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Component based computational model for bipedal locomotion

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HIGHLIGHTS

- Modeling of human gait using Hybrid Automaton.
- Construction of atomic components to model human gait.
- Integration of the atomic components and the hybrid automata in the BIP (Behavior, Interaction, Priority) Framework.
- Modeling the interactions between the atomic components.
- Verification of the proposed model in OpenSim for both normal and crouch gait.

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ABSTRACT

Bipedal locomotion has been an active area of research for many decades, it has wide ranging applications in the field of humanoid locomotion, as well as in the understanding of the biomechanics of normal human gait. Inherently human gait is a complex non-linear dynamic system, which is usually modeled by a set of differential equations satisfying a given set of constraints. In this paper an attempt has been made to view gait from the perspective of software engineering. In doing so, the entire gait cycle has been discretized into phases and sub-phases and modeled using a hybrid automaton, subsequently the automaton has been integrated with the BIP(Behavior, Interaction, Priority) framework, thereby creating a component based computational framework for modeling biped locomotion. The correctness of the developed model has been validated and verified through simulation runs in OpenSim.

1. Introduction

Biped Locomotion has been modeled across a wide array of disciplines including robotics, computer vision, mathematics and mechanics are just to name a few. The earliest attempt to quantitatively study biped locomotion was made by Vukotrabovic et al., who had introduced the notion of Zero Moment Point (ZMP) [1]. The Zero Moment Point is a special point, in the base of support of the feet, through which the resultant ground reaction forces pass and hence the net torque is zero. The concept of ZMP was further augmented by Stephens [2], who had introduced a more general form of the ZMP and COP (Center of Pressure) terming it as CMP (Centroidal Moment Point). In the same paper he had introduced the decision boundaries as being a metric for applying different strategies for push recovery (i.e. Ankle Strategy, Hip Strategy, and Stepping). The decision boundaries are closed form loops, which closely resemble Lyapunov [3] exponents. Ankle, Hip strategies were further implemented by Nenchev and Nishio [4] using Reaction Null Space Transformation, the experimental results carried out by them on a HOAP-2 robot confirm the veracity and accuracy of their claim. Capture Points a novel concept introduced by Goswami et al. [5] describe the regions of stable gait on the application of an external push on the biped. All the models described above base their conclusions on the inverted pendulum or linear inverted pendulum model of human gait. Foot placement Estimator [6] also uses the same inverted pendulum model to base its assertions on the lines of stability of normal gait. Further work on biped locomotion involves using Functional Routhian Reduction to study the walking patterns of 3-D bipeds [7]. A Partially Observable Markov Decision Process was employed by Sreenath [8] et al., for studying the locomotion of bipeds on different terrains. Other than such mainstream research, some groundbreaking studies have been undertaken by Morimoto and Atkeson [9], who have applied Poincare-map based Reinforcement Learning to biped robots. Hoffmann [10] has provided a simple and yet robust representation of the locomotion modeling by arguing that only the trajectory of the COM (Center of Mass) is more than sufficient to model the entire gait cycle.

Apart from biped locomotion [11] describes a novel gait methodology in order to obtain an efficient walking capability

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for an original walking free-leg hexapod structure of tri-radial symmetry. Torque analysis is studied to determine the motor torque requirements for each step of the gait so that the robotic structure yields a stable and achievable pose, consequently, a gait generating algorithm is proposed for different types of terrain such as flat, ramp or stepped surfaces. In [12] existing methods for robot–terrain interaction in highly unstructured environments has been studied extensively, the authors have devised an iterative contact point estimation method for static stability estimation of actively reconfigurable robots. The results obtained prove that it is a fast approximate method, comparable to the current state of the art and provides good results in realistic robotic scenarios. Recently authors in [13] have proposed a method of designing a more human-like walking pattern for a bipedal humanoid robot, motivated by biomechanical studies on human walking, they have modeled the walking pattern with continuous and differentiable mathematical functions. Using a pattern generator based on ZMP (Zero Moment Point) the robot has been found to walk with almost stretched knees at low and medium walking speeds. Their propositions have been validated by experiment on the NAO robot. Semwal et al. [14] have proposed an 8 stage gait model based on hybrid automaton for large push recovery and a controller to verify different stages of human locomotion. They have also identified the importance of the human lower extremity for locomotion and push recovery from a large perturbation. The 8 stage gait model proposed there has been further simplified to a 6 state gait model and integrated with the BIP framework in the present study.

In [15] the authors study the walking robot hybrid dynamic control in real time in order to increase movement stability of walking robots on flat terrain, with obstacles or uneven ground, at constant or variable walking speed and variable load. The motion trajectory positions of the robot leg end-effect and/or joints, reaction forces and the walking robot dynamics are analyzed and the virtual projection method is adopted using the Versatile Intelligent Portable Robot Platform VIPRO. The obtained results lead to higher performance in comparison to the existing state of the art. With respect to control of legged locomotion Gabriel et al. [16] have introduced a gait generation framework for multi-legged robots based on max-plus algebra that is endowed with intrinsically safe gait transitions. They present various gait transition schemes which show optimal transitions, in the sense of minimizing the stance time variation, allow for constant acceleration and deceleration on legged platforms. The framework relies on a compact representation of the gait space, it also provides guarantees regarding the transient and steady-state behavior, and results in simple implementations on legged robotic platforms.

In the field of formal controller synthesis Aaron et al. [17] have proposed a two-step approach to formally synthesize control software for bipedal robots so as to enforce specifications by design and thereby generate physically realizable stable walking. In the first step, they have designed outputs and classical controllers driving these outputs to zero, the resulting controlled system then evolves on a lower dimensional manifold and is described by the hybrid zero dynamics governing the remaining degrees of freedom. In the second step, they have constructed an abstraction of the hybrid zero dynamics that is used to synthesize a controller enforcing the desired specifications to be satisfied on the full order model, which has been experimentally verified on the AMBER 2 robot. In the area of reproducing bilateral gait through dynamic model Batista et al. [18] have used kinematic and dynamic motion analyses through model simulation with hybrid system of the lower limbs for training and rehabilitation of the human gait. Using a finite state machine authors in [19] have developed an automatic approach to derivation of Lagrange equations of motion. The software for construction of numerical models for different working modes of the mechanism has been developed and the proposed system has been applied to the problem of planar walking pattern generation for bipedal mechanisms. In relation to developing software for humanoid control Neil et al. [20] have introduced a software synthesis method for speed-controlled robot walking based on supervisory control of a context-free Motion Grammar. They have used Human-Inspired control to identify parameters for fixed speed walking and for transitions between fixed speeds, guaranteeing dynamic stability and then built a Motion Grammar representing the discrete-time control for this set of speeds. They have experimentally validated their claims on the Aldebaran NAO.

In all the approaches described so far, the developed gait models are highly biased i.e., they make certain assumptions about biped locomotion which may or may not be true. This not only limits the application of the models but also fails to create a generic unifying framework for modeling human gait. In comparison our model does not make any such assumption except one that is, the leg can be divided into a set of atomic components (ankle, knee and hip in our case). The interactions between these atomic components and the phase transitions modeled using the hybrid automaton provides a sound and complete picture of normal human gait. The interaction between these atomic components has been modeled using the BIP framework. The framework, originally developed for Rigorous Component Based System Design [21], especially those involving embedded systems, has been ported to meet our specific system requirements. It involves the separation of concerns between different constituent components and follows a layered approach in order to integrate the notion of "correctness by construction", in the three independent layers (i.e. Behavior, Interaction, and Priority) [22].

The main contribution of our work lies in introducing a framework for discrete decomposition of human gait cycle and analyzing the interaction between these phases. The expressive power of BIP in terms of conflict resolution and interaction modeling has been exploited to make the design complete and technically sound. The rest of the paper is organized as follows, Section 2 provides a brief introduction of BIP Section 3 provides the details of the Methodology used and the developed system model. Section 4 provides a glimpse of our experimental observations and implementations. Section 5 concludes the paper by listing the drawbacks of our model and the direction of our future work.

2. Theoretical tools

2.1. BIP framework

It is a layered architecture, which consists of three atomic layers named aptly as Behavior, Interaction and Priority. A component based framework, where each component is atomic in nature. The layers, which are named above are independent of each other and interact with each other, through well-defined semantics. The framework is usually used as a test-bed for both hardware and software components [23]. Other frameworks and architectures can be easily mapped into it using its rich collection of toolsets [24]. The notion of "*correctness by construction*" is embedded in the design phase itself. In our context "*correctness by construction*" implies that BIP provides the basis for study of preservation of properties under architecture or behavior transformations, which means that we can check for the correctness of individual components in the design phase itself. The glue connectors/interactions are explained by a mathematically sound theory often dubbed as the Algebra of Connectors/Algebra of glue [25], which acts like unifying notion to integrate the interaction between several heterogeneous atomic components. The interactions occur through the ports associated with the atomic components, there are only two ports synchron (depicted by a filled complete circle) and