Modelling and Parameter Identification of the Leg of an Ultralight Robotic System

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The authors have developed a novel legged robot system called the Multilegged Autonomous eXplorer (MAX) [1]. MAX is an ultralight, six-legged robot for exploration and traversal of difficult terrain. The system is 2.25m tall at full height and weighs 59.8kg, making it 5 to 20 times lighter than robots of comparable size. The robot has been designed to have low mass/size ratio, high locomotion efficiency and high payload capability relative to the total mass of the system. MAX is a research vehicle to explore modelling and control of Ultralight Legged Robots subject to flexing, oscillations and swaying; algorithms for gait and motion planning under uncertainty; and navigation planning for traversal of complex 3D terrains.

This paper is concerned with modelling and parameter identification of the ultralight robotic leg system designed for MAX. When moving, the robot undergoes rotations and displacements that lead to high inertial moments and forces acting on the components of the robot. These moments and forces result in dynamic bending and torsional deflections in the legs and the body frame of MAX. To model the system dynamics, we propose a lumped-parameter model [2] for the leg. We formulate kinematic and dynamic equations of motion of the system. By taking into account physical consistency constraints (see for example [3] and references therein), parameters of the model are computed and the identification results are evaluated in the working conditions of the robot.

MAX has a nonrigid cuboid body attached to six identical legs. The body houses the on-board avionics, batteries and power distribution system, and the communications and safety systems. Each of the legs of the robot has three actuated joints (in a pan-tilt-tilt configuration) and two flexible links; see [1] for more details. Figure 1 depicts a transverse plane view with a schematic diagram of the leg system attached to the body of the robot. The legs are made out of fibre carbon composite structures to reduce the weight of the system. Three DC motors are used to actuate the joints: the coxal joint (pan) using a rotational actuator, and the femural and tibial joints (tilt-tilt) using linear actuators. The coxal joint is connected to the body by a flexible frame. The femural and tibial links are subjected to rotary and bending deflections, respectively, when the robot is moving. The foot is an elastic ground impact absorber mounted at the tip of the leg and subject to compression.

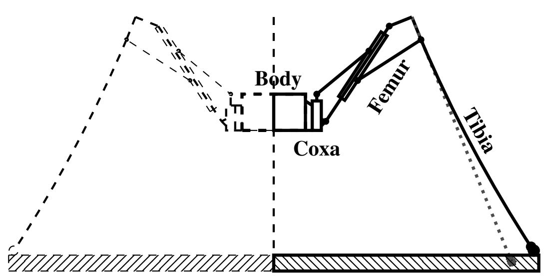

Fig. 1: Schematic diagram of the leg system of MAX

Legged locomotion is characterized by non-smooth transitions between locomotion phases, due to variable impacts, ground reaction forces, and different stance patterns; see [4] and the references therein. As a result, the governing dynamics of MAX are modelled by hybrid systems of differential equations in which the continuous-time vector fields describing the evolution of the system change at discrete times or events. Since the constraints that define these vector fields depend on the status of the leg with respect to the ground, the dimension of the governing vector field changes at an event, and different coordinate systems are called for. The dynamic equations of motion are parameterised by using energy principles. Parts of the leg are assumed to store kinetic energy by virtue of their moving inertia, and to store potential energy due to their position in the gravitational field.

The flexible structure of the leg stores potential energy because of the deflections of the links, joints and drives. Compression stores potential energy due to high compressional stiffness. Torsion of a link stores potential energy but little kinetic energy due to the low mass moment of inertia about the longitudinal axis. Links subjected to bending store potential energy by virtue of their deflection as well as kinetic energy because of their deflection rates. These principals imply physical consistency constraints on the parameters of the dynamic model [3].

In view of the least action principle, the dynamics of the flexible structures in the legs of the MAX can be described by partial differential equations and thus possess an infinite number of dimensions, which cannot easily be used directly in both system analysis and control synthesis. As a result, most commonly the dynamic equations are truncated to some finite dimensional models using either the assumed modes method (AMM), the finite element method (FEM) or the lumped-parameter method (LPM); see [5] and references therein for more details. AMM, FEM and LPM use either the Lagrangian formulation or the Newton-Euler recursive formulation to achieve a dynamical model for the system. In the AMM formulation, the link flexibility is usually represented by a truncated finite modal series in terms of the spatial mode model formulation. The main drawback of AMM is the difficulty in finding modes for links with non-regular cross sections and multi-link systems. In AMM only the first several modes of vibrations are usually retained by truncation and the higher modes are neglected. In the case of FEM, in order to solve a large set of differential equations derived using the method, boundary conditions have to be considered which are often uncertain for flexible structures. For LPM, often use for analysis and control purposes, the dynamics are modelled by the interconnection of generalised spring-damper-mass systems [2]. The parameters of LPM are often derived from FEM, AMM or identification experiments [6]. At the same time, LPM often yields models with relatively larger bounds for the model uncertainty.

In this work, we design and implement system identification experiments to derive the parameters of the proposed model. In the system identification experiments, load cells are used to measure the forces applied by the linear actuators to the femural and tibial links. These sensors are placed in alignment with the rods which connect the linear actuators to their associated links. Spatially distributed fiber Bragg grating optical sensors are integrated in the femural and tibial links to measure the amount of strain along these links over time. The values of strain in the links are used to estimate the amount of bending and rotational deflections and their associated time derivatives. A motion capture system is used to record the movement of the leg. We assume that the model is linearisable in the case when the system is in a single operational state, that is, when the status of the leg in regard to its contact with the ground is fixed. It is assumed that the dynamics associated with the sensing system components, as well as the delays in the data acquisition and and control systems are negligible. In addition, we neglect the effects of friction and nonlinearities, such as backlash in the actuators, joints, links and gears.

The main contribution of this paper is the analytical approach used for modelling and identification of the dynamics of an ultralight robotic leg system. We take into account the physical consistency conditions of the parameters of the system. The resulting dynamics model enables a quantitative approach to studying the relative effects of system deformations as superimposed on the rigid body dynamics of the leg system. The results of the work can be used for estimation of ground impact forces, improving the leg design, and allowing active and/or passive vibration control analysis and synthesis of the leg.

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