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Simulation of a dynamic vertical jump

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SUMMARY

The aim of this paper is to propose a bipedal structure able to follow high acceleration movements. The vertical jump of a human has been chosen as input (coming from experiments) to validate the controller design as it is one of the most complex motion. The study concerns the low level of the biped control that is to say the control design of one leg made of three rigid bodies, each of them moved by a pneumatic actuator. An analogy between a pneumatic actuator and a physiological muscle is first proposed. A dynamic model of the leg is then presented decoupling the dynamic effects of the skeletal (as interactions between segments) from the dynamic effects of the muscles involved. The controller is based on the nonlinear theory (taking into account the actuator and the mechanical models), it ensures a dynamic tracking of position and force. Its originality lays in the consideration of impedance behaviour at each joint during free and constrained tasks. It leads to asymptotically stable (Popov criteria) control laws which are continuous between contact and non-contact phases enabling real-time computations. The simulation results clearly show the tracking of position and forces during the whole jump cycle.

KEYWORDS: Vertical jump; Bipedal structure; Dynamic model; Popov criteria.

INTRODUCTION

One of the interests of robotics, is to build structures able to help humans in difficult tasks or to reproduce motions in order to better understand the way human perform them. Our approach is of the second type. It consists, in this paper, in making an analogy between a human leg and a pneumatic actuated structure for the specific task of a jump. This task is especially interesting as it includes many problems:[1,2] (i) Upward propulsion requires energy storage; (ii) A flying phase needs an accurate position tracking; and (iii) a lending phase must ensure a good impact and force control. This task will clearly show the performance of our structure to reproduce a complex natural motion.

In a general manner, one joint is moved by a set of muscles activated by the central nervous system (CNS) via electrical impulses. The lower limb is usually represented by nine muscle sets.[3] The coactivation of these sets may be modeled as three equivalent muscles, each of them producing a motion of the thigh, the shank and the foot. The main problem consists then of identifying a mechanical actuator which will represent these equivalent muscles. We have focused our researches on the pneumatic actuator the natural damping of which is closest to the one observed in natural muscles.[4] Making analogies with a human joint motion, the input current of the servovalves plays the role of a neural activation of a physiological muscle.

From a control point of view, the mathematical dynamic model of a pneumatic actuated multilink system is highly nonlinear and time-variant, due both to the mechanical coupling effects and to the compressibility of air. The control of such a system is usually based on state feedback approaches. However, applied to dynamic behaviour, these controllers are not robust and fast enough to perform complex tasks, such as coordination or manipulation. Moreover, to achieve these tasks, one must solve problems relative to the dynamic position tracking, as well as constrained motions involving force tracking. Two main problems have then to be tackled: the dynamic motion of a pneumatic mechanism and its behaviour during constrained motion.

To overcome these difficulties we propose a new control strategy inspired by the impedance approach. The principle is to control online the force applied by the robot to the environment by a nonlinear continuous joint controller which is based on a joint behaviour of an impedance type. besides the consideration of pneumatic actuators within the model and control laws, the main originality of this approach lies in the expression of impedance in a joint space. From that principle, we have designed a controller which takes into account the actuator's behaviour of a multilink mechanism interacting with the environment. This controller deals with motions which may have transitions between contact and non contact phases. These conditions are typical of classical applications, e.g. motion of a legged robot during one complete walking cycle,[5] or as manipulation tasks with multifingered hands.[6]

The layout of this paper is as follows: Section 2 is devoted to the development of the model of the leg composed of three pneumatic joints. An analogy between a pneumatic actuator and a physiological muscle is proposed. In section 3, we develop a joint impedance controller. A stability proof based on Popov's theory is given. Simulation results of the vertical jump are presented in section 4 with a decomposition into phases. They point out the performances of the structure when following physiological data. Finally, section 5 outlines further proposed investigations.

2. LEG MODEL

In biomechanics a model of muscles is of two types: Models based on biophysical events at the molecular level,[7] and

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models based on the input-output description of the whole muscle behaviour, as first formulated by Hill in 1938.[8,9] The latter models remain the most appropriate for modelling purposes. The mechanical model is composed of a contractile element in series and parallel with viscoelastic tissues (as springs and dampings). Many researches on modelling the real muscle are focused on the elbow joint. They are based on physiological experiments on reflexive and arcflexive muscles, i.e. muscles obtained from the reflex control circuitry.[10] The force-length (Φ, λ), relationship of the muscle model may be written as:

$$\frac{d\Phi}{dt} = \frac{K_{SE}}{B}\left(K_{PE} * \Delta\lambda + B\frac{d\lambda}{dt} - \left(1 + \frac{K_{PE}}{K_{SE}}\right)\Phi + P(\lambda, f(t))\right) \tag{2.1}$$

where K_{SE} is the series elastic component, K_{PE} the parallel elastic one, B is the viscous resistance opposing force, and P is the active force which depends on the muscle length λ and on the history of muscle activation $f(t)$.

The mechanical structure we present to model the human leg is composed of three rigid segments (thigh, shank, foot). Figure 1 gives the global structure of the leg with the associated frames and joint coordinates.

Each segment is associated with a servovalve controlled by a current i. A thermodynamic study has been used to determine its model.[11] This may be written in the following form:

$$\dot{\tau} = J \cdot i - B \cdot \tau - E \cdot \dot{q} \tag{2.2}$$

The term τ is the torque applied to the joint and f is the torque due to the force exerted by the tip of the system on the environment. J, B and E are constant terms depending on gas characteristics. Vector i represents the input current applied to each servovalve. $\dot{q}$ is the joint angular speed. This thermodynamic model is used for the control design, bearing in mind that it is a very simplified model. In a rigorous form, the equilibrium conditions lead to different coefficients in the two chambers and nonlinearities have to be taken into account. In any case, the aim of this model is to obtain a structure suitable to control design; the parameter uncertainty will be compensated by the control performance. This thermodynamic model validity has already been proven by experimental results.[5]

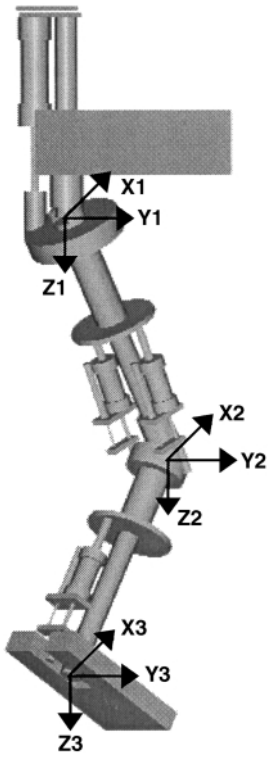


Fig. 1. Leg mechanical structure.

Comparing equation (2.2) representing the pneumatic actuator model with equation (2.1) representing a muscle model, we can make quite easily the analogy. We retrieve all the coefficients except the parallel elastic component which, in reality, exists and is not represented because of the mass flow linearisation assumption.

The dynamic model of this structure comes from the Lagrange formulation and may be written as:

$$M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q) + f = \tau \tag{2.3}$$

where q, $\dot{q}$, $\ddot{q}$ denotes respectively the joint position, speed and acceleration (see Fig. 1). $M(q)$ is the generalised inertia term, $C(q,\dot{q})$ the Coriolis and centrifugal matrix and $G(q)$ is the gravitational forces term.

3. CONTROLLER DESIGN

The aim of this section is to present the design of a controller robust and fast enough to track the position and force trajectories. We consider a pneumatic actuated multilink system which increases the control complexity. Pneumatic actuators are actually well-known to be difficult to control mainly because of the natural low damping of compressed air.[11] In order to overcome this problem, we propose an original joint impedance controller which takes into account the complete model of the arm.

The desired link trajectories are $q^d(t)$, $\dot{q}^d(t)$ and $\ddot{q}^d(t)$. The available information are the joint positions, velocities and the differential pressure between the chambers which are proportional to the joint torque. The tracking errors are defined by:

$$e = q^d - q,\ \dot{e} = \dot{q}^d - q,\ e_\tau = \tau^d - \tau,\ ef = f^d - f \tag{3.1}$$

where f and f^d represent, respectively, the actual and desired forces applied at the end of the system and brought back to the joint by the Jacobian matrix J.

$$f = J^T F,\ f^d = J^T F^d \tag{3.2}$$

To deal with the position and force control, we propose an original impedance joint controller, for which we assume that the relation between torque and position of the joint is of the impedance type. The total required torque is then defined as the necessary torque to move the structure, plus the torque due to the force exerted by the system on the environment. From the position controller previously developed,[5] we propose to modify the reference velocity model as follows:

$$s = \dot{e}_z + \Lambda . e_z,\ \dot{q}_r = s + \dot{q} \tag{3.3}$$

with:

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$$e_z = e + \frac{e_f}{Zimp}, \quad M^* \ddot{e}_{pf} + B^* \dot{e}_{pf} + K^* \ddot{e}_{pf} = (f^d - f) \quad (3.4)$$

where e_{pf} represents the joint position error due to the applied force of the system on the environment. *M, B, K* are the parameters of the joint impedance represented in *Zimp*. The controller's aim is then to make the error signal *s* converge to zero. During non-contact phases, this aim amounts to making position and velocity errors, and during contact phases the position, velocity and force errors converge to zero.

We now propose control laws based on the passivity property of the equivalent feedback system. This method can be viewed as a system energy based control. Figure 2 shows the principle of this controller. From the control laws developed for a position tracking in reference [5], let us consider the following control laws:

$$\tau^d = M(q)\ddot{q}_r + C(q, \dot{q})\dot{q}_r + G(q) + F_v.s + f, \quad (3.5)$$

$$J.i - B.\tau = \dot{\tau}^d + F_p.s + \alpha\, e_\tau. \quad (3.6)$$

where: F_p, α and F_v are positive diagonal gain matrices.

We can write the closed loop equations from (2.2), (2.4) and (3.5), (3.6), see Fig. 3:

$$M(q).\dot{s} + C(q, \dot{q}).s = e_\tau - F_v.s \quad (3.7)$$

$$\dot{e}_\tau + \alpha.e_\tau = -F_p.s \quad (3.8)$$

From Popov's theory, a system is said to be passive if it verifies Popov's inequality between its input and its output.[12] The main interest of this theory lies in the fact that the parallel or the feedback connection of two passive systems remains passive. Therefore, the Equivalent Feedback System represented in Fig. 2 will be passive if the two interconnected blocks are passive, as they are in feedback connections. The study of the two blocks shows that they verify the passivity property.[12] We can then accept the passivity property of each of them. This development allows us to conclude that the signals *s* and e_τ convert asymptotically to zero. Since $\Lambda > 0$ and $s = \dot{e}_z + \Lambda.e_z$, the position, velocity and force errors converge asymptotically to zero. The global symptomatic stability for the proposed controller is then ensured. It is able to follow dynamic position and force trajectories as in a walking cycle.[13]

In what follows, we present the application of this controller to our structure to simulate the vertical jump.

4. VERTICAL JUMP SIMULATIONS

In this section, we present the simulation results obtained for a vertical jump. The physiological data registered are derived from experiments on humans.[3] They give us the trajectories to follow for the hip, the knee and the ankle, as well as the force in the vertical and in the sagittal planes. Each curve has been scaled down to our structure in terms of proportionality for the limb length and weight. Our biped leg is of 0.5 m and weighs 2 kg. The aim is to show that our structure which is close to the natural leg, is able to follow these trajectories for the three phases producing the jump: the upward propulsion, the flying and the landing phases.

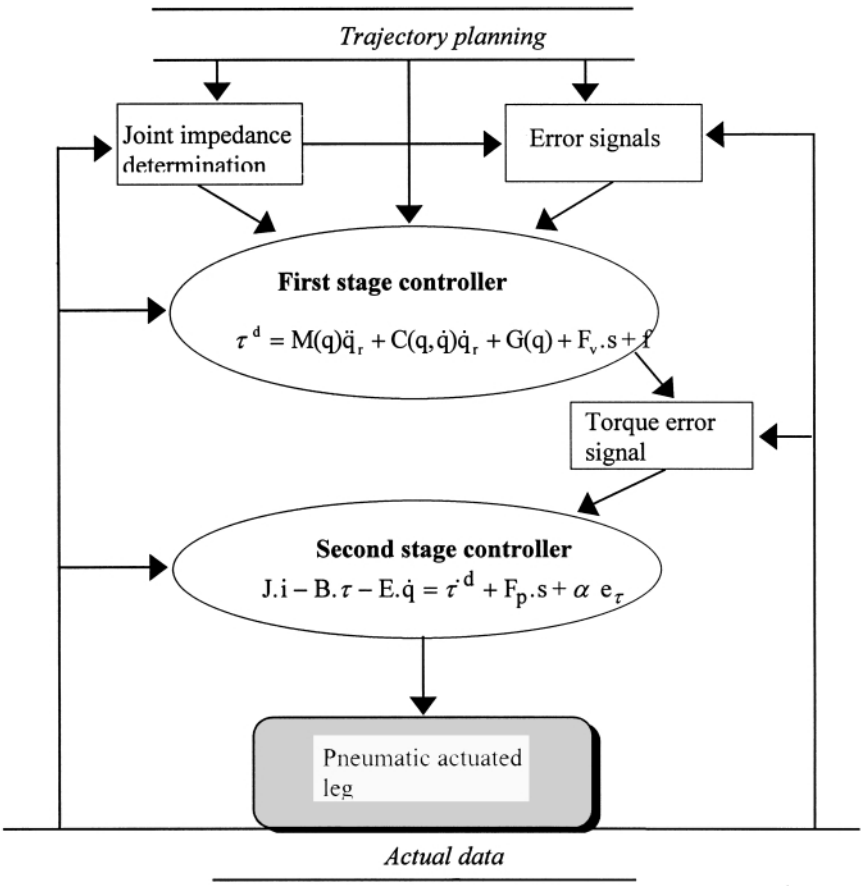


Fig. 2. Controller principle.

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The jump lasts 3s and the sampling rate is fixed to 3ms. Simulations have been performed using SIMNON software. The system is modeled as a continuous system and controllers are discrete entities. To compute the error signal e_z, we rewrite the equation (3.4) into a Laplace representation. Each segment length is fixed to *0.25m*. Joint impedances have been fixed at:

–joint 1: $M = 0.1$, $B = 1$, $K = 5$
–joint 2: $M = 0.1$, $B = 1$, $K = 2$

A more extensive study that shows the effect of those coefficients on the system behaviour has been performed in reference 14.

Figure 4 represents the position trackings for the three joints with the associated joint error position. Figure 5 shows the force tracking performances in the operational frame (*f1*, *f2*) and in the Cartesian frame (*Fx*, *Fz*). In this figure, we have decomposed the jump into 5 phases: 1. impulsion; 2. propulsion; 3. flying; 4. landing and 5. stability recovery.

This trial distinctly shows the performances of the pneumatic actuated system which is closest to the human leg. Our controller allows us to follow quite well the desired trajectories even during the propulsion and the landing phases (2 and 4) which are high acceleration phases. This is mainly due to its asymptotic stability feature.

5. CONCLUSION

In this paper, we have modelled a three joints leg using a pneumatic actuated structure. We propose a complete model with an analogy with physiological data and an original controller which deals with force and position trackings.

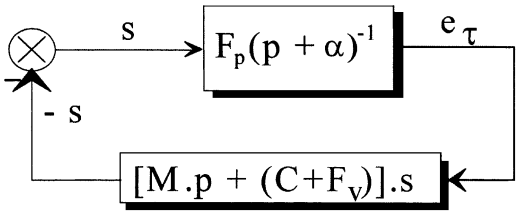


Fig. 3. Closed loop control scheme.

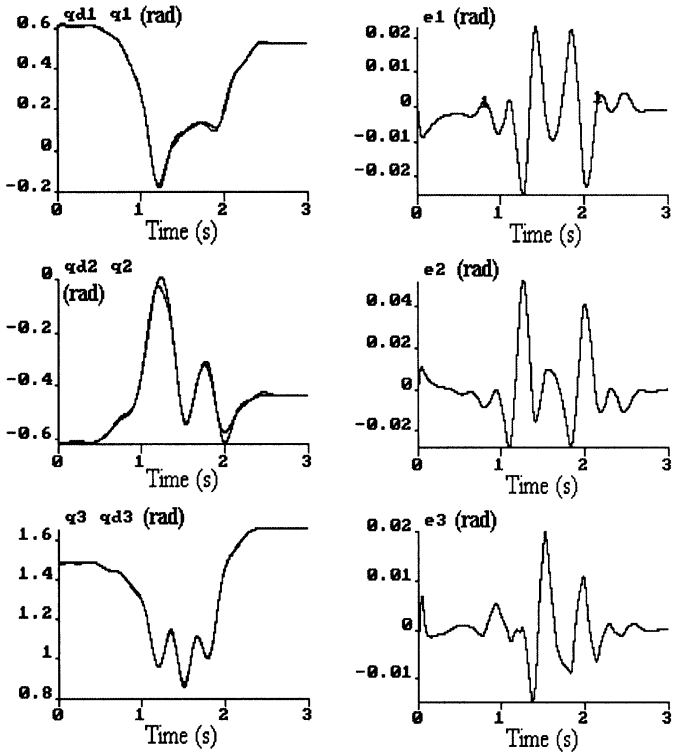


Fig. 4. Joint position trackings.

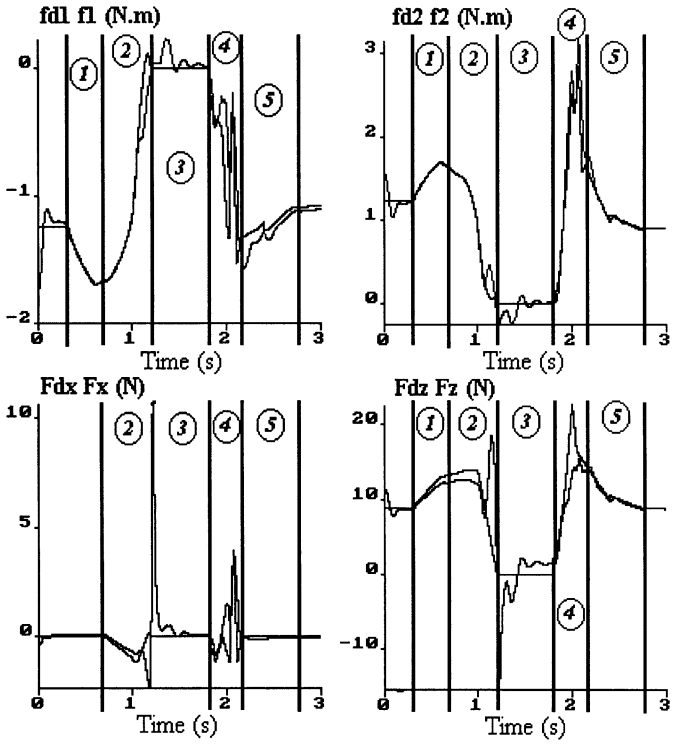


Fig. 5. Figure tracking.

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The stability of the controller is proven and simulation results confirm the performance of the system. The application chosen is the vertical jump because of its complex nature. It actually includes the problems of upward propulsion and of flying and landing phases. Accuracy in the position tracking as well as in force tracking is required and this, in a short time. The impact has also to be well controlled. This task clearly shows that the performance of our pneumatic leg reproduces this natural motion.

This study is a first approach to copy the natural leg. From a theoretical axe, we intend to extend our model to other significant muscles making the leg move and, from an experimental angle, we are applying this controller to our pneumatic biped.

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