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Presented by

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Realtime human motion imitation by humanoid robot with balance constraint

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Abstract

Humanoid robots are made as mirror to the humans. Consequently, the humanoid motion is also expected to be real as human and it is natural to use human motion as an input to generate humanoid motion like a child learning from recogniting an action and imitating. This process in robots is called motion imitation and there are several challenges posed due to kinematics and dynamics of the robot over the past decades. Although the work on the kinematic challenges is actively improving and notably better than dynamics, it allows the robot only to move and imitate slow actions. For the fast paced motions, *momentum* gets build up and needs dynamics to be taken into account. Due to the differences in redundancy between humanoid robots and humans, real-time imitation in humanoid robots while keeping balance and support changes is still an interesting problem that need to be addressed.

On this research, motion retargetting or the motion imitation based on dynamic balance and support with dynamic filtering is planned to be implemented on humanoid robot *NAO v5*, from Aldebaran Robotics. The imitation will be carried out online using marker-based motion capture suit from *Xsens*, specifically *Xsens MVN Analyze* system.

The captured motion from the inertial suit will be preprocessed for its representation in operational space and will be scaled to the robot's dimensions. From this scaled motion, for this thesis, a set of actions are taken and will be addressed for the balance problem in *NAO* robot. The joint, CoM and the ZMP data of the human actor will be mapped to the robot using the scaling function directly. To ensure the stability and to keep up the speed with the human actor, an additional dynamic filter and multi-inverted pendulum based posture control will be implemented.

Notations

CoM	Centre of Mass

Abbreviations

CoM	Centre of Mass
DoF	Degrees of Freedom
ZMP	Zero Moment Point

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Chapter 1

Introduction

The interest of humans in building, controlling and researching complex machines that look and behave like humans is not recent; it started very early in humanity. There has always been numerous models of human-like machines over the centuries crafted by the engineers, mathematicians and craftsman that prove the existence of human-alike machines. After the development of Unimate and Shakey, the robotics has been widely boosted. Indeed, the first Industrial revolution of robotics only considered arm manipulators and wheeled platforms in a structured and defined environments. The interest towards human-like robots or humanoid robots has always grown instead of being only in science fiction. The recent researches and development has proved the possiblity of building humanoid robots or simply humanoids, becoming reality, although not powerful or autonomy as desired.

In order to develop more autonomous interactions in humanoid robots, one of the major and main objective is that it should be able to imitate human motions precisely. This would be a major milestone to be achieved in the field of humanoid robots. Scientists and researchers, over the past decades are thriving to make the humanoid robot movements as close as human motions. Recently, the ability of the humanoid robots to teleoperate increases rapidly. To imitate the motion perfectly, the robot should be able to understand the motion; hence, the importance of motion capture systems has widely increased in robotics especially in humanoid robots.

Nowadays, a variety of technologies exist that allow for high accurate capturing of human motions with high frequency. By imitating captured motion, humanoid robots can be teleoperated and also learn new skills resembling human actions. However, there is a catch because the direct imitation of captured movements is impossible due to the differences in the degree of freedoms and the weight distributions between humans and humanoids. Depending on the complexity of the motion, the challenge of motion generation increases due to various humanoid's constraints including the constraints in stability and the extended period of imitation. This chapter presents the brief introduction on the humanoid robots, their development and behaviour towards human-like motions.

1.1 Service Robotics

According to *International Federation of Robotics (IFR)*, a service robot is defined as a machine that performs useful tasks for humans or equipment excluding industrial automation applications. These robots are mainly dedicated to accompany humans with possibly reduced capabilities and to assist them in dull, dangerous or repetitive tasks. Moreover, *IFR* divides the service robots into two possible categories.

- *Personal Service Robots* - These robots are used for non-commercial and social tasks. The robots are usually trained to operate with non-trained sociologist rather engineers or roboticists.

- *Professional Service Robots* - These robots are used for a commercial task and are usually operate with well-trained operators. The robots tend to work in a professional or well-defined environments are built based on the stack of specialized tasks.

The service robots that are mentioned previously tend to be application-depending and are able to designed to satisfy the specific needs. One of the main aim of the service robots is to co-exist with humans alongside and to help them with any tasks that humans may need assist. However, typical human environments are completely different to the environments that robots experience currently. The robot environments are well-defined with a set of deterministic or stochastic variables that allows the robots for better estimations. Though the robots are able to estimate the environment to an extent, it's abilities are nowhere near for human capabilities. Another important problem is to build a robot that can perform multiple tasks and hold multiple applications. Hence, for a robot to exist among humans and to interact naturally with people, one robot must overcome all these difficulties to some degree of autonomy. Therefore, one of the major challenges in service robotis it to build a general robot that can succeed in all the areas where human beings can. Equivalently, there is a challenge to build robots that also act and behave as humans.

1.2 Humanoid robots

Humanoid robots are expected to exist and work in a close relationship with human beings in the everyday world and to serve the needs of physically handicapped people. These robots must be able to cope with the wide variety of tasks and objects encountered in dynamic unstructured environments. Imagining an humanoid robot collaborates with humans to execute some daily tasks, learn actions from humans and even improve it's ability to teleoperate [2]. When a humanoid robot works in collaboration with human, the interaction through gestures and cooperation is essential.

Besides the satisfaction of human curiosity and imagination, the integration of humanoid robots in our daily lives makes sense for a variety of practical reasons. Robots resembling us would make human-robot interaction more natural and thus more intuitive and pleasurable. Moreover, if robots are to assist people in daily chores, they have to fit the human environment, which is suitable for *human morphology* [3]. Performing tasks with two hands, handling tools, climbing stairs, reaching shelves - to name only a few tasks - require our assistants to have a similar morphology to ours, so robots can adapt to human lives, instead of us having to do the opposite. Furthermore, research in humanoid robots directly contributes to the field of prosthesis and exoskeletons.

The challenges in creating such machines are numerous. Human bodies are energy efficient machines with extremely elaborated mechanics and incredible cognitive and perceptual abilities. Thus, the creation of humanoid robots requires advances in more areas than one, from the improvement of sensors and processing of information, to efficient control techniques and suitable mechanical structures with constraints in shape, size and weight to improve the resemblance to human beings.

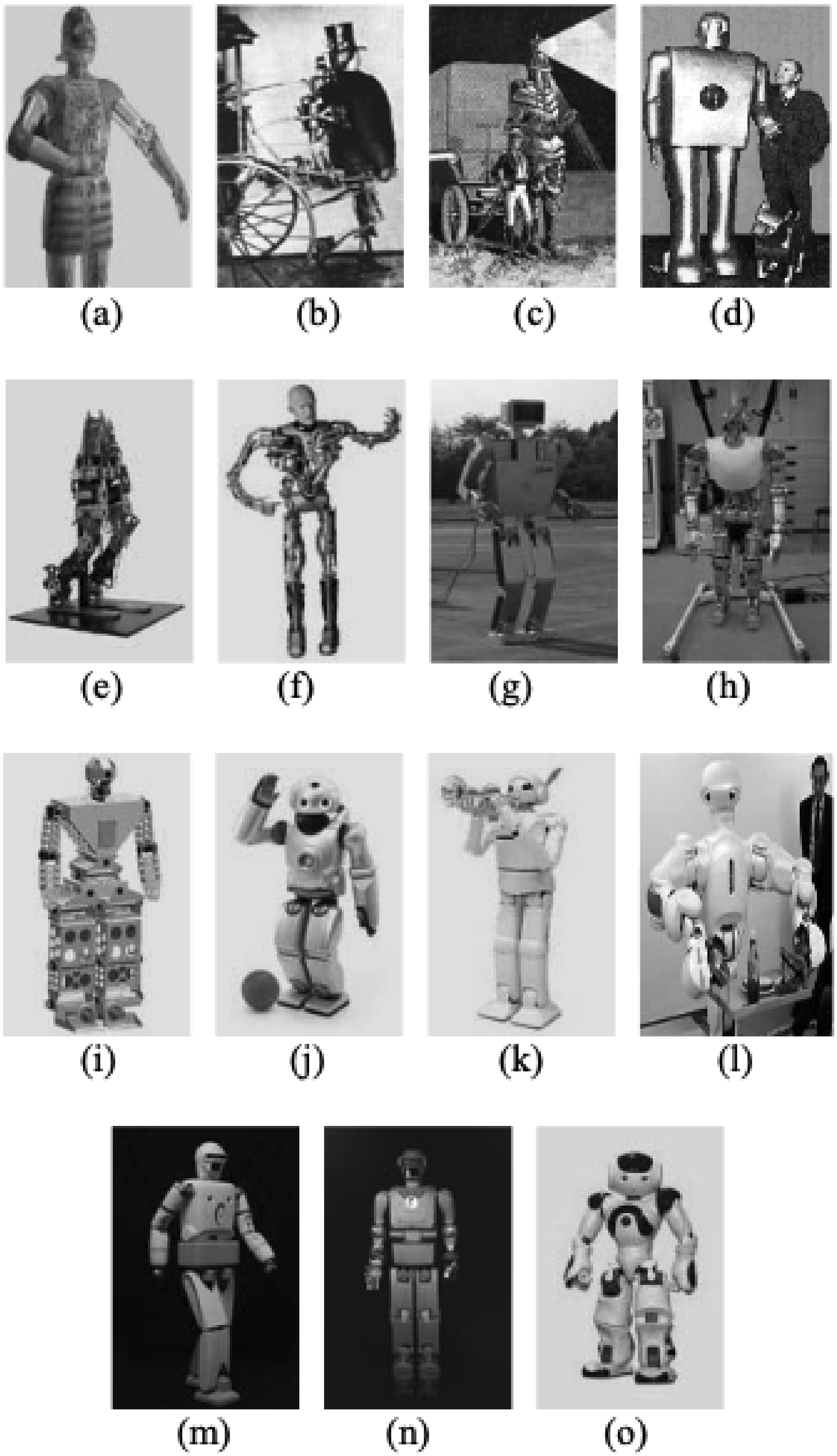

Figure 1.1: Some Bipedal Android robots over decades [4] (a) First humanoid robot by Leanardo Da vinci (b) Steam Mam in 1865 (c) Electric man in 1885 (d) ELEKTRO in 1938 (e) BIPER - 4 in 1984 (f) Tron-XM in 1997 (g) H6 Humanoid robot in 2000 (h) Robot JACK in 2000 (i) GuRoo in 2002 (j) QRIO, Sony in 2003 (k) Partnar Robot, Toyoto in 2004 (l) TwentyOne in 2007 (m) REEM-A in 2007 (n) REEM-B in 2008 (o) NAO in 2008.

The idea of building machines which look and move like humans has been explored by philosophers and mathematicians since antiquity. Nowadays, the concepts of such machines are a part of research in robotics. Humanoid robots can be thought of as mechanical, actuated devices that can perform human-like manipulation, including locomotion as their main skill for displacement. Well before the first modern humanoid robot, one of the biggest steps towards this objective was achieved in 1956 with the first commercial robot manipulator, *Unimate, from Unimation.* The automotive industry was the first to benefit from these kinds of manipulator robots. Recently, the development of humanoid robots for education, research and services has proved the work in multiple ways.

Current goals of research in humanoid robots include industrial and social applications in day-to-day life. A study was conducted by Tanie, [5] and is briefed below

- maintenance tasks of industrial plants,
- security service for home and offices,
- human care, teleoperation of construction machines.
- cooperative work

Since many studies have explored this aspect of robot motion and how to make robots more *human-like* and *human-aware.* Human Robot Interaction (HRI) is now a challenging research field and studies on the efficacy of humanoid robots in human environments are further proceeded.

1.3 Measuring Human Movement

Kinesiology is defined as the scientific study of human movement. To access human motion, Kinesiology involves principles and methods from *biomechanics, anatomy, physiology and motor learning.* Its range of application includes health promotion, rehabilitation, ergonomics, health and safety in industry, disability management, among others. The measurement of human movement is one of the tools that is central in this research field. In 19th century, various devices were built to produce the moving pictures, among those exists the most advanced technique named *chronophotography.* This device allowed to study fast paced human motions by recording and reproducing the captured motion [6]. Another major contribution in motion study is the study on the path of center of mass during human displacement [7].

Figure 1.2: Computation of human locomotion using differential equations by Weber Brothers [7]. The coordination between arms and legs was observed clearly.

The first experimental studies of human gait [7], i.e. determining physical quantities like inertial properties, were conducted by Christian W. Braune (1831-1892) and Otto Fischer(1861-1917). They considered the human body as rigid bodies in form of dynamic links in series. The work of Nicholas Bernstein (1896-1966) in Moscow introduced the 3D analysis based on cameras. The methods for measuring human movement continued improving with the advent of new technologies like electronics and magnetic devices, up until today's motion capture systems based on reflective markers, magnetic or inertial devices. Recently, there has been a huge development in the motion capture systems which evolved the motion study to newer dimensions (discussed in the later chapter).

1.4 Challenges in Motion Imitation

Given the resemblance between humanoid robots and human beings, it is natural to look for inspiration in human movements in order to generate motion for the humanoid. The most straightforward way is to have the robot observe what the human does and reproduce that behaviour, i.e. perform imitation. After all, even human beings themselves are able to acquire skills by imitation and learning.

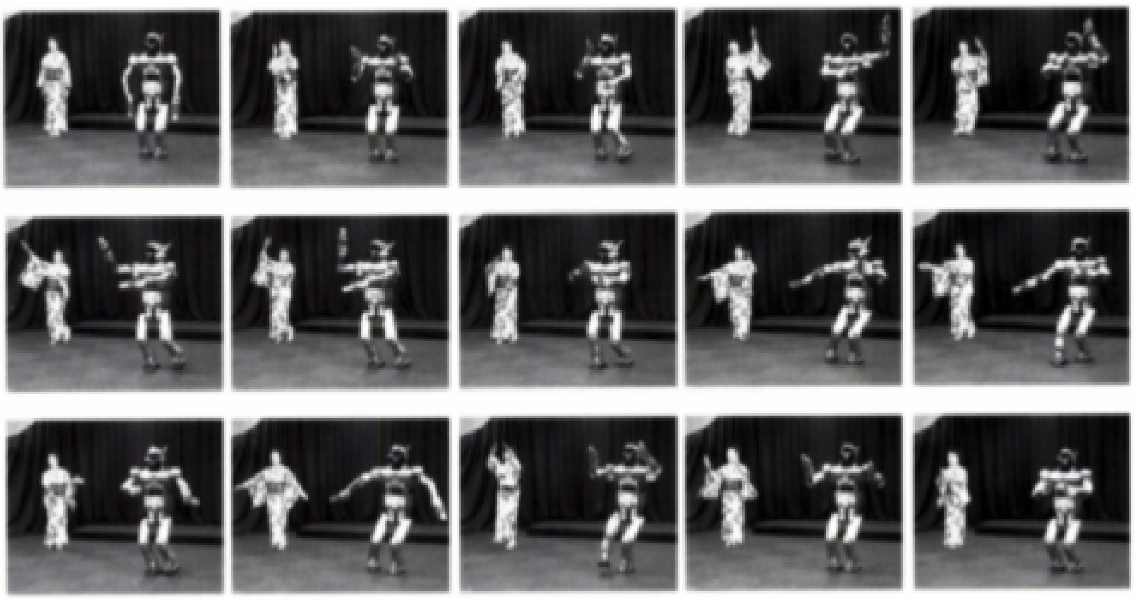

Figure 1.3: A performance based on motion imitation done by HRP-2 humanoid robot

If humanoid robots are to interact with human beings, it is imperative that their gestures are human-like since much of human communication is non-verbal. Programming each aspect of the motion detail by detail in order to make it human-like is time-consuming and not fit to handle the immense variety and complexity of human behaviours. Thus, imitation comes as a more natural and intuitive alternative to classical methods, since more information can be transmitted directly.

Human motion cannot be directly transferred to the robot without choosing beforehand which affects the ocean or what is transferring. The most advanced human robots cannot move completely like a human being. The robots are limited by differences to human counterparts such as the number of degrees of freedom, link lengths, motor torques, etc. Robots which tried to reproduce the whole human body inevitably have never taken dynamic differences from the human body they are trying to represent.

While performing imitations, the physical differences have to be taken into account when mapping the register home movements to the robot morphology. This was addressed by Pollard et al. [5], who limited the captured human motion to a range achievable by the robot by locally scaling angles and velocities in order to preserve as much as possible local variations in the motion imitated by the Sarcos robot.

1.5 Problem Statement

Recently, almost every humanoid robots are able to walk and balance in flat indoor environments and there are robots proved walking on rugged terrains and uneven planes are possible and achievable. A lot of effort is being done to make them more autonomous by incorporating the perception, planning and action loop. One of the ultimate objective of the humanoid robot, as mentioned before is to create the humanoid motion more human-precise. In this sense, robots require real-time imitation processed be higher reactivity compensating the unpredictable nature of human motion.

In humans, imitation is an advanced behavior whereby an individual observes and replicates the action of another human arguably with more accuracy and precision. However in humanoid robots, these kind of motion imitations are possible up to kinematic level through perception; the robot can also be able to imitate the action posture dynamically using its predefined configurations and controllers to an extent. But for a complete imitation at dynamic level, humanoid robots are still struggling to approximately copy the dynamic parameters applied during the action. Presently, to copy the action at dynamic level, feedback data from human during motion or action is mandatory. The motion data from human action is transferred using *Xsens MVN Analyze*. The main objective of the thesis is to define realtime dynamic balance constraint during motion imitation and validate it experimentally using an affordable humanoid robot, *NAO* from *Aldebaran Robotics*. The balancing constraint of the robot is controlled using an Hierachical Quadratic Programming (HQP) and validated on both simulation and real robot.

1.6 Thesis Organisation

Chapter 2

State of the Art

The research and interest in humanoid robotics has greatly increased over the last few years, but inspite of the current abundance of the humanoid robots, their utility is still very limited. One of the most important trials, *DARPA Robotics Challenge (DRC)* in 2013 listed a pack of capabilities and robustness that humanoid robots lacked when performing different tasks. Each task of this challenge should last only up to 30 minutes. These tasks will take less than a minute for a human to complete which explains the powerlessness of the robots. This chapter briefly explains different control strategies that has been carried to keep balance and to handle robot dynamics in humanoid robots.

2.1 Approaches in Humanoid Robot Control

Different methods has been used to make a robot move depending on the application, the complexity of the task, and even the specific nature of the robot. The main control methods used for the humanoid robots are as follows: Motion planning, Kinematic Approach, Dynamic Approach and Optimal Control. Each of the methods and its recent development are discussed below.

2.1.1 Motion Planning

Motion Planning as the name suggests a method where a robot automatically finds its desired or goal state from its initial configuration. For instance, consider a hand moving from it's current pose to another pose, motion planning allows to move to goal pose considering the presence of obstacles and consumption of time and energy. Currently, there are many applications in industrial robots and mobile robots where the robot motion is planned within both structured and non-structured environment.

Even though, motion planning and its researches are progressing majorly within past decades, the recent approaches are combined with artificial intelligence, advantages of computer technology and mathematics. The main approaches can be found in books such as [8, 9]. An desirable concept in motion planning is *Configuration Space (CS)*, which is the set of all possible configurations for a robot to attain. For a robot with n independent degrees of freedom, CS is an n-dimensional manifold $\mathbb{M}$ that contains all the desired configurations $q \in \mathbb{M}$ of the robot. The importance of CS is that changes the problem of moving a body in *SE(3)* to moving a point in CS. The summary of this section is sourced from the literature work [10]. Then there exists,

- CS_{obs} is the *Obstacle Configuration Space* formed to generate self-collision or obstacle collision free set of configurations such that $CS_{obs} \in CS$.

- CS_{free} is the *Free Configuration Space* which holds the set of configurations for a freely roaming robot such that $(CS_{free} \bigcup CS_{obs}) \cap CS$.

Using these configurations, the problem of motion planning can be stated as finding the continuous path $p(t)$ through the desirable configurations from initial state $q(0)$ to goal state $q(f)$ avoiding collisions, that is $p : [0, 1] \rightarrow CS_{free}$ where t defines time parameterization.

Generic methods

The solution to motion planning problem can be processed through classical approaches using deterministic, sampling-based or path optimization algorithms. Each of the types are briefed below.

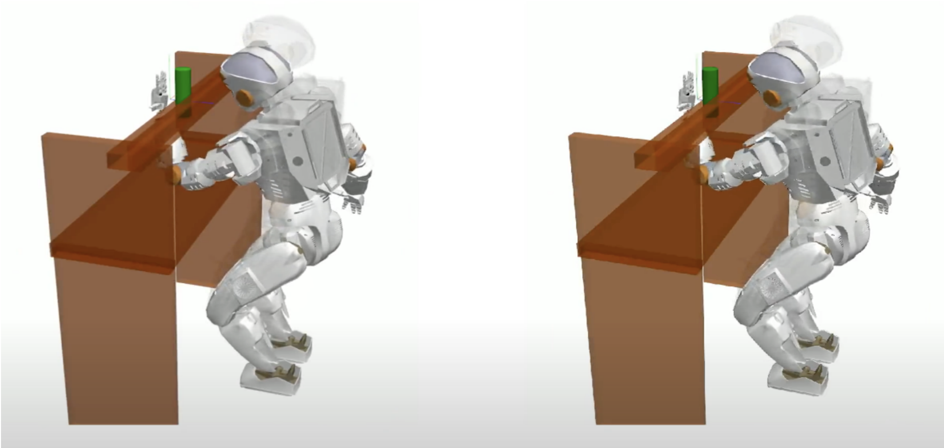

Figure 2.1: Sampling based motion planning of NASA Valkyrie [1]

1. *Deterministic algorithms* - The deterministic algorithms are developed such that it computes the valid path everytime knowing almost all the variables of the environment. Methods such as *cellular decomposition, Voronoi diagrams, visibility graphs, potential fields and Canny's algorithms* rely on mathematical construction of the environment with the obstacles and provide CS_{obs}. Although these algorithms are complete, the computation of high-dimensional space is expensive and the environments are always not deterministic.

2. *Sampling based algorithms* - These algorithms mostly approximate the connectivity of CS_{free} through random sampling configurations from CS and rejecting the configurations using boolean collision detection techniques. The main examples are *Probabilistic Maps and Rapidly-exploring Random Trees(RRT)* in combination with Voronoi diagrams promotes the obstacle avoidance configurations for a robot. The main advantage of sampling based algorithms are to handle the higher dimensional configuration space recovering a higher degree of completeness.

3. *Path optimization algorithms* - These algorithms provide optimization in terms of path planning and trajectory planning starting from a valid initial state to its goal position with the desired configurations. *Greedy optimization* tries to directly connect the start configuration to its goal state that generates a collision free shortest path by discretizing the path into n closest goal configuration relative to previous configuration.

Motion Planning in Humanoid robots

Classical motion planning techniques determine collision free trajectories considering only the geometric model of the robot. However the control of polyarticulated system needs the synthesis of robot models that describe the effect of joint variations on the whole robot configuration. In both the case, for instance considering an arm moving to it's goal position, the robot tends to make it more unusual, inefficient and unnatural movements. To overcome these problems, geometric models are replaced with kinematic models, dynamic models or optimal control and trajectories are generated. Additional constraints like multiple contacts and dynamic balance of the system are considered. For instance, motion primitives that have been predefined by a human expert based on prior knowledge can be used to guide the planner [11].

In case of humanoid walking, the planner can be generated using deterministic approaches with dynamic alterations of the foot transition model considering the smooth transition of the trajectories for posture transitions. For these cases, sampling-based algorithms are considered to improve the degree of completeness. Either way, the higher dimensional configuration space is handled so that the problem is solved successively. An example is presented in [12] where a 36 degree of freedom robot is reduced to a 3 degrees of freedom bounding box and a PRM is applied for the path planning problem of the box. Another example is to present the constraints in the form of sub-manifolds of *CS* where a union of separate manifolds like contact limb position and static balance constraints can be used to plan the configuration space. In such cases, static balance control in humanoid robots and other legged robots can be obtained [13].

2.1.2 Kinematics Approach

Generally, *kinematics* is defined as a branch of science which deals with the study of the position, velocity and acceleration of a mechanical system without considering forces and the dynamic properties of the system (such as mass or inertia) that generate the motion. In humanoid and manipulator robots, the system is represented as rigid bodies composed of actuators and sensors. In contrast with the manipulators, the humanoid robots are not fixed to any environment and are highly mobile. This makes the humanoids (or humanoid robots) more redundant than the manipulators. This section briefs the state of the art and concepts of kinematic approach used in humanoid control.

Basic Concepts

The *joint space* is also called as *configuration space*, of a robot with n degrees of freedom (DoF) is a n-dimensional manifold Q containing all the possible joint values for a joint q can take. For humanoid robots, this space can be generalized to the operational points [14], which can represent any part of the body that may be of interest. In robotics, there exists four subdomains of kinematics namely, *(i) forward kinematics (or direct geometry), (ii) inverse kinematics (or inverse geometry), (iii) forward differential kinematics (or simply forward kinematics), and (iv) inverse differential kinematics (or simply inverse kinematics).*

- **Direct Geometric Model:** For a robot with n DoF in a n-dimensional joint space such that $q \in Q$, there exist a pose $x \in SE(3)$ represented as

$$x = f(q)$$

described by a map $f : Q \rightarrow SE(3)$.

- **Inverse Geometric Model:** For a robot with n DoF in a n-dimensional joint space with $q \in Q, x \in SE(3)$, the joint space can be represented from a given pose for a certain operational point as

$$q = f^{-1}(x)$$

described by a map $f : SE(3) \to Q$. But there is a possibility for non-unique solution or non-existing solution (known as singularity).

- **Forward Kinematic Model:** For a robot with n DoF in a n-dimensional joint space such that $q \in Q, x \in SE(3)$, the operational twist $\xi \in SE(3)$ due to the joint variation $\dot{q}$ is described as

$$\xi = J(q)\dot{q}$$

Here, J is the basic Jacobian such that $J : T_q(Q)$ where $T_q(Q)$ is the tangent space of the Q space. Instead, the Jacobian J can be formulated analytically using the pose variation $\dot{x}$ and joint variation $\dot{q}$ as

$$\dot{x} = \frac{\partial x}{\partial q}\dot{q} \quad or \quad \dot{x} = J\dot{q}$$

then J is the task Jacobian.

- **Inverse Kinematic Model:** For a robot with n DoF in a n-dimensional joint space such that $q \in Q, x \in SE(3)$, finding the joint variations $\dot{q}$ that produce a pose variation $\dot{x}$ of the end effector as

$$\dot{q} = J^{-1}\dot{x}$$

and it can be solved iteratively.

Kinematics Approach in humanoid robots

2.1.3 Dynamics Approach

2.1.4 Optimal Control

2.2 Approaches in Humanoid Balance Control

2.2.1 Linear Inverse Pendulum Approach

Consider a simple inverted pendulum model as in figure [2.2] with mass m and link length l_1, the kinematics and dynamics for the model can be represented as,

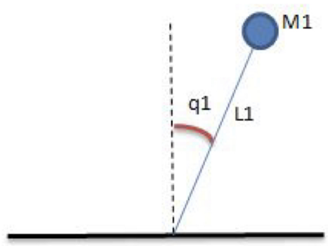

Figure 2.2: Simple Inverse Pendulum Model

Position:

$$\begin{aligned} x_1 &= -l_1 \sin q_1 \\ y_1 &= l_1 \cos q_1 \end{aligned} \tag{2.1}$$

Velocity:

$$\begin{aligned} \dot{x_1} &= -l_1 \cos(q_1)\dot{q_1} \\ \dot{y_1} &= -l_1 \sin(q_1)\dot{q_1} \end{aligned} \tag{2.2}$$

Acceleration:

$$\begin{aligned} \ddot{x_1} &= l_1 \sin(q_1)\dot{q_1}^2 - l_1 \cos(q_1)\ddot{q_1} \\ \ddot{y_1} &= -l_1 \cos(q_1)\dot{q_1}^2 - l_1 \sin(q_1)\ddot{q_1} \end{aligned} \tag{2.3}$$

Forces and Torques:

$$\begin{aligned} m_1\ddot{x_1} &= F_{x1} \\ m_1\ddot{y_1} &= F_{y1} - m_1 g \end{aligned} \tag{2.4}$$

$$\tau_1 = m_1 l_1^2 \ddot{q_1} + m_1 g l_1 \sin q_1 \tag{2.5}$$

where F_{x1} and F_{y1} represent the reaction forces on the link from the fixed point.

2.2.2 Double Inverse Pendulum Approach

Consider a double inverted pendulum model as in figure [2.3] with mass m and link lengths l_1 and l_2, the kinematics and dynamics for the model can be represented as,

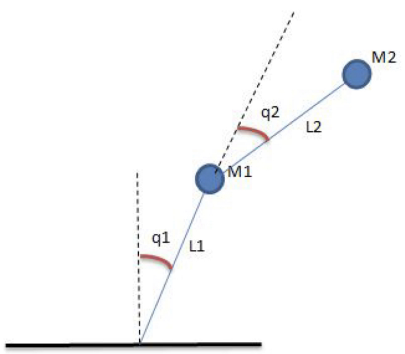

Figure 2.3: Double Inverse Pendulum Model

Position:

$$\begin{aligned} x_1 &= -l_1 \sin q_1 \\ y_1 &= l_1 \cos q_1 \end{aligned} \tag{2.6}$$

$$\begin{aligned} x_2 &= -l_1 \sin q_1 - l_2 \sin(q_1 + q_2) \\ y_2 &= l_1 \cos q_1 + l_2 \cos(q_1 + q_2) \end{aligned} \tag{2.7}$$

Velocity:

$$\begin{aligned}\dot{x_1} &= -l_1\cos(q_1)\dot{q_1}\\ \dot{y_1} &= -l_1\sin(q_1)\dot{q_1}\end{aligned} \tag{2.8}$$

$$\begin{aligned}\dot{x_2} &= -l_1\cos(q_1)\dot{q_1} - -l_1\cos(q_1+q_2)(q_1 \dot{+} q_2)\\ \dot{y_2} &= -l_1\sin(q_1)\dot{q_1} - -l_1\sin(q_1+q_2)(q_1 \dot{+} q_2)\end{aligned} \tag{2.9}$$

Acceleration:

$$\begin{aligned}\ddot{x_1} &= l_1\sin(q_1)\dot{q_1}^2 - l_1\cos(q_1)\ddot{q_1}\\ \ddot{y_1} &= -l_1\cos(q_1)\dot{q_1}^2 - l_1\sin(q_1)\ddot{q_1}\end{aligned} \tag{2.10}$$

$$\begin{aligned}\ddot{x_2} &= -l_1\cos(q_1)\ddot{q_1} + l_1\sin(q_1)\dot{q_1}^2 - l_2\cos(q_1+q_2)(\ddot{q_1}+\ddot{q_2}) + l_2\sin(q_1+q_2)(\dot{q_1}+\dot{q_2})^2\\ \ddot{y_2} &= -l_1\sin(q_1)\ddot{q_1} + l_1\sin(q_1)\dot{q_1}^2 - l_2\sin(q_1+q_2)(\ddot{q_1}+\ddot{q_2}) + l_2\cos(q_1+q_2)(\dot{q_1}+\dot{q_2})^2\end{aligned} \tag{2.11}$$

Forces and Torques:

$$\begin{aligned}m_1\ddot{x_1} &= F_{x1} + F_{x_2}\\ m_1\ddot{y_1} &= F_{y1} + F_{y_2} - m_1 g\end{aligned} \tag{2.12}$$

$$\begin{aligned}m_2\ddot{x_2} &= F_{x2}\\ m_2\ddot{y_2} &= F_{y2} - m_2 g\end{aligned} \tag{2.13}$$

where F_{x1},F_{x2},F_{x3} and F_{y1},F_{y2},F_{y3} represent the reaction forces on the link from the fixed point.

$$\begin{aligned}\tau_1 &= m_1 l_1^2\ddot{q_1} + m_1 g l_1\sin q_1\\ \tau_2 &= m_2 l_2^2(\ddot{q_1}+\ddot{q_2}) + m_2 g l_2\sin(q_1+q_2)\end{aligned} \tag{2.14}$$

2.2.3 Cart Table Model

2.2.4 Spherical Inverse Pendulum Approach

2.3 Approaches in Posture Control and Motion Retargetting

2.3.1 Mansard's work

2.3.2 D. Gucci's work

2.3.3 Kumar Munirathinam's work

Chapter 3

Dynamics Based Whole Body Imitation

3.1 Dynamic Considerations

3.1.1 Rigid body constraints

3.1.2 Multi body constraints

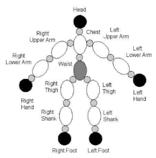

Figure 3.1: A rigid-body representation of humanoid robot

3.1.3 ZMP

3.1.4 Dynamic Model of humanoid robot

3.1.5 Simplified dynamic model using LIPM

3.2 Control Approach

3.2.1 Balance Control

CoM tracking and scaling

ZMP tracking and scaling

3.2.2 Posture Control

Multi-Double Inverted Pendulum Model (M-DIP)

3.2.3 Acceleration Control

3.3 Task Specification Approach

3.3.1 Joint trajectory tracking

3.3.2 Balance Control

3.3.3 Posture Control

3.3.4 Joint Limits Avoidance

Chapter 4

Implementation

4.1 NAO robot

4.1.1 NAOqi C++ SDK

4.1.2 CopelliaSim support

4.2 Xsens MVN Analyze

4.2.1 Sensor Setup

4.2.2 Xsens Networking Protocol

4.2.3 Network Streaming

Conclusion

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