Energy Efficient Control of Running Legged Robots. A Case Study : The Planar One-Legged Hopper

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Abstract: The paper addresses the problem of energy-efficient control of running legged mechanisms via the case study of the planar one-legged hopper. Due to its mechanical simplicity, the planar one-legged hopper is generally considered as the basic prototype of mechanisms capable of ballistic running gaits. What makes this system particularly interesting is that, endowed with a proper selection of springs, it can be controlled without spending much actuation energy. Giving core to this possibility has already motivated a few studies, but has not yet, to our knowledge, been extensively explored. The present study is another attempt in this direction. Being primarily motivated by control design and analysis aspects, we have tried to set the basis of a methodology for the derivation of a new class of simple controllers capable of stabilizing passive periodic motions. Elements of this class are explicited by making specific choices about the model used for control design and the control actuation setting. Although stability analysis is not complete, for reasons which are explained in the paper, the soundness of the proposed approach is illustrated via simulation. The study also unveils new results and intriguing questions, among which some could prove to be central to a better understanding of legged locomotion in general, its potentialities and also its limitations.

Key-words: Legged robots, planar one-legged hopper, passive running gaits, feedback stabilization, energy consumption.

(Résumé : tsvp)

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Commande énergétiquement efficace de robots à pattes pouvant courir. Un cas d'étude : le monopode planaire

Résumé : Le rapport traite, via le cas d'étude du monopode planaire, du problème de commande efficace sur le plan énergétique des mécanismes à pattes coureurs. Du fait de sa simplicité mécanique, le monopode planaire est généralement considéré comme le prototype de base des mécanismes capables d'allures de course avec phase ballistique. Ce qui rend ce système particulièrement intéressant, lorsqu'il est doté de ressorts adéquats, est qu'il peut être commandé en consommant peu d'énergie. La mise en oeuvre de cette possibilité a déjà motivé quelques études, mais n'a cependant pas encore, à notre connaissance, été explorée de manière approfondie. La présente étude est une nouvelle tentative dans cette direction. Etant principalement motivés par les aspects de synthèse et d'analyse de la commande, nous avons essayé de dégager les principes d'une méthodologie pour l'obtention d'une nouvelle classe de lois de commande simples permettant de stabiliser les mouvements périodiques non-dissipatifs du système. Des éléments de cette classe sont explicités en faisant des choix sur le modèle utilisé pour la synthèse de la commande et la façon d'utiliser les actionneurs. Bien que l'analyse de stabilité ne soit pas complète, pour des raisons expliquées dans le rapport, le bien-fondé de l'approche retenue est illustré par des simulations. L'étude met également en lumière de nouveaux résultats et aspects intrigant du problème, dont certains pourraient s'avérer centraux pour une meilleure compréhension de la locomotion articulée en général, de ses potentialités et aussi de ses limitations.

Mots-clé : Robots à pattes, monopode planaire, équilibres dynamiques passifs, stabilisation par retour d'état, consommation énergétique.

1 Introduction

It is commonly acknowledged that legged locomotion can be superior to wheeled locomotion in some situations. For example, when considering displacements on rugged terrains, perturbations resulting from the system's interaction with the ground are intermittent and discretized in space in the case of legged vehicles, while their effects on the vehicle are permanent in the case of wheeled locomotion. Also, some obstacles can be dealt with more easily by taking advantage of flight phases during which the system does not interact with the ground. If it is not difficult to imagine applications for legged robots once they become operational, it also appears that the development of such systems has been slow and that studies devoted to them are still not numerous. There are obviously economical and technological aspects to explain this situation. Lack of scientific maturity of the domain may also be invoked. Indeed, much remains to be understood about the working of legged systems; not only the artificial mechanical devices designed by Man, but also the comparatively much more complex legged organisms that Nature has populated the Earth with (the human biped, to start with). While the observation of Nature's doings is certainly an important source of inspiration for the mechanical engineer involved in the design of artificial legged systems, it may conversely be expected that the study of human-built legged mechanisms will be helpful to better understand the solutions chosen by Nature. For example, it has been observed [11] that mammals tend to naturally adopt walking or running gaits which minimize energy expenditure for a given displacement velocity. Reasons for saving energy in the case of human-built systems is also clear to everyone. The invention and widespread use of the wheel is directly connected to this type of preoccupation: ideally, when discarding the contribution of friction forces, a wheeled vehicle can maintain any constant speed on a flat horizontal ground without spending energy. From this sole fact one may infer that, for many applications, autonomous (or semi-autonomous) legged robots will not constitute an attractive practical solution as long as they will be significantly more energy-consuming than wheeled vehicles. Although the energy-cost preocupation for legged robots is not new (see [1, 14], for example) the issue has not often been formulated and systematically addressed with the Automatic Control viewpoint, even in the case of the "simple" one-legged hopper (the most basic running mechanism) which is considered here. The present study describes a new attempt in this direction.

Ever since Brown and Raibert built the first prototype in the early eighties [12, 13], the planar one-legged hopper has amazed control engineers with the simplicity of its mechanical design and the complexity of its dynamics. Raibert designed a control law for the planar one-legged hopper. Extensive experiments have established that it was robust, but also very demanding energetically. Trying to solve this problem, Thompson and Raibert [14] modified the original mechanical structure of the planar one-legged hopper, providing it with an additional hip-spring so that, if the joints are assumed frictionless, the robot is able to run at constant speed on a horizontal flat terrain without spending energy (just like a wheel). Raibert's control method has further been investigated in [7]. The specific gaits associated with non-dissipation of energy are called *natural regimes*. Their existence depends on the mechanical design and, more specifically, on the adequate use of mechanical devices (such as springs, which may be seen as the equivalent of animal tendons [11]) which allow for storage of potential energy and its restitution in the form of kinetic energy. A way to reduce the energy consumption of the one-legged hopper is to take advantage of such passive regimes and use control just for the purpose of stabilizing them. Following this idea, Ahmadi and Buehler [4, 5] have proposed an analysis and a method for the determination of trajectories which approximate these associated with the natural regimes, and, from there, have adapted Raibert's controller so as to monitor, in continuous time, the tracking of the predetermined trajectories. They have tested this controller in simulation and observed a substantial reduction of the energy consumption, in comparison with Raibert's early algorithm.

In this paper, we propose an alternative analysis and a somewhat different control strategy for the planar one-legged hopper. More precisely, we view natural regimes as periodic orbits of the system which can be mapped and stabilized on a Poincaré-like section (or return map). This approach has previously been used by McGeer [10], to study the passive walking gait on an inclined plane of a compass-like biped, and more recently by Espiau and Goswami [8, 9] who have also addressed the problem of actively controlling the walking compass. The introduction of a Poincaré return map naturally suggests a discrete-time oriented control design: the control inputs are no longer calculated in continuous time, as done in [4, 5], but rather consist of impulsive or equivalent piecewise-constant forces which are calculated at the beginning of each hopper's step and applied at adequately distributed time-instants. Besides the important energetic aspect, this strategy has also the advantage, with respect to continuous-time controllers, of significantly reducing the amount of on-line computations and of simplifying the control implementation.

The paper is organized as follows. The planar one-legged hopper is described in Section 2 and modelling equations of the hopper's dynamics are derived. In particular, the important phase of contact between the hopper's foot and the ground, at landing, which is not explicited in [4, 5], is here modelled as an inelastic impulsive impact, as done in [10] and [8] for the study of the walking compass. The resulting complete model is the one that we have used in the simulations in order to test the control performance. For practical purposes, the confidence that one may have in the reported results thus depends on the accuracy of this model and its ability to represent a physical system. A mathematical difficulty attached to this model comes from the stance phase (during which the hopper is in contact with the ground) which yields non completely integrable equations. As a result, we have not been able to analytically characterize the "exact" natural regimes associated with this model.

In order to overcome this problem, we have based the control design on an "approximated" simplified model which is described in Section 3. The idea is to obtain an integrable model which matches the "exact" model well enough so that it can reasonably be expected that a robust control design based on this approximated model will perform correctly on the exact model. This is a common control approach when dealing with complex (nonlinear) systems. It should however be pointed out that the proposed approximated model does not correspond to a classical linear tangent approximation of a nonlinear system about one of its equilibrium points. As a matter of fact, it is not even possible to derive such an approximation since the equilibria of the original system (which in the present case would correspond to the natural regimes) are not known. Simulation has thus been used to "validate" the proposed approximated model for displacement velocities up to 3 m/s. To this purpose, it is shown in Section 3 that unforced periodic solutions exist for this model and that they can be characterized analytically. These periodic solutions are called *nominal regimes* in order to distinguish them from the *natural regimes* associated with the exact model. Simulation results are given to show that, when starting at some point on such a solution, the uncontrolled one-legged hopper is capable of performing several hops before falling down. This means that the nominal regimes are not "far" from the natural ones and therefore that the approximated model can be used to predict the natural regimes of the hopper, up to some level of accuracy which depends on the displacement velocity (in this respect we have been surprised to observe that the best performance is not obtained for the lowest velocities).

The next step has consisted in designing a feedback control law which stabilizes, at least locally, the nominal regimes of the approximated model. This is done in Section 4, after deriving a discrete linear tangent approximation of the approximated nonlinear error model and after analysing the controllability properties associated with this linear error model. It is shown that the nominal regimes intersect the Poincaré section on a one-dimensional manifold. This is sufficient to prove that the nominal regimes cannot be asymptotically stable. Another consequence is that the nominal regimes, and the set of corresponding error models, can be parametrized in terms of a single variable, the hopper's desired forward velocity, for example. The number of control actions to be applied during a single step of the hopper can be deduced from the requirement of controllability of the approximated error model. In this respect, it is shown that a single force impulse in the leg during the stance phase, complemented with two torque impulses applied at the hip during the flight phase, are sufficient, whatever the desired forward velocity of the hopper. Nonetheless, more control actions could also be considered in practice, if this proved to be useful for robustness enhancement. Once the conditions for the controllability of the linearized error model are met, any classical linear control design method can be used to determine a stable linear controller and the corresponding matrix of control gains. We have used an optimal Linear Quadratic method.

As shown in the Section 5, control impulses can be replaced by equivalent, but more easily implemented, piecewise constant inputs. Although only local stability of the approximated model of the hopper is analytically established, simulations results illustrate that the proposed control strategy performs well on the exact model of the hopper. As expected, the energy spent by the control to stabilize the hopper is very small compared to the global mechanical energy of the system. This was our prime motivation when starting this study. It is however clear that the input energy cannot asymptotically tend to zero since the stabilized hopper's gait does not exactly coincide with a natural regime. The discrepancy between natural regimes and nominal regimes is also responsible for closed-loop steady-state errors. This reflects for example on the controlled forward velocity of the hopper which converges to a value slightly different from the desired one.

The aforementionned velocity-bias can be removed by complementing the controller with a simple integral action, as shown in Section 6. Simulation results also indicate that the controller so-obtained is robust to various sources of modelling errors (unprecise knowledge of springs' stiffnesses, or unmodelled friction in the robot's joints, for example).

Concluding comments are finally given in the last Section 7.

2 Modelling equations and notations

The planar one-legged hopper considered throughout the paper is represented in **Figure 1**. Like the one studied by Ahmadi and Buehler in [4], it is based on Raibert's earliest prototype [12]. It is composed of a body and a telescopic leg. The center of mass $\mathbf{G_B}$ of the body is at the intersection of the hip-joint's axle and the