Dynamic control of a hexapod robot using compliant contact force models

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EXTENDED ABSTRACT

1 Introduction

The design of autonomous hexapod robots for rescue or exploratory missions aims to achieve high-performing and efficient locomotion, which must be able to adapt to complex environments with variable terrain topology. In this sense, the contact forces developed during the interaction between the robot's feet and the ground can cause undesirable trajectory deviations and increase the torso instability during locomotion. Thus, the utilization of limbs' control strategies that take into account those dynamic loads has a high potential to improve the locomotion performance, by decreasing both the joints efforts and the energy consumed [1, 2]. Moreover, the dynamic modeling of the hexapod robot and the knowledge of the foot-ground collision forces can be employed design process of active and passive suspension models for the robotic limbs. This work aims at developing a detailed multibody model to study the dynamic behavior of the hexapod ATHENA (All-Terrain Hexapod for Environment Navigation Adaptability). For this desideratum, a python-based in-house software has been developed to compute and solve the equations of motion and control the multibody model.

2 Multibody model

The ATHENA robot contains six limbs displaced around a main rectangular-shaped body known as the torso. Figure 1(a) presents a schematic representation of one limb, which is composed of four different segments denoted as coxa, femur, tibia, and foot. Although these segments of different components, they do not present relative motion, therefore, it is fair to assume that this multibody system includes 25 rigid bodies. In this study, the motion between the tibia and the foot is neglected and they are considered to be a single body. Therefore, the multibody model is simplified into 19 rigid bodies, which are constrained by kinematic revolute joints. Each leg of the hexapod holds three active revolute joints as depicted in Fig. 1(a). The system's equations of motion are computed through the Newton-Euler formulation in the following form [3],

$$\begin{bmatrix} \mathbf{M} & \mathbf{D}^{\mathrm{T}} \\ \mathbf{D} & \mathbf{0} \end{bmatrix} \begin{Bmatrix} \dot{\mathbf{v}} \\ \boldsymbol{\lambda} \end{Bmatrix} = \begin{Bmatrix} \mathbf{g} \\ \boldsymbol{\gamma} - 2\alpha\dot{\boldsymbol{\Phi}} - \beta^2\boldsymbol{\Phi} \end{Bmatrix} \tag{1}$$

where $\mathbf{M}$ is the system mass matrix, $\mathbf{D}$ represents the Jacobian matrix of the constraint equations, $\mathbf{g}$ expresses the vector of external generalized forces, $\boldsymbol{\gamma}$ denotes the right-hand side vector of the accelerations constraint equations, $\dot{\mathbf{v}}$ is the vector of bodies generalized accelerations, and $\boldsymbol{\lambda}$ contains the Lagrange multipliers, which represent the joint reactions. To keep the violation of position and velocity constraints under control, the Baumgarte stabilization method is directly included in the equations of motion. In this sense, $\boldsymbol{\Phi}$ and $\dot{\boldsymbol{\Phi}}$ denote the position and velocity constraint equations vectors, respectively, and α and β represent the control constants. Following the representation of Fig. 1(b), each revolute joint between bodies i and j can be fully characterized by defining a position of a point P on the joint axis with respect to both bodies, $\mathbf{s}^P_i$ and $\mathbf{s}^P_j$, a vector $\mathbf{s}_i$ along the joint axis with respect to body i, and two vectors $\mathbf{a}_j$ and $\mathbf{b}_j$ normal to the joint axis in body j. The contribution of each joint k to the Jacobian matrix and the right-hand side vector of the acceleration constraints can be expressed as

$$\mathbf{D}_k = \begin{bmatrix} -\mathbf{I} & \tilde{\mathbf{s}}_i^P & \mathbf{I} & -\tilde{\mathbf{s}}_j^P \\ \mathbf{0} & -\mathbf{a}_j^{\mathrm{T}}\tilde{\mathbf{s}}_i & \mathbf{0} & -\mathbf{s}_i^{\mathrm{T}}\tilde{\mathbf{a}}_j \\ \mathbf{0} & -\mathbf{b}_j^{\mathrm{T}}\tilde{\mathbf{s}}_i & \mathbf{0} & -\mathbf{s}_i^{\mathrm{T}}\tilde{\mathbf{b}}_j \end{bmatrix} \tag{2}$$

$$\boldsymbol{\gamma}_k = \begin{Bmatrix} -\dot{\tilde{\mathbf{s}}}_i^P\boldsymbol{\omega}_i + \dot{\tilde{\mathbf{s}}}_j^P\boldsymbol{\omega}_j \\ -\mathbf{s}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{a}}_j - \mathbf{a}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{s}}_i - 2\dot{\mathbf{a}}_j^{\mathrm{T}}\dot{\mathbf{s}}_i \\ -\mathbf{s}_i^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_j\dot{\mathbf{b}}_j - \mathbf{b}_j^{\mathrm{T}}\tilde{\boldsymbol{\omega}}_i\dot{\mathbf{s}}_i - 2\dot{\mathbf{b}}_j^{\mathrm{T}}\dot{\mathbf{s}}_i \end{Bmatrix} \tag{3}$$

where $\boldsymbol{\omega}_i$ is the vector of global angular velocities of body i.

In this work, both the gravitational and foot-ground contact forces are treated as external forces and included in vector $\mathbf{g}$. The contact definition follows an elastic approach, in which the local geometrical and material properties of the contacting bodies are incorporated. As a first approach, the ground is considered to be flat and rigid, which might be unrealistic for irregular and/or deformable terrains. The normal contact force is computed through a Hertzian-based model, while the tangential contact force follows the modified Coulomb model, can be written as [4]

$$\mathbf{f}_{\mathrm{n}} = c_{\mathrm{d}} k_{\mathrm{n}} \delta \mathbf{n} \tag{4}$$

$$\mathbf{f}_{\mathrm{t}} = \mu_{\mathrm{k}} f_{\mathrm{n}} \tanh\left(k_{\mathrm{t}} v_{\mathrm{t}}\right)\left(\mathbf{v}_{\mathrm{t}} / v_{\mathrm{t}}\right) \tag{5}$$

where c_{d} is the damping factor that depends on the impact velocity, k_{n} denotes the generalized contact stiffness parameter, δ represents relative penetration, $\mathbf{n}$ is the contact normal unit vector, μ_{k} is the kinetic friction coefficient, f_{n} is normal contact force, k_{t} represents the slope of the model for null velocity, preventing the existing numerical discontinuity in the Coulomb model, the $\mathbf{v}_{\mathrm{t}}$ and v_{t} are the relative tangential velocity vector and corresponding magnitude, The equations of motion are solved using the standard procedure presented by Nikravesh [3].

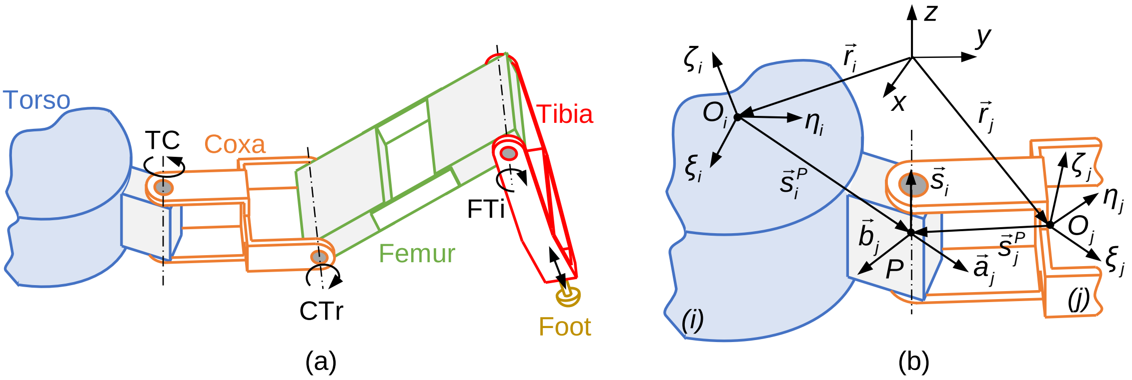

Figure 1: Representation of (a) the kinematic chain of each limb, and (b) the definition of a general revolute joint.

3 Control strategy

During locomotion, the legs perform different trajectories according to the corresponding gait phase. The joints' actuation follows a kinematic control, which neglects the positional deviations that occur during the stance phase and that are caused by the foot-ground interaction. This work proposes a PID-based corrective approach to adjust the joints angular positions according to tangential contact forces to reduce the foot slippage. Besides, a virtual suspension model is implemented in the robot limbs to adjust the system response with the normal contact force. The correction of the foot position is added to the legs' t, and the joints' actuation is re-calculated using the model inverse kinematics. This method is assessed for the locomotion of ATHENA across a regular surface, and the obtained results are compared against a conventional control scenario.

4 Concluding remarks

This work presents the development of a detailed multibody model of a hexapod robot, including its interaction with the surrounding environment, to ultimately improve the control of its locomotion. The main objective is to estimate the discrepancies in the feet trajectory against the use of kinematic motor commands and to adjust the legs' actuation accordingly. The computational simulations test the hexapod locomotion in a regular plane. Other terrain topologies will be further studied.

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