Considerations of limb impulse capabilities enable low-bandwidth multi-level control for online gait emergence and adaptation

Chiheb Boussema[a,b], Patrick M. Wensing[c], Auke Ijspeert[a], Sangbae Kim[b]
[a]Institute of Bioengineering, EPFL, Switzerland
chiheb.boussema@alumni.epfl.ch, auke.ijspeert@epfl.ch
[b]Department of Mechanical Engineering, MIT, USA
sangbae@mit.edu
[c]Department of Aerospace and Mechanical Engineering, University of Notre Dame, USA
pwensing@nd.edu

Abstract

Because real-world legged locomotion constantly departs from periodicity, reliance on an internal clock and discrete hard-coded situation-specific reflexes for gait control poses challenges to the deployment of adaptive dynamic legged robots. In this study we argue in favor of the necessity for robots and animals to have a sense of their physical capabilities in terms of impulse generation. Specifically, we introduce the Feasible Impulse Set, a notion that extends aspects of the classical wrench cone to include a prediction horizon into the future. This set allows the quantification of notions of leg utility through simple and physically-intuitive metrics that are used to coordinate adaptive lift-off and touchdown of stance legs. The proposed framework thus integrates local reflex-like mechanisms with more centralized interlimb coordination and single step planning. Without fixed timings or predefined foothold sequences, we show the online emergence and transition of gaits with speed, push recovery and gait adaptation. Validating experiments are performed on the MIT Cheetah 3 robot, which is shown to automatically adapt to different ground speeds for different legs.

Keyword: Legged robots, gait emergence, gait adaptation.

1 Introduction

Gait studies in animals have traditionally investigated either neurophysiological or mechanical aspects [1, 2]. Such studies provided enormous insight into animal and robotic locomotion, emphasizing the importance of clever mechanics as well as the neural architecture. Although not universally agreed on, central pattern generators (CPGs) in the central nervous system (CNS) have attracted much attention in gait generation. However, apart from detailed Hodgkin-Huxley models investigating restricted circuitry [1], most pattern-generating models are phenomenological in nature with varying degrees of abstraction [2]. While such models are useful in testing localized hypotheses about locomotion, the phenomenological nature and abstraction from basic components lead to the risk of missing out important underlying generative components that allow adaptability, especially in robotics control. In particular, neuromorphic, mostly feedforward, CPG implementations do not relate to physical capabilities and translation of the CPG output into leg trajectories is hand-tuned. Sensory feedback regulation has allowed partial compensation of this and excellent work has been produced in this regard [3]. However, results have shown that the activation of specific muscle synergies is closely linked to a sense of physical abilities, whereby "constraints at the performance boundaries" uniquely determine muscle activation patterns even at submaximal operational modes [1]. By contrast, the phase variable in CPGs often carries no physical information, making control more difficult. We thus argue that physically-motivated metrics of leg capabilities would be more suitable for adaptive leg control and interlimb coordination.

2 Leg Utility Control Framework[1]

Beyond classical force and center of mass (CoM) acceleration considerations, we conjecture that a sense of impulse[2] generation capabilities is of primary importance for locomotion. Indeed since impulses take into account the dynamics over extended time frames, impulse considerations allow a higher level of abstraction to reason about the timing and locations of contacts. To formalize this, we consider the set of impulses that can be generated by the contact legs, individually and combined. We name such a set a Feasible Impulse Set (FIS), and use its volume to generate physically-intuitive metrics of leg utility, from the perspective that the larger the volume of the set, the greater the capabilities. These metrics, along with the FIS, then endow the robot with a sense of its own capabilities within a stride, allowing adaptive foot touchdown and swing onset. With these tools we show that periodic entities like CPGs are not required to produce unprescribed gait transitions and adaptive behavior. In particular, our framework allows both periodic and aperiodic movements as fit to the situation.

[1]More details can be found in [4].
[2]The integration of forces over time.

2.1 Feasible Impulse Set

Feasible force sets (FFS), $\mathscr{F}$, are traditionally used to represent the set of forces that can be generated by a leg while respecting friction and torque limits. We extend the notion of FFS to span a time horizon by making a discrete integral (Minkowski sum, $\bigoplus$) of the FFS polytopes along a trajectory, i.e., along a number of nodes in a discretized foot workspace. We name the resulting set the Feasible Impulse Set (FIS), $\hat{\mathscr{F}}$, given by Eq. (1):

$$\hat{\mathscr{F}} = \bigoplus \mathscr{F}_i \cdot \delta t_i, \qquad (1)$$

2.2 Leg Utility Metrics & Locomotion Control

The volume of the FIS is used to compute a *utility* metric measuring the remaining impulse capability of a leg. Swing onset is then triggered in a reflex-like fashion when utility is low. A *marginal utility* metric is also defined, measuring the relative importance of a leg to the overall impulse generation capabilities. The latter is akin to a more centralized integration of information for interlimb coordination and only allows swing onset when the marginal contribution of a leg is low[3]. Finally, more agility metrics are derived by further refining the notion of FIS to quantify different impulse capabilities[4] (Figure 1). A tradeoff between these sets, emphasizing different needs, is used to decide foot touchdown position. The possibility to make libraries of metrics and associated foot positions allows for reflex-like stepping, while the online change of considered tradeoff is akin to efferent modulation that allows seamless transitions, e.g. from forward to backward motion. Figure 1 illustrates the above.

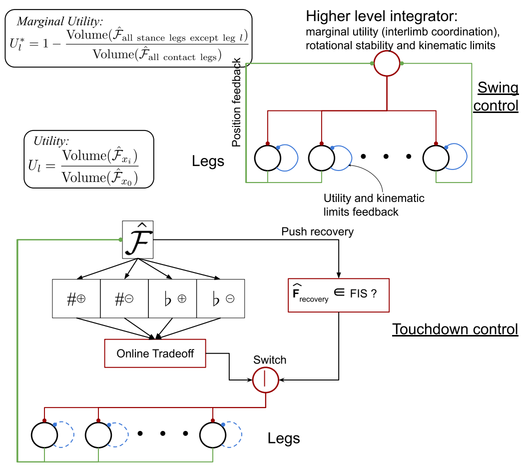

Figure 1: Overview of the locomotion control strategy. The notations $\sharp$ ($\flat$) refer to forward (backward) motion FIS, and $\oplus$ ($\ominus$) refer to the positive (negative) FIS subsets.

3 Results and Discussion[5]

Experiments, some of which are shown in Figure 2, were performed on the MIT Cheetah 3. By understanding the individual and relative leg impulse capabilities, contact periods were able to adapt automatically as swing onset only happens when necessary. This feature allowed the asynchronous control of legs, resulting in the emergence of periodic and aperiodic locomotion, and unprescribed gait transitions with speed. Gaits that emerged were an L-walk, a 3-beat "half trot", and a trot gait. We noticed a hysteresis in gait transitions depending on speed change direction [2]. Aperiodic behaviors include adaptation to legs experiencing different ground speeds, and multi-legged N-step push recovery. We also show adaptation to injury, and reduction of the mechanical cost of transport (CoT) with gait transitions.

We justify the consideration of impulse capabilities by the fact that impulses take into account motion dynamics over extended time frames and filter out instantaneous low level details. In this sense, they comply with low cognitive bandwidth constraints for "trivial" locomotion tasks.

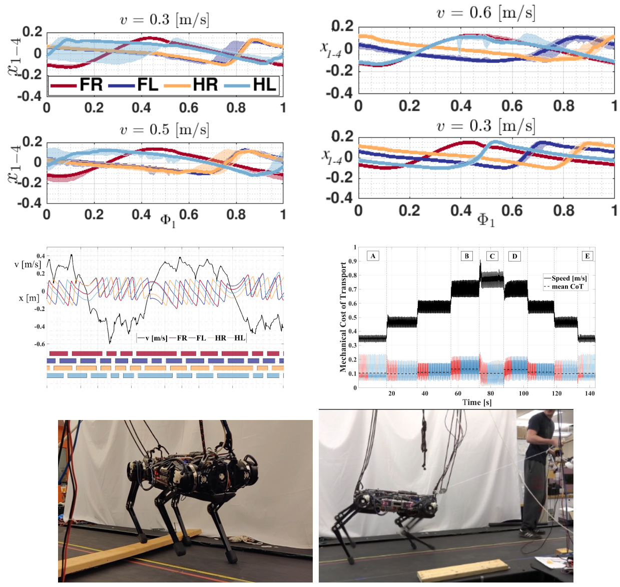

Figure 2: (Top) Gait transitions with speed [foot positions vs FR's phase]. (Middle) Stance phase adaptation, and CoT change with gait transitions† [A,E: L-walk, B,D: intermediate gait, C: half trot]. (Bottom) Automatic adaptation to a partially-moving walkway† and to continued pulling. †Reproduced from [4] with permission from IEEE.

4 Conclusion

Leg impulse considerations allowed for the integration of reflex-like mechanisms and low bandwidth computations from higher centers of command. This approach achieved natural looking behaviors of adaptive touchdown and liftoff.

[3]These two utility metrics bear qualitative similarity with the phase-delaying loading condition in [3].

[4]While FIS computations are in the sagittal plane, locomotion is in 3D.

[5]Additional results and a broader discussion can be found in [4].

References

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