Digital Communications and Networks (2015) 1, 141–151

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# A novel approach to gait synchronization and transition for reconfigurable walking platforms

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Received 9 February 2015; received in revised form 15 April 2015; accepted 18 April 2015
Available online 11 May 2015

**KEYWORDS**
Legged robot;
Static stability;
Reconfigurable mechanism;
Jansen mechanism;
Walking platform

**Abstract**
Legged robots based on one degree-of-freedom reconfigurable planar leg mechanisms, that are capable of generating multiple useful gaits, are highly desired due to the possibility of handling environments and tasks of high complexity while maintaining simple control schemes. An essential consideration in these reconfigurable legged robots is to attain stability in motion, at rest as well as while transforming from one configuration to another with the minimum number of legs as long as the full range of their walking patterns, resulting from the different gait cycles of their legs, is achieved. To this end, in this paper, we present a method for the generation of input joint trajectories to properly synchronize the movement of quadruped robots with reconfigurable legs. The approach is exemplified in a four-legged robot with reconfigurable Jansen legs capable of generating up to six useful different gait cycles. The proposed technique is validated through simulated results that show the platform's stability across its six feasible walking patterns and during gait transition phases, thus considerably extending the capabilities of the non-reconfigurable design.


## 1. Introduction

Legged robots have always been a preferred choice for a variety of applications like search and rescue given their versatile and rugged locomotion capabilities. The choice of legged mechanisms often responds to design requirements such as the ability to move through irregular terrains or to increase stability, maneuverability or energy efficiency.

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http://dx.doi.org/10.1016/j.dcan.2015.04.003

However, any valid gait reconfiguration – *i.e.*, a useful change of walking pattern – in these legged robots poses numerous opportunities as well as research challenges. Legged animals coordinate a wide range of components and systems to walk adaptively and efficiently under a variety of speeds, terrains and task goals including chasing, courtship and stealth.

The robotics literature shows a variety of design strategies to generate different gait patterns in legged robots, including, to name a few: structural combination of rigid and tensile structural elements [1], morphological computation [2], oscillator controller with pneumatic actuators [3] and biomimetic adaptations based on ground contact timing [4] or using sensorimotor coordination [5]. Alternatively, walking platforms based on one degree-of-freedom reconfigurable planar leg mechanisms, that are capable of generating multiple useful gaits, while maintaining simple control schemes can also be proposed. For example, in [6], a reconfigurable Jansen leg that varies its hardware morphology to produce a wide set of novel gaits by parametric changes of its components and subassemblies was discussed. To ensure safe locomotion across a difficult terrain, a robot must be able to stably switch between gaits either at rest or in motion. Literature points a number of efforts to this end, [7] proposes an approach based on acyclic feed forward motion patterns that allow a robot to switch from one gait to another. Ref. [8] applies nonlinear oscillators to model Central Pattern Generators (CPGs) that is able to initiate/stop locomotion; generate different gaits, and to easily select and switch between the different gaits according to the speed and/or the behavioral context. Ref. [9] attempts to induce a quadruped robot to walk and switch gaits dynamically on irregular terrain and run on flat terrain by using a nervous system model.

A fundamental problem of the gait reconfiguration solutions based on reconfigurable legged robots is to reach stability both in motion and rest, as well as while transforming from one configuration to another with the minimum number of legs, while the complete range of walking patterns is available. In this paper, we discuss a method for the proper generation of input joint trajectories to synchronize the different gait cycles and gait transitions of quadruped robots with one degree-of-freedom reconfigurable legs. In order to exemplify our approach, we focus on a four-legged robot with reconfigurable Jansen legs (Fig. 1). Theoretically, such walking platform is capable of generating up to six useful different walking patterns, resulting from the different gait cycles of a reconfigurable Jansen leg. It will be shown how, by using the proposed technique, all these feasible patterns can be successfully attained. In this way, the capabilities of a quadruped robot based on standard non-reconfigurable Jansen legs are considerably extended. In particular, the synchronization and the gait transitions are realized by utilizing a trajectory generator based on fifth-polynomial interpolation. Our presented reconfigurable platform, a novel approach of reconfigurable robot contained within a nested reconfigurable concept [10], needs applications for the synchronization for walking as well as the gait transitions between the gait patterns. However, to design applications for each synchronization and each gait transition is meaningless due to infinite complexities. Hence, the biggest challenge of this paper is to achieve these with the simplest application as much as possible. This paper reports that all synchronization and gait transitions can be achieved by only one gait generator by utilizing fifth-polynomial interpolation.

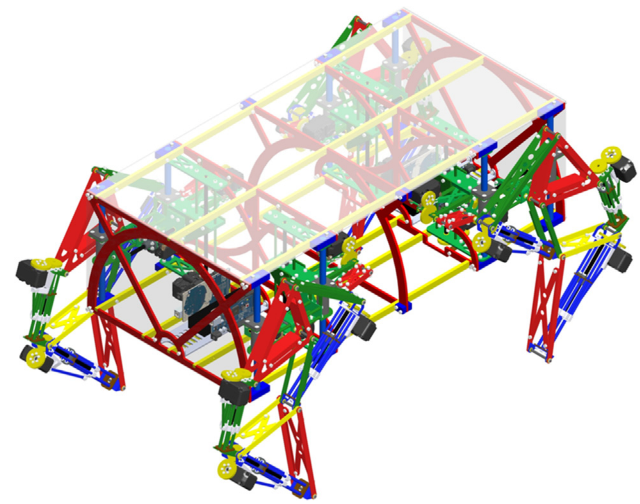

**Fig. 1** Legged robots based on one degree-of-freedom reconfigurable planar leg mechanisms may operate in environments and tasks of high complexity while maintaining simple control schemes. This four-legged robot is based on reconfigurable Jansen legs capable of generating up to six different gait cycles.

The rest of the paper is organized as follows. Section 2 presents the specifications of the reconfigurable Jansen platform under test. Section 3 deals with the formulation of the trajectory generator. Section 4 puts forward the synchronization strategy for coordinating multiple leg movements to achieve the six distinct stable walking patterns. Section 5 presents the static stability analysis of the synthesized walking gaits. Detailed characterization of the realized gait transitions for both static and dynamic cases are dealt in Section 6. Static stability analysis of the gait transitions is presented in Section 7. Finally, section 8 concludes this study.

## 2. Specification of the reconfigurable Jansen platform

In this section, specifications of a developed reconfigurable Jansen legged robot are discussed. This reconfigurable walking platform is used herein as case study for the generation of input joint trajectories to synchronize multiple reconfigurable one-degree-of-freedom legs for realizing stable walking gaits.

In a previous study, we reported a reconfigurable approach to robotic legged locomotion that produces a wide variety of gait curves, opening new possibilities for innovative applications [6]. Such robot can vary its hardware morphology by parametric changes of its link lengths. In particular, this reconfigurable linkage switches from a pin-jointed Grübler kinematic chain to a five degree-of-freedom mechanism with slider joints during the reconfiguration process. The identified novel gait patterns are shown in Table 1.

An essential consideration in most legged platforms that determines the required number of legs is the ability to attain stability both in motion and rest. Previous works related to legged platforms based on standard non-reconfigurable Jansen legs have overcome the stability issues by utilizing more than four legs – *e.g.* [14]. However, increasing the number of legs gives rise to a range of other problems including greater cost and size, a more complex electro-mechanical control system,