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DESIGN AND INTELLIGENT CONTROL OF AN ENERGY-EFFICIENT HUMANOID ROBOT

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And we never give up

It's all about never givin' in

And we never give up

It's about will and who wants it the most

And we never give up

It's all about havin' a heart of a champion

(PP)

Abstract

This work of thesis deals both with design and intelligent control of a humanoid robot, and its main aim is to develop an energy-efficient and dynamically stable locomotion.

In the first part, we present a systematic method to evaluate the energy efficiency of a biped robot. This method is then used to obtain some information about the performance of materials and actuators that could be used for design. Results collected are integrated with the experience of previous works, and finally summarized to suggest some efficient configurations. These indications are meant to be used for future developments of LARP, the humanoid robot of the AIRLab, Politecnico di Milano. The

method adopted, however, is general enough to produce valid results for any robot, and we hope our considerations will also help in evaluating design choices for future humanoid robots.

In the second part, instead, we propose some possible enhancements to the controller developed at Institute Mihailo Pupin, Belgrade, Serbia, in order to improve its performance in terms of stability and efficiency of the robot. Moreover, the on-line joint trajectories update we developed makes the robot capable of learning from the experience acquired.

These two parts, combined together, permitted us to go through all the main steps of the process of development of an energy efficient and dynamically stable humanoid robot.

Sommario

Il lavoro di tesi presentato in questo documento affronta tanto il design, quanto lo sviluppo di un sistema di controllo per robot umanoide. L'obiettivo primario è ottenere una camminata dinamicamente stabile ed energeticamente efficiente.

Nella prima parte è presentato un metodo per valutare sistematicamente l'efficienza energetica di un robot bipede. Questo metodo è poi utilizzato per confrontare le performance energetiche della camminata a seconda delle diverse scelte di design considerate; in particolare l'attenzione è focalizzata sulla scelta dei materiali per la struttura del robot e sugli attuatori. I risultati osservati sono poi integrati con le indicazioni ricavate

da esperienze di ricerca precedenti, e riassunti in possibili configurazioni da adottare per ottenere il design di un robot efficiente. Queste indicazioni saranno utilizzate per lo sviluppo di LARP, il robot bipede dell'AIRLab del Politecnico di Milano. Il metodo utilizzato è però sufficientemente generico da rendere queste informazioni valide per lo sviluppo di altri robot umanoidi.

Nella seconda parte della tesi ci concentriamo invece sul controllo del robot. Grazie alla collaborazione con l'Institute Mihailo Pupin di Belgrado, Serbia, abbiamo avuto la possibilità di basare la nostra ricerca sull'ultima versione del sistema di controllo ivi sviluppato. Abbiamo individuato due possibili miglioramenti al sistema corrente, che permettono di aumentare le prestazioni della camminata in termini di stabilità ed efficienza. La prima modifica prevede di introdurre una traiettoria di riferimento dello ZMP variabile. La seconda permette invece di aggiornare on-line la traiettoria di riferimento dei giunti, rendendo quindi il robot in grado di migliorare le prestazione della propria camminata con l'esperienza acquisita.

La combinazione di queste due parti della tesi, design e controllo del robot, ci hanno permesso di affrontare le principali fasi dello sviluppo di un robot umanoide dinamicamente stabile ed energeticamente efficiente.

Acknowledgements

This document is the result of more than two years of work, performed at Politecnico di Milano, Italy, at University of Illinois at Chicago, USA, and at Institute Mihailo Pupin, Belgrade, Serbia. I first want to say thanks to my thesis advisor, Prof. Giuseppina Gini, of Politecnico di Milano, and to Prof. Milos Zefran, that supervised my work at University of Illinois at Chicago, for supporting my work, and for always having been good guides for my research. I also want to thank Prof. Aleksandar Rodic and Prof. Dusko Katic for having hosted me at Institute Mihailo Pupin. Their suggestions and practical help were precious to me, and resulted fundamental for completing the work.

I then want to thank Ing. Paolo Belluco and Ing. Matteo Maglio, both PhD candidates at Politecnico di Milano, for their expertise on EAPs actuators and on servomotors, respectively. Thanks also to Prof. Vittorio Zaccaria, for helping me in the analysis and validation of the results obtained.

Considered the interdisciplinary nature of this work, it is just thanks to these people that I could fulfill the objectives of the thesis, and obtain the results I did.

Finally, I want to thank my parents and family, for always having supported me, and my friends all.

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Chapter 1

Introduction

"A robot in every home". This is the title of the article Bill Gates, founder and leader of Microsoft Corporation, published on January 2007 in Scientific American. Robots are indirectly already part of our world, given they are at the core of modern manufacturing industry, even if we don't encounter them directly in our everyday life. But when the person that more than any other contributed to that which I would call the "computers revolution" refers to robotics, he clearly has in mind the concept of personal robot. A personal robot is far beyond the state of the art of to-

day's technology. It is closer to the robot described by the Czech novelist Harel Capek in his play R.U.R (Rossum's Universal Robots), published back in 1920. He thought of robots as artificial people so identical to humans to be mistaken with real humans; completely independent entities taking care of things people don't like doing, a sort of modern slaves, or, also, a modern version of the legendary Jewish Golem.

1.1 Robotics

The field of robotics, indeed, is huge. The term robot encompasses all sorts of artificial machines able to do tasks on their own, starting from the already cited industrial robots, to the most sophisticated space robots, such as Spirit and Opportunity, the famous rovers used for the exploration of the surface of Mars, passing through service robots, that help us keeping the house cleaned and the backyard grass cut, and the first prototypes of biologically inspired robots, an example of which is the humanoid robot.

1.2 Humanoid Robotics

Humanoid robotics is then just a small part of robotics itself, but it's maybe the most challenging task in the field: being still in an embryonic phase, most of the new solutions proposed represent a significant development of the state-of-the-art. Except for some isolated examples, such as Leonardo Da Vinci's robot project, up to now science-fiction has been the natural environment for humanoid robots, and the enormous success and diffusion of these novels is probably the reason why when we talk about robot we usually intend humanoid robots. Isaac Asimov created a whole futuristic scenario in which humans and highly sophisticated robots cohabit in a deeply described universe. Motion picture industry built a fortune on the representation of the futuristic worlds described by science-fiction novelists. On a parallel row, otherwise, since the 1956's conference held in Dartmouth College, NH, USA, when professor John

McCarthy used for the first time the term Artificial Intelligence, many research institutions, mainly universities, contributed to the concrete growth of this field. Some with small steps forward, some others with works that produced results that became milestones in the evolution of humanoid robotics.

1.2.1 Humanoid Robotics: why and how?

The first issue to be addressed by any researcher that enters the world of humanoid robotics is *"Why to develop humanoid robots?"*. Robots are meant to do tasks in place of humans, maybe because the environment is dangerous, maybe because the task itself is tough or repetitive, or maybe because robots can do it faster and more precisely. It looks obvious anyway that highly specialized robots will perform specific tasks way better. The rovers developed by NASA are for sure more efficient than any humanoid robot for the goal of planet exploration. At the same time, the cleaning robots already on the market are more comfortable in performing their task than any humanoid robot will ever be. And so on for any kind of goal-oriented robot already in use or under development. But it comes evident, on the other hand, that all of these robots will always be also limited by their being specialized. A cleaning robot doesn't have the necessary features to serve in a manufacturing factory. And it maybe might be used, after considerable changes, in space robotics, but the results of his performances are expected to be definitely unsatisfactory.

If then we want to build a robot that could perform the highest number of tasks a human person meets in his every day life, then we should think of it as similar as possible to a human. It will perform the single task less efficiently then a robot thought to be optimal in that exact goal, but it will be able to adapt to the most different situations. This is why a major effort of humanoid robotics researchers is addressed in understanding the dynamics of the "system-human" works: the way we reason, the way we learn, the way we walk, the way we see, and so on. Humans are the best model for humanoid robots, and understanding ourselves in-depth is fundamental to imitate our features.

On the other hand, developing systems that aim to reproduce our functionalities helps us in understanding better ourselves, and this new knowledge may be used for instance in the medical context. It comes out that the study of the human capabilities, and the reproduction of these in the development of a humanoid robot, form a closed loop: the more we know about the "system-human", the better we can replicate it in a robot, and the more detailed our research in robotics is, the bigger the amount of new information about ourselves will be.

1.2.2 Humanoid Robotics: subtasks

Being the model we refer to the most sophisticated system on earth, the goal of developing a robot that imitates the highest number of its features in the most accurate way is, of course, enormous. This is the reason why in robotics research different subtasks are identified. One big area of research goes under the name of Cognitive Robotics, and aims to reproduce the way we reason, we learn, we remember things, and mainly all that has to do with our brain activity. Another field of research concerns with our capability of relating with the external environment through senses, and in particular thanks to vision, studied by Computer Vision researchers. A third main area regards the mechanics of the robot, that can be divided again into two more specific tasks: manipulation and locomotion.

This work of thesis concerns with locomotion of humanoid robots. In Subsection 1.2.3 we'll focus our attention on this topic, and present in detail its characteristics.

1.2.3 Humanoid Robotics: locomotion

When we talk about locomotion we refer to the capability, in this case of a humanoid robot, to walk or to perform more complex actions like running or climbing stairs. The quality of a robot locomotion can be measured taking into consideration some characteristics: the first, and maybe the most important, is the stability, necessary to have a robot that walks correctly, followed by the energy-efficiency and the smoothness of the generated gait. Going more deeply into details:

1. *Stability:*

   in all of the instances of the gait generated to perform the walking, the robot must assume a configuration that is stable, otherwise you can't prevent it from falling. A first restrictive criterion is known as static stability, that is sufficient to guaranteed the correctness of the locomotion, but imposes very strong limitations. Professor Miomir Vukobratovic, in 1968, was the first to demonstrate that static stability was not necessary, and that in fact dynamic stability was sufficient to have a correct gait. He precisely defined the concept of dynamic stability, and presented a method, Zero Moment Point (ZMP), to evaluate it. The ZMP is the point on the ground where the sum of all the moments of the active forces is equal to zero. If this point is within the convex hull of all contact points between the foot and the ground, the robot is dynamically stable. In the following years many other methods, that can be used as an alternative to ZMP, have been developed, some of the which extend its validity to more complex situations. In general, anyway, up to now ZMP resists worldwide as the most commonly used method to control the dynamic stability of a robot.

2. *Energy efficiency:*

   a robot is a complex mechanical system. Humanoids, as other robots, like mobile robots, or service robots, have to be autonomous. In the last years researches in new materials and chemistry permitted the development of batteries that are always smaller, lighter, and at the same time longer lasting. Results reached, anyway, are still not sufficient if we want our robots to perform complex actions for a long period without recharging. Locomotion is one of the most energy consuming tasks. It then becomes fundamental to have a robot optimized to require as less energy as possible to walk correctly. The more energy efficient the robot is, the more autonomous it consequently will be.

3. *Smoothness:*

   this last feature is in a certain way accessory, but it is a good indicator for the two preceding ones: if our robot walks following smooth trajectory it will risk less to fall out of its region of stability, and it's probable that its current energy consumption is close to optimal.

There are two specific phases in which we can interfere with the goodness of the robot locomotion for what concerns these criteria: the design of the robot and the control of the locomotion itself. Making a good design of the robot means taking the best decisions about the material and the actuators to be used, the number of degrees of freedom to provide the robot with, some particular solutions to be adopted, for instance, in the implementation of some specific joints. Once the robot has been built, then, the quality of the locomotion depends only on the controller. A good control system prevents the robot from assuming dynamically unstable configurations, and maintains smoother and more energy efficient trajectories; moreover, it should also be capable of adapting to unpredictable situations, and learn from past experience. These kinds of controllers go under the name of Intelligent Controllers, and take advantage of the so called Soft Computing techniques.

1.3 Aims of the work of thesis

Given a synthetic overview of the field of robotics, and identified the point where we can locate this work, we can now start describing it more into details. As already anticipated, this thesis deals with locomotion, and, more in the specific, aims to provide all of the information necessary to design an efficient robot, and to develop a robust control.

To achieve the first goal, a formal criterion to determine the goodness of the choice of materials and actuators to be used is presented. This results are integrated with some considerations obtained by the analysis of what experienced in previous works on humanoid locomotion made at the *AIR-*

Lab, Politecnico di Milano, and at other considerable research institutions. This will permit us to suggest some configurations, given the financial and technological availabilities, for the development of an humanoid robot.

For what concerns control, instead, we based our research on the controller developed at Institute Mihailo Pupin, Belgrade. After an in-depth analysis of the current controller is given, we will propose some possible enhancements meant to improve its performance in terms of stability and efficiency. Moreover, the new controller will be able to learn from experience: this means that its performance will become better and better with training on the field.

1.4 Organization of the document of thesis

In Chapter 2 we'll briefly give an overview of the best state of the art humanoid robots, emphasizing their main characteristics and what made them innovative with respect with the other robots. Then, in the same chapter, *LARP*, the humanoid robot developed at the AIRLab, Politecnico di Milano, and the Institute Mihailo Pupin controller will be presented in details. Last section, instead, is dedicated to the analysis of human gait, and to the definition of the anatomical terminology we will adopt. Next chapters are the very core of this dissertation: in Chapter 3 a formal method to determine the energetic performance of the robot, given materials and actuators, will be presented; in Chapter 4 we'll report and give an interpretation to the results obtained. Next, in Chapter 5, our proposed improvements to the control system developed at Institute Mihailo Pupin will be described. Finally, in Chapter 6, we'll summarize the conclusions we got to, and propose possible developments to this work.

Chapter 2

Background and preliminary considerations

Aim of this Chapter is to report the preliminary information necessary to introduce the work we did, that will be, instead, presented in next chapters. In the first section of this chapter, we will list those humanoid robots that we consider to be the most significant in the state of the art for what concerns the results they achieved in locomotion, briefly analyzing and exposing their main characteristics. Then, in the second section, we'll present *LARP*, the robot developed at the *AIRLab, Politecnico di Milano*, on which this work is based. Next, in the third section, the current Institute Mihailo Pupin controller will be analized, and its strengths and weaknesses will be discussed. Finally, in the last section, we'll introduce the anatomical terminology we adopt, and briefly analyze human gait.

2.1 State of the art

Among the most skilled robots in the world, on date, deserve a special mention *Asimo*, which is the last robots produced by a private company, the Japanese *Honda*, and *Wabian-2R*, that is the last result of the efforts of the researchers of the *Atsuo Takanishi Laboratory, Waseda University, Japan.* Last robot that we are presenting is *Petman*, that on date still hasn't seen the light of day, of the American *Boston Dynamics.* This project, financed by *DARPA*, is the natural evolution of the quadruped robot *BigDog*, and is supposed to be completed in 2011. For the moment just some videos of a first prototype are available, but already its skill impress in a very positive way.

2.1.1 State of the art: robot Asimo

Robot Asimo (Figure 2.1), acronym for ”Advanced Step in Innovative MObility”, with its most recent version presented in 2005, is the result of the research held by the Japanese private company Honda, that invests in robotics since 1986.

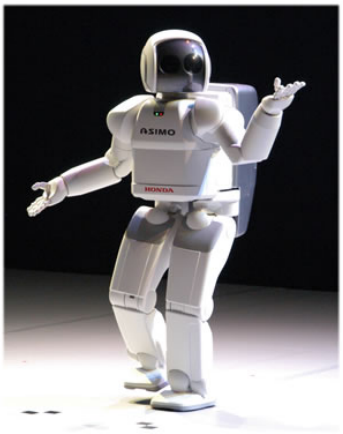


Figure 2.1: Robot Asimo, of the Japanese Honda

Asimo is probably the most famous humanoid robot all over the world, and has been produced in over 100 units.

The robot is 130 cm tall for 54 kg, and can walk at a speed of 2.7 km/h, or run at up to 6 km/h. Its 34 degrees of freedom, of which 6 in each leg, are actuated by servomotors. Its dynamic stability is guaranteed by a Zero Moment Point (ZMP) controller.

2.1.2 State of the art: robot Wabian-2R

Second, in chronological order, is robot Wabian-2R (Figure 2.2), of the Japanese Atsuo Takanishi Laboratory, Waseda University, Japan, unveiled in 2006. This humanoid, whose height is 150 cm and weight with batteries is 64 kg, is the one that on date performs the most natural and human-like gait, with stretched knees and heel-contact and toe-off motion, resulting very innovative in the field of humanoid locomotion.

What made it possible to achieve these results is the use of a redundant mechanism: recognizing that the pelvis motion plays a significant

Figure 2.2: Robot Wabian-2R, developed at the Atsuo Takanishi Laboratory, Waseda University, Japan

role in human's gait, the Japanese researchers developed a 2 degrees of freedom waist that, working in addiction to the 6 degrees of freedom per legs, permitted to overcome the mechanical constraints that forced the other robots to walk with bent knees. Wabian-2R also has two 1 degree of freedom passive joints in its feet to enable it to bend its toes in steady walking, that sum up with the other 39 active joints in the whole body, actuated by servomotors. Also in this case ZMP is the criterion adopted to ensure stability.

2.1.3 State of the art: robot Petman

Last of the robots we're presenting is Petman (Figure 2.3), acronym for "Protection Ensemble Test Mannequin", the last challenge of the American Boston Dynamics, supported by DARPA, supposed to be completed in 2011. At the moment not much information about it is available, but for some demonstration videos of its first prototype, that, by the way, already anticipate the incredible skills of the robot.

Petman is the evolution of the most famous BigDog, a quadruped robot, and takes the magnificent results achieved in locomotion by his predecessor as starting point for its development. Of course, the control system of BigDog, its main strength, has to be adapted to the more difficult context of bipedal locomotion, being bipeds notoriously less stable then quadrupeds. Another problem the American researchers will have to face concerns with actuators: BigDog is powered by a big, noisy com-

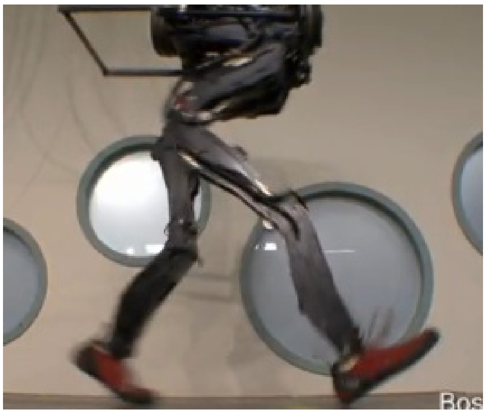


Figure 2.3: Robot Petman, evolution of BigDog, of the American Boston Dynamics

bustion engine, which drives a hydraulic pump; this high pressure oil is then distributed to 12 hydraulic actuators. Petman, being smaller then BigDog, will also need smaller motors. Basing on some recent documents regarding Petman, its actuators will be a combination of electric and hydraulic motors, choice constrained by the requirements of the system.

2.2 Robot LARP

After this brief analysis of the state of the art humanoid robots, built, or under development, in the most advanced research centers in the world, we can now describe the robot we based on for this thesis work.

The Light Adaptive-Reactive biPed, referred as *LARP* now on (Figure 2.4), is the humanoid robot developed at the AIRLab, Politecnico di Milano, and is its main platform for studies on bipedal locomotion. Work on LARP started in 2003, with the Master's thesis of Ing. Umberto Scarfogliero, advised by Prof. Giuseppina Gini and Ing. Michele Folgheraiter: the design and a first control for the robot was presented. Being focus on locomotion, it was decided to start just building the lower part of the robot, from the pelvis down.

The structure of the robot is in polycarbonate, but for some small parts in carbon-fiber. The reason that led to this decision was not only the good strength/weight ratio, but also the fact that this material is way cheaper then others widely used in robotics. The robot is 90 cm high,

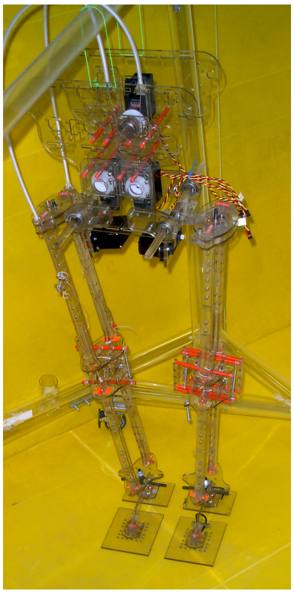


Figure 2.4: Robot LARP, developed at AIRLab, Politecnico di Milano

has 12 active degrees of freedom, 6 per leg, distributed in 3 in the hip, 1 in the knee, and 2 in the ankle, and 4 passive degrees of freedom, 2 in each foot, representing the heel and the toe. The target of building a light robot is completely satisfied, being LARP weight less then 5 kg. Moreover, dimensions, mass distribution, and range of motion of each joint reproduce those of an average human being. In order to dispose masses in the desired way, and, at the same time, obtain a very light leg, the 12 servomotors that provide the torques are located in the pelvis. Transmission is then performed by a system of cables and levers. To permit the joint stiffness control proposed, each servomotor is equipped with a spring and a damper. To test the behavior of the system, on a parallel row, the robot has been modeled in Matlab and in MSC Adams (Figure 2.5).

Work on LARP has then continued with the theses of many students of Politecnico di Milano, under the supervision of Prof. Gini. Among these, those that contributed the most to the evolution of the robot are the Bachelor's theses of A. Sgarlata and R. Sormani, in 2006, that provided the static walking to LARP, the Bachelor's thesis of M. Forloni, of the same year, with a first analysis of energy consumption, and the Bachelor's theses of F. Moro and A. Giovanazzi, in 2007, that developed the dynamic walking, implementing a stability control and correction using the ZMP method.

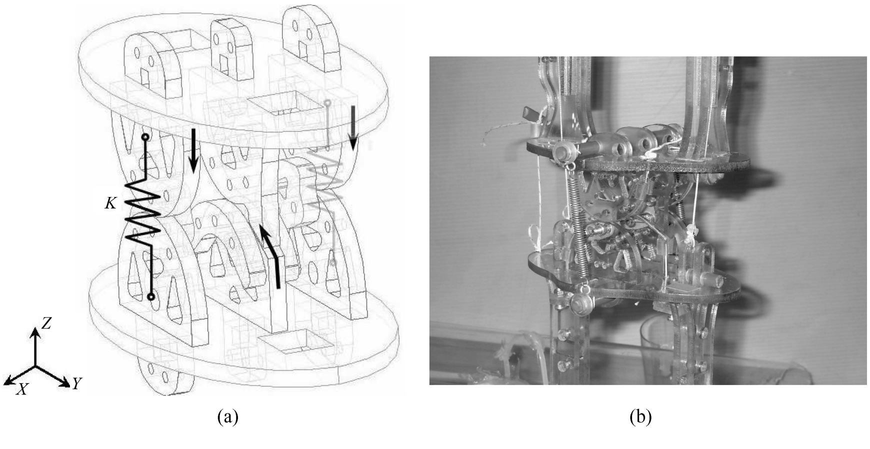
Concluded this overview on the robot, in the next sections we'll see more in the specific two characteristic details of the mechanical design of

LARP, the knee (Section 2.2.1), and the foot (Section 2.2.2).

Figure 2.5: 3D model of robot LARP, developed using MSC Adams

2.2.1 Robot LARP: the knee

Most of the humanoid robots have a knee simply realized with a pin joint. Looking at prosthesis field, on the other hand, the approach in many cases is different. Passive knee prosthesis usually perform the bending using inertial torque generated by the forward acceleration of the thigh, in a manner that reminds the basic functioning of passive dynamic walkers. To achieve good results in this, the most advanced prosthetic knees are built using a multi-axial mechanism, in which the center of rotation is not fixed, as in a pin joint, but moves along a trajectory that depends on the mechanism structure itself. Considering that the stability of the knee during the stance phase strongly depends on the center of rotation position, it is possible to control its properties varying the proportions of the mechanism.



(a)

(b)

Figure 2.6: The knee of robot LARP, design (a) and prototype (b)

Inspiration for the design of this kind of joint is the human knee itself: the lower part of the femur and the upper extremity of the tibia can be represented by two rolling surfaces kept together by several ligaments (Figure 2.6), that allow the articulation to move along one degree of freedom. This solution reduces significantly friction. To ensure the necessary rigidity to torsional forces and external disturbance, a special structure has been designed to make the articulation more firm. Moreover, elastic actuators have been used to exploit inertial forces due to hip actuation. This features improve the efficiency of LARP knee, producing better results for what concerns energy consumption and stability, with respect with the solution adopted by large part of the other robots.

2.2.2 Robot LARP: the foot

The design of the foot is a crucial phase in the development of an humanoid robot. Both stability and energetic efficiency are strongly affected by the goodness of choices made on what kind of solution to adopt. Almost all biped robots have a big flatfoot, in order to obtain a higher stability. Results on energy consumption, however, are not satisfactory, and, for sure, far from human performance. When the foot comes in contact with the surface, it is subject to the ground reaction force. If no structure aimed to handle it is developed, this force may result in a disturbance to the entire system, and, even worse, a lot of energy goes wasted at every step. For this reason, many humanoid robots have heavy dampers to smooth out the heel strike, but this solution is not flexible enough, and still the behavior of the foot doesn't reflect that of a human foot.

Another simple solution, proposed mainly on passive dynamic walkers, is the round foot. In this case the ankle is moved forward during the rotation, and this results in a better energetic performance. On the other hand, the contact surface is reduced to a thin area, and this appears to be a problem for the stability of the robot.

The solution proposed for LARP aims to be a trade-off between stability and efficiency. The foot is composed by an arc, acting as the structure of the foot, and by 2 passive degrees of freedom, representing the heel and the toe (Figure 2.7). This solution permits to manage the energy received by the ground reaction force, and doesn't constrain the ankle in one fixed position, and these reduce energy consumption. At the same time, a big portion of the foot is in contact with the surface at any phase of the step, giving a stable support to the robot.

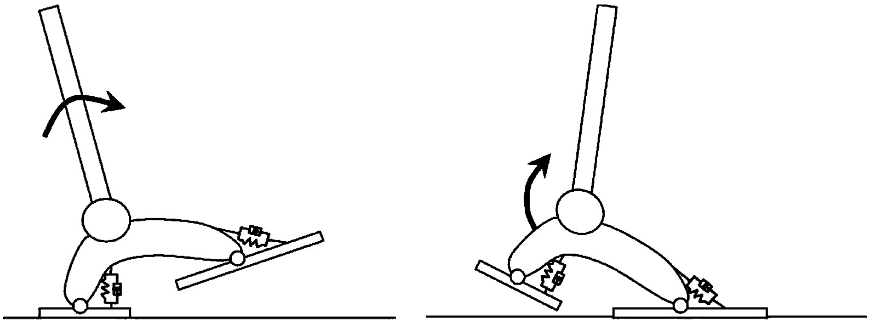


Figure 2.7: The design of the foot of robot LARP

The solution adopted for robot LARP, furthermore, fits perfectly with the heel-strike and toe-off gait, that best reproduces the human-like walking, and, again, gives the most satisfactory results for what concerns energy efficiency.

2.3 Institute Mihailo Pupin controller

As anticipated, for the control of the robot we based our research on the hybrid integrated dynamic control system developed at Institute Mihailo Pupin, Belgrade, Serbia, by prof. Dusko Katic. Before reporting the enhancements we propose to further improve its performance (Chapter 5), in this section we describe the features of the current system, analyzing its strengths and weaknesses.

2.3.1 Introduction to the IMP controller

The hybrid dynamic control system developed at Institute Mihailo Pupin is a sophisticated example of intelligent control based on Soft Computing techniques.

The main objectives of the controller can be summarized in:

1. accurate tracking of the desired joint trajectories;
2. maintenance of the dynamic stability during the motion;

3. minimization of the effects caused by the impact of the foot with ground during the gait;
4. minimization of the dynamic loads on the joints;
5. development of a human-like gait.

Some preconditions are specified:

1. the model of the robot describes with sufficient reliability the real system;
2. the desired joint trajectories, performing a dynamically balanced gait, are known and constant;
3. the geometric and dynamic parameters of the mechanism and of the driving units are known and constant.

The system proposed bases on these assumptions, and aims to satisfy the objectives set. As you can see in Figure 2.8, the system integrates three feedback loops:

1. a basic dynamic controller for the trajectory tracking;
2. a dynamic reaction feedback at the ZMP based on a reinforcement learning structure;
3. an impact force compensator.

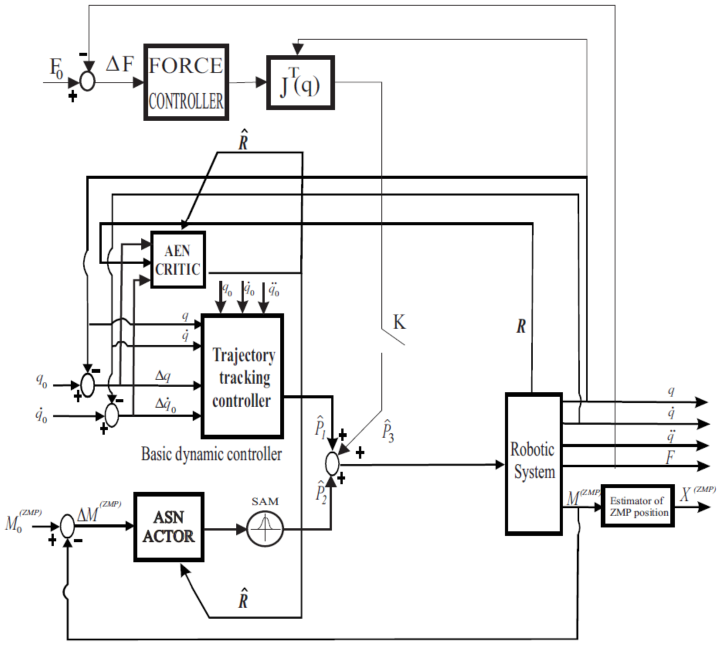


Figure 2.8: Block-scheme of the intelligent control system developed at Institute Mihailo Pupin, Belgrade, Serbia

While the first and the third loops are developed reproducing a traditional position-force control, and introducing a basic compensation of the impact forces, respectively, the real innovation is in the second feedback loop. We're going to describe it more in detail in the next section.

2.3.2 Compensator of dynamic reactions

The reinforcement learning structure, developed to compensate the dynamic reactions at the ZMP, is based on Actor-Critic methods. The system is represented in Figure 2.9.

There are two basic elements: the Actor, that defines the control strategy, and the Critic, that evaluates the control actions made by the Actor. Then we have two reinforcement signals: an external reinforcement signal (Reward) R, and an internal reinforcement signal (Temporal Difference - TD error) $\hat{R}$.

The Reward is set to 1, if the ZMP error is greater than a chosen limit, otherwise it is set to 0. The Critic is a standard 2-layes feedforward neural

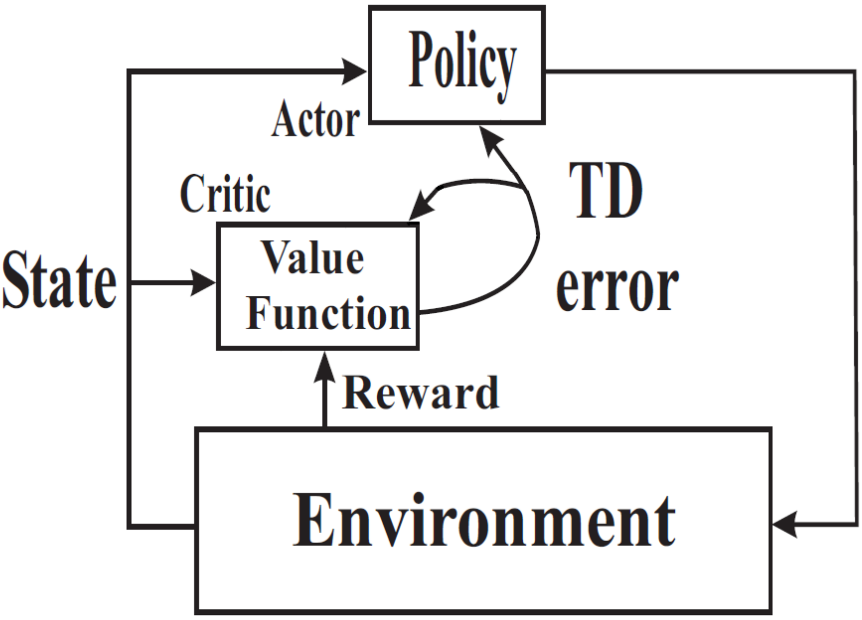


Figure 2.9: The Actor-Critic architecture

network, that receives as inputs the Reward, and the position and velocity errors on the joints. The output is a scalar v. This value is important to evaluate the TD error $\hat{R}$, that is then defined as:

$$\hat{R}(t+1) = R(t) + \gamma v(t+1) - v(t),$$

where γ is a coefficient between 0 and 1.

The Actor, instead, is an ANFIS Sugeno-type adaptive neural fuzzy inference system, that receives as an input the error on the ZMP, and returns a recommended control torque. A Stochastic Action Modifier (SAM), then, uses the recommended control torque from the Actor and the internal reinforcement signal to produce the final control torque P_{dr}. It is defined by a Gaussian random function, where the recommended control torque is the mean, while the standard deviation is defined as:

$$\sigma(\hat{R}(t+1)) = |(1 - e^{-|\hat{R}(t+1)|})|.$$

After a period of training the standard deviation converges to zero, thus eliminating the randomness of the output.

At this point, according to the kinematics of the robot, the final control torque P_{dr} will be distributed on the active joints to compensate the dynamic reactions. In the single support phase only the active joints of the supporting leg are considered, while in the double support phase the active joints of both legs are involved.

This system has been tested in a Matlab simulation environment. Different situations have been reproduced, such as the walkind on a slope when the reference joint trajectories were defined for walking on a plain: the reinforcement learning control proved robust enough to compensate the deviations of dynamic reaction generated by the uncertainty on the ground surface inclination. The performance of the whole system, compared to that of the basic joint trajectories tracking control, show evident improvements. When controlled by the complete IMP system, the error on the joint trajectories and velocities, as well as the error on the ZMP, converge to zero in less than 1 second.

2.4 Anatomy of the human body and gait cycle

In this last section of the chapter, we briefly analyze the anatomy of the human body (Section 2.4.1) and of the gait (Section 2.4.2), introducing those terms that we'll use in the next chapters to describe our work on biped locomotion.

2.4.1 Anatomy of the human body

A first useful information is the mass distribution of the average human body. Data are reported in Table 2.1.

A first observation is that limbs are really light with respect with the total body weight. Then we can notice that around 70% of the mass is in the upper part of the body. This keeps the center of mass high, and makes it easier to correct the posture in cases of instability. As explained before, the idea behind robot LARP was to reproduces at best the human

Table 2.1: Mass distribution of the average human body

	%	**Qty**	**Total %**
Head, neck, torax	31	1	31
Upper arm, forearm, hand	5	2	10
Abdomen, pelvis	27	1	27
Thigh	10	2	20
Calf, foot	6	2	12

body features. Considered that, currently, LARP doesn't have an upper body, all of the 12 servomotors were located in the pelvis. This solution permits a center of mass in high position, just like it is the human body.

In order to describe locomotion, we need to define the possible movements of the body. Hence, we can introduce the so called anatomical planes. There are three planes, as shown in Figure 2.10. The saggital plane divides the body into sinister and dexter (left and right) portions. In particular, if the two portions are symmetrical, the plane is called median, or midsaggital plane. All other saggital planes, parallel to the

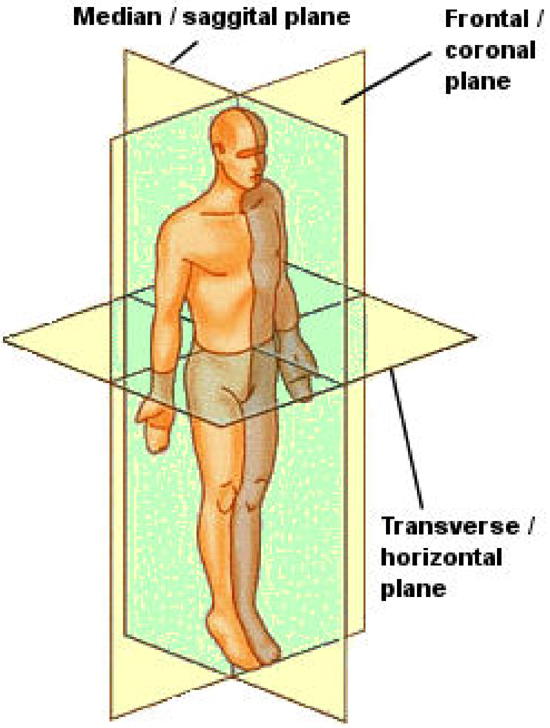


Figure 2.10: The anatomical planes of the body

median plane, are, instead, called parasaggital planes. The frontal, or coronal plane divides the body into dorsal and ventral (back and front, or posterior and anterior) portions. Last, the transverse, or horizontal plane divides the body into cranial and caudal (head and tail) portions.

Anatomical planes are useful to describe movements. If the movement would not cross a plane, it is said to occur within it. In Table 2.2 the main joint movements are described.

Table 2.2: Joint movements description

Movement	**Definition**
Flexion	Narrowing joint angle in saggital plane
Extension	Increasing joint angle in saggital plane
Abduction	Lifting a body part away from body midline (in frontal plane)
Adduction	Returning a body part to body midline (in frontal plane)
Rotation	Turning a body part on axis (transverse plane)

In straight walking the most significant movements are the flexion/extension of the hip, of the knee, and of the ankle joints. This is the reason why, in next chapters, we'll focus our attention in particular on these movements.

2.4.2 The gait cycle

To conclude the description of the adopted terminology, we need to talk about the gait cycle. The gait cycle is defined as the period between two successive contacts of the same limb with the ground. Is some cases the term step is used as a synonym of gait cycle. In some others it is defined as half of the gait cycle, which means the period between two successive contacts of different limbs with the ground. Even though this second definition is maybe the most common in colloquial, in this thesis when we talk about step we refer to the first definition, using, instead, the term half-step for the half period.

However, the gait cycle, as shown in Figure 2.11 is divided into two distinct phases: the stance phase, and the swing phase. In the stance phase, which usually represents a little more then 60% of the gait cycle, the leg is in contact with the ground. On the contrary, in the swing phase the leg moves forward to the next contact point.

The moment when the foot touches the ground is called heel-strike, while, on the opposite, the moment when it leaves the ground is called toe-off.

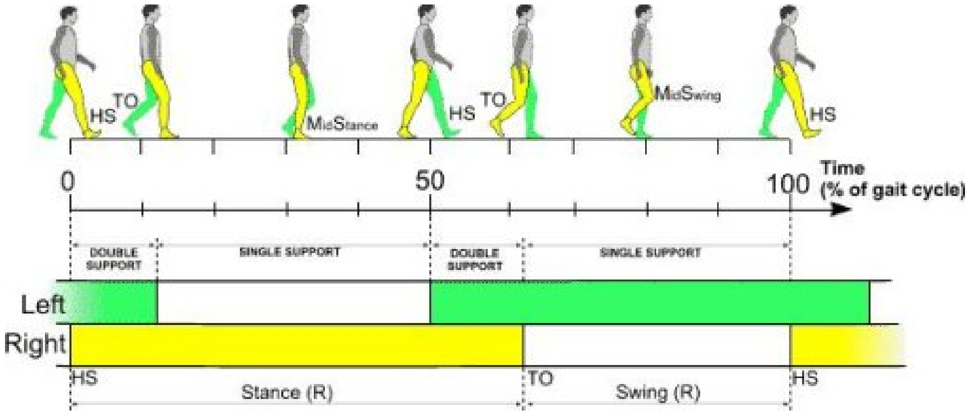


Figure 2.11: The gait cycle

The succession of the two phases for the different legs is synchronized so as to have the double support for around 20% of the gait cycle. The rest is divided into 40% in single support on one leg, and 40% in single support on the other leg. In spite of this, considered that the single support phase is the most dangerous for stability, most of the motion of the center of mass is concentrated in the double support phase.

Chapter 3

Design of the robot: what and how we did it

In the two previous chapters, the aim of this research and the context in which it falls have been described, and a brief analysis of the state of the art, of the current LARP configuration, and of the current Institute Mihailo Pupin controller have been presented.

In this chapter, instead, we introduce the study of the energy consumption we performed, and explain how we used it to obtain information useful in the phase of design of the robot. Main goal of this work is to develop a formal, reproducible method, not constrained by the specific characteristics of the robot, to determine the efficiency of certain configurations. The system developed is represented in Figure 3.1. Results obtained are supposed to be valid, and sufficiently reliable, to be useful indications for researchers in the field of humanoid robotics, that are defining the design of their robot, and are taking some decisions on which design solution to adopt.

The first step we made to achieve this target was the modeling of the robot in a simulation environment. We decided to work in Matlab, and had the opportunity to base on the first version of the *Humanoid robots simulation platform*, now on referred to as *HRSP*, developed at the *Institute Mihailo Pupin, Belgrade, Serbia.* We detected those parameters (analyzed in Section 3.2) that, in our opinion, affect the most the energetic performance of a robot, deciding, hence, to concentrate on the material used for the structure, and the actuators. So, exploiting the opportunities provided by the HRSP toolbox, we defined a parametric model of the robot, described in details in Section 3.1.

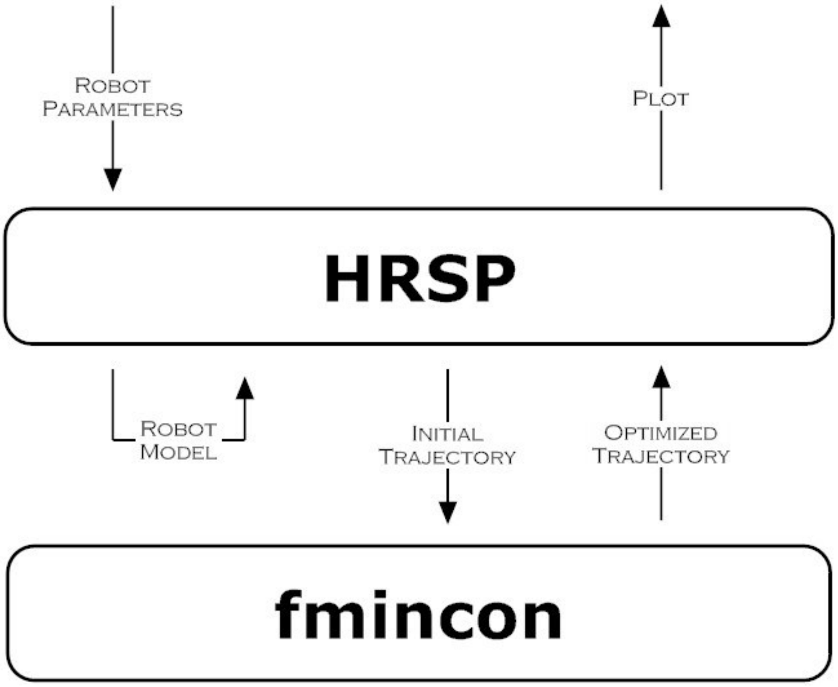


Figure 3.1: Schema of the system developed to evaluate the energy efficiency of the different design solutions

At this point, we needed a way to evaluate the goodness of the performance of the different configurations of the robot. That is, determine whether the robot is more efficient when a certain material and a certain kind of actuators is used, with respect with other possible solutions. The plan was to let *fmincon*, a function provided with the *Optimization toolbox*, optimize the joints trajectory, and compare the energy consumption necessary to execute it in the different configurations. The way the optimization module was set is reported in Section 3.3.

3.1 The model of the robot

HRSP is a Matlab toolbox developed at Institute Mihailo Pupin, Belgrade, Serbia, by prof. Aleksandar Rodic. We had the opportunity to use it for the definition of the robot, though this is just one of its many features. The model we built reflects the characteristics of robot LARP. It has 6 degrees of freedom in each leg, divided in 3 in the hip, 1 in the knee, and 2, that guarantee the flexion/extension and the abduction/adduction movements, in the ankle; Denavit-Hartenberg notation with multiple kinematic chains is used to define it. In this model, by the way, we didn't reproduce the mechanics of the knee and the foot described in the previous chapter: we just adopted a pin joint knee and a flatfoot. Height of the model, instead, respect that of real LARP, while weight, of course, depends on the material of the structure and on the actuators considered. By the way, if parameters are set to represent the current LARP configuration, the model weight, again, respects that of the real robot. For completeness, the measures of the single parts of the robot, as they are inserted in the simulation model, are summarized in Table 3.1.

Table 3.1: Measures of the parts of LARP model

	Measure [cm]
Pelvis width	27.63
Femur length	35.1
Tibia length	37.25
Foot length	21.5
Foot width	10

To reflect the dynamic behavior of the real robot, not only measure and masses are specified, but also the relative center of gravity of each link, and its inertia matrix.

In Figure 3.2 you can see the LARP model in standing posture, to visualize the proportion between the different parts of the robot, and the disposition of the 12 degrees of freedom. As you can see, the rotational axes of the hip joints are decoupled.

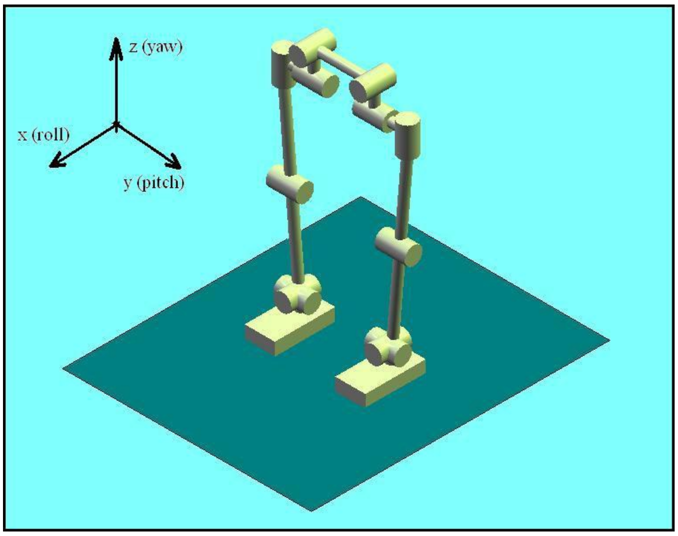


Figure 3.2: Robot LARP: dimensions and degrees of freedom disposition

3.2 The parameters

As anticipated in the previous sections, the main goal of this thesis is to determine the way certain choices made in the design phase reflect on the energetic performance of the robot. In particular, we identified in the material of the structure and in the actuators those parameters that affect the most the efficiency in terms of energy consumption. Currently, LARP structure is mainly in polycarbonate, and necessary torques are provided by 12 servomotors. Other materials frequently used in building robots are aluminium, titanium, and inox steel. These have different weight, different mechanical features, and different costs: all factors to be considered to decide which among these materials to use. Choice on actuators is even more complicated. Most of the state of the art robots are moved by servomotors, mainly because this is the simplest and most consolidated available technology. Other solutions, as electro-active polymers actuators (now on referred as EAPs actuators), are to date still an objective of research: they have great potential, but still some technological limitations have to be overcome. In recent research, though, some interesting prototypes of EAPs actuators, meant to be used in robotics applications, have been proposed, and in next years some more definitive versions are supposed to be put on the market.

In Section 3.2.1 the characteristics of the materials considered are analyzed more in detail, while in Section 3.2.2 we'll focus our attenction on actuators.

3.2.1 The parameters: structure material

First decision to be taken when designing a robot is what material to use to build its structure, that is those parts that behave like bones for humans. Many different solutions are available (the main features of the materials we considered are reported in Table 3.2). All of them have strengths and weaknesses. Candidate materials must satisfy certain requirements: it must be light, strong, and, possibly, not too expensive.

LARP, at the current state, is made of polycarbonate, a thermoplastic

Table 3.2: Main characteristics of the materials considered for the structure of the robot

	Density [g/cm^2]	**Young's modulus** [GPa]	**Tensile strength** [MPa]	**Cost**
Polycarbonate	1.2	2	65	Low
Aluminium alloy	2.7	69	310	Medium
Titanium alloy	4.4	110	1000	High
Stainless steel	7.9	193	570	Medium

material widely used in the engineering field because of its features. In fact, it has a really high strength to weight ratio, being its density only 1.2 g/cm^2, a restrained cost, and is easy to fabricate. Unfortunately, experience tells us this material is not strong enough for robotics applications. Possible impacts have to be taken into account, and this material turned out to be too fragile to tolerate them.

Hence, currently LARP is not reliable for what concerns its resistance to impacts. This is the reason why the other materials we decided to consider are all definitely stronger. *Young's module* is the most used measure of the stiffness of an elastic material among the several elastic moduli available, while the *tensile strength* indicates the edge to pass from an elastic deformation to a plastic deformation. These mechanical parameters describe the performance of a material in terms of its strength. We focused our attention on three materials widely used in high-performance engineering applications, such as military vehicles, aerospace, aeronautics, marine, high-pressure hydraulic systems, and some expansive sport cars.

The first material is the tempered 6061 aluminium alloy, which has a density of 2.7 g/cm^2, Young's modulus of 69 GPa, and tensile strength of 310 MPa. It contains magnesium and silicon as its major alloying elements, and is one of the most common alloys of aluminium. The high availability of raw material, aluminium is the most abundant metal in the Earth's crust, and the limited processing costs, due to its low melting point and its diffusion, make it an affordable solution.

The second material we considered is the titanium 6Al-4V alloy, also known as titanium alloy grade 5. It has a density of 4.4 g/cm^2, Young's modulus of 110 GPa, and tensile strength of 1000 MPa. It has a chemical composition of 6% aluminium, 4% vanadium, and remainder titanium, and is significantly stronger then pure titanium, while having the same stiffness. Because of these properties it is the most commonly used titanium alloy. Compared to the aluminium alloy just described, it has better mechanical features, though remaining light enough. It's main weakness is cost: both raw material and processing are expensive, and this is a big limit to the diffusion of its usage.

A more affordable material is the third alternative we're going to present, the 316 stainless steel, a solid solution of iron with alloying elements, main of which are Cr, between 16% and 18%, and Ni, between 10% and 14%. It has a density of 7.9 g/cm^2, Young's modulus of 193 GPa, and tensile strength of 570 MPa. This means that its mechanical features are comparable or even better then those of the titanium 6Al-4V alloy, though its cost is way lower. Unfortunately this material is heavier then the others, and this would affect a lot on the total weight of the robot and, consequently, on its efficiency, with an incidence that we're going to evaluate with the method we developed.

3.2.2 The parameters: actuators

A second parameter we're studying is the actuators. The choice of a certain solution has a big impact on energy efficiency, in a way that is less predictable than in the materials case. Currently LARP has 12 *HITEC HS-805BB* servomotors (main features, as reported by the official producer specification sheet, are summarized in Table 3.3), that provide up to 24.7 kg cm torque each. A system of coramide tendons (with a tensile strength of 800 N, for a diameter of 0.5 mm) transmits the torques from the pelvis, where servomotors are located, to the joints. Having the motors in this position makes keeps high the center of mass of the robot, making it easier to correct the stability. Furthermore, the legs that result are really light. On the other hand, friction generated by the transmission tendons represents a big loss in terms of energy.

In the field of robotics, the solution of servomotors has been adopted

Table 3.3: Main characteristics of the Hitec HS-805BB servomotors

Control system	+pulse width control 1500 usec neutral
Operation voltage range	4.8V to 6.0V
Operationg temperature range	-20°C to $+60$°C
Operating speed	0.19sec/60° at no load (at 4.8V) - 0.14sec/60° at no load (at 6.0V)
Stall torque	19.8 kg cm (at 4.8V) - 24.7 kg cm (at 6.0V)
Operation angle	45°/one side pulse traveling 400 usec
Direction	clock wise/pulse traveling 1500 TO 1900 usec
Current drain	8 mA/idle and 700 mA/no load running
Dead band width	8 usec
Connector wire length	300 mm
Dimensions	66x30x57.6mm
Weight	152g

in most of the cases, being this technology well known and economically affordable. If the system is correctly set, an average efficiency of 80% can be reached. Yet, this is not the only available solution. Some advanced robots are actuated by pneumatic or hydraulic linear actuators. These systems, however, are driven by auxiliary components, such as compressors, high pressure cylinders, or engines, that are heavy, noisy, and need a lot of space, often not available in a humanoid robot. This turns out to be a big limitation, that reduces the field of use to academics. A more sophisticated solution is given by ElectroActive Polymers actuators, shortly EAPs actuators, polymers whose shape is modified when a voltage is applied to them. Interesting for robotics applications are the linear stack actuators based on dielectric EAPs, or multi-layer dielectric EAPs actuators. Different realization have been proposed by different research groups (one is shown in Figure 3.3), but the concept that remains is generally similar. The classical structure of dielectric EAPs, where a passive silicone or acrylic elastomer film is coated on both sides with electrodes, is replicated, stacking up several layers of this basic unit. This approach makes it possible to enlarge force and deformation in thickness direction, and, even more interesting, this kind of actuators, controlled by the applied voltage, behave in a way that is really similar to human muscles. This devices are extremely light, and can reach an average efficiency that is major than 90%. Of course, the use of linear actuators to drive rotational joints implies an additional loss, that depends also on the varying angle of the joint, and the simulation model we developed takes it into account. Though the great perspectives for what concerns energy efficiency, this technology, to date, is still an objective of research: some prototypes have been presented, and results obtained are really promising, but there's no finite product on the market, yet. Moreover, their dynamic nature makes the control of these systems more complicated then in the case of servomotors.

Summarizing, stack dielectric EAPs have an enormous potential and tremendous room for improvement, but on date they are not ready for real applications, yet. However, some research groups predict to produce the first reliable prototypes, ready to be used on real systems, in the very few years. This is the reason why we decided to analyze the effect this new technology would have on the energy efficiency of humanoid locomotion, comparing it with the more consolidated servomotors solution.

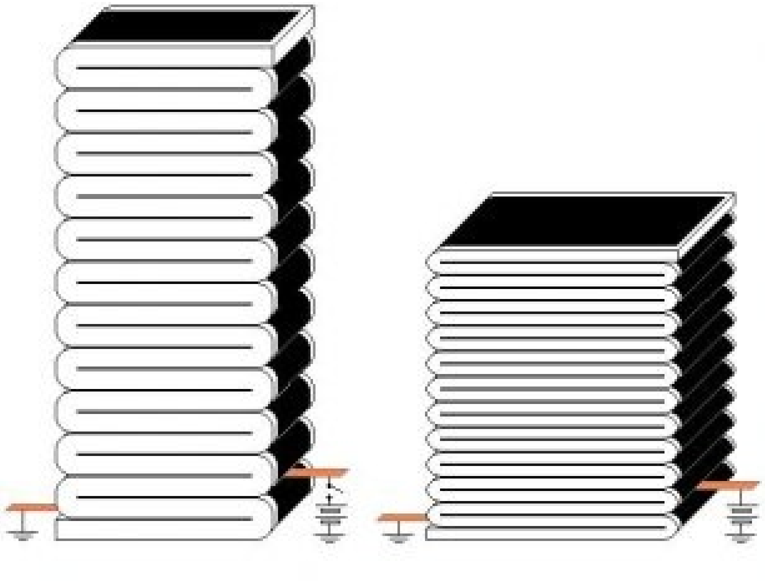


Figure 3.3: Design of the implementation of a stack dielectric EAPs actuator, as proposed by the researchers of Centro E. Piaggio, Università degli Studi di Pisa, Italy. In this form they're called folded dielectric EAPs actuators.

3.3 The optimization module

Once we have developed a parametric simulation model of robot LARP in Matlab environment, we need to define a way to obtain an evaluation of the performance of the different solutions analyzed, in order to compare them in the perspective of possible future enhancements.

We decided to use fmincon, provided by the Optimization toolbox, that finds the minimum of a constrained nonlinear multi-variable function, to determine which joints trajectory minimizes the energy consumption for each determinate configuration. This gives us the opportunity to evaluate the energy efficiency of the different configurations, and then to compare them to define which solutions are the most convenient, in order to build an efficient robot. The fmincon problem is specified in the following way:

$$\min_x f(x) \text{ such that } \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A \cdot x \leq b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub \end{cases}$$

where

$x, b, beq, lb, ub:$ vectors;

$A, Aeq:$ matrices;

$c(x), ceq(x)$: functions, possibly nonlinear, that return vectors;

$f(x)$: objective function, possibly nonlinear, that returns a scalar;

1. In our case, x is an vector containing the concatenation on the joints angles at the different frames of an half-step. For half-step we intend one single-support phase plus one double-support phase: this is the minimum periodic sequence in the bipedal walking.

2. $f(x)$, the objective function, is the evaluation of energy consumption to achieve one half-step, following a certain trajectory described by x. We started from the dynamic equation of motion: $H(q)\ddot{q} + C(q, \dot{q})\dot{q} + N(q) = \tau$, where H is the inertia matrix, C includes the Coriolis and centrifugal forces, and Gravity terms are included in the vector N. Velocity and acceleration vectors $\dot{q}$ and $\ddot{q}$ are the first order and the second order derivatives of the vector q, respectively. The mechanical energy is then computed as $M = \int_0^T \dot{q}^T \tau \, dt$. The efficiency of the different actuation solutions, and the additional losses given by linear actuators are then taken into account to evaluate the

electrical energy E necessary to perform the desired trajectory. All of these equations are discretized to be used in Matlab environment.

3. It was then necessary to define the constraints the optimization problem must satisfy. With lb, lower bound, and ub, upper bound, the possible configurations of joints are limited into a certain physical range. With the linear inequalities also velocity and acceleration of the joints are limited, while with the linear equalities the starting and the final position of the robot are fixed. The last constraint, that we defined with the nonlinear inequalities, is given by the ground, considered that during the swing phase the foot should obviously avoid any contact with it.

The structure of the program we developed is then the following: HRSP provides a geometric starting trajectory for the LARP model we defined, and passes it to the optimization module; this module, after many steps, finds a new trajectory that optimizes the objective function, respecting the constrains, and returns it to HRSP, that then can use it to define the gait of the robot.

3.3.1 Difficulties encountered and solutions adopted

The method described in the previous section, unfortunately, turned out to be computationally too complex. The length of vector x is equal to the number of joints multiplied by the number of frames in one half-step. Even if we set the time step to be long enough, as we did, obtaining only 50 frames per half-step, complexity remains too high. Some test simulations, taking into account just one leg per time, that is 6 degrees of freedom, took months to get to a result. A complete simulation, with all 12 degrees of freedom of the robot, would require fmincon to find the 600 values of a vector x that minimizes the objective function, not violating an enormous amount of constraints, in an enormous solution space; this would mean, reasonably, years of simulation before returning the result.

A first solution we investigated was to use distributed computing. Unfortunately, the basically sequential nature of fmincon makes it impossible to take advantage of the benefits of parallelism, and makes it necessary for us to look for an alternative solution. We hypothesized that this alternative could be given by the use of genetics algorithms: we substituted the fmincon function with the similar *ga* function, provided with the Genetic Algorithms toolbox, but results were not satisfactory. Given the high number of constraints, it takes a big initial population to just find a solution respecting all of them: setting a big initial population, on the other hand, makes the ga function even slower then fmincon, and, consequently, of little help to solve our problem. We also tried the optimization platform provided by *Tomlab*, but, again, the problem was too complex, and also this solution turned out to be not sufficient to handle it.

At this point, evaluated all the possible solutions, we tried to approach the problem in a different way. We identified some possible simplifications that wouldn't affect the results we are looking for. This way, the complexity of our problem would reduce enough to allow fmincon process it in a reasonable time.

We decided to respect a basic assumption: considered that this work aims to define whether certain changes in the LARP design can improve its efficiency, any approximation have to be conservative with respect with the current LARP configuration. This is important, in particular, for what concerns actuators. The simplifications we adopted are, in a certain way, penalizing the choice of EAPs actuators: thus, in case we obtain that, from our simplified model, they require less energy to perform the robot walking then servomotors, we're sure that, in the real system, their use would guarantee an enhancement that is equal or major then that reached in the simulation environment. For this reason we decided to evaluate only the energy required to perform the swing phase of one leg, with fixed pelvis, when the robot is performing a rectilinear walking. Taking into consideration only one leg per time reduces the degrees of freedom to 6. The weight of the leg depends mainly on the material of the structure: the choice of actuators, instead, doesn't really affect it. On the contrary, using EAPs definitely reduces the weight of the pelvis, where, in LARP, the 12 servomotors are located. The energy required by the 6 degrees of freedom we're not considering, then, will be higher in the servomotors case.

Moreover, the fact that we decided to set the robot walking trajectory as rectilinear makes it superfluous to evaluate all of the 6 degrees of freedom in the swinging leg: most of the work will be done in the saggital plane, as in the case of planar robots. We can then just consider the 3 degrees of freedom, 1 one in the hip, 1 in the knee, and 1 in the ankle, that permit the motion of the leg in this plane, and reduce the length of vector x to 150. Last approximation stands in the modeling of the linear actuators: for each joint, we set the two application points at the same distance from the joint itself. This solution is not meant to be the best possible, but reduces a lot the weight of the calculation of energy consumption, further reducing the computational complexity. A more detailed study of the location of the application points of linear actuators would surely lead to results that would be even better for EAPs actuators.

The approximations we have just described, finally, got us to a model whose energetic performance could be evaluated by the fmincon function in a reasonable time: every simulation took 10 to 14 hours, and, in around one week, we had the results of all of the 8 simulations, corresponding to the possible combinations of the 4 materials and the 2 actuators considered.

3.3.2 The solver

The fmincon optimization function has four available solvers:

- *interior point;*
- *sequential quadratic programming;*
- *active set;*
- *trust region reflective.*

The trust region reflective algorithm is not applicable to our optimization problem, because of its many restrictions on constraints. We decided to use the active set algorithm, which is supposed to be best suited to our problem. The method implemented in fmincon is similar to that presented by *Gill and Murray* in the first part of 1980's, and is one of the more efficient and accurate in the state of the art.

This algorithm divides the constrains $g_1(x) \geq 0,\ ...,\ g_k(x) \geq 0$, that define the feasible region, or solution space, of the problem, into the set of the active constraints at x, if $g_i(x) = 0$, and the set of inactive constraints at x, if $g_i(x) > 0$. Equality constraints, of course, are always active. The set of active constraints is fundamental in this algorithm, because it is thanks to them that the problem can be reduced to a smaller subproblem. This method is iterative, and stops when the magnitude of search direction, or its directional derivative, are less then a certain predefined value, and the maximum constraint violation is less then a certain tolerance value.

The fmincon function, by the way, doesn't guarantee global optimality, regardless of the algorithm used: in complex problems, as ours is, it is quite typical that the solution found is only a local minimum. However, improvements from the starting point, whatever geometric joint trajectory you might have decided to adopt, are relevant, at the point that energy consumption with an optimized trajectory is even orders of magnitude less with the starting one. This, as we'll see more in details in the next chapter, happens because the peaks of energy consumption are eliminated. In general, trajectories result to be smoother, and the performance of the walking improves.

Chapter 4

Design of the robot: what we got

In the previous chapter we described how we built the model and set the parameters. We can finally report the results we obtained with the optimization performed by the fmincon function.

A first observation regards the effect of local minima in the search for the optimal trajectory. As anticipated, fmincon doesn't ensure results returned are globally optimal. In most of the cases, though, repeating the same simulation supplying different starting points gives a valid esteem of the goodness of the obtained result, and helps identifying local minima. Unfortunately, as the complexity of the problem and the size of the search space increase, it becomes impossible to avoid local minima, and, inevitably, these will affect the final result. As we'll see in next sections, we still found a way to get good indications about the efficiency of the different configurations. But before reporting them, we introduce a simple notation adopted to identify the considered configurations, in order to make the exposition clearer and more concise. The different actuators are numbered: *1* refers to servomotors, and *2* to EAPs actuators. To the materials for the structure of the robot, instead, is associated an alphabetical letter: *a* to polycarbonate, *b* to the aluminium alloy, *c* to the titanium alloy, and *d* to the stainless steel. This means that when, for instance, we refer to the configuration 1a, we intend the current LARP configuration, with polycarbonate, and servomotors as actuators.

4.1 Energy-efficiency of the different configurations

We performed 8 simulations, one for each configuration. All of them return a new joints trajectory and a value indicating the energy consumption. For the reasons explained in the previous section, these values are not directly comparable, because they may refer to different local minima. The trajectories found, though, are way more efficient than the starting one, as we'll see in details in Section 4.2. Hence, we have a pool of 8 good trajectory, and what we did was to calculate the energy consumption for the different configurations for all of these trajectories. Since these values take into account only the energy necessary to move the swinging leg in the single support phase, absolute values are not actually significant. What we're interested in is the ratio between the different configurations, and in particular the ratio between current LARP configuration and the other analyzed. In fact, this information will help us detect those modifications that could enhance the performance of our robot. These data are reported in Table 4.1, together with the average values and the standard deviations, and represented in Figure 4.1.

Table 4.1: Energy consumption, relatively to the current LARP configurations, in the different trajectories

	Traj 1	**Traj 2**	**Traj 3**	**Traj 4**	**Traj 5**	**Traj 6**	**Traj 7**	**Traj 8**	**Average**	**SD**
1a	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0.0000
2a	2.5474	1.5394	1.5613	1.5037	2.4754	1.5596	1.2939	1.3802	1.7326	0.4901
3a	4.3324	2.6448	2.2149	2.0779	4.1892	2.6497	1.7021	1.8209	2.7040	1.0197
4a	8.0527	4.9873	4.1762	3.3427	7.7580	4.9969	3.1683	2.8112	4.9117	2.0155
1b	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.8889	0.0000
2b	2.2643	1.3684	1.3878	1.3367	2.2003	1.3863	1.1501	1.2268	1.5401	0.4356
3b	3.8510	2.3509	1.9688	1.8470	3.7237	2.3552	1.5103	1.6186	2.4032	0.9068
4b	7.1579	4.4331	3.7122	2.9699	6.8960	4.4417	2.9162	2.4988	4.3657	1.7917

First thing to notice is the high standard deviation. In spite of this, it is interesting that in the single trajectories the ranking of the performance of the different configurations doesn't change: in particular, the order is always 1b, 1a, 2b, 2a, 3b, 3a, 4b, 4a. What changes a lot, instead, is how much these parameters influence the performance, in the different trajectories. It turns out that in some of these, as for instance trajectory 7, using different configurations doesn't affect to much the efficiency. In some others, as trajectory 1, the influence of the choice of the parameters is clearer. This gives the high standard deviation observed.

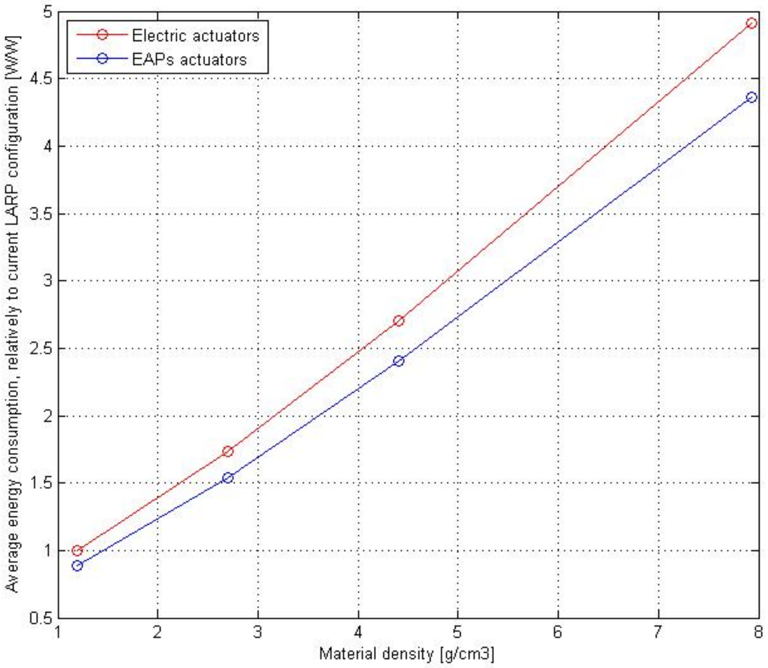


Figure 4.1: Energetic performance comparison, varying materials and actuators

In next sections we'll see more in detail the correlation between the parameters, and relate these data to those others fundamental for the choice of the best configurations.

4.1.1 Correlation between parameters

From data reported in 4.1, you probably noticed that the ratio between the performance of configurations 1a and 1b is constant. Whatever trajectory you consider, configuration 1b has an energy consumption that is 0.8889 of that of configuration 1a. Observed this, we decided to investigate the correlation between the two parameters we considered. We verified that also the 2b/2a ratio, as well as 3b/3a and 4b/4a, is 0.8889. This means that, fixed the material, the use of EAPs reduces energy consumption, that then will be around the 89% of that of servomotors. This percentage, furthermore, is an upper bound: it's important to remember that all of the approximations adopted to model our robot are penalizing EAPs. This means that, in the real system, these results would probably appear even better. Anyway, the observation we made tells us that the influence of the actuators on the energetic performance does not depend on the material of the structure, and vice versa. Hence, we can continue our analysis of the effects of the choice of parameters, considering them independently. First, in Section 4.1.2 we'll try to make a synthesis of the information available on the materials. Then, in Section 4.1.3, we'll concentrate on actuators.

4.1.2 Material selection

The first decision to make in the design of a robot is which material to use for the structure. In Section 3.2.1 we've described the main characteristics of the materials we considered, in particular those features that describe their strength and their cost. Also, as we have seen in the previous sections, the structure material has a high influence on the energetic efficiency of the robot. We can finally synthesize all this information to define which materials are best for an use in robotics.

We can start from polycarbonate, the material currently used for robot

LARP. It had been chosen because of its low weight, and its really competitive cost. The energetic performance, depending mostly on the weight, is also good. Unfortunately, this material turned out to be too fragile, and for this reason not reliable enough to be used as main material in the structure of a robot, that is supposed to resist to small impacts without suffering major damage. Another material that doesn't satisfy the minimum requirements imposed is the stainless steel, but for the opposite reason. It's an extremely strong material, and its cost, though higher than that of polycarbonate, is not excessive. Being a heavy material, yet, makes this material really inefficient, and, for this reason, not a good candidate for an use in this field.

The aluminium alloy and the titanium alloy, then, are the most suitable materials to be adopted for the structure of the robot: they're both a good trade off between strength and efficiency. The choice between these two depends mainly on the economical availability of the institution that is developing the robot. The titanium alloy is way more expansive then the aluminium alloy, but its structural characteristics are definitely better, as to be comparable even to those of the stainless steel. Furthermore, being lighter, the aluminium alloy also makes the robot a little more efficient, even if the difference is not too critical. Our suggestion is then to use the titanium alloy, when the cost is not a big issue. If, on the contrary, the titanium alloy is not affordable, the aluminium alloy represents an absolutely valid, and more economic, alternative.

4.1.3 Actuators selection

Choice on actuators is in a certain way simpler. We selected only two possible solutions, and, in this case, we base our considerations on energy efficiency, and on technological aspects. In perspective, EAPs have a greater potential then servomotors. Being their structure similar to that of human muscles, the movement they produce is smoother and definitely more natural. They're also more efficient, as shown in the previous sections. Moreover, these actuators have a great room for improvement. But the fact that this is a young technology makes this solution more risky than servomotors. Researchers of the field predict to produce the first complete EAPs actuators in three years, but the process could suffer unpredictable delays, or maybe results will be below expectations. An institution that is defining the design of its own robot should take into account all of these possibilities, and must decide what is willing to risk. In the very next years, by the way, we'll see whether the results reached with this new technology will meet expectations. If so, EAPs will become a really interesting solution for humanoid robotics.

4.2 Further considerations upon the optimization module

As explained in the previous sections, the fmincon function doesn't guarantee global optimality, and, in complex cases like ours, it is pretty common that it returns a local minimum. Theoretically, this would represent a serious limitation. Experimental data, instead, reveal the goodness of the method we adopted. We checked the energy consumption before and after the optimization, for all of the eight simulations, and found that there is a consistent improvement of the performance. On average, the optimized trajectories require only the 1.97% of the energy necessary to perform the initial trajectory. In the best case this percentage decreases to 0.65%, in the worst it is 3.61%.

We report the example of one of the eight simulations, precisely that of the current LARP configuration. Figure 4.2, Figure 4.3, Figure 4.4, and Figure 4.5 represent the comparison, respectively, of the trajectory of the joints, of their velocity, of their acceleration, and of the torques required, before and after the optimization. Only the three joints whose energetic consumption has been minimized are considered. Just looking at the trajectories, it's not easy to understand why their performance is so different. The velocity figure starts helping, but it is in the accelerations and in the torques figures that it becomes clear how the optimization produced smoother trajectories: the highest peaks in accelerations and torques are eliminated, in particular in the hip joint, that is the one that requires more energy to move. In Figure 4.6 we can see the energy consumption, frame by frame, for each joint. To eliminate the peak around frame 15, the new trajectory might require more energy at some other instants, but the consumption now remains approximatively constant, and the comprehensive result, on the complete half-step, is excellent.

To conclude, we report some considerations upon the resulting foot trajectory. The constraints we formulated didn't impose any particular condition on the gait, but its correctness, that is guaranteed avoiding the contact with the ground while the leg is swinging, and fixing the joints configuration at the first and the last frames. All of the other constraints specified are limitations on position, velocity, and acceleration of the single joint. It is interesting to notice how the returned trajectories generate a gait that really reminds the human one. The foot always remains closer to the ground than with the original trajectory. And the movements are not only smoother, but also look a lot more natural. This could also be considered as a confirmation of how energy efficiency is one of the main goals in the human gait.

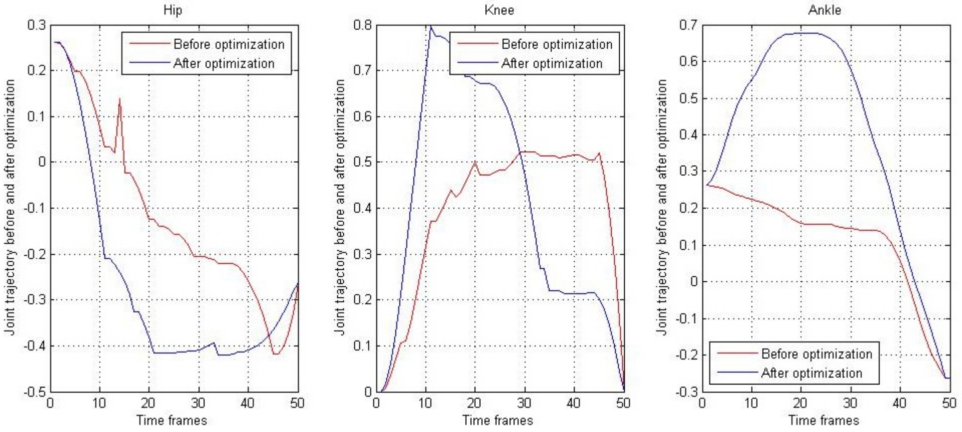


Figure 4.2: Comparison of joints trajectory, before and after optimization

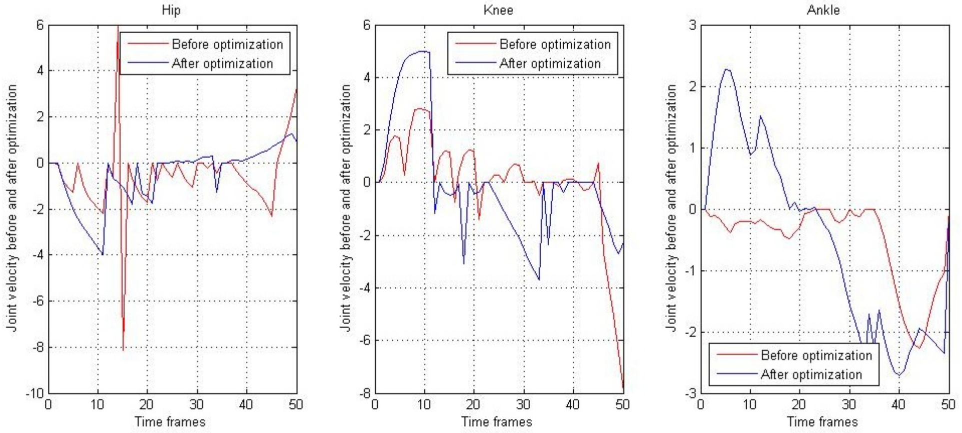


Figure 4.3: Comparison of joints velocities, before and after optimization

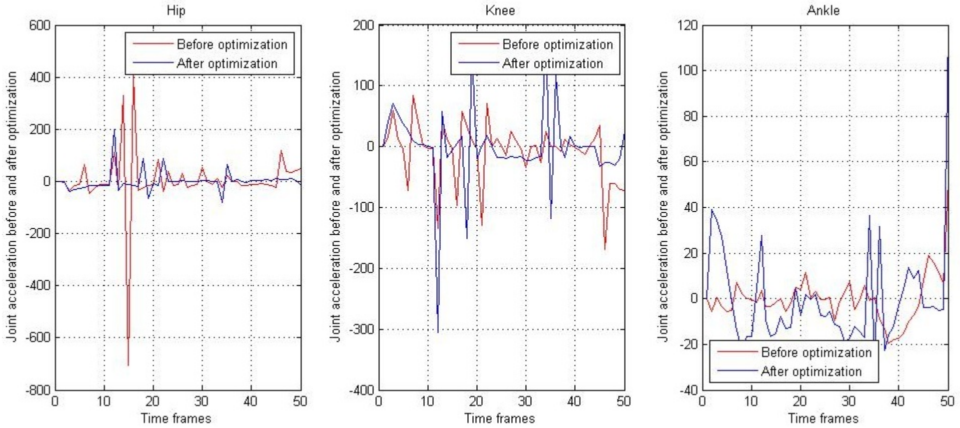


Figure 4.4: Comparison of joints accelerations, before and after optimization

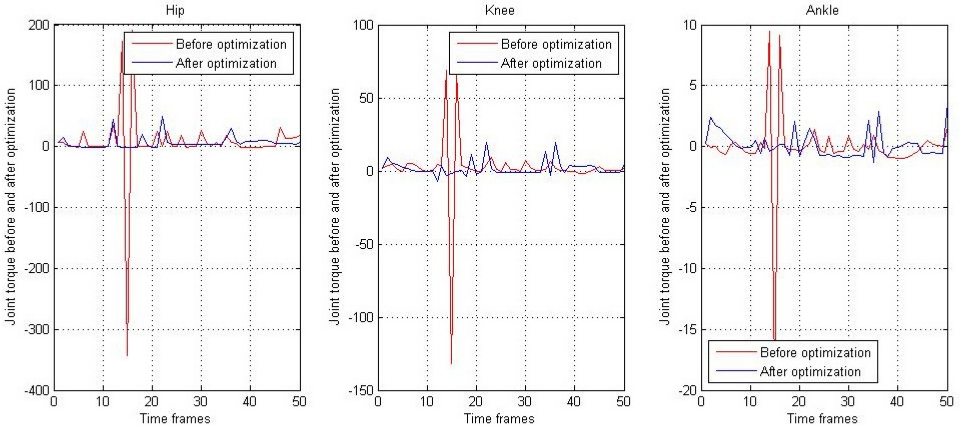


Figure 4.5: Comparison of joints torques, before and after optimization

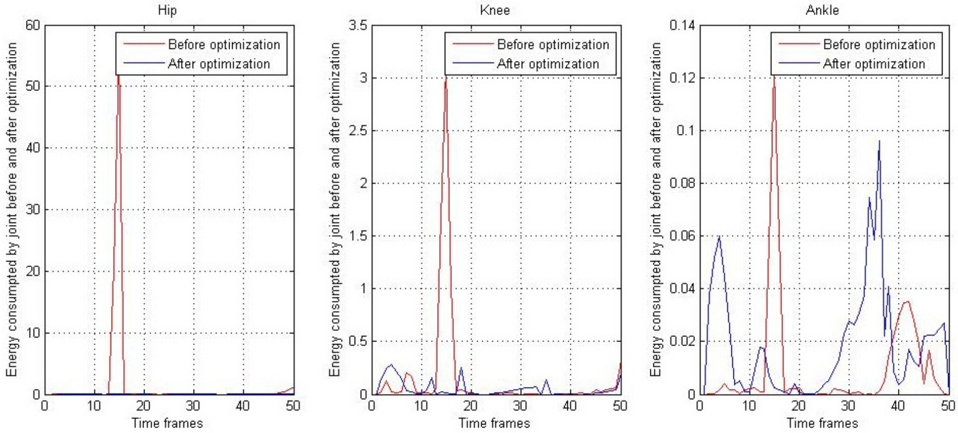


Figure 4.6: Comparison of energetic consumption of each joint, before and after optimization

Chapter 5

Intelligent control: proposed improvements

In this chapter we focus on the second part of our work of thesis, the control of the robot.

Basic controllers proved reliable enough to guarantee the stability of the robot only when the conditions of the motion are simple enough and well known. If we want our robot to be really autonomous, and to be able to behave in the real world, we need to provide it with some features that guarantee a certain degree of flexibility and adaptability to the unpredictable conditions of a dynamic environment. For instance, we want our robot to be able to walk on rough terrains, or on a surface with variable inclination. Those control systems that make use of Soft Computing techniques, such as Neural Networks, Fuzzy Logic, Genetic Algorithms, and Reinforcement Learning, or a combination of these, in order to fulfill the above mentioned complex tasks, go under the name of intelligent controllers. The controller developed at Institute Mihailo Pupin, Belgrade, and described in Section 2.3, is one of the most successful example of intelligent control in the state of the art.

Thanks to a collaboration with the researchers of Institute Mihailo Pupin, we had the opportunity to base our research on the current version of their controller. In following sections we'll describe the enhancements we propose to further improve its performance.

5.1 Variable ZMP reference

The first enhancement we propose regards the reference (or ideal) ZMP. To evaluate the stability of a robot, the actual position of the ZMP is compared to the reference ZMP, a point that, in the IMP controller, as in most of the cases, is set in the center of the foot of the supporting leg, in the single support phase, or in the center of the convex hull described by the two feet, in the double support phase.

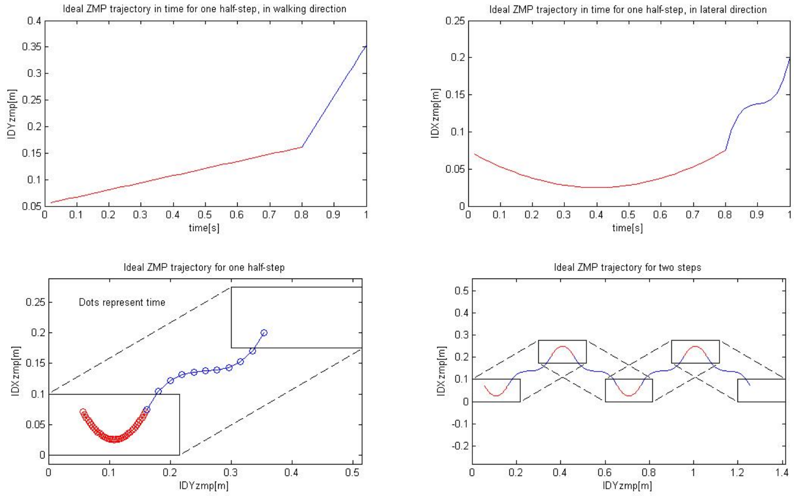


Figure 5.1: Ideal ZMP trajectory for one half-step

Research on the human gait, though, reveals how this point moves following a certain trajectory on the ground. We described this trajectory, synthesizing it geometrically (see Figure 5.1 for the graphical representation), taking care to reproduce all the characteristics of the human one, and to maintain it smooth.

In the single support phase, that covers about 80% of the gait, the ideal ZMP moves along a parabola; a security margin of the dimension of 1/4 of the foot is always maintained, in both directions.

In the double support phase, even if it lasts for only 20% of the gait, we have the biggest ZMP displacement: this is because in this phase the robot is more stable. The ZMP moves along a cubic to point where the foot of the swinging leg will touch the ground. The points where the parabola and the cubic meet also have the same first order derivative. This solution is supposed to improve the stability of the locomotion: if in the traditional method the ZMP position changes with sudden jumps when the motion switches phase, now it moves smootly along the trajectory we defined. The locomotion also would look more human-like, since this solution reproduces the human behaviour. Last, using a variable ZMP reference, we can reduce a previously existing conflict between joint trajectories tracking, and minimization of the error on the ZMP. The reference joint trajectories imposed to the robot are usually human-like, and the corrisponding actual ZMP will not be fixed in the center of the stability area: this means that the forces generated by the control on the ZMP might be in conflict with those generated by the contol on the trajectory tracking. If we impose a ZMP trajectory, like the one we synthsized, it will likely be closer to the actual ZMP generated by the imposed joint trajectories. To eliminate this conflict, though, we propose a second enhancement, that we're going to present in next section.

5.2 On-line update of the reference joint trajectories

In this section we present the second enhancement we propose to improve the performance of the IMP controller. This enhancement is more structural than the one we've just presented in the previous section, and is supposed to increase stability, and reduce energy consumption of the locomotion, as the robot acquires experience.

As reported in Section 2.3.1, three preconditions to the development of the IMP controller were specified. The seconds says that *"the desired joint trajectories, performing a dynamically balanced gait, are known and constant"*. We decided to modify this part of the system. Using fixed reference trajectories is a big limitation to the performance of the locomotion of the robot.

First of all, these trajectories can even be optimized off-line for the model of the robot, but, then, the real robot will never be exactly identical to the model, and it may result that our trajectories are no more the best possible. We want our trajectories to adapt, in a certain way, to our real robot. Of course if we don't trust the complete reliability of our model it means we're also weakening the first precondition: *"the model of the robot describes with sufficient reliability the real system"*.

Moreover, the reference trajectories are generated to guarantee a good, or even optimal, locomotion under certain conditions. If our robot is meant to move in the real world, though, it becomes obvious that it will have to be able to adapt to a dynamic and not completely known environment.

These are the reasons why we decided to propose an alternative, and more flexible solution. We added an external loop to the current version of the IMP controller: at every half-step, the smallest period of the gait, the performance of actual trajectories is evaluated and compared to that of reference trajectories; if the new gait is better than reference, then the trajectories that generated it become themselves new reference.

Then we need an algorithm to evaluate the performance of joint trajectories. We want to take into account both stability and energy efficiency. If we call P the performance, we can define it like:

$$P = S + k \cdot E,$$

where S is an evaluation of the stability, E is minus the energy consumption, and k is a positive coefficient. Modifying k we can give more or less importance to efficiency with respect to stability.

We still need to define more precisely how we determine the value of S. It is, indeed, the sum of the measure of instability of the robot, taken negative, at every time frame:

$$S = -\sum_i (s_x(i) + s_y(i)),$$

where i is the frame, and $s_x(i)$ and $s_y(i)$ are the instabilities in the two directions at frame i. To calculate $s_x(i)$ and $s_y(i)$ we have to compare the actual ZMP to the reference ZMP. Of course, if we're using a variable ZMP reference, as the one we defined in Section 5.1, we compare the actual ZMP at frame i to the reference ZMP at the corresponding frame.

For the sake of simplicity, now we only explain the way we find the value $s_x(i)$ for a generic frame i. $s_y(i)$ is defined in exactly the the same way, just on the other direction. $X_{zmp}(i)$ is the location of the actual ZMP on the x-axis at frame i, while $IDX_{zmp}(i)$ is the position of the reference ZMP on the x-axis at frame i. Then we can define $s_x(i)$ in the following way:

- take the straight line passing through $X_{zmp}(i)$ and $IDX_{zmp}(i)$;
- the $IDX_{zmp}(i)$ is always inside the stability area, defined as the foot plant, in the single support area, and as the convex hull described by the two feet, in the double support phase; this means that this line will always pass through the border of the stability area in two distinct points;
- if $X_{zmp}(i)$ is not on the segment between these two points, then
$$s_x(i) = \infty;$$
- otherwise, considering the two points of intersection between the line and the border of the stability area, we call $X_b(i)$ the one such that we have $IDX_{zmp}(i)$, $X_{zmp}(i)$, and $X_b(i)$ in this sequential order on

the line, and define:

$$s_x(i) = \tan\left(d(X_{zmp}(i), IDX_{zmp}(i)) \cdot \frac{d(X_b(i), IDX_{zmp}(i))}{\pi/2} \right),$$

where $d(\cdot,\cdot)$ is the operator distance.

You can try and see that:

- if $d(X_{zmp}(i), IDX_{zmp}(i)) = 0$ then $s_x(i) = 0$;
- if $0 < d(X_{zmp}(i), IDX_{zmp}(i)) < d(X_b(i), IDX_{zmp}(i))$ then $0 < s_x(i) < \infty$, and
  - for $d(X_{zmp}(i), IDX_{zmp}(i)) \to 0$, $s_x(i) \to 0$, and
  - for $d(X_{zmp}(i), IDX_{zmp}(i)) \to d(X_b(i), IDX_{zmp}(i))$, $s_x(i) \to \infty$;
- if $d(X_{zmp}(i), IDX_{zmp}(i)) \geq d(X_b(i), IDX_{zmp}(i))$ then $s_x(i) = \infty$.

This means that, for a fixed frame i, $s_x(i)$ is equal to zero if and only if the actual ZMP position and the reference ZMP position are coincident on the x-axis. Then, as the distance between the two points grows, the value of $s_x(i)$ grows, too, until the actual ZMP meets the border of the stability area, where $s_x(i)$ goes to an infinite value. In Figure 5.2 and Figure 5.3 you can see how $-(s_x(i) + s_y(i))$ varies as the actual ZMP at frame i changes, for $i = 27$ (single support phase) and $i = 43$ (double support phase), respectively, in the simulation we performed.

Notice that, if, at any frame, either $s_x(i)$ or $s_y(i)$ is equal to ∞, then P, the entire evaluation of the gait, is equal to $-\infty$. This is because a gait with the actual ZMP that goes out of the stability area, even if for one frame only, is an unstable gait.

Furthermore, both S and E are always at most equal to zero, and k is always positive: so we can deduce that also P is always less than or equal to zero. An hypothetical $P = 0$ would indicate that the gait we're evaluating has an actual ZMP that tracks perfectly the reference ZMP trajectory, and doesn't require any energy to be performed. In a realistic scenario, P will always be negative, and the more it is close to zero, the better the gait is.

The comparison between current gait and reference gait is performed at every half-step, and, as the robot acquires experience, the performance becomes better and better, and the reference will converge to an optimal. Of course, if the controller tracking the reference joint trajectories is accurate enough, the actual trajectories will always be in the neighborhood of the reference, and this makes the convergence slow. There will never be big jumps in the update of reference trajectories: it is then suggested to provide the controller with good initial reference trajectories, defined off-line before starting the training of the robot. Starting from these initial trajectories, then, the controller will begin making them even better, compensating the unavoidable differences between the model of the robot, and the real robot itself, and adapting to a real external environment.

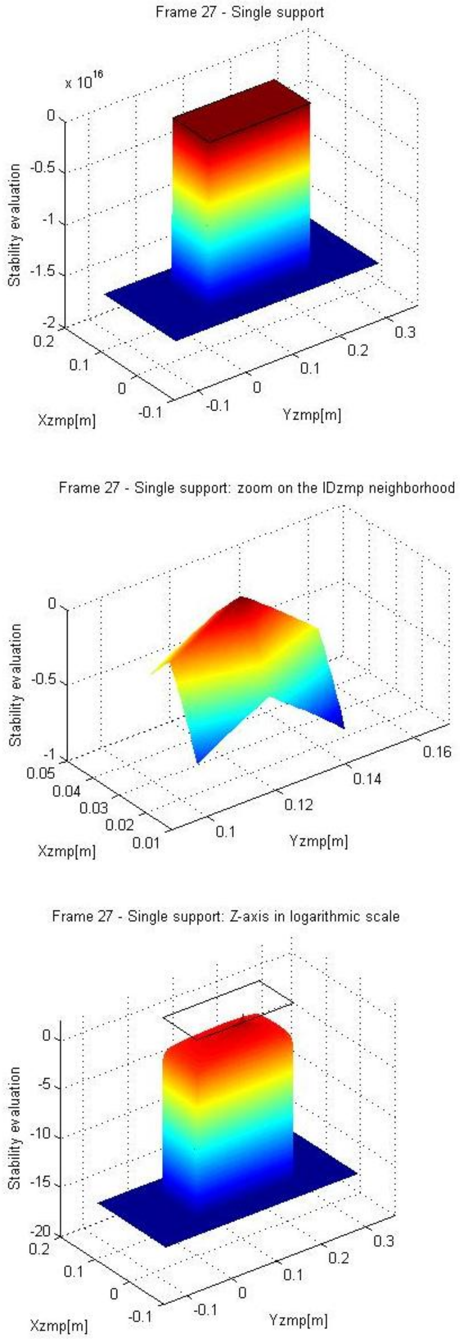


Figure 5.2: Graphical representation of the relation between actual ZMP position and evaluation of the stability, at frame 27

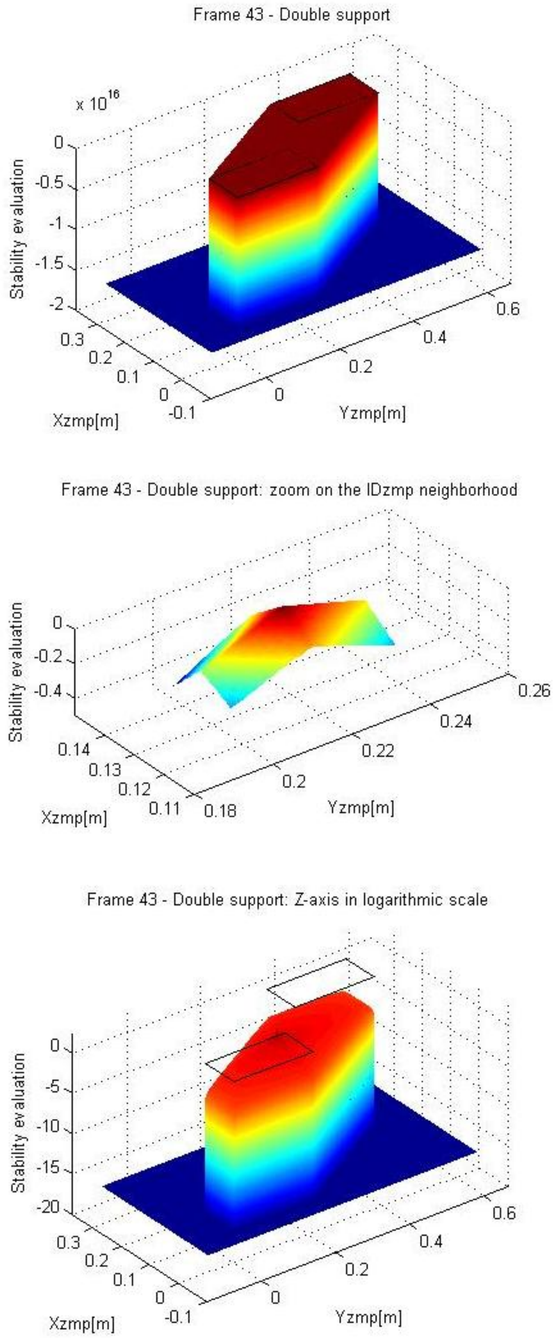


Figure 5.3: Graphical representation of the relation between actual ZMP position and evaluation of the stability, at frame 43

Chapter 6

Final remarks

In Chapter 3 we described the procedure used to formulate and solve the optimization problem that is the basis for evaluating energy efficiency of bipedal walking. In Chapter 4 the results we obtained were reported in detail. In Chapter 5 we focused our attention on control, proposing some possible enhancements to the intelligent control system developed at Institute Mihailo Pupin, Belgrade, Serbia.

In Section 6.1 we can now summarize the findings of this thesis, while in Section 6.2 we suggest a possible configuration for the design of the robot, integrating our results with those of previous works. Finally, in Section 6.3, we discuss possible development for future research.

6.1 Conclusions

Energy optimization is one of the most important objectives of research in robotics. Autonomous robots, as humanoid robots are, need to reach a certain degree of independence from human intervention for a reasonable time to be effectively useful. If, on the one hand, new generation batteries last longer than they used to, on the other hand, it is fundamental to develop robots that are intrinsically efficient. Humans are an example of efficiency. Our locomotion, in fact, is the result of millenia of evolution. We have seen, in Section 4.2, how dramatically the definition of the gait influences the energetic performance. Our interpretation of the goodness of the results we achieved is that the approach we proposed to generate trajectories itself is different. Usually, trajectories of the endeffector (in this case the foot) are imposed to follow a certain geometric shape. Joints trajectories are then obtained from the foot trajectory using inverse kinematics. These joints trajectories may result not smooth at all, and this generates the peaks of energy consumption we've shown in 4.6. Our method, instead, imposes only the correctness of the foot trajectory. Attention is then focused on the joints. The contribution of every single joint to the overall energy consumption is decisive for the choice of the trajectory. This approach has proved to be effective, and results obtained exceed expectations.

Moreover, the choice of using the fmincon function has another advantage. It works completely independently from the context of robotics, unaware of the fact that what it is optimizing is the foot trajectory. This means that the results we got cannot be affected by a priori considerations. Returned trajectories, though, really remind those adopted in human locomotion, definitely more than the geometric trajectories generated on the basis of theoretical assumptions. This represents an important validation to the indications we obtained on the performance of the different parameter we considered. The data we collected about energy efficiency, integrated with additional information on the strength and the cost of the materials, and the technological limitations of EAPs, provide a comprehensive overview of the available solutions for the design of a humanoid robot. Results obtained in this first part of thesis were presented at the *2nd International Conference on Simulation, Modeling, and Programming for Autonomous Robots* (see *F. Moro, G. Gini, M. Zefran, and A. Rodic - Simulation for the Optimal Design of a Biped Robot: Analysis of Energy Consumption - SIMPAR 2010, Darmstadt, Germany*).

A good design on its own, anyway, is not enough to guarantee that locomotion will be really efficient: providing the robot a reliable control system is fundamental to permit to the robot to adapt to a dynamic environment, reducing energy consumption, while, at the same time, maintaining a good balance. We had the opportunity to base the foundations of our research on the solid results achieved by the IMP controller. The first update proposed, described in Section 5.1, is supposed to make the motion more human-like, and to reduce possible conflicts between concurrent controllers. The enhancement described in Section 5.2, instead, is more substantial: introducing a new loop that updates the reference trajectories we make it possible to improve the performance of the gait as the robot acquires experience, for what concerns both stability and efficiency. As we said before, to reach a satisfiable performance in the locomotion, it is important to concentrate on both design and control of the robot, because the goodness of the results achieved in one task affects the quality of the other. Choosing to dedicate to both these aspects gave us the opportunity to have an overlook on the entire process of development of an efficient and dynamically stable humanoid robot.

Before analyzing some possible future developments, in last section we'll make a detailed suggestion on how to design an efficient and solid humanoid robot, integrating the results of our research with those of previous valuable works.

6.2 Suggestions upon the design of the robot

First decision to take is what material to use for the structure of the robot. As we've seen in Section 4.1.2, there are two materials that satisfy all of the requirements to be considered as good solutions: the tempered 6061 aluminium alloy, and the titanium 6Al-4V alloy. The second overcomes the first for what concerns strength, though being not too heavy. Unfortunately, this is an expensive solution. The aluminium alloy, instead, is a valid, and more affordable, alternative. Remaining on the structure of the robot, it is possible to achieve a considerable improvement in the energetic performance by adopting the solutions described in Section 2.2.1 and in Section 2.2.2, respectively for the design of the knee, and for the design of the foot. A multi-axial knee, in fact, permits to reduce friction with respect with the classical pin joint. While the 2 additional passive degrees of freedom in the foot, representing the heel and the toe, reduce energy consumption by managing the energy received by the ground reaction force. Further improvements can be achieved by providing the robot with a 2 degrees of freedom waist. This solution as been adopted for the development of robot Wabian-2R, described in Section 2.1.2. A combination of these solutions would make the robot able to perform a knee stretch walking, increasing energy efficiency. Furthermore, the resulting gait would look more natural and human-like. Considered that a redundancy in the mechanism of the robot made it possible to achieve most of the capabilities of the human locomotion, the last suggestion we can make, again regarding the structure of the robot, is the introduction of a third degree of freedom in the ankle. Humans have 7 degrees of freedom per each leg. Most of the robots have just 6 degrees of freedom per leg, because the third degree of freedom in the ankle is usually not considered as fundamental to produce a correct gait. By the way, if you want your robot to be able to reproduce all of the movements a human can achieve, it becomes necessary to provide it with all of the 7 degrees of freedom, included the third degree of freedom in the ankle.

Once the design of the structure of the robot has been defined, next decision to take regards the actuators. We've shown in Section 4.1.3 how potentially EAPs actuators may overcome the performance of servomotors. The choice of this solution, however, could be risky, on date, because of the technological limitation explained. A safer solution, for now, is represented by the more consolidated servomotors. In this case, it also becomes important to decide where to locate them. Considered their weight, different solutions affect significantly mass distribution. In robot LARP they have been included in the pelvis structure, to respect the average human mass distribution. Tendons transmission, however, introduced an additional energy loss, caused by friction. If the robot was completed with an upper body, though, it would be possible to locate servomotors closer to the joints they actuate, maintaining also a mass distribution similar to that of human body. Furthermore, the development of an upper body would improve even more energy efficiency. Although we usually associate arms with manipulation, they also play an important role in human walking. In fact they are used to counteract the rotation of the pelvis. This permits to achieve consistent improvements in energy efficiency and stability.

6.3 Future works

Robot LARP, at the current time, only has a lower body. Some researchers at Politecnico di Milano are concentrating on the design of an upper body, focusing in particular on the task of manipulation. It would be interesting to integrate the different works for the common objective of developing a complete humanoid robot. In fact arms and, more in general, the whole body, play an important role in human locomotion. The motion of the arms counteracts the rotation of the trunk, making the walking more efficient. Humans also use arms and the trunk to maintain a correct balance. It could then be interesting to think of a whole-body posture correction, to reproduce the way humans maintain stability. In this way the robot wouldn't only modify the characteristics of the gait, as the distance in length and width between the contact point of the two feet, but, for instance, would also change the trunk inclination, and use arms, to correct any instability.

Another important work to be done in the next years would be testing the first reliable prototypes of EAPs actuators. The results of our work have shown the incredible potential of this technology for application in robotics. It will be interesting, then, to verify whether expectations will be satisfied.

Of course, even if the information we obtained with this work is finalized to practical applications on robot LARP, we hope it will also be useful for the development of other humanoid robots.

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