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Biomimetic Design and Optimal Swing of a Hexapod Robot Leg

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Abstract

Biological inspiration has spawned a wealth of solutions to both mechanical design and control schemes in the efforts to develop agile legged machines. This paper presents a compliant leg mechanism for a small six-legged robot, HITCR-II, based on abstracted anatomy from insect legs. Kinematic structure, relative proportion of leg segment lengths and actuation system were analyzed in consideration of anatomical structure as well as muscle system of insect legs and desired mobility. A spring based passive compliance mechanism inspired by musculoskeletal structures of biological systems was integrated into distal segment of the leg to soften foot impact on touchdown. In addition, an efficient locomotion planner capable of generating natural movements for the legs during swing phase was proposed. The problem of leg swing was formulated as an optimal control procedure that satisfies a series of locomotion task terms while minimizing a biologically-based objective function, which was solved by a Gauss Pseudospectral Method (GPM) based numerical technique. We applied this swing generation algorithm to both a simulation platform and a robot prototype. Results show that the proposed leg structure and swing planner are able to successfully perform effective swing movements on rugged terrains.

Keywords: biomimetic design, legged robot, optimal control, biological movement principle, Gauss pseudospectral method

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1 Introduction

Animals' ability to readily adapt to changing natural environment has attracted the attentions of engineers and roboticists in their quest to build functional mobile machines[1–7]. One of the fascinating subjects is the field of legged robots inspired by humans, mammals, insects and other arthropods. Indeed, legged systems theoretically offer the potential to better traverse rough terrains than traditional wheeled and tracked designs due to no need for paths of continuous contact with the ground, and also their bionic prototypes do reveal surprising ability in nature. Generally speaking, robots with more legs mean higher adaptability to irregular terrains, but inevitably lead to a more complicated control system. Of all the legged systems, six-legged robots seem to be a logical trade-off between adequate adaptability and control complexity, and therefore have been given great concern[8–10].

A powerful six-legged robot system strongly depends on both sophisticated mechanical structure and efficient motion planning algorithm, and as a result, various studies related to structures and movements of legs have been reported in the literature. In these designs, the legs mainly differ in number and form of Degrees of Freedom (DoF), drive and transmission systems, and sensors to be integrated. The overall trend has been toward higher power-to-weight ratio and stronger perception abilities[9–11].

Motion planning for an autonomous six-legged robot system has proven to be an intractable task. The robot has to sense its internal states as well as external environment continuously and generate feasible leg motions rapidly according to the sensory information. In our opinion, a layered control architecture consisting of a binocular stereo vision based navigation layer, a motion planning layer and a walking layer seems to be a promising strategy. The navigation layer allows the robot to recognize visual scenarios and plan proactively an approximately optimal path from the start to the goal; the motion planning layer is responsible for calculating sequences of footsteps and body posture, accounting for the influence of terrain shape; the task of the walking layer is to produce basic movements (swing and support) for

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each leg according to the footsteps from upper planning layer and external environment from sensory readings. Support movement of a leg involves motions of the robot body and must be in coordination with other supporting legs. Whereas leg swing is comparatively free and needs to be planned deliberately to enhance obstacle avoidance ability of the robot and smoothen the actuator torques. Some researchers utilize fixed curves or composite curves such as polynomials[9] and sinusoids[11] to predefine the leg swing trajectories. While this is conceptually straightforward and computationally efficient, there is a disadvantage that could lead to a waste of energy in level ground or a collision in rugged terrains. Erden optimized the leg protraction to minimize the integral of torque squares which is used as an index of energy consumption[12]. By introducing a modified version of gradient descent, many unfeasible and inefficient local optima are jumped over to some extent. However, this approach might suffer from a drawback of long duration, which is seriously terrible in the situation where rapid responses are required. In addition, this work ignores the complexity of terrains surrounding the robot, limiting the mobility and usable range of operation. Lewinger and Quinn proposed a neurobiologically-based method to produce stepping actions for a multi-jointed robot leg[10]. The basic movements of each joint were generated by one neural oscillator network located at the corresponding joint and coordinated by sensory feedback such as joints angles and leg load.

Despite considerable efforts in swing movements of a walking robot leg, these works are either using a onefold engineering approach or partially imitating animals' nerve-muscle control mechanism. In this study, we focus on an alternate method, which combines both engineering solution and reasonably achievable principles distilled from biology, to plan swing movements for a small six-legged robot leg over extreme terrains. First, biomimetic design of the leg mechanism is proposed. The design inspiration is taken from the musculoskeletal structure of insect legs with necessary approximations and extensions. As with swing movements, we formulate the problem as an optimization procedure that minimizes a biologically-inspired objective function under the premise that the robot has obtained surrounding terrain models and accurate localization. Finally, we demonstrate the swing generation algorithm on both a simulation platform and a robot prototype.

2 Biomimetic design of the walking robot leg

2.1 Biological inspiration from hexapods

Insects are considered as ideal models on which to base robot designs owing to their spectacular locomotivity and agility. This pronounced trait relies to a relatively large extent on their sophisticated musculoskeletal system in legs. Typically, each insect leg is made up of five basic segments connected by joints and these are, from proximal to distal: coxa, trochanter, femur, tibia, and tarsus, as depicted in Fig. 1. Among them, trochanter is a small part of femur connecting to coxa, and tarsus is used for helping hold onto walking surfaces[13]. Motions of each segment are imparted through contracting and relaxing muscles, which involve complex biomechanics, neural control and muscle characteristics. It seems impractical to directly copy the anatomical arrangement of insect legs due to the complexity of biological system itself and technical limitation in materials, actuators, sensors and processor. To this end, the key elements that are contributed to the desired agility on insects must be identified and implemented using available and mature technology. According to the results of biological studies[14,15], four key elements for the artificial legs are listed, taking accounting of the technical availability. They are, 1) kinematic structure; 2) effective leg length; 3) actuation system; 4) compliance characteristics.

2.2 Biomimetic design of the robot leg

2.2.1 Kinematic structure

Simply copying the 5-DoFs anatomical arrangement of insect legs may increase the cost of both mechanisms and control. From the perspective of mechanism theory, 3-DoFs have been proven the minimum number for a leg of walking robots capable of omnidirectional walk[11]. As an eventual compromise, trochanter and tarsus are neglected due to their functions and small size, and the robot leg with three segments,

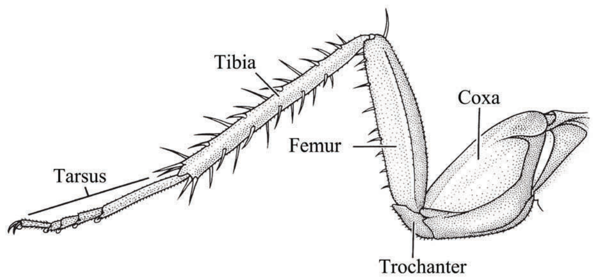

Fig. 1 Anatomical structure of a typical insect leg[13].