

Energy Efficient Explosive Motion with Compliant Actuation Arrangements in Articulated Robots

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Abstract—This paper presents the trajectory and elastic element pretensions optimisation for a jumping motion of a 3-DoF leg using recently introduced asymmetric compliant actuator configurations which provide energy efficient actuation for explosive motions. Two actuation branches with significantly different stiffness and energy storage capacity properties driving a single joint make up the actuator design. An optimisation problem is formulated to optimise the elastic element pretensions and the joint trajectories for energy efficient vertical jumping motions. Several configurations of the asymmetric compliant actuators have been investigated. Optimization studies of the jumping motions demonstrate SOMETHING.

I. INTRODUCTION

In the past robot applications were found predominantly in static industrial settings, but over the past years robots have been introduced to more dynamic settings, operating with and among humans. This change in application is accompanied by a change in requirements on robots. One of the primary challenges today is letting robots match human-like behaviour in terms of motion. This requires light-weight actuation systems that allow for energy efficient explosive motion, large instantaneous forces with short duration, and matching motion planning and control. A prime example of an exacting explosive motion is the vertical jump. Several approaches have been investigated over the years to design robotic systems capable of energy efficient explosive motion. The use of sensorization of moving parts of rigid machines and active control tends to be costly, encombrant, and unreliable. Therefore, often systems with compliant properties are used. The ‘Bow Leg’ hopping robot is a compliant hopping leg with a curved leaf spring made of laminated fibreglass and strings that hold the leg in compression to store elastic energy which shows us that low power motors can be competent for actuation [1]. A small bipedal jumping robot called ‘Mowgli’ uses compliant muscles antagonistic to its pneumatic artificial muscles made of rubber tubes in order to simplify its body while being able to store and release energy rapidly enabling it to jump as high as 0.5 m [2]. A switchable form of Parallel Elastic Actuation (PEA) has shown to utilize the benefits of compliant properties whilst maintaining a high degree of control when the compliance is not needed [3]. The introduction of Series Elastic Actuation (SEA) ensured more accurate and stable force control leading to increased energy

efficiency over PEA [4], [5]. Further optimisation of synchronized variation of stiffness and velocity for movement in the shortest time while limiting possible impact forces has been reached using Variable Stiffness Actuation (VSA) [6] and the importance of the optimisation of joint trajectories besides the actuation parameters has been shown to be a major factor in the increase of energy efficiency [7]. Also bi-articulation, spanning multiple joints simultaneously with a single muscle as is seen in nature, increases energy efficiency drastically [8], [9]. Comparative jumping experiments with single actuator bi-articulated robots opposed to multiple actuator robots show increased performance in jumping for bi-articulation configurations [10]–[12].

More recently, Roozing et al. [13], [14] presented the development and control of a novel asymmetric antagonistic actuation scheme characterised by large energy storage capacity that enables efficient execution of motions, as well as a novel method to select the design parameters of asymmetric compliant actuation (ACA) schemes to improve the energy efficiency of multi-DoF articulated robots powered by this type of actuators. This paper extends these previous works and contributes by using the ACA design to execute optimal explosive vertical jumping motions submitted to different objectives concerning jump height and energy efficiency. An optimisation problem is formulated to optimise the joint trajectories for energy efficient vertical jumping motions of a 3-DoF leg and three different configurations of the ACA’s are investigated.

The paper is structured as follows. Section II describes a 3-DoF leg model, the asymmetric actuation and three different actuation configurations used to demonstrate the effectiveness of the ACA design for the execution of energy efficient explosive motions. Section III describes the dynamics of the leg and the dynamic computations performed to aid the jumping motion optimisation. Section IV describes the optimisation parameters, the objective criteria and the optimisation algorithm. The optimisation results are presented in Section V followed by a discussion of results in Section VI and conclusions in Section VII.

II. LEG DESIGN

A. Leg model

The design of the 3-DoF leg model is inspired by the human lower limb. The dimensions and mass distribution of the human limb were investigated, and compared with those of existing humanoid designs such as WALK-MAN [15] to set specifications for a semi-anthropomorphic design. The leg, shown in Fig. 3, features three actuated degrees of

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freedom: ankle, knee and hip. *SEA*'s drive the joints, which are mounted above the joints for the knee and ankle and transmit their forces through four bar linkages to decrease the legs moment of inertia with respect to the hip joint. The trunk is weighted with mass corresponding to that of a full humanoid robot.

B. Assymmetric Compliant Actuation

For the concept of Assymmetric Compliant Actuation, or *ACA*, a combination of two parallel actuation branches with very different power and stiffness properties is used as shown in Fig. 1. The Power Branch (*PB*) is a rotary *SEA* which consists of a high power motor *M1* in series with a torsional elastic element *SE*. The Energy Storage Branch (*ESB*) consists of a lower power motor *M2* with a high reduction linear transmission which transfers its power through a unidirectional series elastic element *PE*.

C. Configurations

In nature, bi-articulated muscle structures, muscle structures that actuate multiple joints simultaneously, can be found on humans and other animals. An example of a bi-articulated muscle structure are the hamstrings, which span both the hip and knee joint. *ACA*'s can be utilized to realize bi-articulated actuation by letting the *PB* drive a joint directly, and letting the *ESB* tendon span a second joint by means of a pulley. Bi-articulation is one of three actuation configurations of the leg considered for the jumping optimisation:

- 1) The *ACA*'s are not considered and jumping optimisations are performed for the leg with fixed compliance *SEA*'s only.
- 2) The *ACA*'s are introduced to perform jumping optimisations on a mono-articulated version of the leg.
- 3) A bi-articulated version of the leg is considered for optimisation.

The leg actuation configurations are shown in Fig 2. The designs of the actuation configurations have been optimised to select actuation parameters that yield high electrical energy efficiency and reduction in peak torque and electrical power requirements [13].

III. DYNAMIC MODEL

A. Forward Dynamics

The leg consists out of four links which are connected by the actuated ankle, knee and hip joints, denoted q_1, q_2, q_3 , with torques τ_1, τ_2, τ_3 as shown in Fig. 3. The links have masses m_1, m_2, m_3, m_4 and rotational inertiae J_1, J_2, J_3, J_4 . Their CoM is assumed to be located on the line connecting

Picture of ACA branches

Fig. 1. ACA branches

Picture of configurations

Fig. 2. Actuation configurations

the proximal and distal joints at a distance of r_1, r_2, r_3, r_4 from the proximal joint for all links except for the foot; the model includes a floating base to allow for realistic modelling of the ground reaction forces (GRF). Together, the configurations of the bodies describe the system:

$$x = [x_1, y_1, \theta_1, x_2, y_2, \theta_2, x_3, y_3, \theta_3, x_4, y_4, \theta_4]^T. \quad (1)$$

The Euler-Lagrange formulism with generalised coordinates $\mathbf{q} \in \mathcal{Q} \subset \mathcal{R}^6$ is used to derive the dynamic equations for the system:

$$\mathbf{q} = [x_1, y_1, \theta_1, q_1, q_2, q_3]^T \quad (2)$$

leading to:

$$M(\mathbf{q})\ddot{\mathbf{q}} = \boldsymbol{\tau} + \mathbf{G}(\mathbf{q}) - C(\mathbf{q}, \dot{\mathbf{q}})\dot{\mathbf{q}} - D\dot{\mathbf{q}} + J_{GRF}^T \mathbf{F}_{GRF} \quad (3)$$

Here, the damping matrix is denoted by $D = \text{diag}(0, 0, 0, d_1, d_2, d_3)$, the generalised actuation forces are denoted by $\boldsymbol{\tau} = [0, 0, 0, \tau_1, \tau_2, \tau_3]$, the generalised gravitational forces are denoted by $\mathbf{G}(\mathbf{q})$, the Coriolis matrix is denoted by $C(\mathbf{q}, \dot{\mathbf{q}})$ and the generalised inertia matrix is denoted by $M(\mathbf{q})$. The Jacobian for the heel and toe is denoted by J_{GRF}^T and the ground forces in generalised coordinates are subsequently expressed as $J_{GRF}^T \mathbf{F}_{GRF}$. Spring-dampers define \mathbf{F}_{GRF} in the vertical direction and Coulomb and viscous friction define the horizontal component, proportional to the vertical forces.

B. Inverse Dynamics

For formulation of the optimisation problem described in Sec. IV, we first need to derive the inverse dynamics of the system in order to compute the applied active torques [16]. The configuration vector \mathbf{q} can be split in its passive joint and active joint components:

$$\mathbf{q} = [\mathbf{q}_p, \mathbf{q}_a]^T \quad (4)$$

with

$$\mathbf{q}_p = [x_1, y_1, \theta_1]^T, \quad \mathbf{q}_a = [q_1, q_2, q_3]^T. \quad (5)$$

Similarly, $\boldsymbol{\tau} = [\mathbf{0}, \boldsymbol{\tau}_a]^T$. Substituting these into (3) yields:

$$\begin{bmatrix} M_{pp} & M_{pa} \\ M_{ap} & M_{aa} \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_p \\ \ddot{\mathbf{q}}_a \end{bmatrix} + \begin{bmatrix} \mathbf{B}_p(\mathbf{q}, \dot{\mathbf{q}}) \\ \mathbf{B}_a(\mathbf{q}, \dot{\mathbf{q}}) \end{bmatrix} = \begin{bmatrix} \mathbf{0} \\ \boldsymbol{\tau}_a \end{bmatrix} + \begin{bmatrix} J_1 \\ J_2 \end{bmatrix} \mathbf{F}_{EXT}(\mathbf{q}, \dot{\mathbf{q}}) \quad (6)$$

Where \mathbf{B} denotes the gravitational, Coriolis and damping forces. Rearranging (6) allows for an inverse formulation:

$$\begin{bmatrix} M_{pp} & 0 \\ M_{ap} & -I \end{bmatrix} \begin{bmatrix} \ddot{\mathbf{q}}_p \\ \boldsymbol{\tau}_a \end{bmatrix} = \begin{bmatrix} M_{pa} \\ M_{aa} \end{bmatrix} \ddot{\mathbf{q}}_a - \mathbf{B}(\mathbf{q}, \dot{\mathbf{q}}) + J_{EXT}^T \mathbf{F}_{EXT}(\mathbf{q}, \dot{\mathbf{q}}). \quad (7)$$

An expression for the active torques is now easily achieved by inversion of the left-hand side mass matrix.

Picture leg

Fig. 3. Leg model

IV. DYNAMIC OPTIMISATION

The search for an optimal motion requires finding active joint trajectories over time. Expressing these trajectories over time directly poses an extremely high dimensional optimisation problem which is laborious to solve. Consequently, the optimisation we wish to perform needs to be reformulated from a large scale trajectory optimal control problem into a lower-dimensional optimisation problem [17].

A. Trajectory Parametrization

One can use basis splines, or B -splines, combined with a time-scale factor to reduce the complex problem into a parameter optimisation [11], [18]–[20]. A B -spline curve can be described by its basis functions $B_i(t)$ and control points $\mathbf{P} = [p_1, \dots, p_n]$ which are evenly spaced over time. The active joint trajectories are then computed:

$$q_a(t, p) = \sum_{i=1}^n B_i(t) p_i \quad (8)$$

Using the control points as optimisation variables, an optimal set of control points can be determined and the corresponding B -splines yield optimal trajectories for the joint angle displacements, velocities and accelerations.

B. Pretension positions

The series elastic element in the ACA scheme described in Sec. II can be set up with a pretension by deformation of the ESB elastic element. The elastic element pretension is an interesting parameter to include in the optimisation as different pretensions will yield different jumping behaviour. The pretension can be defined with the pretension position p ; the position of the elastic element attachment relative to its undeformed attachment position. For each actuation configuration described in Sec. II an ESB topology matrix $T \in \mathbb{R}^{M \times N}$ with $M = 3$ actuators and $N = 6$ leg DoFs is formulated to fully describe the location and articulation of all three $ESBs$. For actuator m , a corresponding topology row vector $\mathbf{t}_m \in \mathbb{R}^6$ from T maps the positions of the leg DoFs to the deformation of the ESB elastic element of that actuator:

$$\Delta_{p,m} = p_m + \mathbf{t}_m \mathbf{q} \quad (9)$$

This formulation allows for the optimisation of p_m , with $m \in \{1, 2, 3\}$.

C. Objective criteria

The objective function is comprised out of three criteria which 1) reward the performance of the leg, 2) penalize excessive torque needed to complete a movement and 3) maintain the postural stability of the leg. A minimization of the objective functions with these criteria is represented by:

$$\min_{\mathbf{p}} J = J_{performane} + J_{torque} + J_{stability} \quad (10)$$

In the following objective criteria, c_1, c_2, c_3, c_4, c_5 and c_6 denote scaling constants.

1) *Performance*: For the performance of the leg we distinguish two different objectives:

- 1) Jumping a maximum height, where the height is defined as the y -coordinate of the centre of mass of the leg with respect to the ground:

$$J_{performane} = -c_1 \cdot y_{CoM}^2 \quad (11)$$

- 2) Jumping to a certain height efficiently, where the maximum y -coordinate reached by the centre of mass of the leg y_{CoM} is to equal a set height y'_{CoM} and the energy use is to be minimized:

$$J_{performane} = c_1 \cdot E^2 + c_2 \cdot |y'_{CoM} - y_{CoM}| \quad (12)$$

Here, E is defined as the cumulative electrical energy consumption in Joules according to the integrated positive power model [21]:

$$E_{elec,pos} = \int \max(0, P_{source}(t)) dt \quad (13)$$

- 2) *Torque*: The active torques pose a problem as the upper and lower bound constraints on the applied torques can become non-linear. Therefore it is chosen to express the torque limits by means of a penalty function in the objective criteria and to terminate the simulation when the torque limits are violated. The active torque τ_a is to be kept low and within the maximum and minimum deliverable torque. This is enforced by means of a penalty function which incorporates the 2-norm of the realised values of τ_a :

$$J_{torque} = c_3 \cdot \|\tau_a\|_2^2 \quad (14)$$

- 3) *Stability*: To ensure postural stability a stability criterion is introduced. The leg posture is considered stable when the x -coordinate of the centre of mass of the leg is equal to its initial x -coordinate, $x_{CoM} = 0$, at the end of the jump, i.e. when the centre of mass reaches its maximum height. Also, the motion is assumed to be stable when the mean value of the absolute x -coordinates of the centre of mass equals zero. Higher stability is also assumed for a low rotational momentum L at maximum height of centre of mass. For an N number of time segments, this is achieved with the minimization of:

$$J_{stability} = c_4 \cdot x_{CoM}(t_h)^2 + c_5 \cdot \sum_{i=1}^N \frac{|x_{CoM}(t_i)|^2}{N} + c_6 \cdot L(t_h)^2 \quad (15)$$

Here, t_h denotes the point in time where the centre of mass reaches its maximum height. Let t_f denote the final time segment of the optimisation motion where either the maximum CoM height y_{CoM} has been reached or the jump is unsuccessful and the leg has fallen over. For successful jumps $t_h = t_f$.

D. Algorithm

The objective criteria described above require information concerning the kinematic and dynamic state of the leg. Both forward and inverse dynamic calculations are to be performed while the leg states are set by adjusting the earlier described B -spline joint trajectories. This dependence is managed by the optimisation algorithm. The algorithm in words yields:

- Provide initial guess trajectory and pretension positions
- Create control points
- ◊ Create trajectory with B -splines
- ◊ Check joint angles, continue if limits are not exceeded else, vary control points and repeat ◊ steps
- ◊ Run simulation of motion through forward dynamics
- ◊ Calculate active torques through inverse dynamics, continue if limits are not exceeded else, vary control points and repeat ◊ steps
- ◊ Evaluate objective function
- ◊ Exit if local minimum is reached, else, vary control points and pretension positions and repeat ◊ steps

Figure of initial motion

Fig. 4. Initial motion

V. RESULTS

The optimisation has been performed for the upward movement of the leg performing a jumping motion with a maximum duration of 0.3 seconds. The initial position of the leg yields a squatting posture and the optimisation is concluded when the centre of mass reaches its highest point for successful jumps or when the leg has fallen over for unsuccessful jumps. The initial guess is a manually constructed motion as shown in Fig. 4. The optimization results for the objectives presented in Section IV are shown in Tables I and II.

TABLE I
MAXIMUM JUMP HEIGHT FOR DIFFERENT CONFIGURATIONS

Configuration	Maximum jump height [m]	Pretension positions [m]
Only SEA		
Mono-articulated		
Bi-articulated		

VI. DISCUSSION

Comparison of actuation topologies.

VII. CONCLUSIONS

Conclusions

TABLE II
MINIMUM ENERGY USE FOR DIFFERENT CONFIGURATIONS

Configuration	Minimum energy use [J]	Pretension positions [m]
Only SEA		
Mono-articulated		
Bi-articulated		

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