of the HFE and KFE joints, Fig. 7b shows the desired and actual trajectory of the foot's tip, Fig. 7c shows the torque of each joint, and Fig. 7d shows the angular velocity of HFE and KFE joints.

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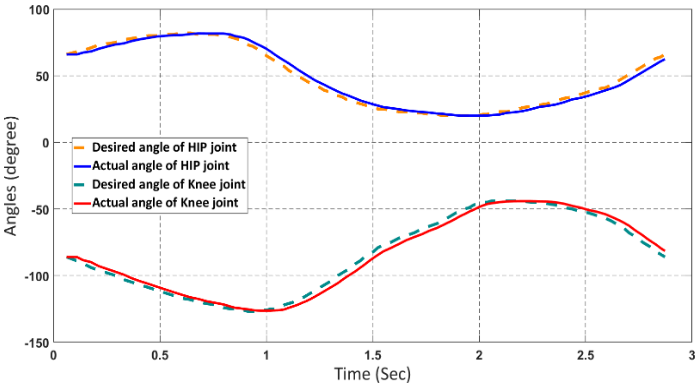
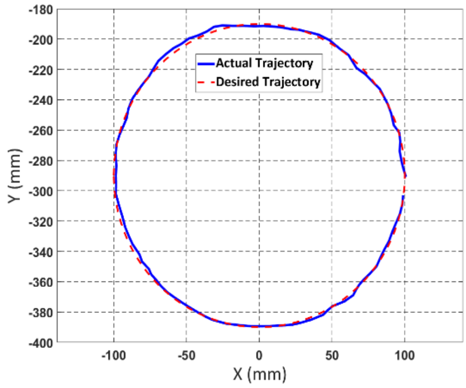
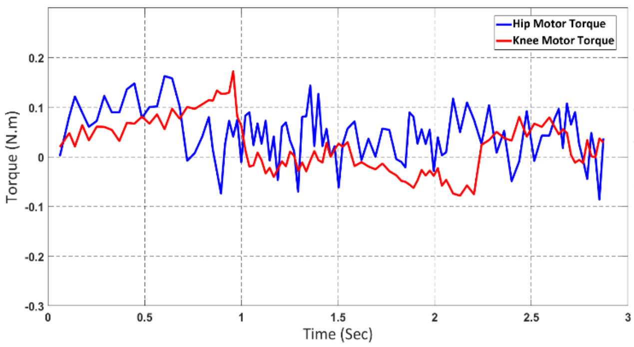
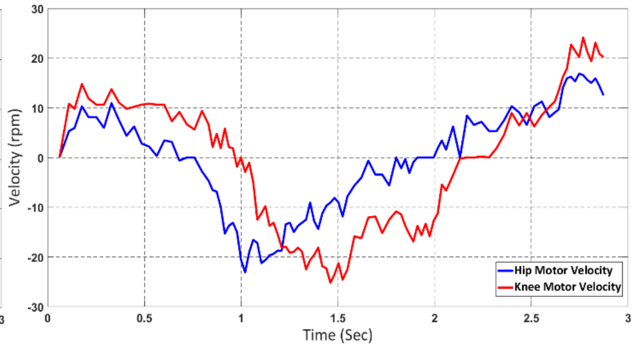




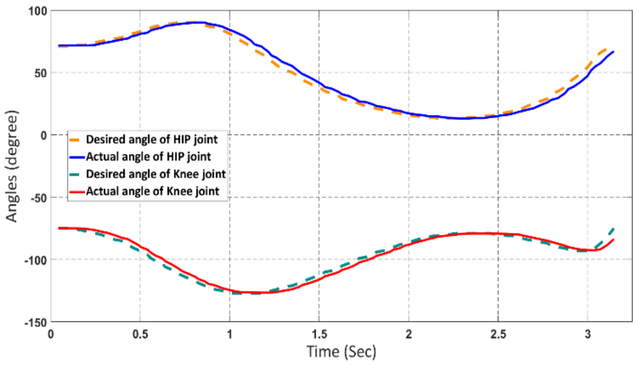
(a) The desired and actual angle of each joint (b) The desired and actual foot trajectory

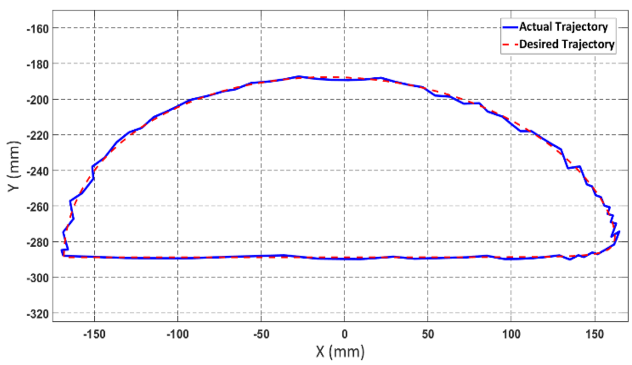




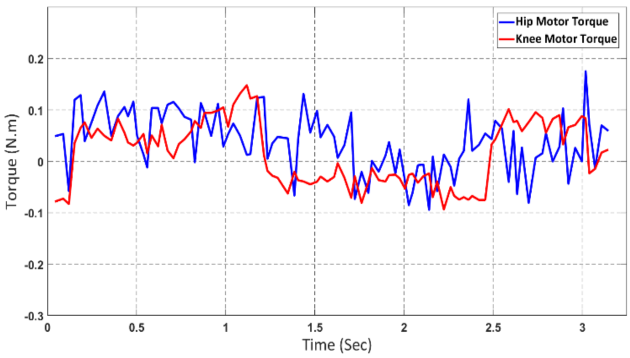
(c) The torque of each joint (d) The angular velocity of each joint

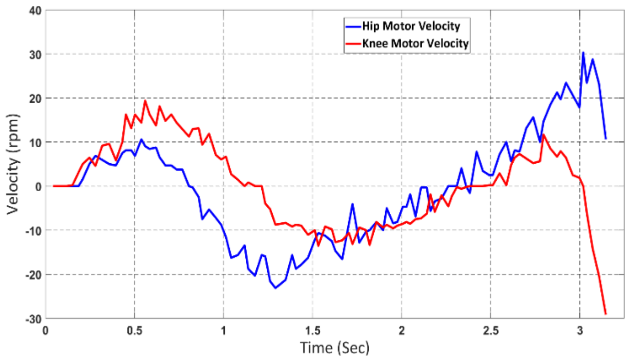
Figure 7. Full circle trajectory results





(a) The desired and actual angle of each joint (b) The desired and actual foot trajectory





(c) The torque of each joint (d) The angular velocity of each joint

Figure 8. A combination between cubic polynomial and straight-line trajectory results

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From these results, it can be seen that the proposed cascaded PID trajectory tracking controller succeeded to track the desired circular trajectory with high accuracy.

TABLE II. THE ROBOTIC LEG CHARACTERISTICS.

Parameter	Value
Actuator Mass	550 g
Actuator Outer Diameter	94 mm
Actuator Axial length	42 mm
Actuator Maximum Torque	17 Nm
2-DOF Leg Total Mass	1.6 Kg
Upper Link (Hip) Length	200 mm
Lower Link (Shin) Length	200 mm

Similarly, the experiment results of the generated trajectory from the combination between a cubic polynomial for the swing phase and a straight line for the stance phase can be demonstrated in Fig. 8. It can be seen that the cascaded PID trajectory tracking controller succeeded to track the desired combined trajectory with high accuracy. Based on these experimental results, we can conclude that the proposed trajectory tracking controller has high accuracy and is robust to perform different trajectories tracking.

VI. CONCLUSIONS

In this paper, a quadruped robotic leg is introduced with its mechanical and electric design. The robotic leg kinematics is presented with its two types; forward and inverse kinematics. A cascaded PID trajectory tracking controller is developed to control the position, velocity, and torque of each robotic leg joint to perform tracking of the desired trajectory. The developed quadruped robotic leg is used for implying trajectory tracking framework via numerical simulation and experimental tests using the proposed controller framework, which succeeded in tracking different desired trajectories with high accuracy such as full circle trajectory and a combination between cubic polynomial and straight line trajectory.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

El-Dalatony conducted the research and wrote the original draft, Dr. Attia proposed the project idea and analyzed the results, Prof. Ragheb revised the results and the final draft, Prof. Sharaf revised the manuscript and approved the final version

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