View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Maastricht University Research Portal

Maastricht University

# An energy efficient gait for humanoid robots walking on even and uneven terrains

**Citation for published version (APA):**

Sun, Z. (2019). An energy efficient gait for humanoid robots walking on even and uneven terrains. Maastricht: Maastricht University. https://doi.org/10.26481/dis.20190327zs

**Document status and date:**
Published: 01/01/2019

**DOI:**
10.26481/dis.20190327zs

**Document Version:**
Publisher's PDF, also known as Version of record

**Please check the document version of this publication:**

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

**General rights**
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:

www.umlib.nl/taverne-license

**Take down policy**
If you believe that this document breaches copyright please contact us at:

repository@maastrichtuniversity.nl

providing details and we will investigate your claim.

Download date: 04 Dec. 2019

# SUMMARY

The term **robot** comes from the Slavic word *rabota*, which means labour or work. It was first introduced into English vocabulary by the Czech playwright Karel Capek in his 1920 science fiction play *Rossumovi Univerzální Roboti (Rossum's Universal Robots)*. Since then the term has been applied to a great variety of mechanical devices, such as industrial manipulators, autonomous land rovers, underwater vehicles, etc. The machine that is autonomous or semi-autonomous, usually in the control of the computer, can be called a robot, which presents many challenging and interesting research problems. To solve the problems, Robotics becomes a rapid-developing field of cross-disciplinary technology, which includes mechanical engineering, electronics engineering, computer science, and others. These technologies are exploited to develop robots that can replicate human actions and replace human labor. Robots can be used in any situation and for any purpose, but today many are used in manufacturing processes, and in dangerous environments such as military operations area, nuclear power plant, skyscraper, etc.

To date, robots perform great feats of manipulation, especially in the industrial area. They can move heavy objects, and repeat assemble work that usually requires high precision. Commercially available robotic toys and vacuum cleaner inhabit our living spaces, drones soar in the sky and unmanned underwater vehicles have dived into the deep water. These successes appear to omen an explosion of robotic application in our daily lives. But without advances in robotic motion, many promising robotic applications will not be possible.

A common problem faced by the robotic researchers is the movement of the robot. Depending on the environment in which they operate, mobile robots can be divided into several categories such as: flying robot, amphibious robots and land robots. The latter can be divided according to the way they move. There are wheeled robots and legged robots. Each of the robot designs has its merits and drawbacks. Compared to the wheeled robot, which are able to move in a high efficient way on even surfaces, legged robot are capable of stepping across the obstacles on uneven terrains. The modern mobile robots have a large amount of motor actions to move the whole body from one point to another. Bipedal walking (the self-propelled movement of the robots with two legs) could be considered the most representative behavior. The most common approach to control the walking behavior and balance of a robot with two legs is called Zero Moment Point (ZMP) [157]. This approach computes the point where the whole foot needs to be placed in order to have no moment in the horizontal direction. In other words, ZMP is the point where the sum of the vertical inertial and gravity force equals zero. Most state of the art platform like ASIMO [133], HRP-4 [81] and HRP-3 [80] make use of the ZMP concept. One of drawbacks of ZMP arises from the need to have the whole foot in contact with a flat surface, which can be problematic on uneven terrains. Moreover, this method requires a model of the robot and a known environment. Finally, the ZMP can only be controlled indirectly and control methods have to be found indirectly influence the ZMP so that it stays within the stable region.

Another problem that motivates researcher in their pursuit of a more energy-efficient walking robot, is because a legged robot needs to carry its energy source of the limited capacity. Needless to say, a low energy consumption can directly contribute to a longer working duration. In the paper of [27], the gait of humans is assumed to be one of the most energy-efficient ways of walking. The experimental studies of human locomotion [57, 64] support the hypothesis that the choice of a gait pattern is influenced by energy considerations. In the repetitive motion of walking, the motion controller may attempt to produce walking pattern that is energy efficient because it exploits physical properties of the robot. Bearing this in mind, a possible solution for enabling an energy-efficient walk on the bipedal robot is to:

1. Characterize the biped motion in terms of a set of locomotion variables.
2. Search for the optimal locomotion variables that minimize the fitness function that concerns the energy cost.
3. Establish the correlation between these locomotion variables and the energy cost.

The two core challenges of bipedal walking, namely stability of biped walking in unknown environments and energy efficiency of the biped locomotion have led us to the following problem statement:

*How to synthesize a biped walking gait with energy efficiency and dynamical stability on a humanoid robot with high degrees of freedom on uneven terrains ?*

We identify six research questions which guide the research with regards to the problem statement. The questions address the problems of (1) dynamics model, (2) energy efficiency of locomotion in sagittal and lateral direction, (3) lateral stability, (4) controller design, (5) gait optimization on level ground, (6) gait optimization on uneven terrains.

**Research Question 1:** *Can the planar inverted pendulum model be used to create a bipedal gait with a high energy efficiency?*

**Research Question 2:** *What is the influence of the double support phase on the biped gait in the sagittal plane?*

**Research Question 3:** *What are the requirements of a double support phase with respect to lateral stability of a gait?*

**Research Question 4:** *How to design the controller for gait generation?*

**Research Question 5:** *How to optimize the energy efficiency for the walk gait on flat floor?*

**Research Question 6:** *How to optimize the stability of the walking gait on uneven terrains?*

In Chapter 1, we introduce the reader to the field of biped walking on humanoid robots. Firstly, we introduce motivation of the development of the humanoid robot. In the second section, we discuss the history and state of art in the field of the humanoid robots and the biped walking. We also present a brief overview of the core research challenges in the field of biped walking on humanoid robots. In the fourth section, we introduce and discuss the problem statement and research questions which guide the thesis. In the final section, we introduce the structure and overview of the thesis.

In Chapter 2 we provide general information about Aldebaran Nao, a humanoid robot deployed in this thesis as the experiment platform. Further, we introduce the common techniques that are applied for the purpose of kinematics analysis.

Applicable techniques for biped walk gait generation are introduced in Chapter 3. We first enumerate the different simplified models that are usually employed to describe the dynamics of biped walking. Further, we introduce the stability criteria that are applied for establishing the stability of the system. Additionally, we provide a brief survey of existing approaches for walking gait generation.

Chapter 4 answers the first three research questions. The core problem concerns the energy consumption of the walking gait modeled by a conventional (linear) inverted pendulum and the improvement in the energy efficiency. This walking gait requires stiff joints and bent legs, which result in high energy consumption. We address the research question by investigating an inverted pendulum model with telescopic legs and a leg-length policy that determines the length of the telescopic leg. With this model, we identify the leg-length policy that minimize the energy consumption of a walking gait. Moreover, we make the ankle joint under-actuated by setting its stiffness to zero to further decrease the energy consumption. Our evaluation shows that the application of our approach reduced the energy cost of knee joint in a planar walker. Additionally, we extended the model with a double support phase to improve the stability of the walking and proposed a force policy to control the lateral movement of the CoM. Our method is to manipulate the force on the swing leg by means of a force policy which is generated by regulating the knee stiffness of the swing leg. We also investigated the effect of force policy on the leg-length policy. The experiment showed that the different force policies have no significant influence on the leg-length policy, which indicates force policy is independent and does not influence the behavior of the leg-length policy.

The research questions tackled in Chapter 5 concern the implementation of the controller for gait generation and the optimization with respect to the energy efficiency of the walking gait on a level ground. To answer the question, we propose a controller that provides the appropriate joint functionality consisting of two motion generators, which are supervised by a finite state machine. The controller has 9 control parameters which can be grouped into four categories: (a) sagittal motion (b) lateral motion (c) stability (d) time control. The core problem is that given such a controller, we need a method to find the parameters that minimize the energy consumption and maximize the stability. For this purpose, we use a method of policy gradient reinforcement learning and proposed a fitness function concerning the energy cost and the stability of the walking gait. We use this method to estimate the policy's gradient in the parameter space and then follow the gradient towards an optimum where the value of the fitness function is maximal. We repeated the learning experiment 500 times, each time starting from a randomly generated parameter. In every experiment the parameters converge to the same optimum. From this result, we conclude that the optimum is likely the global optimum. The evaluation on a real Nao robot shows that the implementation of our approach can result in a walking gait that reduces the energy consumption by 41%, compared to the standard gait of the Nao robot provided by Aldebaran. Lastly, we investigated the stability of the proposed walking gait through its projection of the acceleration vector on the ground, since the stability criterion ZMP is not feasible in our case. Although the ground projection of the acceleration vector overshoots the support point of the new stance leg, the ground projection of the CoM does not and the proposed walking gait can still keep stable and cyclic. From this, we conclude that given the proposed controller with optimized parameters, in the absence of areas of support, our method can synthesis a walking gait that ensure the dynamical stability and energy efficiency on a level ground.

Chapter 6 addresses research question 6, which concerns the stability problem of the walking gait on uneven terrains. We assumed that each step of a robot's walk on an uneven ground can be viewed as a step on a (virtual) slope. In this way, the uneven terrains can be modeled as slopes of variable angles. We used the same method described in Chapter 5 to obtain the optimal control parameters while let the robot walk on a specified slope in both sagittal and lateral direction. The learned parameters and the corresponding information (include the slope angles represented by the height difference of two feet) from the data are used to adapt the gait controller. We presented a feedback controller based on three neural networks that adapts the gait parameters to ensure the robot's stability while walking on an uneven terrain. All of the neural networks have a simple structure with one hidden layer and use Sigmoid as the activation function. The core task is the learning, for which we used the collected data to train the neural networks using back propagation method. The first neural network has four inputs to outputs the sampled angle of the knee joint on the stance leg. The second one has three inputs and its output is the sampled knee stiffness of swing leg. The last neural network is the most simple one, which uses control parameter *Knee Bending* as the input and outputs the control parameter *Torso Roll Inclination*. With the trained networks, we implemented a controller that enables a Nao robot walk on uneven terrains. For our approach, we utilized simulator *Webots* in order to design an evaluation experiment for testing the stability of the generated walking gait. Using the parameter *perlinNOctaves* of the terrain generator in Webots, we can generate uneven terrains with specified roughness. Our evaluation revealed that the walking gait generated by the proposed controller is stable on the terrain with hills and high inclination. We provide a video [1] shows the Nao robot walking on an uneven terrain with our proposed gait controller in the Webots, which implies that our controller can handle the altitude differences of the foot placement and adjusts the control parameters to maintain balance. Moreover, we evaluated the energy consumption of our walking gait on uneven terrain against the Aldebaran gait on the flat ground, the result indicates that the our gait has better performance not only with respect to the stability but also with respect to the energy efficiency on uneven terrains.

Chapter 7 provides the conclusion of this thesis and discusses possibilities of future research. Taking the answers of the research questions into account, we conclude that

---

[1] `https://youtu.be/owHiGQm8WSg`

our proposed method can synthesize a biped walking gait with energy efficiency and dynamical stability on a humanoid robot on level ground and uneven terrains.