Maneuvering and Stabilization of Reduced Complexity Legged Robots Using Bioinspired Robotic Tails

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I. Introduction

Legged robots have made significant progress in recent decades and are actively deployed in hazardous environments due to their excellent traversability on unstructured terrains. A well-known example is the 2015 DARPA Robotics Challenge where legged robots were required to use tools used by humans and respond quickly to disasters scenarios. However, the results showed that most of the robots that participated exhibited poor performance in terms of balance and had difficulty achieving fast and dynamic locomotion. Looking to nature, animals frequently utilize tails to work alongside or in place of their legs to maneuver, stabilize, and/or propel. For instance, cheetahs are observed to use their tail to maneuver during hunting, monkeys use their tail to balance their motion on branches, and kangaroos are found to use tails to propel and power their locomotion. Therefore, if ground contact cannot be guaranteed (for example, in an unstructured environment with uncertain ground support), the legs' ability to stabilize and maneuver is severely hampered. Integrating a robotic tail on legged robots would provide a means of influencing the robot dynamics independently of the legs' ground contact. As a result, the tail could carry the burden of stabilization and maneuvering, leaving the legs primarily responsible for propulsion. Following this idea, a new quadruped locomotion paradigm might be feasible such that the leg complexity (i.e., in terms of number of DOF) could be reduced on the account of incorporating an articulated multi-link bioinspired robotic tail mechanism on-board.

A. Problem Statement

Although single-link tails [1-3] are proved to be dynamically efficient for maneuvering mobile platforms, animal-like multi-link tails show more dexterous mobility and generate more inertial loading, thus are thought to be more suitable for accomplishing the maneuvering and stabilization tasks. Therefore, the objective of this research is to investigate and implement the dynamic functionalities of articulated multi-link robotic tail structures on legged robots so that the resulting tailed legged robots can achieve animal-like agile maneuvering and stabilization behaviors.

B. Social Benefits and Scientific Impacts

With the concrete understanding of the functionalities of multi-link robotic tail structures, bioinspired robotic tails could be used to enhance the dynamic performance of legged robots, which will eventually benefit the successful use of legged robots in humanitarian, or disaster relief operations. In addition, the scientific community can benefit from this research too, with the introduction of novel bioinspired multi-link robotic tails and the new tailed legged robot paradigm.

II. Methodology

The complete understanding and successful implementation of robotic tails on legged robots require theoretical investigations to obtain the mathematical insights of the system and empirical investigations to validate the proposed theories.

A. Theoretical Research

Theoretical research of tailed legged robots mainly includes dynamic modeling and control. A high fidelity unified dynamic model incorporating both the legged robot subsystem and the tail subsystem is necessary to understand the tail dynamic effects on mobile platforms and feedback controllers may be designed to achieve the maneuvering and stabilization tasks. The controller further includes an outer loop controller to generate robot trajectories or virtual constraints based on tasks (maneuvering or stabilization), and an inner loop controller to track the generated trajectories or virtual constraints.

B. Empirical Research

Empirical research of tailed legged robots includes developing the robotic tail and legged robot subsystems, and the subsequent integration of the two subsystems. Specific design requirements (for instance, mass distribution between the tail subsystem and the legged robot subsystem) should be taken into consideration in order to maximize the performance of the tail subsystem. Before the full implementation of the tailed legged robot, hardware-in-the-loop (HIL) techniques may be used to evaluate the tail performances on simulated legged robots. The empirical research also includes field tests of the proposed controllers.

III. Preliminary Results

Following the proposed research methodology, important progress has been made and the preliminary results are summarized in Fig. 1.

A. Robotic Tails Development

Two different robotic tail design paradigms are proposed and implemented. The first paradigm is a biomimetic design, which mimics the universal joint structure and the compliant-to-obstacle feature of animal tails. The universal spatial robotic tail (USRT) [5] and the RML Tail [6] belong to this category since they are both driven by cables and equipped with elastic components. The only difference is that the RML Tail requires fewer actuators than the USRT due to the

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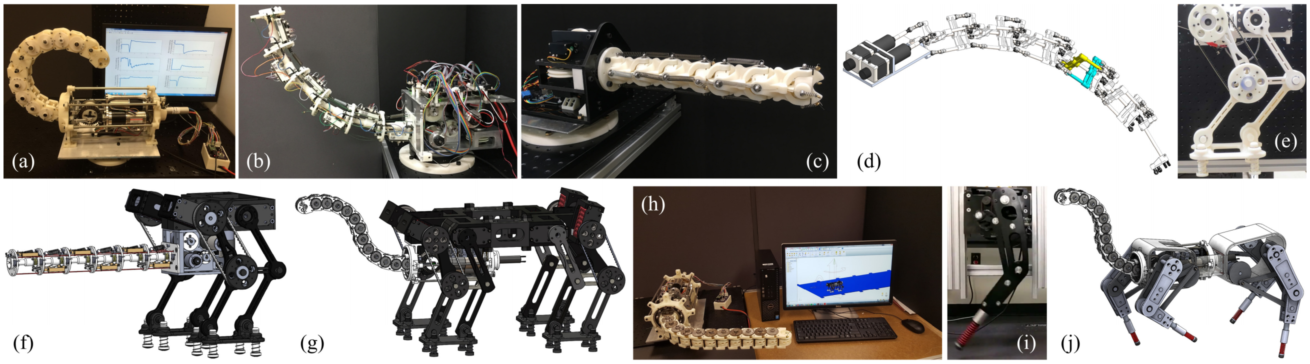

Figure 1. Existing and proposed multi-link robotic tails and tailed legged robots: (a) roll-revolute-revolute robotic tail (R3RT) prototype [4], (b) universal spatial robotic tail (USRT) prototype [5], (c) RML Tail prototype [6], (d) Rigitail design [7], (e) robotic modular leg (RMLeg) prototype [8], (f) hardware-in-the-loop (HIL) model of a tailed biped consisting of two RMLegs and the USRT [9], (g) HIL model of a tailed quadruped consisting of four RMLegs and the R3RT [10], (h) HIL experiment set up of the tailed quadruped in (g), (i) bioinspired one-degree-of-freedom leg for trotting (BOLT) prototype [11], and (j) proposed tailed quadruped consisting four BOLT legs and the R3RT.

specifically designed cable routing. The second paradigm is a bioinspired design, which was conceptualized based on engineering considerations rather than biomimetic considerations. The roll-revolute-revolute robotic tail (R3RT) [4] and the Rigitail [7] belong to this category since they both utilize rigid transmission to increase the system's stiffness (thus improve the system frequency response characteristics). The only differences are that the R3RT uses cable-driven mechanism while the Rigitail uses link-driven mechanism, and the R3RT has a separate roll degree of freedom (DOF) while the Rigitail does not.

B. *Reduced Complexity Robotic Leg Development*

Since the burden of maneuvering and stabilization may be performed by robotic tails, the leg mechanism complexity could be reduced such that it may be primarily responsible for locomotion/propulsion. This idea leads to two reduced complexity leg designs: a two-DOF robotic modular leg (RMLeg) [8] and a bioinspired one-DOF leg for trotting (BOLT) [11]. The RMLeg abandons the abduction mobility while the BOLT is further simplified by mechanically coupling the hip and knee motions.

C. *Hardware-in-the-loop Experiments*

To test the tail performance without building the actual legged robots, HIL techniques have been implemented. Two different tailed legged robot models were tested: a biped with the USRT [9] and a quadruped with the R3RT [10]. Both legged robots consist of the RMLeg and both models utilize decoupled control. The maneuvering and stabilization tasks are studied when the robots are airborne and a model-based feedback linearization control is used as the inner loop controller. The results show the effectiveness of the feedback controllers and validate the dynamic functionalities of the tail subsystem. However, limited by the HIL environment and the lack of unified dynamics, the experiments reveal significant deficiencies in terms of modeling, controller design, and experimental implementations.

D. *Unified Dynamics Modeling*

To address the deficiencies encountered in the HIL experiments, one of the most recent theoretical developments for multi-link robotic tail research is the unified dynamic model which incorporates both the tail subsystem and a general 6-DOF quadruped. This newly developed high fidelity model enables performance evaluation of different tail structures and thus could serve as a design tool for robotic tail research. With the establishment of the unified dynamics, the design of a unified controller, that treats the tail subsystem and the legged robot as one system, becomes feasible too.

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