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IFAC-PapersOnLine 48-13 (2015) 170–175

Morphological computation in a fast-running quadruped with elastic spine

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Abstract: In high-speed locomotion, control is best shared between "brain" and "body": if the natural body dynamics already exhibit desired behaviour, control action can be restricted to stabilising this behaviour, or providing energy to keep it going. This morphological computation can be modelled and designed using Port-Hamiltonian systems (PHS) theory, since the basis of both is the interconnection of dynamic elements. In this paper, we explore the application of PHS to morphological computation, showing that a three degrees-of-freedom elastic spring functioning as spine in a quadrupedal robot can lead to forward locomotion—without any complicated control action whatsoever.

Keywords: Robot dynamics, Control by interconnection, Locomotion, Numerical simulation, Port-Hamiltonian Systems

1. INTRODUCTION

Usually, control in robotics focuses on measuring the system state and providing a feedback through actuators; stabilising at a position, following a desired trajectory or realising a controlled impedance. For some years now however, a new field of *embodied artificial intelligence* or *morphological computation* has begun to develop, wherein it is recognised that the morphology of the robot itself has a large influence on the behaviour; and that control of the robot could—or rather, *should*—be shared between "traditional" control and the morphology of the robot (Pfeifer et al. (2007)). Good examples of research into this intelligence embodiment include the robots "Puppy" of Iida et al. (2005) and "Scout" of Poulakakis (2006), both bounding quadrupeds with active hip joints and passive sping-like legs; the "Salamander", a undulatory walking and swimming robot in Ijspeert et al. (2007); and the kangaroo-like resonance-based robots of Maheshwari et al. (2012).

The aim in our project is to design a quadruped robot, a "cheetah", exhibiting very fast locomotion with a low energy cost. We believe that in order to achieve this, the desired behaviour (bounding or galloping) has to be at least partly present in the natural dynamics of the system. An energy-based modelling approach is a natural choice when studying energy-efficient locomotion. Port-Hamiltonian Systems (PHS) theory should be very suited for studying morphological computation, considering the similarity between them: exploiting natural body dynamics means obtaining desired behaviour by choosing a proper morphology, in other words the *interconnection of e.g. masses and springs*; PHS theory explicitly expresses, in an energy-consistent way, the *interconnection of various energy storage elements*, such as masses and springs, mathematically represented by a Dirac structure (Cervera et al. (2007); Schaft and Jeltsema (2014)).

In this paper, we investigate the effect of an elastic spine on quadrupedal running. It is shown that an otherwise completely symmetrical robot model exhibits desired behaviour—forward locomotion—through an asymmetry introduced by an elastical spine. Furthermore, we show that Port-Hamiltonian systems theory, especially in the form of geometrical bond graph modelling, is an excellent way of investigating and designing highly dynamical systems with embodied intelligence.

It has already been shown in multiple quadrupedal runners that an elastic rotational joint in the body or an actuated rotational spine can improve performance: see for instance Culha and Saranli (2011); Cao and Poulakakis (2012); Pouya et al. (2012); Haueisen (2011). However, in this case the spine is a full-dimensional spring with both rotational and translational compliance—moreover, it is solely responsible for any forward locomotion, being the only asymmetry in the model.

Note that, in the final system, control will be shared between "body" and "brain", where the body—through morphological computation—crudely generates the desired locomotion behaviour, while a separate controller, the "brain", will be used to stabilise the gait. This paper adresses the first part, the high-speed morphological computation.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.10.234

1.1 Geometrical bond-graph modelling

Bond graphs are a graphical, energy-consistent modelling language, where storage elements, frictional elements and energy sources are interconnected by bonds that describe power flow between those elements, in the form of effort and flow: generalised force and velocity. The bonds can go through a transformer or gyrator to interface different physical domains or to model power-continuous transformations. In geometrical modelling [1], the effort is a wrench and the flow is a twist, both of which have a geometrical interpretation of a screw (Stramigioli (2001)). Geometrical reasoning gives direct insight in how to model motions, coordinate transformations and, as is shown later in Section 2.1, a three-dimensional spring (Fasse and Breedveld (1998); Stramigioli (2001)).

Straight running happens mainly in the sagittal plane, so considering the large number of parameters associated with the elastic spine, the quadrupedal robot is modelled in the sagittal plane only. Coordinate frames are indicated by Ψ_i, Ψ_j with a coordinate change from frame i to j represented by a 3×3 homogeneous matrix $H_i^j \in SE(2)$. The velocity of a body A with respect to body P, expressed in Ψ_k can be expressed as a twist $T_A^{k,P} \in \mathfrak{se}(2)$. Wrenches are elements of $\mathfrak{se}^*(2)$; $W^{k,A}$ is a wrench exerted on body A, expressed in Ψ_k.

Coordinate transformations of twists and wrenches are calculated by the Adjoint map (Duindam et al. (2009)):

$$T_A^{j,P} = \mathrm{Ad}_{H_i^j} T_A^{i,P}; \quad W^{j,A} = \mathrm{Ad}^{\top}_{H_j^i} W^{i,A} \tag{1}$$

2. MODEL

As explained in the introduction, the quadruped robot is modelled in the sagittal plane and as such is two-dimensional. It consists of interconnected rigid bodies and is fore–aft symmetrical, with exception of the spine.

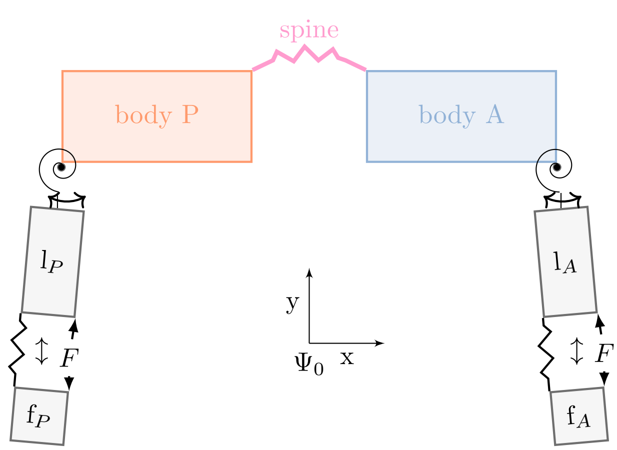

Fig. 1. The two-dimensional quadruped robot model. All joints are equipped with passive, linear springs; the ankle joints also feature a force actuator.

Bodies Both the anterior and posterior part consist of three rigid bodies: the body, the leg and the foot, respectively indicated with "body A/P", "$l_{A/P}$" and "$f_{A/P}$" in Fig. 1. Dimensions and inertial properties of these bodies can be found in Table 1 and were chosen to result in a realistic robot model.

[1] The application of Port-Hamiltonian Systems on manifolds

Table 1. Body dimensions and inertial properties.

	Width	Height	Mass	Inertia
Body	0.5 m	0.2 m	1 kg	$0.02\,\mathrm{kg\,m^2}$
Leg	0.5 m	0.1 m	0.5 kg	$0.02\,\mathrm{kg\,m^2}$
Foot	0.01 m	0.01 m	0.05 kg	$0.001\,\mathrm{kg\,m^2}$

Table 2. Stiffness parameters. Rest configuration is the distance between the foot and the bottom of the leg for ankle spings; the outward rotation (extension) for hip springs.

	Hip spring	Ankle spring
Stiffness	$33\,\mathrm{N\,m\,rad^{-1}}$	$300\,\mathrm{N\,m^{-1}}$
Rest configuration	5°	25 cm

Springs Stiffness parameters for the hip (K_h) and ankle (K_a) joints are listed in Table 2 and were chosen as follows. Firstly, the ankle springs should carry the full body weight without having the feet hit the legs, whilst facilitating bouncing and a stance time that is long enough to allow the controller (see Section 2.2) to insert a sufficient amount of energy. A maximum deflection of 25 cm provides enough stance time. Cavanagh and Lafortune (1980) found that during running, the ground reaction force is typically 3–5 times the body weight, so a stiffness of $300\,\mathrm{N\,m^{-1}}$ allows for 25 cm of spring deflection.

The hip spring stiffness was chosen such that it allows large deflection during running (±45°) but does not collapse under the body weight. For anteroposterior stability during running, the rest configuration points the legs slightly outward (5°) for a wider stance.

2.1 Spine

The spine is modelled as a geometric spring parameterised by a centre of compliance, where the spring locally behaves as a decoupled rotational stiffness k_z and translational stiffness $K_t = \begin{pmatrix} k_x & 0 \\ 0 & k_y \end{pmatrix}$. The elastic wrench is applied in frames Ψ_i and Ψ_j that are connected to body A and B respectively; the minimal-energy configuration i.e. equilibrium position is when Ψ_i and Ψ_j coincide and thus $H^j_{i\,,\mathrm{eq}} = I_3$. See Fig. 2 for a schematic drawing.

For the three-dimensional case an expression for the elastic wrench is known to be (Stramigioli (2001)):

$$W^i = \begin{pmatrix} m^i & f^i \end{pmatrix} \tag{2}$$
$$\tilde{m}^i = -2\,\mathrm{as}(G_o R_i^j) - \mathrm{as}(G_t R_j^i \tilde{p}_i^j \tilde{p}_i^j R_i^j) - 2\,\mathrm{as}(G_c \tilde{p}_i^j R_i^j)$$
$$\tilde{f}^i = -R_j^i\,\mathrm{as}(G_t \tilde{p}_i^j) R_i^j - \mathrm{as}(G_t R_j^i \tilde{p}_i^j R_i^j) - 2\,\mathrm{as}(G_c R_i^j),$$

where $H_i^j = \begin{pmatrix} R_i^j & p_i^j \\ 0 & 1 \end{pmatrix} \in SE(3)$ and $G_{\{o,t,c\}}$ are the co-stiffness matrices for orientational, translational and coupling stiffness, respectively. $\mathrm{as}(M)$ is an operator that returns the antisymmetric part of a matrix M : $\frac{1}{2}(M - M^T)$. The tilde form $\tilde{v}$ is a 3×3 skew-symmetric matrix for which holds $\tilde{v}w = v \times w$, if v and w are three-dimensional vectors.