Design of biped robot inspired by cats for fast running

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A novel design of a biped robot inspired by domestic cats for fast running is introduced. The skeletomuscular system of a cat is analysed and applied to determine the link parameters and the linkage structure of the proposed mechanism. The linkage design of the leg mechanism is explained and a kinematic analysis based on vector loop equations is performed. The effectiveness of the proposed mechanism is verified experimentally. The biped robot runs at an average speed of 2 m/s at a step frequency of 4 Hz. This leg mechanism can facilitate the development of fast running robot systems.

Introduction: For the past several decades, various types of legged robots have been developed. The planar biped has two telescoping legs that are driven by hydraulic actuators and use pneumatic springs to absorb ground reaction forces. Each leg has two degrees of freedom (DOF) and is driven by a leg actuator (which varies leg angles with respect to the body) [1]. The Tekken II is a small quadruped robot that was inspired by biological systems. The leg mechanism of the Tekken II has three motor-driven joints (i.e. a hip pitch joint, a knee pitch joint and a hip yaw joint) and a passive ankle joint. The ankle joint has a spring-disk mechanism that adds compliance to the leg [2]. The MIT Cheetah has four limbs that were inspired by biological systems. The forelegs are powered by doubly concentric actuators at the shoulder that reduce its moment of inertia, and the elbow joints are actuated by a four-bar linkage. A Kevlar tendon is used to provide compliance and reduce bone stresses [3]. In view of its design simplicity and efficiency, the Scout II is a representative example. Each leg of the Scout II has only one motor that is located at the hip. The leg of the robot consists of upper and lower parts that are connected by a spring as a compliant linear sliding joint [4]. Although legged locomotion has been studied and developed by many researchers, achieving high-speed movement is known to be still a difficult problem. To achieve fast legged locomotion, the mechanical system of the leg structure must be designed to take advantage of dynamic properties (i.e. light weight, a small moment of inertia etc.). The design concept of this Letter relies on the under-actuated linkage system to achieve light weight, a small moment of inertia and a cat-inspired leg structure. Note that a domestic cat is the fastest feline considering the leg length of its body; thus, the biological characteristics of the domestic cat are worth adopting in a robotic leg design to achieve fast locomotion. Starting from the biological observation of a cat, a leg mechanism using a single actuator is newly proposed. The effectiveness of the proposed leg is verified by kinematic analysis and experiments.

Leg modelling: Cats are fast ground runners. Considering the hip height of a domestic cat at the mid-stance is 25.4 cm, the cat has a normalised ground clearance varies from 41 to 47% of the leg length. The results of a step frequency of 4 Hz. This leg mechanism can facilitate the development of fast running robot systems.

Kinematics: In this Section, analytical solutions are presented for the position of the robotic leg using the vector loop equations. Position vectors are denoted on the robotic leg as shown in Fig. 2a. An analysis of the overall system can be divided into three parts as denoted by: the first (blue), second (red) and third (green) vector loops. The first vector loop forms a four-bar linkage. This vector loop includes the crank, the base, the femur and the coupler links. \( R_1 \) is attached to the body of the robot, whereas \( R_5 \) and \( R_6 \) are on the femur, the coupler and the crank links, respectively. The lengths of the vectors are denoted by \( a, b, c \) and \( d \). The angles of the links with respect to the \( x \)-axis are denoted by \( \theta \). The vector loop equation is as follows:

\[
R_1 + R_2 + R_3 + R_4 = 0
\]

Using Euler's formula, (1) can be rewritten in complex domain, as

\[
ac \text{e}^{j \theta_1} + bc \text{e}^{j \theta_2} + cc \text{e}^{j \theta_3} + dc \text{e}^{j \theta_4} = 0
\]

Thus, it is straightforward to show that

\[
\theta_{1,2} = 2 \tan^{-1}\left(-\frac{2C \pm \sqrt{4C^2 - 4(A + B)(A - B)}}{2(A - B)}\right)
\]

where

\[
A = -b^2 + a^2 + c^2 + d^2 + 2ad \cos \theta_1 \cos \theta_2 + 2ad \sin \theta_1 \sin \theta_2
\]

\[
B = 2ac \cos \theta_1 + 2cd \cos \theta_4
\]

\[
C = 2ac \sin \theta_1 + 2cd \sin \theta_4
\]

Link positions of the first loop can be fully solved based on the solution of \( \theta_1 \). In a similar manner, the other angles such as \( \theta_1-\theta_2 \) can be solved. Position analysis lets us determine the leg configuration during the step cycle as the crank rotates. Fig. 2b shows the discrete trajectory of leg movement during a step cycle. The blue dots represent the ankle trajectory, and the red dots represent the distal part of the metatarsal. The maximum hip height at mid-stance is 194 mm with rest length of the Achilles spring and 155 mm with the fully stretched spring. The minimum height is 102.6 mm at the swing phase. Therefore, its
show that the leg configuration and ground clearance of the proposed leg is similar to the behaviour of feline animals [6].

Running experiment: We developed a biped robot using the leg mechanism. The frame of the robot is made of aluminium alloy to hold the mechanical components. Since legs experience large impact from the ground repeatedly and need to be light for reducing the moment of inertia, an acrylonitrile butadiene styrene plastic was chosen for the leg material. To dissipate impact from the ground during the stance phase, two layers of damping material are attached, which form a toe under the metatarsal link. Beneath the toe, a high friction polymer is attached to generate traction force in the travelling direction. The biped robot is attached to the tether boom as shown in Fig. 3. The tether boom consists of the base, link 1, link 2 and link 3. Link 1 rotates against the base and makes a circular motion in the x-direction. Link 2 generates up and down motion in the y-direction. The experimental set realises two DOF quasi-planar motions of the robot. The total mass of the biped robot is 0.465 kg and its hip height is 200 mm. 

Control inputs for driving both the cranks have the phase difference (A–D), the robot keeps moving forwards. Fig. 5 shows the rotational speed of both the cranks, the speed of the mass centre and the hip height. The average speed was 2 m/s, which equals to 10 leg-lengths/s. The biped robot shows relatively faster motion due to the under-actuated and cat-inspired leg structure compared with the other legged robots.

Conclusion: In this Letter, a novel robotic leg design inspired by cats is developed for fast running. The structure and link parameters of the robotic leg were designed using an analysis of the skeletal and muscular systems of a cat. An analysis of the proposed mechanism was conducted through the vector loop equations. We have demonstrated that the leg configuration and the ground clearance of the proposed leg are similar to the behaviour of feline animals. We conducted a running test for a biped robot to evaluate its running performance. The biped robot achieved an average speed of 2 m/s at a step frequency of 4 Hz. We plan to optimise the leg structure in terms of the length of the links. Along with that, a control architecture will also be developed to stabilise the biped robot.

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One or more of the Figures in this Letter are available in colour online.

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References

Fig. 3 Experimental setup of biped robot attached to boom

Fig. 4 Sequence of running biped robot on flat ground with step frequency of 4 Hz

Fig. 5 Control inputs of cranks, speed of centre of gravity in x-direction and hip height