Towards Understanding Visually Guided Locomotion over Complex and Rough Terrain: A Phase-Space Planning Method

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I. Introduction

As legged robots maneuver over increasingly complex and rough terrains, designing motion planners with the capability of predicting future footsteps becomes imperative. In turn, these planners provide a valuable tool for understanding the fundamental principles underlying human locomotion [2, 3]. In this study, we use our previously proposed phase-space planning framework [1] to analyze human walking over complex terrain. In particular, we highlight (i) the center of mass (CoM) apex-state-based feature of the phase-space planning, and (ii) the role of vision in CoM apex state selection during human walking over complex terrain [2].

II. Phase-space Planning

Phase-space planning [1] is a planning and control framework for robust and agile legged robot locomotion over highly irregular terrain and constraint environment. This framework focuses on the center of mass (CoM) dynamics, which characterize essential features of the dynamic locomotion model. Using 3D inverted pendulum dynamics and given a sequence of desired phase-space apex states, we present a phase-space planner that can precisely negotiate various challenging terrains. A step transition strategy is defined as the phase-space trajectory intersection that enables the planner to dynamically track the non-periodic apex states. We define phase-space manifolds and derive a Riemannian distance metric to measure deviations due to external disturbances. A hierarchical robust control strategy is proposed to steer the locomotion process towards the planned trajectories. A salient feature of phase-space planning is its CoM-apex-state-based property as shown in Fig. 2. Instead of using the initial state of each walking cycle, our planner chooses CoM apex states as the keyframe, which is more suitable for future foot placement planning.

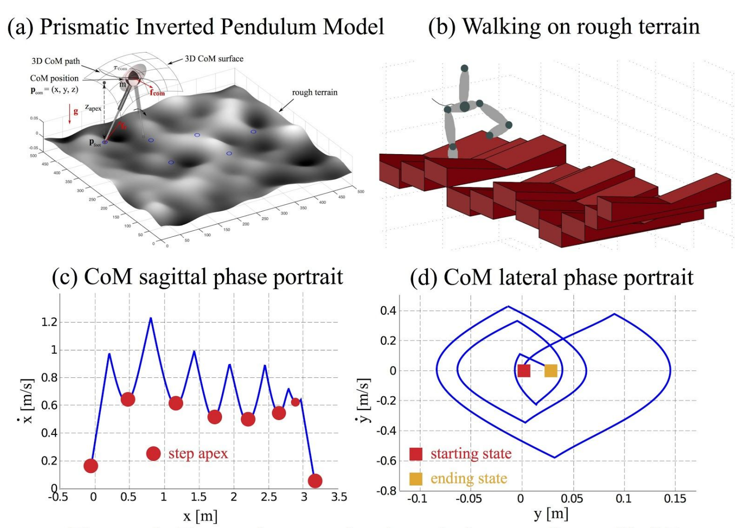

Figure 1. Dynamic complex terrain locomotion with 3D inverted pendulum model and phase-space motion planners.

III. Visually Guided Human Walking over Complex Terrain

During locomotion over complex terrain, humans use visual information about the upcoming to select safe, stable footholds and avoid environmental impediments [4]. Recent research suggest that visual planning of future footsteps occurs during a particular phase of the gait cycle, that is, that there is a critical phase for the visual control of foot placement that occurs during the second half phase of the preceding step [4]. We interpret this *critical control phase hypothesis* within our phase-space planning framework in Fig. 2. In the second half phase of the preceding $(k-1)^{th}$ step, the phase-space planner needs to makes adjustments to the upcoming apex state based on visual information about the k^{th} target foothold. Once the CoM state starts the k!! step, the visual information about that target is no longer necessary as the planner begins to enact the changes necessary for the $(k+1)^{th}$ step.

IV. Interpretation of Visually Guided Human Walking by Phase-Space Planning

Phase-space planning is inspired from human walking over complex terrain. In this study, we compared human walking data and the phase-space planner as shown in Fig. 3 (a) and identified several common features. The apex state and toe-off timing correlated fairly well while the heel-strike timing showed larger differences. The blue trajectory segments represent the dual contact phase for step transitions. In Fig. 3 (b), we compare the sagittal phase-space trajectories of human walking with and without foothold targets. When walking without foothold targets (dotted blue line), the walker adopts preferred gait cycle based on its natural inverted pendulum dynamics. When walking with foothold targets (solid red line), they must modify that gait cycle and adjust their apex states according to visual information about upcoming targets.

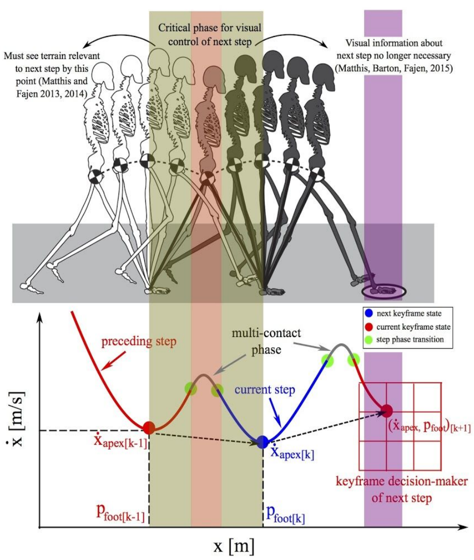

Figure 2: Phase-space illustration of the critical phase hypothesis for visual control of the next foot placement.

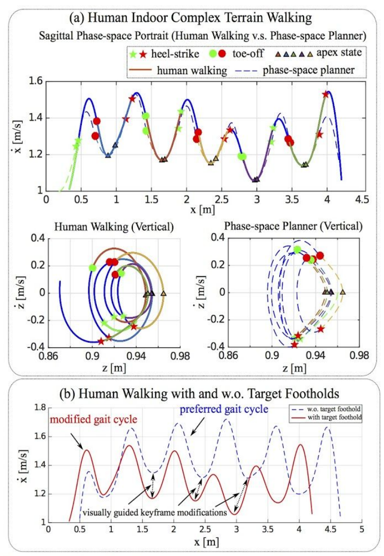

Figure 3 (a) CoM phase-space portraits of complex terrain human walking, comparisons with the phase-space planner, and (b) changes in the sagittal phase portrait during walking with and without visually specified target footholds.

V. Discussion and Future Directions

Matthis and Fajen [4] showed that planning two footsteps ahead allows humans to control foot placement as accurately as they do with an unlimited visual horizon. This observation may assist in the development of an optimal footstep planner within our phase-space framework. We also plan to devise a theoretical method to explore how humans incorporate visual information about upcoming footholds into future keyframe decisions as shown in Fig. 2.

In this study, we leverage our phase-space planning framework from robotics to investigate the biomechanical principles underlying visually guided human walking. In the future, we would like to study human walking under disturbance and use the phase-space robustness metric to quantify deviations from the nominal gait cycles. Also, we would like to validate the hypothesis that planning future 2-4 steps is important for not only the foot location but also the CoM apex velocity.

This work also sheds new information on how we might understand rehabilitation and recovery following physical and cognitive injuries that impact human locomotion. For example, Parkinson's patients suffer from a compromised ability to control gait, and these issues are dependent on the available perceptual information. Understanding how the role of perceptual information in locomotion depends on the mechanics of walking (and thus the underlying control processes) can provide crucial insight into how locomotor maladies (such as those in Parkinson's) might be treated.

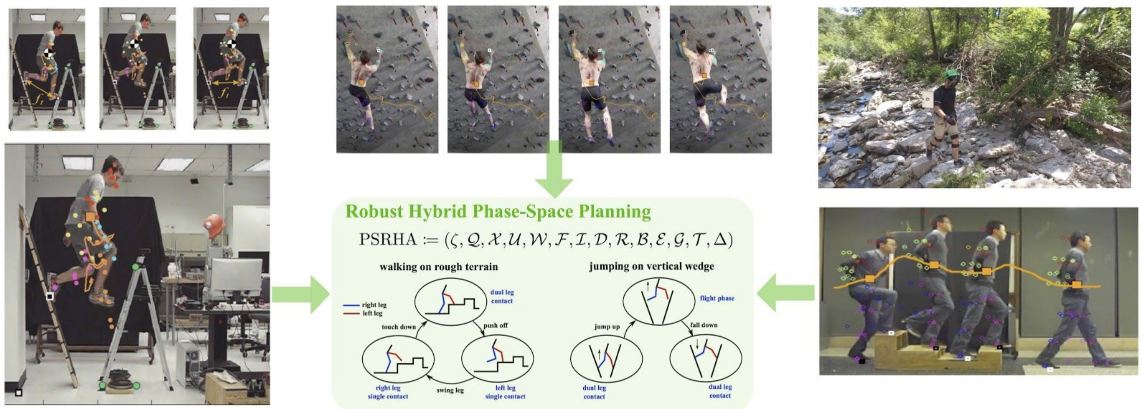

Figure 4. Generalized human locomotion behaviors over challenging terrains

Another future direction of our interest is to leverage human-understandable language (e.g., temporal logic methods which are well-established in computer science and control fields) to understand human brain logic and decision-making mechanism during human walking, especially for those maneuvering over the constrained environment. Recently, we have been exploring contact-based robot decision makers according to sensed discrete environment actions [6]. A two-player game was formulated to synthesize a non-deterministic automaton and generate a winning strategy such that the robot is guaranteed to win the game against the possibly-adversarial environment, i.e., safety guarantee. A hypothesis we are conjecturing is that human instinctively follows certain type of logic mechanism to make high-level locomotion decisions. Given this hypothesis, how can we exploit temporal logic to represent human behaviors, and synthesize meaningful decision makers generating locomotion actions that are consistent with real human actions. In that sense, we could potentially understand the fundamental logic principles that human follows during their walking or more generalized motion behaviors as shown in Fig. 4.

Reference

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