Approximate Models and Their Stability for Biped Robots

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Abstract— Multiple degree of freedom because of number of joints and inherent unstable configuration makes biped locomotion as dynamically unstable and coupled problem to deal with. Gait patterns provide guidelines to achieve stable and efficient locomotion in the case of model-based methods. Mathematical modelling of full system gives accurate result but it is intensive in calculation, difficult to adapt changes and sometimes became mathematically difficult to implement. A reduced approximate model with feedback control is used to represent biped in an abstract way to replicate complete model. A study has been carried out on Zero Moment Point (ZMP) stability criterion and its updated versions for flat footed robots with approximate models to achieve efficient bipedal locomotion.

Keywords— Biped, Humanoid, Zero Moment Point, Approximate model

I. Introduction

Making objects in their likeness has always been one of humanity's biggest goals. They walk on two feet and have created a variety of living and transportation systems that are safe for human usage. The most suitable and adaptable robots in this setting are humanoid ones. One of the forerunners and fathers of bipedal robots, Ichiro Kato, created the first full-scale humanoid, Wabot-1, at Waseda University in 1973. It was able to walk with static stability with five DoF in each of the legs of WL5. The Wabot-1's static stability condition for mobility made it more of a victim than a walker. When the centre of mass (CoM) is inside the bipedal foot support, static stability is a stability condition.

In 1972, Vukobratovic and Stepanenko introduced the ZMP stability criterion [1], which revolutionized the field of humanoid research. Numerous humanoids with flat feet have been created. ZMP is the point on the ground floor where the lateral moment gets close to zero. According to the dynamic stability criterion of biped locomotion, the ZMP should be inside the convex hull of the foot print on the ground or the foot support polygon. The biped legs of the WABOT family, the WL-10RD, were tested for dynamic stability [2] at Waseda University in Japan in 1984. In a similar vein, Marc Raibert has worked on the dynamic stability of legged systems and the development of dynamic gaits, ranging from single-leg hopping to four-legged locomotion [3]. HONDA developed the humanoid robots ASIMO, P2, and P3. Advanced Industrial Science and Technology (AIST) has worked with various companies to build the HRP series of robots. H6 and H7 models are developed by the University of Tokyo. The Korea Advanced Institute of Science and Technology (KAIST) produced the HUBO series of humanoid robots, while the Technical University of Munich produced Johnnie and LOLA. Later, flat-footed humanoids based on ZMP stability [4] were developed, such as the German Aerospace Centre's TORO.

Biped locomotion is a highly non-linear and coupled dynamics problem due to the intrinsic instability of humanoid robots and their many degrees of freedom. Full-scale modelling requires a lot of computing power, and occasionally the solution becomes difficult to figure out. In place of full-scale models, approximate model with lesser DoF is used. It makes it simpler to build motion equations in three dimensions. Additionally, the solution is developed with the use of feedback control.

The following are some examples of the approximation models: Inverted Linear Pendulum with two-dimensional and three-dimensional model-based models [5]. Additionally, models that are spring-loaded or have a flywheel in inverted pendulum model to incorporate the stiffness and the rotating inertia effect into the model.

Approximate models are referred to as reduced order models. LIPM has been a classical model utilized to formulate motion equations. A study has been conducted to develop an optimized reduced order model; nevertheless, the feasibility of ensuring that the projected motion can be converted to the full model remains unresolved [6].

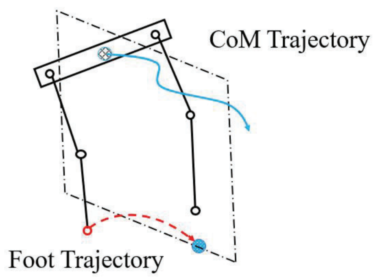

Fig. 1. Trajectory generation of feet and CoM

CoM trajectory is an essential attribute to have a stable and energy efficient bipedal locomotion. Trajectory of CoM and feet is generated for stable locomotion of bipedal system using Physics of motion with the help of reduced model in task space as shown in Fig. 1. Temporal joint positions in joint space are generated from task space with the help of inverse kinematics for modal based methods. Table Cart Models are also used as reduced model. A similar work has been done using Rolling Sphere Model. Where a sphere is assumed to be rolling on the top of a table with massless legs. A consistent and stable CoM trajectory of biped has been generated [7]. Capture Point (CP) method to model biped another updated method of ZMP based method where foot positions are modified while tracking CP [8].

In the current study, a comparative analysis of bipedal movement was conducted by examining humanoids such ASIMO, HRP, WABIAN, HUBO, LOLA, NAO, and Atlas. Studies have been conducted on their methods of producing effective bipedal locomotion through the use of Zero Moment Point (ZMP) and its upgraded variants, and these methods have been compared.

II. Humanoids

A. WABIAN

In 1973, Professor Ichiro Kato and his team developed the first humanoid robot, making Waseda University in Japan a prime example of an institution that conducts research on humanoids [2]. The most recent addition to the series, which has 41 degrees of freedom, is WABIAN-2. Each of the legs of the robot has six degrees of freedom. Joints in the toes are passive joints that have a single degree of freedom. In order to replicate the way in which humans move; the torso is equipped with two degrees of freedom (roll and yaw) at the waist. WABIAN has a height of 1.48 meters and a weight of 64 kg.

WABIAN-2 has shown that it is capable of walking like a human being with its knee extended. An experiment has been conducted in order to compare walking with bent knees versus walking with stretched knees. It has been noticed that, when one is walking via a walk assist with the knee bent, a single pressure peak is detected on the response forces of the foot. On the other hand, twin pressure peaks have been detected in the case of walk with stretched knee, which is an action that is analogous to human walking. As a result, when it comes to WABIAN-2, walking with the knee in an extended position is considered to be near to andromorphic walking state.

The purpose of the foot's arch structure is now understood. The relationship between changes in the height of the foot arch and changes in the flexibility of the medial foot arch has been investigated. The study of human gait patterns provides insight into the necessity of yaw and roll movements in the pelvis joint. The transformation of the medial arc during walking has been observed and implemented in gait. When the foot is in the stance phase, the arch of the foot is lower, but when the foot is bent, the arch of the foot is higher. When walking, the passive toe joint is utilized in order to facilitate the windlass mechanism in the foot.

In the process of constructing an offline trajectory, ZMP has been utilized as a dynamic stability condition. This trajectory is located inside the footprint of a biped. The motion equation has been created by establishing a relationship between the movement of the waist and the lateral torque. The CoM is located at the waist, and its location is being determined using a Fast Fourier Transform (FFT) in the frequency domain. Furthermore, the motion of the waist is estimated in the time domain while using Inverse Fast Fourier Transform. Inverse kinematics is used to produce walking patterns. The calculation time is lessened with the help of the FFT.

B. ASIMO

Understanding and learning from human beings was the foundation upon which the Honda humanoid program [9] was built. When a human is in the process of falling, they will attempt to remain upright or to halt their fall by pressing the ground more forcefully with the soles of their feet and by making adjustments to their bodily parts, such as their legs, feet, and chest. They make sure that they do not fall by placing their foot forward in a manner that prevents them from doing so if these measures are not enough.

The control and stabilization technologies that Asimo utilizes are also based on ground reaction force control, model ZMP control, and foot landing position control. In order to minimize slipping and spinning and make it possible for it to even run, a gait generation technology was developed. The development of ASIMO was completed in the year 2000, while research had already begun in 1986.

A system known as i-WALK, which is both intelligent and adaptable and operates in real time, has been developed for the purpose of walking on limited paths and climbing stairs. The predictive control feature has been incorporated into i-WALK, which is an enhancement of the earlier technology that allowed for walking control.

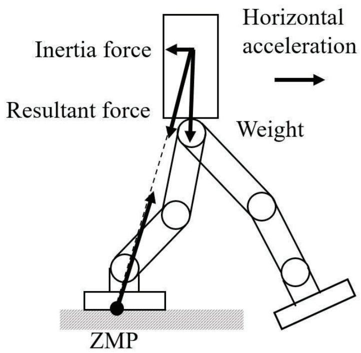

Fig. 2. Zero moment point of biped

As demonstrated in Fig. 2, the straight walking pattern has a ZMP is expected to be located around the geometric centre of the footprint. When the robot is taking its turn, the body must make accommodations for the centrifugal force, which is a lateral component of force. When walking in a straight line and then turning, the i-WALK [4] causes a computed shift in the CoM. ASIMO is able to walk at a speed of 2.7 kmph, and its speed when running is six kmph. Its height is 1.3 meters, and it has 34 degrees of freedom. ASIMO has a mass of 48 kilograms and is capable of carrying a payload of 11 kilograms.

C. Johnnie and LOLA

Johnnie and LOLA are robots that resemble humans. They were created at the Technical University of Munich (TUM). Johnnie, who was created in 2003, was the first robot to be full-sized for adults. He has achieved a maximum speed of 2.4 kmph and has a height of 1.8 meters and a weight of 52 kilograms. It allowed him to become the fastest robot. Jonnie has a total of 19 degrees of freedom (DoF).

LOLA, which was developed in 2012, is an updated version of Johnnie and features twenty-four degrees of freedom. The walking controller and Johnnie are similar in that paths are planned in Task space, and stability is achieved through the management of ground contact by means of an inner position control loop. LOLA is participating in studies on the hierarchical regulation of walking. The pace and direction of locomotion have been dictated by the upper layer, while the lower levels have been in charge of making the necessary adjustments.

Preparations are under underway to determine the trajectories of the feet. The real-time walking pattern CoM is constructed by utilizing the trajectory of the feet in real time. This is achieved by optimizing referential torque and utilizing a technique known as spline collocation [11]. The approximation model is a model that makes use of three different locations of mass. Lola is able to circumvent obstacles in her path by utilizing real-time vision, planning, and motion creation.

D. HRP series

The Humanoid Robotics Project (HRP) was a project that was supported by the Government of Japan with the goal of developing humanoids that were both safe and dependable. The evolution of the Honda humanoid P2 in the year 1996 served as the inspiration for this advancement. This was a project that was built on a platform. The first thing that was developed was the HRP platform. The upgraded version of Honda P3 is called Honda Research Project 1 (HRP-1), and it was developed by Honda. Nevertheless, HRP-2 was one of the earliest polished humanoids manufactured by AIST, Kawada Industry Japan.

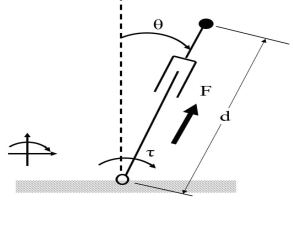

Fig. 3. Linear inverted pendulum model of HRP2

One of the humanoids that is exquisitely constructed, the cooling system of which is organized in such a way that it allows for ventilation of the interior of the body while also providing a link for cooling of motors and electronics. HRP-2 has the ability to walk at a speed of 2.5 kmph while carrying a battery. The robot weighs 58 kilograms and measures 154 centimetres in height. The ZMP is used as the standard for stability during the walking process. In the early stages of research [5,10,12,13,14], the entire model of HRP was approximated by using LIPM Fig. 3. It is presumed that the entire mass of the body is concentrated at the CoM. It is taken for granted that the torque at the location where the two surfaces meet is equal to zero. Within the pendulum, there is a mechanism that allows for the application of kicking force. The length of the pendulum is not constant; it varies. The height of the CoM is presumed to remain the same. In the LIPM, the force exerted by the kick should be sufficient to generate a vertical component of force that is equivalent to the weight of the body. The lateral component of the force exerted by the kick is what propels the biped in lateral directions. The relationship between ZMP and CoM is developed based on the status of the ZMP. For the single foot contact and double-foot contact phases of the entire walk, the developed ZMP is used to extract the CoM. The concept of orbital energy is used in order to facilitate the exchange of feet. Inverse kinematic was used to produce patterns of gait. For the sake of balance and control, model preview control has been employed in this case. HRP-2 has been utilized for an extensive period of time as a humanoid research platform in a wide range of institutions. The most recent addition to the HRP series [15] of robots is HRP-5P, which was created in the year 2018. Weighing 101 kg, and standing 1.83 meters tall. It is quite difficult to work on projects that require cooperation with others.

E. HUBO

HUBO is a humanoid robot that is the size of an adult. It was created by the HUBO Laboratory, which is part of the Korea Institute of Science and Technology (KIST). The HUBO Laboratory is well-known for winning the Defence Advanced Research Projects Agency (DARPA) Robotics Challenge (DRC) in 2015. Since the beginning of the research project in the year 2000, there has been a series of HUBO humanoid platforms produced, starting with KHR-0 and continuing through HUBO 2 (KHR-4). KHR-2 is regarded as the first complete humanoid robot, standing at a height of 1.2 meters, weighing 56 kilograms, and possessing forty-one degrees of freedom. It was capable of reaching a walking pace of one kilometre per hour.

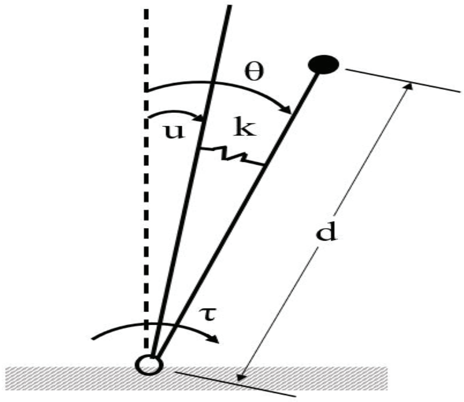

Fig. 4. Spring loaded linear inverted pendulum model of HUBO

The most recent version of the HUBO humanoid series is known as DRC-HUBO, which was created in the year 2013. During the development phase, the Zero Moment Point (ZMP) was used as a stability metric; however, the preview-based method of walking pattern generation was employed with height correction of the CoM. The unit step walking pattern, in conjunction with inverse kinematics, has been utilized to create the joint positions necessary to accomplish the online gait pattern. In the lateral direction, the implementation of the CoM trajectory constraint has taken place. Since the CoM is always located in the middle of the hip, it is presumed that this is the case. The spring-mass single inverted pendulum, which is depicted in Fig. 4, has been utilized as an approximate model with the ZMP as the standard for stability [16]. For certain designs of feet, there is a step duration limit as well as a ZMP constraint. When walking is accomplished, three conditions are taken into consideration at the same time: the CoM, the ZMP, and step time. In order to maintain equilibrium in real time while taking into account external disturbances, real-time feedback control has been utilized.

F. Atlas

Boston Dynamics has begun research into the construction of a number of humanoid robots that are actuated hydraulically and are well-known for their ability to improve balance by utilizing angular momentum. There were two prototypes of PETMAN that were developed. PETProto, which has proved that it can walk quickly and, in a manner, similar to that of humans, was developed in the year 2009. Furthermore, the humanoid robot known as PETMAN, which was designed in 2011, is used to test chemical protective equipment for the Army [4]. PETMAN has exhibited motions that are similar to those of humans, and it has also performed movements from the sport of gymnastics. Three different versions of ATLAS have been created by Boston Dynamics. The performance of PETMAN served as the inspiration for the ATLAS robots. The Atlas Proto robot was created in the year 2012, and it was able to display dynamic negotiation of stairs and obstacles that were located indoors. In 2013, the company Boston Dynamics created Atlas, which was the first fully humanoid robot they had ever produced. It was equally adept in navigating tough terrains both inside and outside buildings. It has displayed exquisite balancing through the use of angular momentum. The DARPA Robotics Challenge includes trials that are conducted with Atlas-DRC, which is a tethered humanoid. The final competition made use of a solo, untethered system called Atlas-Unplugged. In 2015, seven different teams made use of Atlas humanoid platforms during the DRC. Reactive foot placement control is the mechanism by which Atlas locomotion functions on uneven and sloped ground. They have made progress in the development of state estimation and angular momentum-based fine balancing control. Furthermore, they have made improvements to the PETMAN balance algorithm so that it will function in a variety of directions. In this case, we apply Capture Point (CP) methods, which were first developed by [8, 17]. In order to achieve a complete rest of the CoM in infinite time, the foot must be placed on the ground plane at the position CP. It is a method of controlling the diverging components of motion that involves taking things one step at a time. ZMP has been upgraded, and the result is CP. The motion equation of the ZMP is broken down into two linear differential equations of motion. The equation that is used to calculate the CP is divergent in nature, and it is solved in order to arrive at the trajectory of the CoM. As a result of inverse kinetics, the positions of the robot's joints are determined as a function of time. Starting in April 2024, the hydraulic Atlas will be withdrawn from service. The Atlas has been released in a new form that is completely electric, and this release has been done with the commercial market of humanoids and its competitiveness in mind.

G. NAO

A miniature humanoid robot with the name NAO was created by Bruno Maisonnier, who works for Aldebaran, a company located in France [19]. Bruno was the one who started the Aldebaran corporation. Nao is a humanoid who is nice in appearance and has a programming language that is simple to use. Academics and researchers alike make use of NAO as a study platform for humanoids that is inexpensive. Because of Robocup, NAO has also become well renowned. University students from around the world compete against one another in Robocup, which is an international competition. The classical method of zero moment point (ZMP) [10] serves as the foundation for the gait pattern development of NAO. NAO is able to move in any direction. NAO's steps can be adjusted in terms of both height and length. The fastest possible walking speed is forty centimetres per second. [18] has conducted research on the velocity of the North Atlantic Oscillation (NAO), and it has been shown that accelerations cause the velocity to vary in different models. NAO is capable of stepping over an impediment that is 0.5 centimetres in height. Among developers, the ability to alter joint stiffness in NAO is highly valued. In the event of a sudden shock, the joints are flexible and move rather than breaking.

III. CONCLUSION

A thorough investigation has been conducted into the bipedal locomotion of a variety of humanoid platforms. ZMP has been chosen by ASIMO as the stability criterion, and the i-WALK algorithm has been enhanced in order to accommodate situations like when the CoM shifts during a turn. Running is made possible by the restricted amount of slipping and spinning. HRP-2 was among the humanoids that were fully functional and had the ability to display steady walking. It was able to achieve this by the use of orbital energy, 3D-LIPM, and preview control on ZMP stability. The most recent in its class, HRP-5P is highly skilled when it comes to cooperative duties. WABIAN-2 replicates human movement by imitating the stretching of the knee as well as the contraction and expansion of the medial arc. The CoM trajectory is determined by applying an inverse fast Fourier transform (IFFT) to the CoM in frequency domain, which has been calculated using the fast Fourier transform (FFT). In order to produce steady movement, HUBO of KIST has utilized simultaneous three conditions, which include the CoM, the ZMP, and step time. When it comes to producing movement, LOLA employs a control system based on the hierarchical walking principle. In this case, point collocation is used to extract the CoM trajectory from the foot trajectories, which are planned here. Point collocation is distinct from all other methods. The locomotion of NAO is derived by the application of traditional zero moment point methods. In Atlas, it has been noticed that the capture point is used in conjunction with momentum control to provide precise state estimate and augmentation of balance. CP is nothing more than an upgraded ZMP approach that captures a diverging parameter in the motion equation. The ZMP continues to be the major factor, either directly or indirectly, in determining the stability of a flat-footed bipedal system, according to observations. The most classic method of becoming an approximate model is to use the LIPM approach. Because of the fact that it is challenging to determine which approximation model is ensuring the possible full model trajectory, the optimization of the approximate model is still not decided upon. A humanoid robot named ATLAS, which is powered by hydraulics, as well as electromechanical actuators that fall into six main categories, have been the subjects of the research that has been conducted. The scope of future studies includes humanoids that have been recently produced, such as the Digit from Agility Robotics, the Tesla Optimus, the electric Atlas, and others.

REFERENCE

[1] M. Vukobratovi´c and J. Stepanenko, “On the stability of anthropomorphic systems,” Mathematical Biosciences, vol. 15, pp. 1–37, 1972.

[2] Y. Ogura *et al*., "Human-like walking with knee stretched, heel-contact and toe-off motion by a humanoid robot," *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Beijing, China, 2006, pp. 3976-3981, 2006.

[3] M. H. Raibert, “Legged robots that balance,” USA: Massachusetts Institute of Technology, 1986.

[4] A. Goswami and P. Vadakkepat, Ambarish. “Humanoid Robotics: A reference,” Springer Nrtherland, 2019.

[5] S. Kajita and K. Tani, “Study of dynamic biped locomotion on rugged terrain-derivation and application of the linear inverted pendulum mode,” in Proceedings. 1991 IEEE International Conference on Robotics and Automation, pp. 1405–1411 vol.2, 1991.

[6] Y.-M. Chen and M. Posa, “Optimal reduced-order modeling of bipedal locomotion,” in 2020 IEEE International Conference on Robotics and Automation (ICRA), pp. 8753–8760, 2020.

[7] K. K. Sharma, S. Nimje, and S. E. Talole, “Consistent com trajectory generation for biped locomotion,” 10th International Conference on Signal Processing and Integrated Networks (SPIN), pp. 756–760, 2023.

[8] K. K. Sharma, S. Nimje and S. E. Talole, “Stable CoM Trajectory Generation for Biped Robots based on Heuristic Capture Point Tracking Approach,” IEEE Pune Section International Conference (PuneCon), Pune, India, pp. 1-5, 2024.

[9] H. Masato and O. Kenichi, “Honda humanoid robots’ development,” Philosophical Transactions A, vol. 365, pp. 11–19, 2007.

[10] S. Kajita, F. Kanehiro, K. Kaneko, K. Yokoi, and H. Hirukawa, “The 3d linear inverted pendulum mode: a simple modeling for a biped walking pattern generation,” in Proceedings 2001 IEEE/RSJ International Conference on Intelligent Robots and Systems.

[11] T. Buschmann, S. Lohmeier, M. Bachmayer, H. Ulbrich, and F. Pfeiffer, “A collocation method for real-time walking pattern generation,” in 2007 7th IEEE-RAS International Conference on Humanoid Robots, pp. 1–6, 2007.

[12] S. Kajita, F. Kanehiro, K. Kaneko, K. Fujiwara, K. Harada, K. Yokoi, and H. Hirukawa, “Biped walking pattern generation by using preview control of zero-moment point,” in 2003 IEEE International Conference on Robotics and Automation (Cat.No.03CH37422), vol. 2, pp. 1620–1626 vol.2, 2003.

[13] S. Kajita, H. Hirukawa, K. Harada, and K. Yokoi, “Introduction to Humanoid Robotics.” STAR Springer, 2015.

[14] S. Kajita, M. Benallegue, R. Cisneros, T. Sakaguchi, S. Nakaoka, M. Morisawa, K. Kaneko, and F. Kanehiro, “Biped walking pattern generation based on spatially quantized dynamics,” in 2017 IEEE-RAS 17th International Conference on Humanoid Robotics (Humanoids), pp. 599–605, 2017.

[15] K. Kaneko, H. Kaminaga, T. Sakaguchi, S. Kajita, M. Morisawa, I. Kumagai, and F. Kanehiro, “Humanoid robot hrp-5p: An electrically actuated humanoid robot with high-power and wide-range joints,” IEEE Robotics and Automation Letters, vol. 4, no. 2, pp. 1431–1438, 2019.

[16] J.-W. Heo and J.-H. Oh, “Biped walking pattern generation using an analytic method for a unit step with a stationary time interval between steps,” IEEE Transactions on Industrial Electronics, vol. 62, no. 2, pp. 1091–1100, 2015.

[17] J. Pratt, J. Carff, S. Drakunov, and A. Goswami, “Capture point: A step toward humanoid push recovery,” in 2006 6th IEEE-RAS International Conference on Humanoid Robots, pp. 200–207, 2006.

[18] J. Cristiano., D. Puig, and M. A. Garcia, “On the maximum walking speed of nao humanoid robots,” in Conference: XII Workshop of Physical Agents, (Albaceta, Spain), September 2011.

[19] SOFTBANK (2024) Softbank Robotics Documentation for Humanoid NAO.