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A review on numerical models and controllers for biped locomotion over leveled and uneven terrains

Navaneeth Varma*, K.G. Jolly[a] and K.S. Suresh[b]

Department of Mechanical Engineering, N.S.S College of Engineering, Akathethara, Palakkad-678 008, Kerala, India

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Abstract. The evolution of bipedal robots was the foundation stone for development of Humanoid robots. The highly complex and non-linear dynamic of human walking made it very difficult for researchers to simulate the gait patterns under different conditions. Simple controllers were developed initially using basic mechanics like Linear Inverted Pendulum (LIP) model and later on advanced into complex control systems with dynamic stability with the help of high accuracy feedback systems and efficient real-time optimization algorithms. This paper illustrates a number of significant mathematical models and controllers developed so far in the field of bipeds and humanoids. The key facts and ideas are extracted and categorized in order to describe it in a comprehensible structure.

Keywords: biped gait; Zero Moment Point (ZMP); non-linear dynamics; passive walkers

1. Introduction

Human locomotion can be modeled and imitated effectively through a two legged mechatronic system called biped robot. A Human locomotion is always associated with a system of non-linear equations. The task of simulating the behavior on a biped or humanoid can be cumbersome if the exact model is considered for the gait generation. So, normally a simplified and linearized model of the original non-linear system is employed for the design of control algorithm for the robot. The early development of biped actions was purely based on kinematic model of the planar robot on flat terrains. Golliday and Hemami (1977) derived a dynamic model for a knee-less biped using Lagrangian dynamics constrained to the sagittal plane for arriving at a simplified model. Later on, researches started focusing more on linearizing the non-linear dynamic models for designing robust control systems similar to the one shown in Fig. 1. Such robust controllers were essential for adapting biped locomotion under disturbances in the form of ground uncertainties and the presence of obstacles as well.

A number of researches were focusing on walking of biped on flat ground. The problem of

∗Corresponding author, M.Sc., E-mail: mg.navaneeth@gmail.com
[a]Ph.D., E-mail: kgjolly@hotmail.com
[b]Ph.D., E-mail: sureshsethu@rediffmail.com

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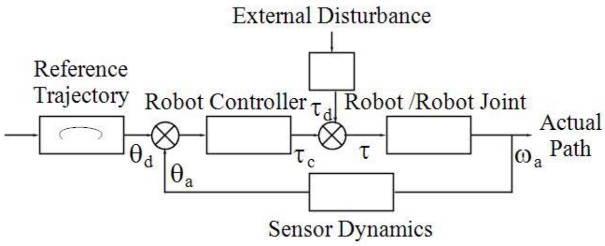

Fig.1 A typical control system for a robot joint

biped locomotion on more difficult terrain has been addressed by Zheng and Shen (1990). The paper proposed a novel method to enable the SD-2 biped robot (constructed at Clemson University) to climb the sloping surface, by tilting of representative upper body mass and manipulate the position of CoM projection on support area. This static walking strategy was found to be applicable to quasi-dynamic as well as dynamic walking provided the computing time needed to be much lesser. Only climbing the slope was addressed and a negative slope as well as walking on an uneven terrain were future scopes.

The invention of more sophisticated and versatile drive systems aided in minimizing the size and improving the performance of humanoids. Servo motors integrated with encoders, position, velocity and acceleration sensors, sophisticated regulators etc. made it easier for optimization of the calculated robot trajectories. The biped robot locomotion can be categorized into two major fields such as passive walking and active or actuated walking. This classification is based on whether the joints are actuated by gravity or by actuators.

2. Gait generation and control

2.1 Passive walking

The passive walkers are generally used for understanding the dynamic behaviors of the human locomotion and for developing solid mathematical governing models along with analytical optimization methods for applying it to biped robot systems. Inada and Ishii (2004) investigated the execution of biped walking using a Central Pattern Generator (CPG) based on Matsuoka neuron model. The target time series parameters of hip, knee and ankle joints are optimized using genetic algorithm and output of neurons are set as target joint angles. The results are simulated using MATLAB and DADS (Dynamic Analysis and Design System). CPG was also used in an analogous passive walking strategy for a five-link biped along with simple feedback control and spring-damper control to speculate the reasons behind falling of the biped with large torso mass was proposed (Hoshino *et al*. 2011). Narukawa *et al*. (2011) presented a numerical approach to find out the optimized walking of a biped with torso and two hip actuators without knee and ankle joints. The comparison of torque costs under simple feedback and optimized control is also carried out. Adding springs at the hip joints reduced the torque costs up to 70% at a walking speed of 0.9 m/s and 95% at 1.4 m/s because of the drop in peak torque after impact with the ground. Rushdi *et al*. (2014) experimentally studied the passive dynamic biped walker on a ramp and on a treadmill to reach at a number of significant conclusions. The closeness of center of mass towards the hip leads to higher step length, higher hip velocity and lower step period. The angle of inclination was found to have more influence on step length than step period. The dependency of static center of mass had limited control over step period compared to other dynamic factors which can be the future scope of this study. Instead of gravity driven passive walkers, Alghooneh *et al*. (2014) put forward a passive bipedal walker having 3 DOF which are one hip, two knee joints and fixed round-ankle to the shank. It can walk on flat surfaces compared to normal slope walkers by utilizing the energy stored in a torsion spring attached to the hip joint. About 40% of the gait cycle is engaged by the energy delivered from the spring and rest of the cycle is covered by the natural dynamics of the body. The biped performed a highly efficient and dynamic locomotion with a transportation cost of 0.236 which is a superior value that is comparable among current stage humanoids.

2.2 Active walking

The unpredictability of the profile of the surface on which the biped has to walk makes it critical to design appropriate and sensitive actuators equipped with feedback capabilities for trajectory generation and tracking. Hirai (1999) described about the evolution of Honda Humanoid Robot P2 and P3 which were the earlier versions of Asimo. The control system modeling was performed by deeply understanding human body and its locomotion. Various factors involved in the human locomotion like dimensional features of the legs, position and effectiveness of leg joints, joint torques, sensory systems involved etc. are studied in detail. The initial static walking model developed was then converted into dynamic walking model through a control scheme that minimizes the distance between desired ZMP and Center of ATGRF (Actual total ground reaction force). The tipping moment was thus controlled. Though P2 was bulky in size, heavy, low efficiency of high torque brushed motors, they were corrected by scaling down the components in P3. The robot was however operator driven which lacked autonomous path planning and obstacle avoidance skills with the help of visual information.

2.2.1 Fundamental control rules and exemptions

The conventional control laws for biped locomotion such as ZMP tracking and LIP model were used for controller designs in earlier times. Later on, many complex and hybrid controllers were introduced which were assisted by firm mathematical and analytical models. Plestan *et al*. (2003) modeled and simulated the stable walking of a 7 DOF biped. The controller was designed based on two assumptions: rigid contact between leg and the floor and, an instantaneous double support phase. Instead of numerical methods, Poincare map with asymptotic stability control was employed and validated. Disturbance rejection capabilities were also verified. Optimized feedback control was the next stage of this research to exploit natural dynamics for stable walking motions. Similarly, the simulation of a seven link biped robot was illustrated by Mousavi and Bagheri (2007) and it was performed based on the system given break points and third-order spline for trajectory generation. The simulations have been done for single and combined paths as well as for fixed and moving ZMP. Only sagittal stability was considered and frontal considerations were ignored. As an extension of the above, the same biped robot was simulated by Mousavi *et al.* (2008) in a combined trajectory path environment involving mathematical models that focus on the effect of hip height over torso's modified motion to achieve the desired ZMP position, considering only the sagittal stability. Also, it was proven that a higher hip height will prevent the velocity discontinuities of links. The conventional biped motion control using inverse kinematics of the planar biped is presented by Bajrami *et al*. (2016), and Mandava and Vundavilli (2016). The theoretical inverse kinematic solution and trajectory planning of a 10 DOF biped was derived in former work using conventional single support phase (SSP) and double support phase (DSP) of the human gait cycle. Trajectories of the hip as well as the foot were used for joint angle calculations supported by constraints for repeatability of the gait and continuity of hip motion in sagittal plane. The inverse model was tested on a real biped and the results were upright. The latter also illustrates the forward and inverse kinematic solutions of a human-like bipedal which has 18 DOF. The locomotion was generated based on calculation of joint angles for lower and upper limb end-effector trajectories represented using cubic polynomials. The dynamic balance of biped was established using the ZMP tracking.

Above models were concentrating more on a stable walking under disturbances. The problems in reality like foot penetrating the ground and elastic or bending behavior of robot links were also becoming noticeable in reducing the error between the planned path and the actual path. Addi and Rodić (2010) analyzed the impact dynamics between the foot and ground involved in the biped locomotion subjected to two circumstances; rigid contact between the two surfaces using Linear Complimentarity Problem (LCP) and dynamic foot contact based on spring-mass-damper system supported by an elastic pad using the Impedance model.

Other than the walking pattern generation, activities like running, jumping, crawling etc. were also brought in to the line of thought by a number of investigators across the globe. Such a study is put forth by Goswami and Vadakkepat (2009) in which the stability of a four-link planar biped with jumping gaits in landing on the ground is analyzed. A new concept of Switching Zero Dynamics (SZD) is introduced in which the toe touching the ground on landing is considered as an additional passive DOF. The switching occurs between the biped configurations with foot rotation and with a flat foot (original). Closed loop dynamics (CLD) are also employed and the theoretical model is validated using simulation in MATLAB and experiments on BRAIL 2.0 biped.

2.2.2 High performance controllers and optimizing algorithms

Evolution of high performance computers and sophisticated control systems led to better controller designs based on highly efficient and reliable algorithms. Bououden and Abdessemed (2012) proposed the controller design for a 7 DOF biped by converting the nonlinear dynamics into a 0-flat canonical form. The flat outputs are formed and it is evaluated using computer simulations at different walking speeds. Application of same strategy can be extended for biped walking on uneven surfaces and varying ground reaction forces were the future scope for applicability in real scenario. Wang *et al*. (2014) also demonstrated a control law for a planar biped that involves ZMP tracking with swing ankle rotation controller and a partial joint angle controller. An additional phase in which the heel of standing leg lifts and rotates about the toe is introduced in the gait such that an under-actuated motion occurs. A parametric representation of the reference path was thus used to cope up with this condition and the stability of the gait is studied using Poincare method in a condensed space to prove that the selection of the partial joints by the controller directly affects the stability. The next stage would be simplification of the control algorithm by avoiding online calculation of the inverse dynamics of the planar biped.

Similarly, Danilov *et al*. (2016) discussed about a gait pattern generation technique using Kinect based Motion Capture system (MoCap). The biomechanical characteristics of human locomotion like joint velocities and angular momentums are derived from the Kinect2 3D video depth sensor data. ZMP and GCOM trajectories are generated using iPi Soft and MATLAB off-line. Human body was considered as both single point mass and multiple points mass for data acquisition and comparison. As a future step, the mathematical model generated using this method is to be tested on Russian humanoid AR-601M.

Batts *et al*. (2015) described about an innovative Virtual Neuromuscular Controller (VNMC) to generate the desired joint torques for the biped ATRIAS reserved in sagittal plane. The optimized simulation yielded better dynamic performance of the biped on terrains with unevenness up to ±7 cm. The controller showed robust performance under both internal and external disturbances. The resistant nature of the VNMC towards modeling errors and sensor noises makes it a solid alternative to execute healthier bipedal locomotion.

Nguyen *et al*. (2016) recommended a novel approach for stable bipedal locomotion by applying Differential Evolution (DE) algorithm to the objective function optimized using Artificial Neural Network (ANN) which was comparatively easier than ZMP tracking. The robot foot was provided with a toe and simulated in Adams multi-body dynamic software. The studies over performance of biped over uneven terrain have led to the analysis of dynamic walking over steps by Zhong and Chen (2016). The trajectory was generated using ANN and Fuzzy Logic Controller (FLC) and, for overcoming the inability of modifying the control functions, the Mixed Particle Swarm Optimization (MPSO) was applied to modify the weight parameters of ANN and rule base of FLC. The controller was simulated on NAO robot for different optimization methods like PSO, Mixed PSO, and Co-evolving PSO etc. for the validation of the better performance of the proposed model over the conventional biped control models.

An enhanced controller structure is elucidated by Zachariah and Kurian (2016) using a Hybrid-state Driven Autonomous Control (HyDAC) algorithm which is capable of controlling the biped over level ground as well as on slopes and steps. The two-level hierarchical control algorithm has an outer shell consisting of human motivated heuristic primitive controls and the inner shell or the task level has been equipped with a quadratic optimization scheme with linear constraints. The output obtained as joint accelerations and ground reaction forces are exploited for joint torque control via inverse dynamics of the biped. The major advantage is that the controller does not require a predetermined trajectory for tracking the biped. The algorithm was successfully tested on a planar human-sized biped model of 12 DOF restricted to the sagittal plane on flat surface and slope of ±20 deg for a walking speed ranges from 0.1 to 2 m/s.

As a result of the search for more accuracy and efficiency of the biped or the humanoid locomotion, the energy cost to execute the dynamic locomotion became another parameter for optimizing the gait. Cousineau and Ames (2015) portrayed a novel method for bipedal walking called Ideal Model Resolved Motion Method (IM-RMM) in which the closed loop dynamics of the system was integrated forward to achieve the desired velocities and position that are fed to the position-derivative (PD) controller. The method was experimented using both feedback linearization and Control Lyapunov Function based Quadratic Programs (CLF-QP) for realizing underactuated biped locomotion where the latter yielded better energy cost of transport. Reher *et al*. (2016) also presented the development of an efficient locomotion of the humanoid robot DURUS of which the electromechanical design was uniquely developed for high efficiency and better dynamic performance. The "control in the loop" design of humanoid leg incorporating feedback regulators and the switching operation of passive and active elements, were experimentally proven to be effective in achieving the lowest cost of transport in DARPA Robotics Challenge Endurance Test in June 2015.

2.2.3 Scalable controller designs

Developing a generic and scalable control design had become a revolutionary idea for its great applicability in the field. Inspired from the biomechanics of human motion, the idea of CPG is used by Matos and Santos (2014) as by Inada and Ishii (2004) to produce bipedal locomotion using basic locomotion primitives which are incrementally added to form a phase oscillator mechanism. This method can be a generalized solution for stable biped locomotion where the primitives can be united, sequenced and scaled according to the required locomotion abilities. Also, feedback elements like ground reaction force sensors, compass, accelerometer etc. can be incorporated for modification and adaptation of the walking phases for a goal-based motion. The task of covering uneven terrains such as stairs and other discrete surfaces are out of scope of this approach because the displacement of center of mass according to the biped orientation on such surfaces was not considered while developing the CPG primitives.

Sadeghnejad *et al*. (2015) delivered another generic biped locomotion controller using feedback linearization or input-output linearization and the simulation of the same on a virtual robot identical to NAO humanoid. The results were compared with conventional optimization controllers to prove that the local stability of the proposed controller was better in compensating the ZMP trajectory. The effect of noise on the performance of the controller was also simulated in the study. The next phase of this research is to test the control method on an actual humanoid.

Nandi *et al*. (2016) proposed a biped trajectory generation model using Hybrid Automata which excludes the limitations in analytical methods like higher degree of freedom, non-linearity of the dynamic model, more number of control variables etc. The vector spaces were defined using data conforming to actual human walking gait recorded using accelerometers to yield a generic and scalable model which can be applied to trajectory generation of any biped locomotion with active knee and ankle joints. Comparative validation of the model was done using the model gait number 2354 in OpenSim software. The scope for the future research includes the calculation of joint torques with the trajectories as input, using inverse dynamics and testing of the developed controller on an actual humanoid. Except the hybrid automata modeled in the Behavior, Interaction, and Priority (BIP) framework, the core idea used by Chakraborty *et al*. (2016) is same as the previous work. The gait cycle was divided into several sub phases for better understanding of the problem and directed each atomic component like knee, ankle, hip etc. checking for exactness with the theoretical model. Gait under disturbances was not covered in this model which is a drawback.

2.2.4 Mechanical elements for improved locomotion and control

A number of significant innovations relating to the modifications in the physical structure of the biped contributed very well for superior gait patterns and enhanced control. Compliance of robot link as well as the basic mechanism of joints is proven to be in accordance with the behavior of the legged robot subjected to locomotion. Wang *et al*. (2007) simulated a 9-link biped robot model with actively driven toe-joint. Its ZMP model implemented in MATLAB environment exhibited the advantages such as smaller joint torques, angles and angular velocities of ankle joints and knee joints, larger walking steps and higher walking speeds. Only sagittal plane variations were observed in this study.

The dynamic stability of a four link minimalist biped is achieved by Mir-Nasiri and Jo (2011), by a counterbalance mass driven by a DC motor and a belt and pulley system. The proportional movement of the mass was generated based on the inverted pendulum model of the biped in frontal plane when the single stance leg rotates with respect to the free joint at the ankle rotating on the frontal plane. The sideways stability was achieved by spring and damper system provided at the free joint.

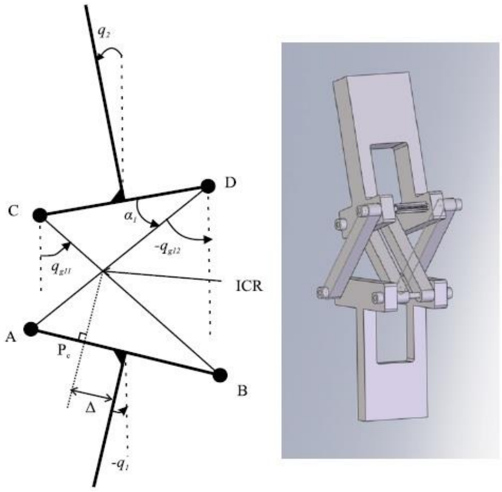

Fig. 2 The Four-bar joint knee and instantaneous center of rotation (Aoustin and Hamon 2013)

Apart from regular uniaxial joints, Aoustin and Hamon (2013) proposed a novel complex walking gait for a biped with four-bar linkage knees, optimized parametrically as double support phase where biped is over actuated, single stance sub-phase with flat floor contact where it is fully actuated and other single stance sub-phase with rotation of the stance foot where it is under actuated. The results showed that the four-bar linkage knee shown in Fig. 2 is not convenient for lower walking speeds but highly efficient at higher walking speeds.

Other than usual joint modification practices, an 8DOF biped robot is modeled by Sarkar and Dutta (2015) with a compliant link instead of the shank of leg which is made of two pieces of aluminum sheet connected using a pin and loaded by a torsional spring. The link is said to be a Pseudo Rigid Body Model (PRBM) that can be convenient for non-linear analysis involving large deflections. The dynamic gait trajectories are generated using splines under ZMP constraint and optimized using Genetic Algorithm. The comparison of performance is carried out for both rigid link model and compliant link model to derive relationships between joint torques, work done, step length and hip height with the vibration amplitude or deflection of the compliant leg. Jerks and disturbances in the actual experiment with the compliant biped were high compared to the simulated model.

3. Conclusions

Earlier controlling rules employed in biped locomotion were limited to linear kinematic models such as LIP. The introduction of ZMP was a milestone in the era of humanoid robot development. Thereafter, many complex mathematical models and numerical optimization techniques have been designed and developed which in turn coded in to sophisticated controllers for experiments and validation. This paper reviews a number of such quality works with quantitative evidence published till 2016. The latest trend in biped/humanoid gait generation and trajectory control is to incorporate the abilities of superfast computing with self-evolving algorithms which can learn from real-time behaviors of the robot and generate responses to eventually adapt to the surroundings.

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