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Modelling of a robotic leg using bond graphs

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ABSTRACT

This paper studies the bond graph model of a robotic leg mechanism, and discusses methods of extracting significant features of system dynamics through simpler models. The goal is to determine a set of simpler mechanisms with similar dynamic behaviour to that of the original leg in various phases of its motion. The paper is divided in two sections. In the first section, a modular bond-graph representation of the leg mechanism is determined. In the second section, two algorithms are applied to simplify the bond graph representation. The first algorithm determines the relevant dynamic elements of the system for each phase of motion, and the second algorithm finds the simple mechanism described by the remaining dynamic elements. In addition to greatly simplifying the control system of the robotic leg, using simpler mechanisms with similar behaviour provides a greater insight into the dynamics of the system.

1. Introduction

Legged robots offer a number of advantages compared with their wheeled counterparts. They are able to navigate rough terrain [1], and deal with obstacles [2]. The study of leg dynamics is also applicable to prosthetics design and human gait research [3].

In order to simplify the control of robotic legs and make the behaviour more tractable and intuitive, the physical model of a leg mechanism must be simplified. Simple models, such as the inverted and double pendulum are used to approximate the legs of walking robots[4], and the Spring Linear Inverted Pendulum (SLIP) model is used to approximate the behaviour of running and hopping robots[2]. The controllers developed according to these simple models perform well if the actual leg mechanism is close to the assumed model; otherwise, specific measures must be taken, depending on the differences between the models and the actual mechanisms. Examples given are the experimentally determined hip torque used in [5] to counteract the difference between SLIP model and the actual leg, and the reduction-by-feedback strategy used in [6] to simplify the model. Consequently, the designer is limited in the choice of mechanical solutions to those that are close to one of the simple and well-studied models. Moreover, the dynamic models are intended for a specific motion phase, such as *stance* phase, when the leg is on the ground, or *swing* phase, when the leg is off the ground. For robots with more than one leg, there are more complex motion phases, each represented by a different dynamic model [7].

The presented work aims at finding simple models, using bond graphs, with approximately similar dynamic behaviour to that of a given leg mechanism for each motion phase. These simple models are real-world mechanisms, not linearized versions of the original leg design, and provide an intuitive understanding of the behaviour of the more complex mechanism, as well as a basis for controller design. In a previous work [8], the design of the leg mechanism is detailed, and the equations of

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motion for the system are obtained using the Lagrangian approach, but the expressions are too complex and non-intuitive to be used for simplification studies. Instead, in here a bond graph representation of the system is derived.

Bond graphs are domain-independent graphical descriptions of dynamical behaviour of physical systems. Bond graphs are based on the concept that energy exchange is a common notion to dynamic systems regardless of their physical domain[9]. Therefore, in a bond graph components are defined by their energetic behaviour; they can either supply or absorb, store or dissipate, and reversibly or irreversibly transform energy [10]. Bond graphs can be used to represent complex three dimensional mechanical systems [11,12], as well as mechatronic systems [13–16].

The first part of the paper, Section 2, expresses dynamics of a leg mechanism using bond graphs in a way that it facilitates further simplifications. The second part of the paper, Section 3, applies a combination of various simplification techniques to the bond graph model to find simpler representation of the system in each motion phase. The behaviour of simpler models is also compared with that of the original model in Section 4. Some concluding remarks are made in Section 5.

2. Bond graph model of the leg mechanism

Bond graphs represent the system dynamics by considering the power exchange between its components. The system variables such as force, velocity, current, and voltage, are unified into two groups, the *flow* and *effort*. By multiplying these generalized variables, the power flow between components can be computed. The bond graph uses the dynamic equations of its components and initial conditions to calculate the behaviour of the system [16]. Furthermore, bond graphs can be linked together in a modular fashion to represent a more complex mechanism. For example, the rigid body in Fig. 1 is represented using a bond graph composed of several modules. The generalized flow and effort variables correspond to velocity and force, respectively. The velocity (flow) of point O_1 is specified using flow source components (C), and the force (effort) applied at point O_2 is represented by effort source components (D). Both velocity and force vectors are expressed in the local coordinate frame of the body. The vectors r_1 and r_2 define the position of points O_1 and O_2 with respect to the centre of mass of the body in the local coordinate frame using transformer blocks (B). The rotational dynamics of the body are represented using an inductor component (A), and the translational dynamics of the body are represented by two inertia components as inductors and two effort sources in the world coordinate frame (F). A coordinate transformation block (E) relates the velocities and forces of the body centre of mass expressed in the world and local coordinate frames.

Using the above-mentioned six blocks the planar dynamics of the rigid body can be calculated, together with the power flow to each component. By linking a number of rigid body modules together, the dynamics of a more complex system, such as the leg mechanism shown in Fig. 2 can be derived.

The robotic leg proposed in [8], called Linkage Leg, is shown in Fig. 2. The leg is composed of four links. The hip joint O_0 connects the body to the first link, the thigh $\{O_0O_1O_4\}$. The tibia $\{O_1O_2\}$, foot $\{O_2O_3O_5\}$ and tendon $\{O_4O_5\}$, together with the thigh, form a four-bar linkage. The lengths $a_1 \dots a_8$ define the geometry of the four links. The two degrees of freedom of the Linkage Leg are the angle between coordinate frames $\{O_0\}$ and $\{O_1\}$, defined as the hip angle θ_1, and the angle between the coordinate frames $\{O_1\}$ and $\{O_2\}$, defined as the knee angle θ_2.

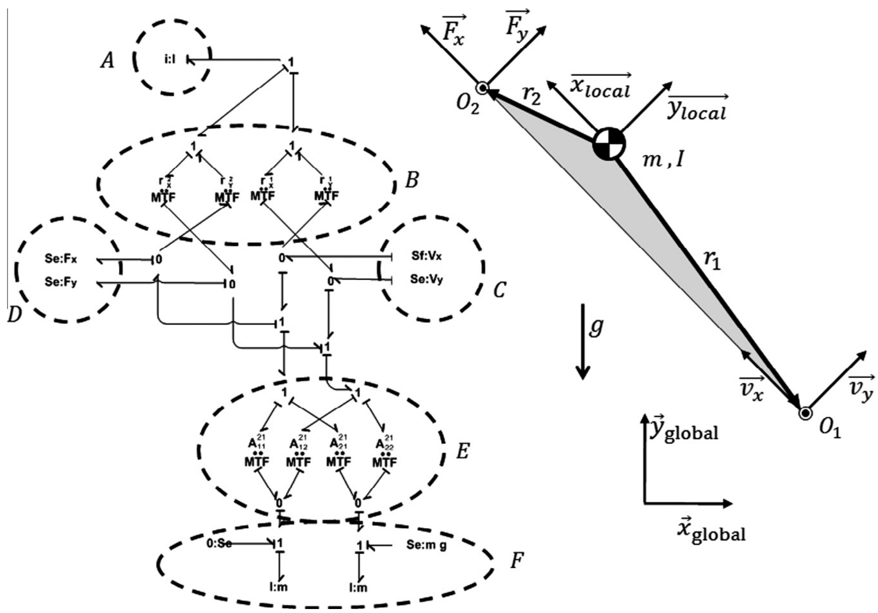

Fig. 1. Bond graph representation of a rigid body dynamics.