

A Review: Robust Locomotion for Biped Humanoid Robots

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Abstract. One of the most interesting and pressing challenges in the study on biped humanoid robots is to achieve high robustness in locomotion. This paper presents a brief overview of work and methods on robust walking and running for bipedal robots. So far, many robust walking methods have been proposed to reject terrain disturbances and impulsive force disturbances. The applications of the proposed methods to real robots improve the robustness and adaptivity of robots by large margin. Up to now, bipedal robots can traverse unknown terrains with ground variation exceeding 20% of leg length. The height of obstacles increases more than threefold compared to decades ago. With regards to unexpected external force, bipedal robots can recover the balance from sudden push not only at stationary state, but also during the walk. On the other hand, the biped running is underdeveloped compared to the robust walking. Still the highest running speed is less than 3.0 m/s, not to mention the poor robustness to large disturbances.

1. Introduction

Over the last decades, biped humanoid robots attract more attention than mobile robots with traditional means of locomotion, like wheels, etc. [1]. The study of bipedal robots has the potential to provide insight into the dynamics of human locomotion. Another significant benefit is that legged mobile robots can be introduced to much more complicated application scenes, e.g. disaster rescue, firefighting and outer space exploration.

Despite decades of research and progress, few humanoid robots have been already applied in our daily life or other practical scenes. Most of developed robot prototypes are restricted to perfectly-structured environments, while practical applications always require the robot to operate stably while dealing with high levels of uncertainty and large external disturbances [2]. In fact, a slight irregularity can undermine the balance of the bipedal robot and destroy its stability. In other words, humanoid robots still tend to tip over easily on complex environments and are short of robustness against various disturbances [3].

In general, the disturbances or uncertainties in bipedal robot locomotion include unknown terrains, unexpected external forces, parametric errors, friction in joints and motors, and sensor errors etc. [4]. The first two are categorized as external disturbances, while the remaining is internal uncertainties typically resulting in differences between control models and actual robots. The first of external disturbances, terrain variation, is pervasively occurred in natural and man-made environment. Most of the terrain in the natural world is not flat, such as rocky mountains, and lots of disaster and dangerous areas are littered with obstacles, like stones and ruins.



The unexpected forces, another external disturbance, often arise from interaction tasks, involving offering to lift unknown loads, collaborative carrying, and unexpected collision. It is obvious that human-robot collaborations are beyond the vision if robots cannot be rejected to unpredicted forces, especially impulsive thrusts. In sum, external disturbances, including rough terrain and unexpected thrust, should be accommodated to achieve robust walking for bipedal humanoid robots.

The defect, lack of robust walking under external disturbances, makes the biped robot less practical in applications of high-speed locomotion, e.g. running. Running can significantly improve the agility and flexibility of bipedal robots by speeding up the movement. Moreover, the running or jumping manoeuvre enhances the capability of robots to locomote over discrete terrains. Unfortunately, even if robust walking is well-developed, it does not necessarily lead to the high-performance running.

This paper overviews the studies on robust walking and running of biped humanoid robots. The paper is organized as follows. Section 2 surveys the researches allowing bipedal robots to traverse various terrains. In Section 3, impulsive external disturbance is concerned and the robust controls to reject it are presented. Following robust walking under external disturbances, Section 4 provides a brief review of state-of-art of biped running. Note that, in particular, this paper concerns the work and researches that are applied to practices and real hardware.

2. Terrain Disturbance

Current robotics research starts to extend applications to include locomotion through unstructured environments where the terrain varies unexpectedly. This extension presents a challenge because a robot that can move perfectly in a controlled environment might fall after its first encounter with a terrain disturbance [4].

Even though numerous researches have been done to improve robustness to ground variation, significant restrictions still remain when bipedal robots walking on rough terrains [5]. Until early 2010s, bipedal robots can only accommodate unplanned obstacles that are less than 6% of leg length [6–11]. This value is unrealistically small when compared to common obstacles in everyday life, such as the height of steps in a building or the curb height of a sidewalk on a city street. Also, ground height variations exceeding a few centimetres must be known a priori. These robots are constrained to the average walking speed of approximately 1.0 m/s.

So far, uneven terrains are traversed at relatively low walking speeds [12–14] to maintain stability and, if applicable, to ensure the accuracy of perception [15,16]. The highest speed of walking seldomly exceed 1 m/s without any knowledge of the ground [17].

HONDA has been developing HRP-series robots from the end of 20th century, among which HRP-2 becomes a successful platform in the research field of humanoid robotics since launched in 2004 [18]. Takubo et al. [19] put forward a Zero Moment Point (ZMP) based criteria to solve the rough terrain walking. The newly proposed method was validated on HRP-2. In this study, Takubo et al. brought up the concept of “step up” and “step down” to describe the variation of regular flat ground [18]. The landing time of walking pattern was adjusted in corresponding to “step up” or “step down” state. The experiments verified the effectiveness of proposed methods, though the heights of “step” were less than 10 cm.

HRP-2 was replaced by HRP-4C and HRP-4 to improve the practicability of humanoid robots. Similar to HRP-2, the processor HRP-4(C) model is also fully actuated where degrees of freedom of robots correspond to the actuation system [20]. Kajita et al. [21] successfully applied the posture/force control to stabilize HRP-4C by simplifying it as a single linear inverted pendulum with ZMP delay. With minor modification of the predetermined trajectory, HRP-4C performed robust walking on outdoor uneven pavement. The maximum inclination of pavement was about 3 degree. Without any knowledge of outdoor ground profile, HRP-4C could traverse the pavement using a prescribed walking pattern for the flat ground, with a quite slowly walking speed of 0.2 m/s.

In 2019, Caron et al. [22] took a breakthrough in dynamic stair climbing of humanoid robot. The stabilization controller for climbing stairs was expanded by two parts: quadratic programming-based wrench distribution and a whole-body admittance controller. Previous to this work, the untethered stair

climbing had been rarely performed to prevent robot falls and ensure the safety. Caron et al. [22] applied the resulting stabilization controller to the dynamic stair climbing of HRP-4. In the two-week reproduced experiment, robust stabilization was verified repeatably and HRP-4 completed to climb an industrial staircase with 18.5 cm high steps.

In contrast to fully-actuated robots, underactuated bipeds become more popular since its dynamic gait is simple and elegant as human's locomotion.

As a planar biped robot, MABEL was actuated by only two motors, one of which controls the angle of the so-called virtual leg and another motor control the length or shape of the virtual leg [23]. Park et al. [5,23] designed a switching controller [24] that allows it to accommodate an abrupt 20 cm variation in ground height. A controller switching is activated when the step-down height is detected and the so-called 'step-down' controller is turned on to reject the terrain disturbance.

As shown in Figure 1, MABEL could step off the platform reaching 20.37 cm high, without falling [23]. In the experiment, MABEL began walking on a flat floor, walked up a ramp to a 17.78 cm platform and stepped off. After completing a second lap, the 17 cm obstacles were replaced by the 20 cm ones. Figure 1 presents the successful step-off with rejection to torso oscillation in snapshots from video capture. Remarkably, the leg length of MABEL is around 1 m, which concludes that the proposed switching control permit the biped robot to walk over terrain variation exceeding 20% of leg length. It is noted that, in the experiment [23], MABEL accommodated unplanned obstacles without any priori information or extra sensor measurement. In other words, MABEL could blindly traverse and be robust to step-up and step-down disturbances.

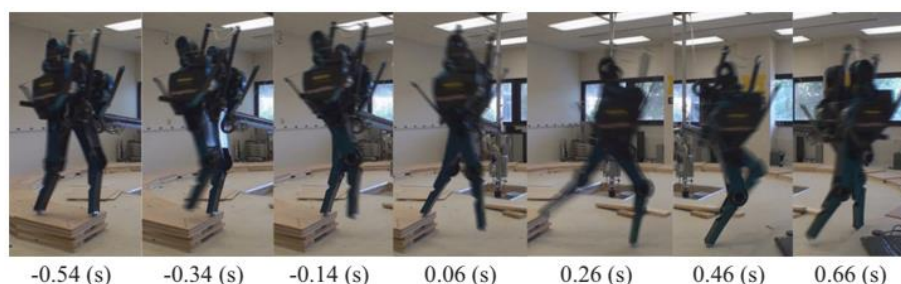


Figure 1. MABEL walking over 20 cm step-down disturbance [23]

Following the MABEL, Griffin et al. [4,25] from University of Michigan developed its successor, MARLO, to continue the study of blind walking [26] for humanoid robots. The aim of Griffin et al. is to address the control strategy that functions well in the presence of terrain disturbance, without reliance on perception and a priori knowledge of ground variation. MARLO extended previous 2-D walking (MABEL) to 3-D locomotion, and did not sacrifice the walking speed at the level of 0.9 m/s. The innovation of work by Griffin et al. was to propose a control strategy that allowed continuous velocity-based posture adjustment via nonholonomic virtual constraints. Additionally, the terrain disturbances were considered in the optimization of walking gaits.

Figure 2 shows an indoor experiment performed to validate the stability and robustness of MARLO when walking over randomly arranged obstacles. Before this experiment, MARLO was tested on the organized stacks of boards. The boards or board stacks in two experiments were varied from 1.2 cm to 7.9 cm. For experiments outdoors in realistic environments, MARLO traversed sloped sidewalks, parking lots and grass fields, all with adaptivity to various sorts of floors and grounds [4].

Though concentrating the same issue as MABEL, MARLO did not follow the design of MABEL with big differences in linkage-leg and actuating methods. In fact, the configuration of MARLO is the Michigan copy of the ATRIAS-series robots by Carnegie Mellon University.

ATRIAS is an underactuated human-size biped robot with two actuators located at each hip joint [27]. The two series motors drive the four-bar linkage in the sagittal plan, while for 3-D walking, another motor controls the leg in the frontal plane. In 2015, Batts et al. [27] developed a motor torque controller to adapt ATRIAS to modest terrain changing. In sagittal plane, the proposed virtual neuromuscular control regulated the motion of the legs by emulating the neuromuscular model. The

simulation tests verified that, up to $[-2, 2]$ cm terrains, the success rate of ATRIAS traversing was up to 90%. This rate sharply reduced to 50% if the terrains height increased to $[-3, 3]$ cm. The robustness to the highest terrains was slightly over ± 7 cm. Up to $[-7, 7]$ cm terrains, the robot easily tipped over and fell backward.

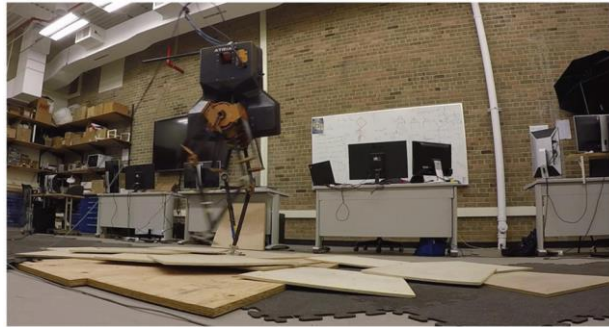


Figure 2. MARLO walking over randomly thrown boards [25]

In 2017, also implemented to ATRIAS, Nguyen et al. [2,28] presented another approach to handle the random changes of the ground. The proposed approach applied the 2-step periodic gait optimization and a gait library-interpolation to achieve desirable step lengths and step heights. The 2-step periodic gait optimization takes into account consider the desired location of the next footstep, enabling to switch between different walking gaits. On the other hand, the gait interpolation allows the adaptation to terrain changes. The research team launch a first experimentally dynamic walking for humanoid robots, using ATRIAS. As presented in **Figure 3**, the terrain variation was emulated by stepping stones, whose step length and step height changed from 30 to 80 cm and from -30 to 30 cm, respectively [28]. In the experiment, ATRIAS achieved fast walking with 0.6 m/s average walking speed and accommodated randomly arranged stepping stones with step lengths in the range of $[23, 78]$ cm.

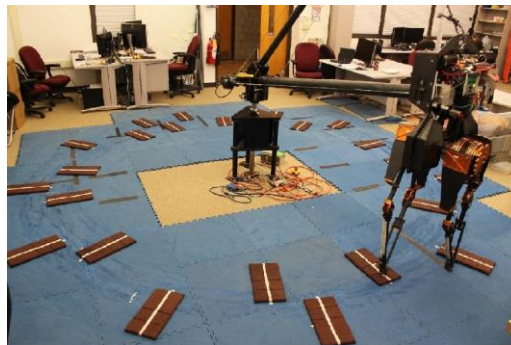


Figure 3. ATRIAS walking over stepping stones [28]

In 2019, Li et al. [29] suggested intelligent methods to improve the robustness and adaptivity of ATRIAS biped to ground disturbances. The deep reinforcement learning was introduced to train the structured controller in a high-fidelity simulator. The structured controller could be separated into two parts: the neural network part was regularly updated, while the rest of the controller stays fixed during the training. This strategy was demonstrated to speed up the rate of learning and result in the feasible control policies. After training, the neural network policy performed robust to ground height disturbance with decent success rate. On the other hand, 80% rate of transfer could be reached between simulation and hardware. Note that the above-mentioned researches on ATRIAS are all restricted in the planar locomotion.

3. Impulsive Force Disturbance

In addition to the terrain variation, the unexpected external force is another universal cause to the fall or tipping-over of biped humanoid robots. Amongst all kinds of external forces, the impulsive thrust or

push is the trickiest one since it requests the rapid response of controllers to hold the stability of robots [30]. If biped robots cannot recover the balance from sudden external impact, there is no way to achieve the safe physical interaction between human and humanoid robots.

The balancing recovery to external forces on humanoid robots has been studied for decades. Yet most of them assumed that the biped robot was standing, i.e. stationary mode, at the sudden of disturbances forced [31]. Fard et al. [31] also claimed that the push recovery of underactuated robots is much more difficult than full actuated ones, even harder when the degree of under-actuation is over two [32]. Despite of the difficulties, many disturbance rejection methods have been designed and experimentally validated [33–35]. Under relatively small disturbances, stability can be held by shifting the centre of pressure within the foothold [36]. This method becomes less effective as disturbances becoming larger and robots becoming more dynamic [37]. As an alternative to ankle strategy, ground contact force based control enables the robot to hold the stance under larger disturbances [38–40], but cannot accommodate the disturbance during the walking. More recently, a more natural and human-like method was proposed by adjusting step placement [41–44].

In 2008, a 0.5 m height biped robot, MANUS-I, was developed by Prahlad et al. [33] to validate sorts of technologies for humanoid robots. One ankle strategy based method was proposed to improve the locomotion stability subjected to disturbances. The compensating torque was computed using the measurement of force sensors located at each foot and injected into the ankle-joint of the foot. The robot was proved to reject different forms of disturbances by experiment. In first case, MANUS-I carried an additional weight of 390 g (17% of body weight) while walking up a 10-degree slope and walked down a 3-degree one. The second case demonstrated that MANUS-I could revert back its ZMP position after several walking cycles adjusting if forced an impulsive push.

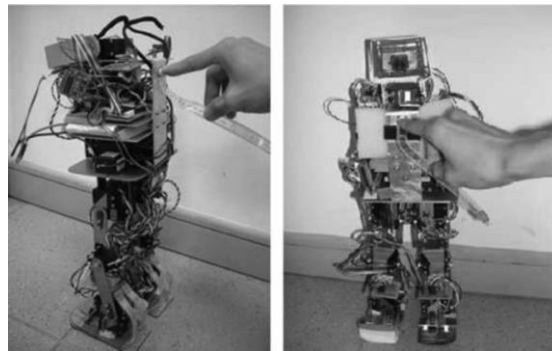


Figure 4. Measurement of disturbance force on MANUS-I [33]

The work of Ott et al. [45] in 2011, is a typical case of using ground contact forces to recover the posture under external perturbations. The proposed balancing controller computed force and torque (wrench) that was distributed among predefined contact points. The distribution of wrench was optimized with the objective of minimizing the Euclidean norm of the contact forces. Two experiments are presented with DLR-biped to evaluate the proposed balancing algorithm [45]. The first experiment presents an impulsive disturbance using a pendulum, providing an impact of approximately 5.8 J on the robot. In the second experiment, the trunk of the robot is pushed by creating different perturbations in position and orientation. The proposed strategy distributed a net wrench required to recover position/posture onto a predefined set of contact points.

HRP3L-JSK is a high-power ability humanoid robot with 12 degrees of freedom in legs. Its robustness to external forces was realized using online footstep replacement [46]. The step replacement was optimized online to track the ZMP trajectory, which targets the trajectory of the centre of mass. **Figure 5** shows that HRP3L-JSK was badly kicked in the experiment. The kick reached 597 N at peak and lasted around 0.1 s. Though with short duration, the kick led to large torque perturbation since the height is bit more than 0.8 m where the body is pushed. As given in **Figure 5**, the online optimization converged the centre of mass to its desired trajectory.

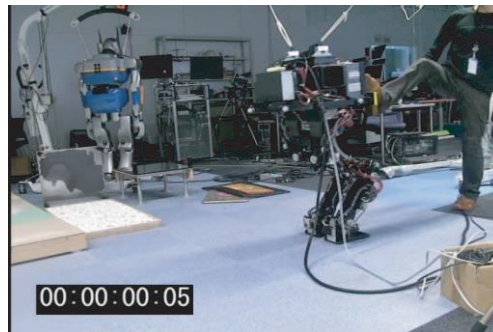


Figure 5. External disturbance on HRP3L-JSK [46]

To handle the large thrust disturbance at walking-state, Yu et al. [37] proposed a footstep placement strategy that also could reduce the foot landing impact. The new foothold placement was estimated by mapping ZMP variations using the body acceleration measurement. The robustness to disturbance could be improved by integrating a PD controller, since the controller effectively abated the body vibrations. In the experiment, the robot is disturbed a sudden external push, in the double phase of the third step [37]. The thrust is about 212 N for a duration of 0.1s, namely 21.2 Ns. **Figure 6** shows from the fifth snapshot when the external push was forced. From the fourth step (the sixth snapshot), the robot calculated the next footstep placement and recovered to stable walking. It is easily found that the right foot (marked by red square) landed on the right of the original foot placement, by comparing the seventh and eighth snapshot with the sixth one. The landing force mitigating strategy operated at the same time. The experiments verified that the stable walking was not achievable if the foot landing impact control was not applied.

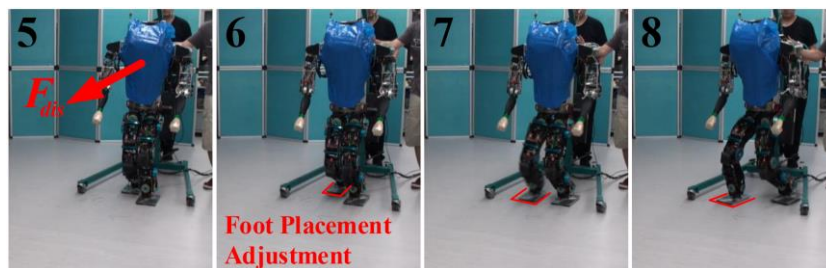


Figure 6. Large thrust forced to robot during robot walking [37]

4. Running

Successive single support phases and instantaneous double support phases constitute the gait of walking. Therefore, legs kept in one single support phase. But the gait of running is composed of stance phases and flight phases. The robust stability margin of biped running is lower than walking [47], since robots needs fast changes in joint variables with large impact force happening.

In the early days, researchers focused on the control of the landing position for robots to realize running [48,49]. In many subsequent studies, the model that describes motion of centre of mass learning from human motion, was used to model and control biped running. Trajectories of the centre of mass in biped running were studied and designed [50–52], also the Linear Inverted Pendulum model [53] and Spring Loaded Inverted Pendulum model were used in running robots [54]. To generate a trajectory, gait pattern using ZMP are employed with methods including gait synthesis, gait algorithm, and gait parameters optimization [55–57]. Poincare map was commonly used for designing running reference trajectories for biped robots [58,59].

A biped robot HRP-2LR was developed, which could jump and run [49]. To follow the desired profiles of the total linear and angular momentum, ZMP patterns of HRP-2LR for running are pre-calculated. In the experiments, a hopping with forward velocity of 0.15 m/s was also realized. In their later study, a running controller is proposed to stabilize the system against disturbances [60]. The running controller consists of posture stabilization, inverted pendulum stabilization, contact torque

control, impact absorbing control, foot vertical force control and torque distribution control. Then, the advanced HRP-2LR [53] makes use of the resolved momentum control method to generate the running pattern. A running pattern was designed with a support duration of 0.3 s, flight duration of 0.06 s, and speed of 0.25 m/s.

Running at 10 km/h (2.8 m/s) was achieved on a real robot whose dimension are same as ASIMO [61]. To achieve this goal, methods to decompose and synthesize a running gait pattern into vertical, horizontal and rotational components were propose so that time-dependent ground friction limits are satisfied. Also, they extended the boundary condition, the divergent component of motion, involving vertical acceleration of the centre of gravity. Especially these methods were suitable to apply to intermediate motions between walking and running, involving no flight phase or walking on ground with small friction coefficients.

To make the biped robot running stably, a balance control was proposed to enable a robot to maintain balance by changing the positions of the contact foot dynamically when the robot is disturbed [51]. They applied compliance control without force sensors, in which the joints are made compliant by feed-forward torques and adjustment of position control. Simultaneously they put feedback control into use, deciding the foot positions by measuring orientation of the robot's torso. The paper implements the fast running motions to a humanoid robot that can run at an average speed of 7.0 km/h, as shown in Figure 7.

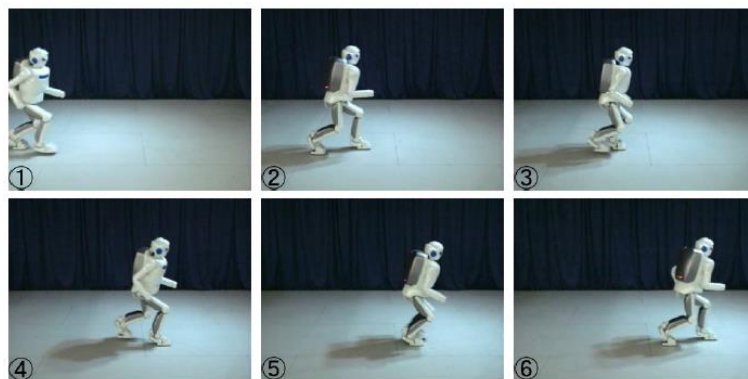


Figure 7. Sequential picture of running at 7 km/h (1.9 m/s) [51]

The biped robot, ATRIAS, had remarkable performance in running with speed of 2.5 m/s [62]. The work in ATRIAS aimed to demonstrate that 3-D bipedal walking and running are not only possible with a passive-dynamics-based approach, but that the result is sufficiently robust to serve as a viable framework for practical locomotion in unstructured environments. Remarkably, ATRIAS can accelerate from rest, transition smoothly to a running gait.

5. Conclusion

Locomotion stabilization is the most basic problem for bipedal humanoid robots with only two legs and point contacts. The pressing challenge in stabilizing biped robots is to achieve high robustness that enabling robots to recover from severe perturbations especially from external disturbances. In addition to the complexity of biped robot itself, the environment robot applied is often complicated and unknown. Despite of the complications, many studies on robust locomotion have been done and experimentally well-validated.

The robustness to terrain disturbances, especially unknown terrains, has been improved by a large margin. Just before 2010, the variation of accommodated terrains was no more than 6% of robot leg length. This number increased to over 20% in the study of Park et al. [23] in 2012. For the experiment of ATRIAS [28], the height of obstacles—stepping stones reached 30 cm, exceeding 50% of leg length.

The disturbance rejection to external disturbances has been studies from different points of view. The most popular approaches at least include ankle strategy, contact force control and footstep

replacement. Amongst, footstep replacement is most prospective to achieve high robustness under dynamics walking. The step replacement strategy successfully recovered the biped robot from sudden push (about 21 Ns) during walking [37].

Biped running is underdeveloped compared to the robust walking. Some bipedal robots, such as ASIMO [61] and ATRIAS [62], has been relatively well-developed and achieved stable running. Yet the best running speed does not break through the level of 3.0 m/s, not mentioning the poor robustness to large disturbances. In short, lots of works need to be done in biped running, especially in high speed running.

Acknowledgments

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