Modeling for control of a biped robot - AAU-BOT1
Another step closer towards dynamic walking

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Traineeship report

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Eindhoven, December, 2012
Preface

This report has been composed during a three month internship running from September 2012 until December 2012 at the Department of Electronic Systems of Aalborg University. It is part of the Master program Mechanical Engineering - Control Systems Technology at the Department of Mechanical Engineering of Eindhoven University of Technology. This internship contributes to a larger project running since 2006 with enabling a humanoid robot, called AAU-BOT1, to perform a stable human like walk as ultimate goal.

The focus during this internship has been to investigate the existing dynamic model of the robot, to improve it if necessary and to do research on joint trajectories. This work is fully based on simulations with an existing model derived by previous project work, and this model has been point of origin of the current project.

Particularly investigating the implementation of the dynamic model of AAU-BOT1 and improving the dynamic model has been a major part of the research carried out in the last three months. This has resulted in the identification of several significant errors in the dynamic model limiting the ability to perform simulations giving appropriate results.

This report includes moreover an enclosed CD with the most recent simulation data and the updated library as described in Appendix E.

To me, the last three months have been a wonderful and moreover instructive and useful contribution to my Master studies, where it was especially exiting to participate in this big project. I would like to thank my coaches prof. Stoustrup, assoc. prof. Helbo, PhD-student Morten Juelsgaard and moreover Rune and Niels for their feedback and discussions. Finally, I hope that my contribution is useful in the future and that within a reasonable amount of time the final goal is achieved and AAU-BOT1 will walk and explore the Lab.

Bart Moris
Eindhoven, December 3, 2012
# Nomenclature

## Greek Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Pitch angle between both thighs</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Coefficient in friction formula</td>
<td>[-]</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Maximum foot clearance</td>
<td>[m]</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Step height</td>
<td>[m]</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Joint angle</td>
<td>[rad]</td>
</tr>
<tr>
<td>$\dot{\theta}$</td>
<td>Angular joint velocity</td>
<td>[rad s$^{-1}$]</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Step length</td>
<td>[m]</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Friction coefficient</td>
<td>[-]</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Torque</td>
<td>[Nm]</td>
</tr>
<tr>
<td>$\varphi$</td>
<td>Pitch angle between foot sole and floor</td>
<td>[rad]</td>
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## Latin Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$a$</td>
<td>Heel position in $x$-direction in fixed world frame</td>
<td>[m]</td>
</tr>
<tr>
<td>$AI$</td>
<td>Anthropomorphic Index</td>
<td>[-]</td>
</tr>
<tr>
<td>$b$</td>
<td>Toe tip position in $x$-direction in fixed world frame</td>
<td>[m]</td>
</tr>
<tr>
<td>$DGM$</td>
<td>Dynamic Gait Measure</td>
<td>[-]</td>
</tr>
<tr>
<td>$F$</td>
<td>Force</td>
<td>[N]</td>
</tr>
<tr>
<td>$H$</td>
<td>Hip height</td>
<td>[m]</td>
</tr>
<tr>
<td>$h$</td>
<td>Ankle pitch joint height with respect to foot sole</td>
<td>[m]</td>
</tr>
<tr>
<td>$k$</td>
<td>Ratio of $GRF$ in $z$-direction and steady state force</td>
<td>[-]</td>
</tr>
<tr>
<td>$l$</td>
<td>Length</td>
<td>[m]</td>
</tr>
<tr>
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<td>Mass</td>
<td>[kg]</td>
</tr>
<tr>
<td>$T$</td>
<td>Period</td>
<td>[s]</td>
</tr>
<tr>
<td>$t$</td>
<td>Time</td>
<td>[s]</td>
</tr>
<tr>
<td>$\bar{v}$</td>
<td>Average velocity</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$x$</td>
<td>Position in $x$-direction</td>
<td>[m]</td>
</tr>
<tr>
<td>$\dot{x}$</td>
<td>Velocity in $x$-direction</td>
<td>[m s$^{-1}$]</td>
</tr>
<tr>
<td>$\ddot{x}$</td>
<td>Acceleration in $x$-direction</td>
<td>[m s$^{-2}$]</td>
</tr>
<tr>
<td>$\dot{\ddot{x}}$</td>
<td>Jerk in $x$-direction</td>
<td>[m s$^{-3}$]</td>
</tr>
<tr>
<td>$z$</td>
<td>Position in $z$-direction</td>
<td>[m]</td>
</tr>
<tr>
<td>$\dot{z}$</td>
<td>Velocity in $z$-direction</td>
<td>[m s$^{-1}$]</td>
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<tr>
<td>$\ddot{z}$</td>
<td>Acceleration in $z$-direction</td>
<td>[m s$^{-2}$]</td>
</tr>
<tr>
<td>$\dot{\ddot{z}}$</td>
<td>Jerk in $z$-direction</td>
<td>[m s$^{-3}$]</td>
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## Vectors

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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</thead>
<tbody>
<tr>
<td>$g$</td>
<td>Gravity</td>
<td>[m s$^{-2}$]</td>
</tr>
</tbody>
</table>
GCOM  Ground projected Center of Mass location in world frame coordinates  [m]

$I$  Inertia tensor  [kgm$^2$]

$S$  State vector

ZMP  Zero Moment Point location in fixed world frame coordinates  [m]

Subscripts

$a$  Additional

$w$  Coulomb property

$desired$  Desired property

$H$  Hip property

$\text{human}$  Human property

$l$  Left foot property

$max$  Maximum value of property

$n$  Normal property

$r$  Right foot property

$s$  Sample property

$st$  Property of stance leg during SSP

$static$  Property of static gait

$\text{stride}$  Stride property

$sw$  Property of swing leg during SSP

$n$  Viscous property

$w$  Friction property

$x$  Property in $x$-direction of the fixed world coordinate frame

$y$  Property in $y$-direction of the fixed world coordinate frame

$z$  Property in $z$-direction of the fixed world coordinate frame

Superscripts

$'$  Mapped property

$DSP$  Double Support Phase property

$s$  Step property

$SSP$  Single Support Phase property

Acronyms

AI  Anthropomorphic Index

$CoM$  Center of Mass

$CoP$  Center of Pressure

$DGM$  Dynamic Gait Measure

$DoF$  Degree of Freedom

$DSP$  Double Support Phase

$EMG$  Electromyogram

$FTS$  Force Torque Sensor

$GCoM$  Ground projected Center of Mass

$GRF$  Ground Reaction Force

$iDGM$  Instantaneous Dynamic Gait Measure

$IMU$  Inertial Measurement Unit

$iZMP$  Imaginary Zero Moment Point
Polygon of Support
Single Support Phase
Zero Moment Point
## Preface

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## A The dynamic model of AAU-BOT1

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Chapter 1

Introduction

This report elaborates on the results of a three month internship at Aalborg University. The challenge faced during the project is generating trajectories and controllers to enable AAU-BOT1 to walk in an anthropomorphic manner. AAU-BOT1 was designed at Aalborg University several years ago to do research in the field of dynamic and static gait in humanoid robotics. AAU-BOT1 is a humanoid robot with 19 Degrees Of Freedom (DoFs) of which only 17 are actively actuated, the other two are spring actuated. The progress made until the start of this project is thoroughly documented in several master theses [17], [9], [8] and [1]. Moreover, the last project group working with AAU-BOT1 created a simulink model to simulate with AAU-BOT1 [1]. Walking in an anthropomorphic manner is a very important research topic nowadays as an anthropomorphic behaving robot is more easily applicable in a human environment interacting with other humans. Moreover, one of the initial goals was to contribute in the medical field with research on disabled people, for example missing a (part of) a leg. An example of the possibilities is a robot called ‘LOPES’ which is capable of robot aided gait training with patient specific support enabling chronic stroke survivors to walk (with assistance) [21]. AAU-BOT1 can be used for the same kind of applications in case it can perform a stable anthropomorphic gait successfully. Due to the small amount of time available in this project the model made by that group is used for simulation purposes. Specific terminology used in this report is mentioned and explained in the following section. Chapter 2 elaborates on the generation of trajectories and all problems and considerations this involves. Especially the design of trajectories is very important as this is at the heart of enabling AAU-BOT1 to walk in whatever way. Attention is paid at gait initiation and termination, stability criteria, gait optimization and to what extent a gait is anthropomorphic. In the Chapter 3 the trajectories are evaluated by means of simulation to test the stability. In order to obtain a dynamic gait which looks human like and moreover is applicable to the real set-up the controllers implemented are tuned. Finally conclusions are drawn and recommendations are formulated in Chapter 4 in order to give handles to future groups for possible directions of further research or improvements.

1.1 Definitions and terminology

In this report, some definitions and terminology is used that is very common in the field of humanoid robotics. To make sure all terminology is clear and does have the right meaning to the reader, the main definitions are given here. Figure 1.1 shows the names of commonly used axes and planes. In this report the axes and planes are always defined according to the definition shown here where angles are defined according to a right handed coordinate system. Besides the definition of planes and axes it is important to specify some terms related to a gait and phases of a gait. A gait is defined as the description of the pattern of motion of the limbs leading to legged locomotion.
Each single person has its own characteristic gait but it is still possible to define general properties which hold for every bipedal human gait. Important is the fact that human gait is usually cyclic and hence repetitive. Each gait consists of several phases related to the configuration of the legs during a gait. The human gait cycle is often divided into a sequence of eight different sub phases which are grouped in a stance phase and a swing phase. A stance phase consists of five sub phases being heel strike, foot-flat, midstance, heel-off and toe-off. The swing phase consists of an acceleration phase, a midswing phase and a deceleration phase. For an average person the swing phase takes up to 40% of a full stride, where a stride is a sequence of two steps. The different measures defining a step and stride are clarified by means of Figure 1.2. However, there is also another way of defining and dividing a gait cycle usually referring to the way of support. This divides a step into a Single Support Phase (SSP) and a Double Support Phase (DSP). During the DSP both legs are in contact with the floor, whereas only the stance leg has contact with the floor during the SSP. An overview
of all phases building up a full gait cycle is given in Figure 1.3. This type of gait leads to a walk, where walking is defined as a movement by putting forward each foot in turn, not having both feet off the ground at once. The prerequisite not having both feet off the ground distinguishes walking from running. Finally, there is another important difference in the nature of a certain gait. A gait can either be dynamic or static which has implications on the means of stabilization. Static gaits are stabilized by forcing the Zero Moment Point (ZMP) and the Ground projected Center of Mass (GCoM) to stay within the Polygon of Support (PoS). The PoS is the convex hull of all points where the considered object has ground contact. The Center of Mass (CoM) is the weighted average location of the mass of a number of bodies and the GCoM is its projection on the floor. One of the definitions for the zero moment point is the point for which the sum of the moment generated due to gravity and inertia is equal to zero. For dynamic gait this restriction does no longer hold as the GCoM is allowed to move out of the PoS for at least a small part of the full stride while only the ZMP should stay inside the PoS. This boils down to loosing stability for some part of the gait cycle and in case it is stable, regaining stability before falling down. Human gait is generated in this way and dynamic gait is for this reason considered to be the goal in this report.

![Figure 1.3: Overview of a gait cycle in terms of the phases. Source: [22].](image)

1.2 Topology of AAU-BOT1

The topology of AAU-BOT1 is described in this section in more detail, especially the joints and the definition of joint angles and distances. All joint names are assigned while respecting the framework depicted in Figure 1.1 and joint angles are indicated with $\theta_i$ where the joint number expressed by the subscript $i$ refers to a particular joint. All joint angles are relative angles between the parent link and the child link. An overview of all joint numbers, joint names, rotation axes, child links and parent links is given in Table 1.1 and in Figure 1.4. Moreover the IMU angles are included in this list. These angles are all with respect to the axes of the fixed world coordinate frame, as shown in Figure 1.1. Important is to mention that the zero position is defined as the position where AAU-BOT1 is standing upright with both feet having ground contact and with the upper arms aligned with the torso and the forearms pointing in positive $x$-direction.

1.3 Simulation model walkthrough

This section describes the simulation model designed by [1], as this is the model used for simulations. The most important features and design strategies are investigated and recapitulated here.
Table 1.1: Number, name, rotation axis, parent link and child link for all joints. Note that joint 18 and 19 are passive, unactuated joints.

<table>
<thead>
<tr>
<th>Joint number (i)</th>
<th>Joint name</th>
<th>Rotation axis</th>
<th>Child link</th>
<th>Parent link</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Right ankle roll</td>
<td>x</td>
<td>Right Foot</td>
<td>Right Shank</td>
</tr>
<tr>
<td>2</td>
<td>Right ankle pitch</td>
<td>y</td>
<td>Right Foot</td>
<td>Right Shank</td>
</tr>
<tr>
<td>3</td>
<td>Right knee pitch</td>
<td>y</td>
<td>Right Shank</td>
<td>Right Thigh</td>
</tr>
<tr>
<td>4</td>
<td>Right hip pitch</td>
<td>y</td>
<td>Right Thigh</td>
<td>Pelvis</td>
</tr>
<tr>
<td>5</td>
<td>Right hip roll</td>
<td>x</td>
<td>Right Thigh</td>
<td>Pelvis</td>
</tr>
<tr>
<td>6</td>
<td>Right hip yaw</td>
<td>z</td>
<td>Right Thigh</td>
<td>Pelvis</td>
</tr>
<tr>
<td>7</td>
<td>Left hip yaw</td>
<td>z</td>
<td>Left Thigh</td>
<td>Pelvis</td>
</tr>
<tr>
<td>8</td>
<td>Left hip roll</td>
<td>x</td>
<td>Left Thigh</td>
<td>Pelvis</td>
</tr>
<tr>
<td>9</td>
<td>Left hip pitch</td>
<td>y</td>
<td>Left Thigh</td>
<td>Pelvis</td>
</tr>
<tr>
<td>10</td>
<td>Left knee pitch</td>
<td>y</td>
<td>Left Shank</td>
<td>Left Thigh</td>
</tr>
<tr>
<td>11</td>
<td>Left ankle pitch</td>
<td>y</td>
<td>Left Foot</td>
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<tr>
<td>12</td>
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<td>x</td>
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<td>13</td>
<td>Pelvis yaw</td>
<td>z</td>
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<td>Waist</td>
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<td>y</td>
<td>Waist</td>
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<td>x</td>
<td>Waist</td>
<td>Torso</td>
</tr>
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<td>y</td>
<td>Right Arm</td>
<td>Torso</td>
</tr>
<tr>
<td>17</td>
<td>Left arm pitch</td>
<td>y</td>
<td>Left Arm</td>
<td>Torso</td>
</tr>
<tr>
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<td>Right toe joint</td>
<td>y</td>
<td>Right Toe</td>
<td>Right Foot</td>
</tr>
<tr>
<td>19</td>
<td>Left toe joint</td>
<td>y</td>
<td>Left Toe</td>
<td>Left Foot</td>
</tr>
<tr>
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<td><strong>IMU</strong> roll</td>
<td>x</td>
<td>torso</td>
<td>Fixed world frame</td>
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<tr>
<td>21</td>
<td><strong>IMU</strong> pitch</td>
<td>y</td>
<td>torso</td>
<td>Fixed world frame</td>
</tr>
<tr>
<td>22</td>
<td><strong>IMU</strong> yaw</td>
<td>z</td>
<td>torso</td>
<td>Fixed world frame</td>
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</tbody>
</table>

The model consists of several simulink components, like a full dynamic model of AAU-BOT1, a forward kinematics feature, inverse kinematics feature, and some features in order to determine the ZMP, GCoM and the foot having ground contact. The full dynamic model of AAU-BOT1 is the main component in simulations and is hence described first. The complexity of the dynamic model is illustrated by the figures in Appendix A showing the big scheme of all links and two pictures showing in more detail how the toe is modeled. Although the model is just discussed briefly in this section, understanding the model and making modifications to the model has been a major part of this project. The different body parts of AAU-BOT1 are modeled as rigid bodies having a certain mass, inertia and division of mass described by the position of the CoM. Two neighboring body parts are connected by means of a rotational joint. Input to the model is a certain amount of current for each actuator. This current is first fed trough a saturation block in order to take motor saturation into account. The saturation levels are set at twice the nominal current, although a higher overload is permitted for a short time interval. The resulting currents are multiplied by the motor constants and gear ratio to convert them to torques applied to the actuators. All actuators are implemented as actuators with friction to account for friction phenomena in the gears. The friction phenomena modeled are stiction as well as coulomb and viscous friction, where it is assumed that the friction is independent of translational loading. All actuators are equipped with sensors to measure relative angles and angular velocities of the child link with respect to the parent link. The CoM of the pelvis is related to the fixed world coordinate frame by means of a six DoF joint and initial conditions on the translations in the directions of the three coordinate frame axes. The ground is modeled as a combination of spring and damper only exerting a force on the foot once
the foot actually touches the ground. Moreover the ground applies a friction force to the foot in case it makes a sliding movement along the ground surface. The detection of actual ground contact is done by checking if at least one of the corner points of the foot or toe is below the zero level defined by the origin of the fixed world coordinate frame. As stated before the toe joints are passive and not actuated. These two joints are modeled as a regular joint without applied torque but with a spring and damper acting on it. In order to measure the forces and torques exerted on the feet by the ground, a [FTS] is implemented in each foot of [AAU-BOT1]. In the dynamic model this is represented by a sensor measuring forces and torques. This sensor is placed between the main foot and the ankle bracket which are interconnected via a weld. The forces and torques are given as output straight away, where no additional conversion is needed as is the case for readings from an [FTS] of [AAU-BOT1]. The [IMU] implemented in the simulation model measures the angle of the torso with respect to the fixed world coordinate frame. Moreover it gives the angular velocities and accelerations along the coordinate frame axes. Some other important features are the fact that the simulations are solved by a variable step solver but the input to the model of [AAU-BOT1] is sampled at 250 Hz as is the case in experiments too. This is done via rate transitions and zero-order hold components. The forward kinematics are also implemented to determine properties like the [CoM] and [GCoM]. The forward kinematics are implemented such that it builds up a tree consisting of several branches each having several [CoM] vectors. The chains used are the left leg chain, right leg chain, waist chain, right arm chain and the left arm chain. These are in the end related to the position of the [IMU] and coupled to the position in the fixed world coordinate frame. Rotations between different coordinate frames are included as multiplications of a rotation matrix and a vector. Moreover the [GCoM] and [CoM] for each foot are determined where the latter one makes use of the division between forces in z-direction between the feet, to determine the stance foot. The inverse kinematics are also implemented in the simulation model but not used during this project. It is implemented in the way described by [1] in section 3.6. Two other important parts of the model are parts that determine the position of the [ZMP] and the position of the [GCoM] and [CoM]. The [ZMP] and the [GRF] for each individual foot are determined from the [FTS] data. This is done by determining the location of the [ZMP] as described by [1] in section 5.1. Furthermore a value for the parameter \(k\) is determined which is the ratio of the actual [GRF] in z-direction and the steady state force indicating which foot has ground contact. The [ZMP] is then determined as a weighted average of the sum of the [ZMP] and the [CoM] for each individual foot. This weighting occurs by the value of the [GRF] in z-direction. The parts of the model used in simulations are now verified in preparation for simulations. The next chapter will elaborate on the design of trajectories which will yield a stable dynamic gait.
Figure 1.4: Joint numbers for all joints of AAU-BOT1 and the IMU.
Chapter 2

Trajectory Generation

Trajectories are the very beginning of obtaining any actively generated walking gait. Humans generate trajectories the whole day for every single movement they make. Although it might seem to be very straightforward to generate trajectories from scratch, at least from a human point of view, it is not in case of (humanoid, biped) robots. There are many variables and design choices which have great influence on the obtained gait. The best illustration of this fact might be the difference between and uniqueness of several humans performing the same task, e.g. walking from A to B. In order to design a challenging trajectory that enables AAU-BOT1 to walk dynamically, some research is performed to investigate the existing knowledge about the basics of trajectory generation, anthropomorphic trajectories and the advantages and drawbacks of on- and off-line trajectory generation. Especially the generation of trajectories that force AAU-BOT1 to exhibit an anthropomorphic gait is emphasized in this report.

2.1 Introduction

There are numerous ways to initiate the process of generating trajectories from scratch. The most obvious way is probably recording human gaits with 3D motion capturing systems and use this data to extract stable trajectories which can serve as a starting point. Another way is to design trajectories for several parts of the body, e.g. the feet, and determine feasible other joint trajectories that render a stable dynamic gait based on these pre-defined trajectories. Finally an approach might be to use simplified models for simulation and trajectory generation. The methods briefly mentioned are described in more detail now. Note that as a first start only the trajectories for the pitch angles are considered as these are the joints that contribute to the forward motion which is the basis of any gait.

- Recorded trajectories of humans
  This method is proposed in several papers and has proven to be successful in simulation [25]. Issues that might play an important role in maintaining a stable gait once the trajectory is applied to AAU-BOT1 is the difference in mass, length and [CoM]. However, this method holds a learning feature which intends to force the trajectories to converge to a stable anthropomorphic gait for AAU-BOT1 as [25] describes, even if the initial trajectories are not very anthropomorphic and dynamic but stable.

- Partially pre-defined trajectories
  A different but straightforward approach is to start with pre-defining some joint trajectories on beforehand by means of defining initial and end conditions and possibly so-called via-points. Via-points are intermediate points on the desired trajectory to force the predefined
trajectory to pass through a certain point. The other joint trajectories can be designed afterwards, possibly online, with as major requirement obtaining a stable gait. A possible tuning trajectory is the trajectory for the hip and pelvis in order to put $ZMP$ in the right position. This method is especially useful if it is desired to modify trajectories online, as one can easily switch between predefined trajectories as long as they are designed in a parameterized way. This method is employed here by describing set-points for the ankle and hip positions. The knee trajectories are derived from the ankle and hip trajectories based on kinematics. The torso pitch trajectory is afterwards determined based on a desired $ZMP$ trajectory in $x$-direction and the known $CoM$ positions and masses of all bodies.

- Static gait
  Finally, the approaches presented before are all based on obtaining the desired dynamic gait right away. A stable static gait was already obtained by [8] and could also serve as an initial trajectory. Although these trajectories are not dynamic as required, optimization towards the human recorded trajectories could result in a dynamic gait while stability is guaranteed. This is the third method which is elaborated.

Next to these approaches, there are other considerations that come into play like the consideration of on-line or off-line trajectory generation and the choice between trajectory generation in the joint or task space [10]. The task space is the space in which the end-effector position is described, and in this specific case the cartesian space in which the position of the different limbs or joints is defined. Each choice has its own advantageous and drawbacks, so a conscious choice is made here. On-line trajectory generation in general enables more freedom in adopting trajectories on the fly once a disturbance has occurred, e.g. someone pushing the robot or a badly estimated friction coefficient. On the other hand, on-line trajectory calculation often requires high computational power and is moreover often a time consuming task. Therefore it is highly dependent on the operating system and the actual task that has to be carried out if it is feasible to use on-line trajectory generation methods. Off-line trajectory generation is in general not as critical as on-line trajectory generation with respect to time consumption but it incorporates less adaptability of trajectories during the walk. A solution to benefit from both strategies is a hybrid technique. This means that part of the trajectories is generated on beforehand, so off-line and another part is generated on-line. The choice between trajectory generation in the joint or task space is strongly related to the method of trajectory generation. Using the task space is mainly useful if set points are defined in the task space, for example once using the method where partially pre-defined trajectories are used. Frequently, the initial- and end-conditions are specified with respect to the task space. Once using the method where human motions are captured using 3D motion capturing systems the trajectories are most likely defined in the joint space as this is probably the easiest way of conversion. With respect to on-line trajectory generation the joint space approach is favorable as it requires less calculations, actuator limitations and hence velocity and torque limits are determined from data sheets and the path planning is not affected by crossing singular configurations. On the contrary, design of trajectories in the task space permits prediction of the geometry of the path. In practice, it strongly depends on the trajectory generation principle and application whether the joint or task space is favorable.

Each trajectory starts at the beginning of a [DSP] to make it more easy to start experiments with AAU-BOT1. A way to start an experiment could be to move all the joints into the initial position of a stride by applying a linear changing reference joint angle changing from the value in zero position to the value at the start of a stride. This procedure should be executed when AAU-BOT1 is lifted from the ground and is suspended in its frame, as shown in Figure 2.1. Once the desired positions are obtained, AAU-BOT1 can be lowered and put at the ground surface after which the reference is switched to the real gait trajectories. This should be a possibility as
During DSP stability is obtained quite easily and automatically as the ZMP, CoM and CoP are usually all within the PoS. This means that balance is indeed present. However, there are no initial speeds present which are in practice present on the beginning of a gait cycle once the subject is performing a steady walk. Designing more sophisticated gait initiation end termination methods accounting for initial velocities requires more research and methods to do so are discussed later on in Section 2.5.

2.2 General requirements

In order to apply at least one of the trajectory generation approaches, the purpose of the methods and the general requirements on the generated trajectories should be clear. This section therefore elaborates on these requirements. The main requirement and probably also the main challenge is to enable AAU-BOT1 to exhibit an anthropomorphic, dynamic gait. Anthropomorphic gaits require the gait to resemble some human gait properties like step length, step frequency, average speed, division between single support and double support phase and continuity of the trajectory to some extend. Moreover, the trajectory must be as such that it can be blend with an initiation sequence and termination sequence. Human gait properties are derived from [15], [23] and [22]. The main gait properties are given in Table 2.1.
Table 2.1: Human gait parameters for normal gait

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value for men</th>
<th>Value for women</th>
<th>Average</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average step length</td>
<td>61.6</td>
<td>59.1</td>
<td>60.4</td>
<td>cm</td>
</tr>
<tr>
<td>Average speed</td>
<td>122.7</td>
<td>124.1</td>
<td>123.4</td>
<td>cm s$^{-1}$</td>
</tr>
<tr>
<td>Step frequency</td>
<td>1.98</td>
<td>2.08</td>
<td>2.03</td>
<td>steps s$^{-1}$</td>
</tr>
<tr>
<td>DSP</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>% of cycle time</td>
</tr>
<tr>
<td>SSP</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>% of cycle time</td>
</tr>
<tr>
<td>Maximum heel lift</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>cm</td>
</tr>
</tbody>
</table>

An important note is the fact that the stride time is slightly changed from the value obtained from the step frequency. This change is applied to ensure that the stride time is compatible with the sample time, which is set in all simulation and experimental programs at a value of 0.004 s. Compatible in this sense aims at the fact that the stride time should be a multiple of the sample time. This is beneficial if data has to be post processed or in case of applying other algorithms incorporating knowledge on the relative position in a gait cycle. The stride time is therefore equated to a value of 0.98 s for all gait cycles designed.

2.3 Optimization objectives

In order to generate anthropomorphic trajectories that are energy efficient, stable and moreover meeting all other constraints shown in Table 2.1, it is important to define optimization objectives in terms of measures that indicate the level of the considered objective. The objectives for the gait are being energy efficient, as anthropomorphic as possible and especially having a high degree of stability. These objectives are translated into measures indicating whether an objective is met or not in the following paragraphs.

2.3.1 Stability measures

Stability criteria are well-defined in static balanced gait, by means of constraints on the position of the CoM and the ZMP. They should both stay within the PoS in order to keep the gait stable. However, this criterion is violated by definition for a dynamically balanced gait in order to obtain such a gait. Hence, other methods are required to assess the stability of a certain gait. Different methods are described in this paragraph in order to give an overview of possible methods and to choose the one that suits this application best.

Orbital stability assessment based on Floquet theory

This method is described in [4]. According to the assumption of Floquet theory, a system is strictly periodic. Therefore, all generated simulation data is cut into samples according to the basic period of the applied signal. In the general case, (2.1) should hold, where $k$ indicates the stride number, $S \in \mathbb{R}^n$ the system state, and $F : \mathbb{R}^n \mapsto \mathbb{R}^n$ is a mapping function, mapping all states $n$ at a specific time instant in a stride, denoted with $i \in \{0, \ldots, \frac{T_{\text{stride}}}{T_s} - 1\}$, to the same time instance $i$ in the proceeding stride. The instance in a stride $i$ is based on a sample time of $T_s$ and a stride time of $T_{\text{stride}}$. Important is that the stride time is a multiple of the sample time to ensure that it is indeed possible to measure all states at the same percentage of a stride during each proceeding stride.

$$S_{i}^{k+1} = F(S_{i}^{k})$$ (2.1)
Limit cycle trajectories are represented by a single fixed point in the Poincaré map which results in

\[
S_{i+1}^k = F(S_i^k) \bigg|_{\text{limit cycle}} = S_i^* = F(S_i^*) .
\] (2.2)

In order to investigate the effect of small perturbations on \( S_i^* \in \mathbb{R}^n \), (2.1) is linearized around \( S_i^* \) by means of a first order Taylor series expansion. The limit cycle state values, \( S_i^* \), are defined as the state values at time instance \( i \) during a stride averaged over all strides considered. Furthermore the equation is expanded to incorporate all strides \( k \in \{1, \ldots, K+1\} \) with \( S^K_i = (S^1_i, \ldots, S^K_i) \), \( S^{K+1}_i = (S^2_i, \ldots, S^{K+1}_i) \) and \( S_i^* = I^{1 \times K}S_i^* \) which results in (2.3). The matrix \( J(S^*) : \mathbb{R}^{n \times K} \to \mathbb{R}^{n \times K} \) is the jacobian and also known as the Floquet Matrix. Equation (2.3) is stable if and only if the eigenvalues of the Floquet matrix, the Floquet multipliers, have a magnitude smaller than 1 indicating that they are all located within the unit circle.

\[
(S_i^{K+1} - S_i^*) = J(S_i^*)(S_i^K - S_i^*)
\] (2.3)

Simulations and experiments on AAU-BOT1 give 17 joint angles and angular velocities as output, which are considered to be the states of the state vector. This implies that at least 36 strides are required to do the analysis. A higher number of strides increases the accuracy of this method and is by consequence desirable. The matrices \( (S_i^{K+1} - S_i^*) \) and \( (S_i^K - S_i^*) \) are in general, also in this case, non-square and hence non-invertible. This is solved using the Moore-Penrose pseudo-inverse instead of the normal inverse \([6]\). The method gives a good notion on the stability of a trajectory and moreover on the margins to unstable behavior. A drawback is that it is only applicable after doing simulations and it is not possible to employ this method for online purposes as a large number of cycles has to be compared and the method is computationally quite demanding.

**Orbital stability assessment based on Dynamic Gait Measure**

A method that enables online assessment of dynamic gait stability is the usage of the so-called Dynamic Gait Measure \([\text{DGM}]\). The measure is introduced by \([14]\) and depends not only on balance criteria, but on both balance criteria and stance foot dimensions. This is important to be able to assess the relative stability, which is the stability of a dynamic gait in comparison to the limiting case of a stable static gait. The \([\text{DGM}]\) is defined as shown in (2.4), where only one \( \text{SSP} \) is considered, starting at \( t = 0 \) and ending at \( t = T_{\text{SSP}} \) and \( a \) indicates the \( x \)-position of the heel of the stance foot and \( b \) indicates the \( x \)-position of the toe tip of the stance foot, i.e. the limits of the \([\text{PoS}]\) in \( x \)-direction.

\[
\text{DGM} = \sqrt{\int_0^{T_{\text{SSP}}} \left[ \text{ZMP}_x(t) - \text{GCoM}_x(t) \right]^2 \, dt \over T_{\text{SSP}}(a^2 + ab + b^2)/3} \quad \quad [\text{[-]}] \quad (2.4)
\]

The distance between the current \([\text{ZMP}]\) position and the \([\text{GCoM}]\) at each time instance provides a measure of how dynamic a gait is and together with the foot dimensions of the stance foot it is related to static walk as well. The \([\text{DGM}]\) is always larger than or equal to 0 and bounded from above by a constant depending on parameters like, link lengths, link masses and \([\text{CoM}]\) locations but also joint angle limits. A value of the \([\text{DGM}]\) between 0 and 1 indicates a static gait, a value of 1 a marginally static gait and values between 1 and the upper bound a dynamic gait, where the degree of dynamic walk increases with increasing \([\text{DGM}]\) value. The concept of the dynamic gait measure is extended with another measure related to the instantaneous stability. The instantaneous \([\text{DGM}]\) gives information on how dynamic the gait is at the considered time instance which is useful in monitoring the source of falling down and is defined as stated in (2.5).
DGM = \frac{ZMP_x(t) - GCOM_x(t)}{GCOM_{lim,x}(t)} \quad [\text{-}] \quad (2.5)

It is important to notice that the expression for GCOM_{lim,x}(t) changes once in DSP, although it is still possible to determine the DGM. The definition of GCOM_{lim,x}(t) both in SSP and in DSP is shown in (2.6), with \( n \in \mathbb{N} \). In case of DSP, the value of \( a \) remains the same while the value of \( b \) changes to the sum of the \( x \)-position of the heel of the swing foot that just made ground contact and the foot length.

\[
GCOM_{lim,x}(t) = \begin{cases} 
\frac{b-a}{T_{SSP}} t + a & \text{if } 0 + n \frac{T_{cycle}}{2} \leq t < T_{SSP} + n \frac{T_{cycle}}{2} \\
\frac{b-a}{T_{DSP}} t + a & \text{if } T_{SSP} + n \frac{T_{cycle}}{2} \leq t < (1 + n) \frac{T_{cycle}}{2} 
\end{cases} \quad [\text{m}] \quad (2.6)
\]

Orbital stability assessment based on Frequency Domain Analysis

A parameter that changes for sure once losing balance is the stride length and especially the stride time. The FTS sensors contain information on the step and stride time as the forces experienced in \( z \)-direction are periodic with the stride time. An increase or decrease of stride time due to losing stability will cause a change in the base frequency present in the force signal in the \( z \)-direction. The tool which is very useful to analyze the base frequency of the force signal in \( z \)-direction is a fourier transformation of the force signal. The dominant frequency will have the highest peak in the amplitude spectrum of the signal. It is questionable if this method works out well, as the changes in step frequency are probably very small and hardly detectable before actually falling.

2.3.2 Energy Consumption measure

Energy consumption of the overall system gives probably also an indication of how natural the applied gait is. The tendency of nature and hence also of humans is to perform all kinds of processes as efficient as possible concerning energy consumption. This is an unconscious process but nevertheless a measure to compare a motion of a biped to a motion of a human of comparable size, mass and mass distribution performing a walking motion with the same gait pattern. Energy is a sum of all power consumed over a specified time interval. Power is the product of torque applied to a rotational actuator and the rotational speed of the actuator. Equation (2.7) shows an expression for the overall energy usage for a discrete system to incorporate the effect of sampling, where \( N_j \) indicates the number of time instances taken into account, \( N_i \) the total number of joints considered and \( \Delta t \) the sampling time.

\[
E = \sum_{i=1}^{N_i} \sum_{j=1}^{N_j} \tau_i(j) \dot{\theta}_i(j) \Delta t \quad [\text{J}] \quad (2.7)
\]

The applied torque to a particular joint is derived by multiplication of the applied current by the torque constant of the particular actuator. The dual actuated joints, being both hip roll joints, both knee pitch and both ankle pitch joints, need special attention to make sure not half of the energy usage or twice the energy usage is determined, depending on the definitions in the model regarding gains and current division.
2.3.3 Measure for resemblance of human gait

It is very hard to measure the degree of resemblance of human gait and express it as a numerical value. In order to do so a ratio is defined, from now on called the Anthropomorphic Index \( AI \),

\[
AI_i(t) = \frac{\theta_i(t) - \theta_{i, \text{human}}(t)}{\theta_{i, \text{human}}(t)} \in \mathbb{R},
\]

which describes the difference between a human reference trajectory and the actual trajectory for a particular joint, denoted with \( i \) at time instance \( t \). This index has a value of 0 if both trajectories are equal, a positive value if the current trajectory has a larger angle than the human trajectory and vice versa. An absolute value of the \( AI \) of 1 indicates a difference between the two trajectories of 100% of the reference trajectory. Another method of expressing the resemblance or difference is the usage of the \( DGM \) which gives an indication of the difference between the position of the \( ZMP \) for the actual trajectory and the human reference. Moreover it gives an indication of the margins to dynamic instability which is useful as a tool to indicate the stability while walking.

2.4 Designing trajectories

This sections describes the off-line design of trajectories based on three different starting points. Afterwards the three methods are compared and conclusions are drawn.

2.4.1 Partially pre-defined trajectory generation

The method described here is based on [23]. As described in Table 2.1 the \( DSP \) usually takes about 20% of the complete cycle time. This is also employed here. Furthermore it is assumed that the hip moves in the \( x \)-direction with a constant speed during \( DSP \) which equals the initial and end velocity of the hip during the \( SSP \). Let the step length be the displacement in \( x \)-direction during a single step defined by \( \lambda \) which also implies that the displacement of the \( CoM \) and the hip should equal \( \lambda \), as this is required for a stable and repetitive gait. Figure 2.2 shows the timeline for a full stride where the transition instances from \( SSP \) to \( DSP \) and vice versa are marked.

![Timeline describing a full stride.](image)

The different time instances indicated in Figure 2.2 are related to each other in a particular way which is described and derived now. The estimated parameter values listed in Table 2.1 serve as a basis for this derivation.

\[
T = T^{DSP} + T^{SSP} \quad [s] \quad (2.9)
\]

\[
T^{DSP} = \frac{T}{5} = \frac{T^{SSP}}{4} \quad [s] \quad (2.10)
\]
The average hip velocity is denoted with $\dot{x}_H = \bar{v}$, where the subscript $H$ denotes a hip property. This enables to express $T^{SSP}$ as function of the displacement of the hip during $SSP$ $\Delta x_H$, and the average hip velocity during $SSP$.

$$T^{SSP} = \frac{\Delta x_H^{SSP}}{\bar{v}^{SSP}} \text{ [s]} \quad (2.11)$$

A comparable strategy can be employed for defining $T^{DSP}$ as shown in (2.12), where $t = 0$ indicates time instance B at the beginning of $DSP$.

$$T^{DSP} = \frac{\Delta x_H^{DSP}}{\dot{x}_H^{DSP}} |_{t=0} \text{ [s]} \quad (2.12)$$

Furthermore, the overall displacement, during one step should equal the sum of the displacement during the $SSP$ and $DSP$.

$$\Delta x_H^{SSP} + \Delta x_H^{DSP} = \Delta x_H = \lambda \text{ [m]} \quad (2.13)$$

Substitution of (2.10), (2.11) and (2.12) into (2.13) expresses $T^{DSP}$ and $T^{SSP}$ as function of $\lambda$, $\dot{x}_H^{DSP}(t = 0)$ and $\bar{v}^{SSP}$.

$$T^{DSP} = \frac{\lambda}{4\bar{v}^{SSP} + \dot{x}_H^{DSP}} |_{t=0} \text{ [s]} \quad (2.14)$$

$$T^{SSP} = \frac{4\lambda}{4\bar{v}^{SSP} + \dot{x}_H^{DSP}} |_{t=0} \text{ [s]} \quad (2.15)$$

In order to quantify the time constants derived above, an estimation of the relation between the mean hip velocity in $DSP$ and the average velocity is used by assuming that the velocity in $DSP$ equals 110% of the average velocity. This assumptions is based on the fact that the hip motion in forward direction can be modeled by an inverted pendulum model which has its maximum value at the beginning and end of the $SSP$. This enables calculation of $T^{DSP}$ and $T^{SSP}$.

In the next paragraphs, the double and single support phases are explained in more detail. It should be noted that in the method proposed by [23] absolute rotations with respect to the transverse plane are used to link the kinematics of the robot to positions in cartesian space. The method on itself is not changed here, which means that first also absolute joint trajectories are derived for a setpoint in the global cartesian coordinate frame. These absolute joint angles are later on transformed to relative joint angles as this is the input to the existing AAU-BOT1 simulation model.

It is important to define proper initial, intermediate and end conditions in order to obtain trajectories that meet the objectives. First the swing leg during the $SSP$ is taken into consideration. In order to be able to handle terrains with obstacles or even walk up or down a stairs the parameters $\gamma$ and $\delta$ are defined, where $\gamma$ is the maximum foot clearance and $\delta$ defines the step height, i.e. the height of one single tread, in case of walking up or down a stairs. If the supporting surface is simply flat, $\delta$ equals 0. The difference in height between the ankle pitch axle and the floor if AAU-BOT1 is in zero position is defined as $h$. As the origin of the system is defined at the toe of the stance leg, the initial and final conditions for the $SSP$ for the swinging foot are:
\begin{align*}
  x_{sw}(0) &= -\lambda \quad [\text{m}] \\
  \dot{x}_{sw}(0) &= 0 \quad [\text{m s}^{-1}] \\
  \ddot{x}_{sw}(0) &= 0 \quad [\text{m s}^{-2}] \\
  x_{sw}(T_{SSP}) &= \lambda \quad [\text{m}] \\
  \dot{x}_{sw}(T_{SSP}) &= 0 \quad [\text{m s}^{-1}] \\
  \ddot{x}_{sw}(T_{SSP}) &= 0 \quad [\text{m s}^{-2}] \\
  z_{sw}(0) &= -\delta + h \quad [\text{m}] \\
  \dot{z}_{sw}(0) &= 0 \quad [\text{m s}^{-1}] \\
  \ddot{z}_{sw}(0) &= 0 \quad [\text{m s}^{-2}] \\
  \end{align*}

In order to have more control on the generated trajectory, an intermediate condition for the ankle height is specified which can be considered to be a via-point. This condition is specified for the time instance where 70% of the SSP is passed as this is usually the time instance with the maximum foot clearance according to [22]. The condition is:

\begin{align*}
  z_{sw}(0.7T_{SSP}) &= \gamma + h \quad [\text{m}] \\
  \dot{z}_{sw}(0.7T_{SSP}) &= 0 \quad [\text{m s}^{-1}] \\
  \ddot{z}_{sw}(0.7T_{SSP}) &= 0 \quad [\text{m s}^{-2}] \\
  \dddot{z}_{sw}(0.7T_{SSP}) &= 0 \quad [\text{m s}^{-3}] \\
  \end{align*}

The initial and final conditions for the hip during the SSP are defined as, where \( H_{\text{max}} \) defines the maximum hip height relative to the ankle height during the SSP:

\begin{align*}
  x_{sw}(0) &= -\frac{\lambda}{2} \quad [\text{m}] \\
  \dot{x}_{sw}(0) &= \dot{x}_{DSP} \quad [\text{m s}^{-1}] \\
  \ddot{x}_{sw}(0) &= 0 \quad [\text{m s}^{-2}] \\
  \dddot{x}_{sw}(0) &= 0 \quad [\text{m s}^{-3}] \\
  x_{sw}(T_{SSP}) &= \frac{\lambda}{2} - x_{DSP} \quad [\text{m}] \\
  \dot{x}_{sw}(T_{SSP}) &= \dot{x}_{DSP} \quad [\text{m s}^{-1}] \\
  \ddot{x}_{sw}(T_{SSP}) &= 0 \quad [\text{m s}^{-2}] \\
  \dddot{x}_{sw}(T_{SSP}) &= 0 \quad [\text{m s}^{-3}] \\
  z_{sw}(0) &= \cos \left( \frac{\alpha}{2} \right) (H_{\text{max}} + h) \quad [\text{m}] \\
  \dot{z}_{sw}(0) &= 0 \quad [\text{m s}^{-1}] \\
  \ddot{z}_{sw}(0) &= 0 \quad [\text{m s}^{-2}] \\
  \dddot{z}_{sw}(0) &= 0 \quad [\text{m s}^{-3}] \\
  z_{sw}(T_{SSP}) &= \cos \left( \frac{\alpha}{2} \right) (H_{\text{max}} + h) \quad [\text{m}] \\
  \dot{z}_{sw}(T_{SSP}) &= 0 \quad [\text{m s}^{-1}] \\
  \ddot{z}_{sw}(T_{SSP}) &= 0 \quad [\text{m s}^{-2}] \\
  \dddot{z}_{sw}(T_{SSP}) &= 0 \quad [\text{m s}^{-3}] \\
  \end{align*}

Note that these conditions are set for both hips in order to avoid a roll or yaw motion of the pelvis to reduce the risk of unplanned behavior. The variable \( \alpha \) describes the angle between both legs at
and is set at a value of $25^\circ$. Furthermore an intermediate condition is set for the hip motion as given below. The variable $H_{\text{max}}$ is at this moment fixed at a value of 0.5 m.

$$z_{sw}(0.5T_{\text{SSP}}) = H_{\text{max}} + h \quad [\text{m}]$$

These reference points are used for generating trajectories by means of polynomial interpolation, as described in [19]. A fifth order polynomial is used for the foot movement in $x$-direction, whereas the foot movement in the $z$-direction is done by means of two seventh order polynomials as trajectories are defined up to the jerk level. This is done to ensure that there are no jumps in the accelerations for example at the via-point. One describes the movement until the maximum foot clearance, and the other from this time instance until the end of the first $SSP$. For the hip trajectories in both $x$-direction and $z$-direction two seventh order polynomials are used to ensure a smooth movement up to the acceleration level by imposing conditions on the jerk too. The derivation of the angles based on the trajectories for the hip and foot in cartesian coordinates is describe in Appendix B. Important is to note that the derivation in the appendix assumes that the swinging foot is always parallel to the ground surface.

For the stance leg in $SSP$ the conditions are different. The foot and ankle are supposed to be fixed at the position of ground contact at the end of the preceding $SSP$. The hip movement is exactly the same as during the $SSP_{\text{wing}}$ for the reason mentioned earlier. The initial and final conditions for the trajectory of foot of the stance leg during $SSP$ are:

$$x_{st}(0) = \lambda \quad [\text{m}] \quad z_{st}(0) = h \quad [\text{m}]$$
$$\dot{x}_{st}(0) = 0 \quad [\text{m s}^{-1}] \quad \dot{z}_{st}(0) = 0 \quad [\text{m s}^{-1}]$$
$$\ddot{x}_{st}(0) = 0 \quad [\text{m s}^{-2}] \quad \ddot{z}_{st}(0) = 0 \quad [\text{m s}^{-2}]$$

$$x_{st}(T_{\text{SSP}}) = \lambda \quad [\text{m}] \quad \dot{x}_{st}(T_{\text{SSP}}) = 0 \quad [\text{m s}^{-1}]$$
$$\ddot{x}_{st}(T_{\text{SSP}}) = 0 \quad [\text{m s}^{-2}] \quad \dddot{x}_{st}(T_{\text{SSP}}) = 0 \quad [\text{m s}^{-2}]$$

During the double support phases, both feet are assumed to be fixed at the position they were at the end of the preceding $SSP$ which is their reference position during this phase. The velocity and acceleration of both feet equal 0. As assumed in the beginning of this section, the hips move with constant speed in $x$-direction, $\dot{x}_{DSP}$, during the $DSP$ and are stationary in $z$-direction at the height they were at the end of the $SSP$.

The joint trajectories of a full stride for the right leg are now composed of a swing motion in $SSP$, a $DSP$, a stance motion in $SSP$ and finally another $DSP$. For the left leg, the order of the swing and stance Single Support Phases is reversed. The trajectories for all pitch joints of both legs are depicted in Figure 2.3.

The upper body trajectory is designed in a particular way to have control over the trajectory in $x$-direction of the ZMP. The method is derived in [16] and modified for this specific application. The simplified model that is proposed to describe the robot is not altered. Based on the known CoM vectors and masses of all parts of both legs and by using the previously derived trajectories, a trajectory for the full upper body is derived. The upper body consists in the method used by [16]
of one single body, where the upper body of AAU-BOT1 actually consists of a torso and a body that consists of a pelvis and waist. This knowledge is employed later on to derive an explicit relation between the $x$-position and the $z$-position of the full upper body \( \text{ZMP} \). The derivation is shown in Appendix C.

### 2.4.2 Human Motion Capture data trajectory generation

3D motion capturing is as stated before a very straightforward way as a starting point in generation of joint reference trajectories. The data for generation of the trajectories presented in this report is taken from [26]. The processing of the rough data given by [20] is described in Chapter 2 of the book. For this reason, the filtered data is used as it is assumed that filtering of the data is applied in the proper way. In order to clarify the medical jargon, an explanatory drawing is depicted in Figure 2.4.

First the data is transformed to absolute angles of the different body links, being the foot, shank,
thigh and upper body. The angle of the foot is calculated by taking the position of the metatarsal and ankle into consideration, the angle of the shank by looking at the position of the ankle and fibula, the angle of the thigh by considering the position of the knee and hip and the orientation of the torso is estimated by considering the position of the base rib cage and hip. The absolute angles of two neighboring body links are afterwards converted to the relative angle of the intermediate joint. The angle of the upper body is related to the angle of the floor, in accordance to the existing model of AAU-BOT1, where the angle of the torso is related to the IMU, which indicates the absolute angle. In this way the most relevant motions of the body are represented as a series of data points as function of time. This is not a continuous description nor is it a discrete description describing the same time instants as will occur in the real time application. Therefore, the generated trajectories are approximated with so-called smoothing cubic splines. The splines are then evaluated at the desired time instance. If the current time is larger than one period of the motion, it is mapped to the corresponding time instance of the first period. There are also other possibilities for fitting the experimental data like a series of sinusoids or a high degree polynomial function. These are not really suitable as the shapes of the trajectories are not resembling the shape of a series of sinusoids or a high degree polynomial very well, which means that the sum of sinusoidal signals should consist of many terms to make a good prediction and that the degree of the polynomial function should be high too. On the contrary, cubic polynomials are sufficient to do the job pretty accurate on smaller intervals. Therefore this approach is followed here in order to reduce the calculation time.
Furthermore, a smoothing cubic spline is chosen as it removes irregularities while it is accurately estimating the true values. The generated relative joint trajectories for the hip, knee and ankle joints are depicted in Figure 2.5, where both the joint trajectories for joints at the right and left side are shown.

![Joint Trajectories](image)

Figure 2.5: Relative joint angles based on raw human motion data in cartesian space. Raw data source: [26].

### 2.4.3 Statically stable gait

Another starting point in designing a dynamic gait for AAU-BOT1 could be the static gait that was generated during one of the preceding projects. A theoretically stable trajectory that was designed is described by [8]. As the purpose is generating dynamic trajectories, a method described in [25] will be exploited in order to modify it. The data used in Chapter 2.4.2 will serve as reference input and achieving a similar gait is the goal of the optimization process. One major difference is the different
cycle times, between the static gait and the human data. This problem is resolved by scaling the
time scale of the static gait to map them to the corresponding time instance in the gait cycle in the
recorded data. The time mapping is done in the following way,

\[ t' = \frac{t}{T_{\text{static}}} T_{\text{desired}}, \]  

(2.16)

where \( t' \) represents the mapped time instance, \( T_{\text{static}} \) the stride time of the static gait, \( T_{\text{desired}} \) the desired stride time of the dynamic gait and \( t \) the time instance that is mapped from the static gait cycle time to the dynamic gait cycle time. Another important difference between these trajectories and the trajectories based on human data is the division between the DSP and SSP. For humans walking the SSP takes about 80\% of a step, whereas the SSP in this specific static gait takes only 60\% of the step time. This is not modified now as it will most likely change if an optimization algorithm is applied for optimization towards stable dynamic human gait. After mapping and conversion of the angles to the convention as used in the most recent simulation models, the joint angle trajectories as function of time are shown in Figure 2.6.

2.4.4 Comparison and conclusions

There are a lot of differences between the resulting trajectories of the three different methods. The biggest difference is present in the trajectories for the pitch angle of the ankle joints. This is due to the fact that it was imposed that the foot should be parallel to the floor in the method which uses predefined initial, intermediate and end conditions. For human gaits, the angle between the foot and the floor is unequal to 0 for most of the stride time which gives rise to the big difference. There are no large deviations between the trajectories for the knee pitch joints and the same holds for the hip pitch trajectories. Another difference which is not visible in the generated joint trajectories is the chance that the trajectories can achieve a stable dynamic gait. The gait of humans is dynamic and stable and therefore these trajectories are probably applicable without the need for very large changes. The gait derived from the stable static trajectory needs large modifications as it is not dynamic and moreover caused problems with saturation even though it was not dynamic and had a stride time of 30 s. The gait derived from the predefined trajectories could be stable for the fact that the torso was used to let the ZMP follow a certain trajectory. But this requires the trajectory for the ZMP to be chosen well. Comparing all the results, the trajectories recorded from humans are most likely the best initial trajectories to arrive at a stable dynamic gait for AAU-BOT1. Chapter 3 elaborates on the simulations performed with these trajectories and the modifications done in order to stabilize the gait and ensure that it is dynamic.

2.5 Gait initiation and termination

Another important aspect of designing walking trajectories is the way a certain designed gait is ini-
tiated and terminated as starting at a certain moment from zero position and stopping at another
moment, most likely not being returned to zero position, is dangerous as balance is not ensured.
Stopping and starting from a position with balance is very important to be able to perform ex-
periments safely and moreover to prevent damaging AAU-BOT1. For these reasons, this section
elaborates in more detail on the initiation and termination of the gait.

2.5.1 Initiation of the gait

According to [20], it takes humans in general about two steps to go from a stable configuration
during quiet standing to a steady and stable dynamic walking gait. The initial goal during gait
Gait initiation is to accelerate the \textit{CoM} towards the desired stance limb and the desired motion of the \textit{CoP} is in opposite direction. This constitutes the release phase. Afterwards the \textit{CoP} moves towards the stance leg and moreover the swing leg hip and knee moves the leg upward and forward. By assuming the right leg is first in swing phase and the left leg is first in stance phase, the \textit{CoP} resides under the left foot, while the \textit{CoM} has moved forward approximately 6 cm. During the swing phase, the \textit{CoP} is still move forward rapidly causing an initial ‘pushoff’. Simultaneously the right leg swings forward and makes heel contact at about 35\% of the first cycle. During the double support phase the \textit{CoP} moves forward towards the right foot. The \textit{CoM} now moved forward about 25 cm and is already in the trajectory it follows during the limit cycle gait.

2.5.2 Termination of the gait

Gait termination is even a bigger challenge with respect to maintaining balance. This process is also described in [26] and takes about two steps where all forward momentum has to be removed and
the CoP is controlled to a position slightly ahead of the CoM as it comes to a near stop. Assumed is that gait termination is initiated after a DSP. During this phase the CoP moves rapidly forward such that the CoM is decelerated rapidly. During the next SSP where the right foot is the supporting foot, the CoP is moved forward even more and at the end of this SSP, the forward velocity of the CoM is reduced to approximately 30% of the value during a limit cycle gait. Moreover the left leg is also decelerated by its hip and knee joints decreasing the step length during this SSP to 50% of the normal value. After heel contact of the left foot it is loaded quickly and this causes a lateral and forward movement of the CoP and after 20% of the next cycle the CoP stops right ahead of the CoM. The last phase of coming to a standstill is a final deceleration of the CoM by moving the CoP posteriorly and slightly towards the right leg which takes until 51% of the next cycle.

2.6 Conclusions

There several different strategies to design trajectories, where designing initial trajectories based on data recorded from humans is most suited for this specific application, as explained earlier. Moreover, there are different optimization objectives like being energy efficient, stable and anthropomorphic as possible. Different tools are available to test these criteria, where the application of Floquet theory is probably the most straightforward way of testing stability. The disadvantage of this method is that it gives only valuable insights after a large number of successful steps. In this respect, the DGM can have additional value since this measure reflects a measure of stability during a gait and moreover enables a comparison to human gait. Gait initiation and termination are very complex and different from the actual gait and require therefore more research in the future. The influence of the initiation is for now ruled out by proper initial conditions in the simulations.
Chapter 3

Simulations

Simulations are used to verify the stability of the joint trajectories designed in the different sections of the previous chapter to obtain results that can be employed for joint trajectory optimization. First the simulation model is inspected to verify the correctness and to make sure there are no errors in the model and moreover to get acquainted with the model and modeling of electromechanical systems in SimMechanics. SimMechanics is part of Simulink® and is used to represent the connection of all body parts of AAU-BOT1. Afterwards the model is changed at some points as this appears to be necessary. Finally, conclusions are drawn on the stability of the trajectories generated and moreover points suited for modifications or additional research are highlighted.

3.1 Basic changes in the simulation model

A first test with the joint trajectories generated from the captured human movements showed that in simulation AAU-BOT1 moved up in the air. After looking into the ground model and the impact model it appeared that the gravity was for some reason not applied. AAU-BOT1 no longer moves up in the air after applying the gravity vector and moreover can now also fall due to a large pitch angle of the torso as expected from basic physical insights. Some other important remarks concerning the generated data are:

- The coordinate system used in SimMechanics is different from the one used in this report. All measurement data which is with respect to a certain axis, e.g. forces and torques from the FTS and data generated by the IMU need an additional transformation to the coordinate frame used in this report in order to analyze the data properly and draw the right conclusions.

- In previous reports the order of data in the vector outputted by the FTS is given. In the simulink model for simulations the torque and force are however switched. A conversion block is created to correct for this difference.

Initial conditions could for the moment take over the role of a proper initiation process. This gives the possibility to focus on the stability of the real trajectory instead of having a large influence of different initial conditions. In practice it will be hard to create an experiment where AAU-BOT1 is also in this initial condition, but for simulations concerning the stability of the main trajectories this is a good approach to rule out the influence of the gait initiation. Initial conditions are defined on the position and angular velocity for the pitch and roll joints that have time varying reference trajectories. The trajectories are all defined by means of piecewise cubic splines, which has the advantage that the first derivative is defined explicitly without the need for introducing numerical difference schemes. However, all masses also have a translational velocity which is included as well.
to obtain proper results. This is done by setting an initial translational velocity for the pelvis with respect to the fixed world coordinate frame and the translational velocity of all other body parts is determined by SimMechanics using the relative angular velocity of a link with respect to its parent link and the distances of a certain CoM to the parent joint. This is verified by adding an additional virtual IMU to other bodies to monitor the velocity of the CoM with respect to the fixed world coordinate frame. Another important modification is related to the initial lift of the pelvis with respect to the ground. Previously, this lift height was fixed at a constant value related to the pelvis height in the absolute zero position. As the initial position is modified and no longer equal to the zero position, the height of the pelvis is now related to the joint angles of the stance leg. This should ensure that AAU-BOT1 is standing on the ground surface with the foot sole of its stance leg when a new simulation is started. All modifications are implemented in a flexible way to have the freedom of changing trajectories without the need for changing all initial conditions by hand and therefore enable an easy switch of trajectories or change in initial conditions. This also permits including a gait initiation phase in the simulation where the robot actually will start from absolute zero position. The signals generated by the IMU and FTS implemented in simulation are not disturbed by offsets, as is the case on the real setup. The corrections which were implemented in the library blocks created by the previous project group are removed. If the models are adopted for experimental applications on the real setup, these blocks need either to be replaced or the corrections have to be implemented again to obtain proper results. Finally it is very important that trajectories are tracked relatively accurate also in this stage where only a basic PID-controller for each individual joint is implemented. Only accurate tracking now can give guarantee for a feasible trajectory with more sophisticated controller structures since the margins on joints angles that render a stable gait are relatively small.

3.2 Simulation results, observations and modifications

- Applying the human recorded trajectory causes the swing foot to hit the ground at approximately 50% of the swing phase. This is shown in Figure 3.1. There are a few reasons which might cause this. There might be a difference in length of the foot, shank and thigh of AAU-BOT1 and the average length of these limbs of the subjects used for data recording. After converting the data of positions in cartesian space to joint angles this might cause the problem of hitting the ground with different link lengths. Another cause could be the stability in the frontal plane, also referred to as stability of the lateral or sideways motion, as the IMU readings indicate an increasing roll angle of the torso which means that AAU-BOT1 is falling sideways in the direction of the swinging leg. This is also indicated by Figure 3.2 where the location of the ZMP and GCoM is depicted together with the stance foot outline. Here is clearly shown that the GCoM is always outside the PoS and this causes the ZMP to move outside the PoS too. Finally AAU-BOT1 falls over to the side at which the ZMP goes outside the PoS. The swinging leg comes in this way closer to the ground with increasing roll angles leading to a collision of the toe with the ground surface, which might not occur under stable conditions in the lateral plane. There are different ways of attacking this problem. First the stability in the lateral plane is improved by investigating the way humans keep their lateral balance. According to [18] humans move their arms outward and inward during a swing as an Electromyogram (EMG) has shown. Another research project shows improved lateral stability by moving the arms not only sideways, along the body, but by swinging outward while swinging forward and inward while swinging backward, where the forward and backward motion of the arms is counteracting the motion of the legs [2]. This indicates that arm movement in the lateral plane at least influences the lateral stability. However, it is not possible for AAU-BOT1 to move its arms in the lateral plane as there is no actuation implemented for the shoulder joints.
to accomplish this movement which gives rise to search for other solutions or a modification of the mechanical design. In spite of this, there are ways to influence the lateral stability for example by modification of the proposed trajectories for the ankle roll, hip roll and waist roll joints. The waist roll angle is the first parameter used to decrease the roll motion of the full body and thereby the instability in the lateral plane. The minimum foot clearance during the swing phase is considered once again only if the lateral stability is maintained. In case the foot still strikes the ground surface, the hip and ankle pitch angles are adopted only locally, in the region of striking the ground surface by multiplication of the original trajectory with a function with the shape of a Gaussian distribution and a minimum value of 1. This ensures smooth joint trajectories although the angles are amplified in a specific region. The main conclusion at this point is that simply applying the trajectories for the pitch joints recorded from humans does not results in a successful, stable, dynamic gait for AAU-BOT1.

Figure 3.1: The swing foot hitting the ground. AAU-BOT1 is shown in the frontal plane.

- Actuator saturation is present with the controller implemented by the previous group once the human recorded data trajectories are applied. Especially at the pitch joints of both hips and the knee joint of the swinging foot. This causes shaky and unstable behavior after increasing the saturation limits. Moreover the reference tracking is far from accurate. This issue is partially solved by changing the controller gains for the proportional and integral action and moreover introducing differential action in order to remove fluctuations around the desired trajectory. However still some saturation remains present which is probably due to the challenging trajectory. Application of this trajectory and controller to the real setup requires additional measures to avoid the consequences of saturation in combination with an integral control action which can lead to integrator windup. There are multiple anti-windup measures all having their own advantages and drawbacks [24]. The techniques commonly used are conditional integration and back-calculation. The back-calculation has the advantage of having an additional tuning parameter which influences the transient behavior and can make it less aggressive in comparison to conditional integration. Noteworthy is that the other techniques mentioned by [24] do not lead to large improvements. For this reason, the back-calculation method is proposed to be used in this project.

- The trajectory was applied in such a way that AAU-BOT1 should be at the start of a SSP where the left leg is the intended stance leg. At the start of a simulation AAU-BOT1 is actually not at the start of a SSP but the right foot is lifted off the ground a substantial distance as shown in Figure 3.3. A closer analysis of what is going on just after initiation of a simulation reveals that
the orientation of the pelvis with respect to the fixed world coordinate frame is not modified during the initiation. The pelvis is however slightly tilted at the end of the DSP as this is necessary to have a flexed knee in the leg that will swing forward in the preceding SSP while having an almost fully stretched leg that will be the stance leg in the preceding SSP. This issue is solved by replacing the joint that described the position of the pelvis with respect to the fixed world coordinate frame. The initiation puts AAU-BOT1 now in a position which indeed induces both feet having ground contact.

Figure 3.3: AAU-BOT1 at the start of the simulation, where the left heel (indicated with green ellipsoid) has ground contact.
In order to stabilize the roll motion, the distance in $y$-direction from the $\text{GCoM}$ to the stance foot outline and the height of the $\text{CoM}$ are considered. It appears that the overall $\text{CoM}$ is positioned at a height of approximately 0.8 m. Since the $z$-position of the $\text{CoM}$ of the torso and arms is just slightly larger than the $z$-position of the overall $\text{CoM}$ and the weight of the torso and arms is moreover relatively small in comparison to the weight of the other body parts, it is not very attractive to use the waist roll joint to stabilize the roll motion of $\text{AAU-BOT1}$. Simulations confirmed this prediction and hence the ankle roll joints are used to stabilize the roll motion. Section 3.2.3 describes the influence of the mass of the torso on the stability and the capability of using the waist pitch and roll joints to make corrections in more detail. The distance in $y$-direction over which the $\text{GCoM}$ has to be moved in order to come close to the stance foot outline is approximately 0.1 m and the difference in height between the $\text{CoM}$ and the ankle roll joint is approximately 0.7 m. To accomplish this shift an angle of approximately $\tan^{-1}(0.1) \text{ rad}$ is necessary in the ankle roll joint of the stance foot. The first trajectory for the ankle roll joints is now designed based on this estimation as the first half of the period of a sinusoidal function with a period of 0.98 s which equals the period of the stride. Simulations with small variations in the maximum roll angle show that the proposed maximum angle is quite large and can cause the robot to fall to the side of the stance leg. The maximum and minimum allowable angle depends on the shape of the trajectory, which was first chosen to be half the period of an ordinary sinusoidal function, whereas it is also possible to take only a quarter of the period of a sinusoidal function with a slightly longer period followed by a quarter of the period of a sinusoidal function with a slightly shorter period to return to 0 as gravity is assisting in the motion back to 0. An example of the trajectory for a leg being first the stance leg and afterwards the swing leg is depicted in Figure 3.4. The angle gets even negative at the end of the $\text{SSP}$ phase in order facilitate the transfer of the major part of the mass to the next stance leg and there is moreover a phase where the angle returns in a linear motion from the minimum value to 0.

Figure 3.4: Example of trajectories for both ankle roll joints.

The $\text{SSP}$ now takes about 0.5 s after which both the left foot and the right foot lose ground contact followed by a $\text{DSP}$ and a $\text{SSP}$ where the right foot is the stance foot. Noteworthy is the fact that
the first SSP takes approximately 0.1 s more than was indicated by [26] which is the source for the data of which the trajectories are reconstructed. There are several different approaches to decrease the duration of the first SSP such as accelerating the torso in order to increase the angle of the waist pitch joint at the time instance being the desired end of the SSP and decreasing the pitch angle of the stance leg ankle to decrease the height of the swing foot ankle at the desired end of the SSP. Moreover changing the knee pitch angle of the stance leg can influence the instance at which AAU-BOT1 enters the DSP. Changing the ankle pitch angle at the desired end time of the SSP appears to be most effective for different reasons. The weight of the torso and arms is of the same order of magnitude as the weight of the limbs positioned below the global CoM. Moreover the upper body CoM is positioned only about 0.3 m above the global CoM in z-direction, creating only small additional moments around the y-axis in case the waist pitch joint is used for modifications and hence hardly any influence on the time instance of the end of the SSP. The ankle pitch joint is positioned on a much larger distance from the global CoM compared to the waist pitch joint and it moves moreover a lot more mass and inertia along which induces a much larger moment around the y-axis. This enables a successful first step with the right duration of the SSP and the DSP. Moreover, the step is dynamically stable as the GCoM moves out of the PoS. The motion of the ZMP and the GCoM is depicted in Figure 3.6 and the reaction force on the foot sole is shown in Figure 3.5.

Figure 3.5: The forces and moments experienced by both feet during the first successful step.
Figure 3.6: The position of the $GCOM$, $ZMP$ and the outline of the stance foot during the first $SSP$ during the first successful step.

The second step however is not performed successfully although all joint trajectories are tracked as accurate as during the first step. A closer analysis of the data and implementation of an additional velocity sensor at the pelvis body shows that the pelvis loses forward velocity and does not regain enough forward velocity at the end of the first $DSP$ in comparison to humans as shown in Figure 3.7. This leads to a situation where the toes of the second stance foot, i.e. the right foot, are slightly lifted from the ground, tilting the full robot backwards even while the joints are accurately tracking their trajectories. The angle between the foot sole and the floor is also derived directly from the data and compared to the values found during the first step in simulation. This reveals that the shape of both trajectories is approximately equal although the actual values are quite different as depicted in Figure 3.8.

Interesting is the big difference during the $DSP$, i.e. between approximately 0.4 s and 0.5 s where the considered foot is the swing foot in the proceeding phase, i.e. the left foot. In the simulation the angle is much smaller compared to the values found from the data which points at a much smaller push in forward direction and by consequence the forward acceleration of the pelvis is much smaller. A way to improve this behavior is implementation of a trajectory update algorithm for the ankle pitch joints accounting for this difference. In the former simulations, the ankle pitch trajectory was just defined as a relative angle between the foot and the shank. However it is also possible to define a desired value for the angle between the foot and the floor as function of time from the data given by $\varphi$. This angle is compared to the value given by $\varphi$ as shown by (3.1), where $\varphi$ is the pitch angle between the floor and a foot and the positive rotation direction is defined as shown in Figure 1.1. The difference between the value for $\varphi$ and the value determined based on the data is then used for updating the desired position of the ankle pitch joint. This also requires an update of the initiation parameters and settings in order to have the same pose at the start of a simulation as after one step except for the fact that left and right are interchanged.
Figure 3.7: Forward velocity of the pelvis in simulation and from the data recorded by [26].

\[ \varphi_r = \theta_2 + \theta_3 + \theta_4 - \theta_{14} + \theta_{21} \quad [\text{rad}] \] \hspace{1cm} (3.1a)

\[ \varphi_l = \theta_9 + \theta_{10} + \theta_{11} - \theta_{14} + \theta_{21} \quad [\text{rad}] \] \hspace{1cm} (3.1b)

These modifications indeed decrease the lost of forward velocity of the pelvis at the end of a [SSP] and cause an increased acceleration during the [DSP]. With these modifications the behavior is even...
more human like and obtaining a dynamic but stable gait should now be possible. The motion of AAU-BOT1 is illustrated in Figure D.1 in Appendix D where the first step is shown by means of six snapshots, taken every 0.1 s. Nevertheless a similar phenomenon is observed in the velocity of the pelvis in y-direction with the currently applied trajectories for the ankle roll joints. One of the reasons for this is the push-off in forward direction in order to keep a periodic forward pelvis velocity. This push-off creates not only a forward acceleration but moreover a moment in around the x-axis of the stance foot in the preceding SSP, because of the non-zero distance to the previous stance foot and the force it generates in upward direction. This gives rise to an increase of the roll motion. The velocity in y-direction is hence not periodic and heavily depending on the trajectory applied at the ankle roll joint and has a large influence on the stability in the lateral plane. It appears to be very hard to stabilize the motion in y-direction which was discovered earlier in other projects as described by [28]. They however also describe a different feedback or trajectory update strategy to stabilize the motion in the lateral direction. For this reason another feedback and reference is proposed here as well. It is possible to derive a trajectory for the CoM in y-direction based on requirements on the ZMP trajectory in y-direction which boils down to the same method as was used in Appendix C to derive the desired motion of the torso in x-direction. The motion in y-direction is planned to be performed by the ankle roll joints giving rise to a rather simple model describing the dynamics of AAU-BOT1 in y-direction. This model is shown in Figure 3.9, where the origin of the coordinate system is placed at the center between the stance foot in y-direction, on the ground surface and in x-direction at the ankle joint. AAU-BOT1 is represented here as an inverted pendulum with a mass at the end of the pendulum equal to the mass of all body parts except for the stance foot. The length of the pendulum equals the height of the CoM of all limbs except for the stance foot. This height is assumed to be constant as the differences in height due to pitch rotations are negligible in comparison to the height itself, besides accelerations of the CoM in z-direction are neglected. In the end, an online trajectory update of the ankle roll angle is proposed to ensure accurate tracking of the desired ZMP trajectory in y-direction which can correct for errors due to these assumptions too. The equation of motion is now derived for the motion in x-direction according to the method described by [16] and is given by (3.2), where m represents the mass at the end of the pendulum and com the CoM position of all limbs except for the stance foot.

![Figure 3.9: The inverted pendulum model in gray for the right leg as stance leg and in black for the left leg as stance leg. The red and green dot indicate the desired ZMP positions.](image)
\[ 0 = m(c) - zmp_y)(-c) + g_z - m(c) - zmp_y)(-c) \] (3.2)

This differential equation is solved as a boundary value problem requiring the roll angles to be equal to zero at the end of a DSP. Moreover the \( y \)-position of the ZMP is fixed two centimeters inward, i.e. in the direction of the center of the robot, relative to the stance foot center which results in the trajectories for both ankle roll joints as shown in Figure 3.10.

![Figure 3.10: Proposed trajectories for both ankle roll joints based on a desired ZMP position.](image)

The trajectories generated by solving the differential equation do however not stabilize the roll motion either. There are several different causes making it very hard to stabilize the roll motion. One of the things that for sure play a role here is the values used for the floor stiffness and floor damping. The values that were used in the dynamic model were 10 kNm\(^{-1}\) and 0.1 kNsm\(^{-1}\) respectively. This results in a rotation of the foot rather than moving the upper body in order to move the CoM and by consequence penetration of the foot into the floor, as shown in Figure 3.11. A comparison of these values to values used for experiments with human subjects walking or jumping, as presented by [5] and [13], shows that the values implemented are very low. For this reason both the damping and the stiffness of the floor are increased by a factor 10 to improve the results and remove penetration of the foot into the floor. Moreover there might be a difference between the trajectories generated by solving the differential equation and the trajectories that humans perform. Figure 3.12 shows a comparison between these trajectories and trajectories directly derived from data recorded from humans, where the data is taken from [7]. This data originates from research conducted by the University of Wisconsin-LaCrosse. A comparison between these trajectories and the trajectories resulting from solving the differential equation for a desired ZMP position shows that the shape of the trajectories is not very different except for some interesting differences. The most important
difference is probably that the target stance leg already starts making an angle before the DSP is left and the subject enters the SSP. Moreover the outward and inward motion is not symmetric with respect to their duration. This is something that was proposed as well for the sinusoidal trajectories that were designed initially. Finally, the amplitude of the motion is approximately 1.5 times larger in comparison to the trajectory designed on the basis of the inverted pendulum model and the desired location of the ZMP.

3.2.1 Friction between foot sole and floor

Another thing that plays a role in obtaining stability in both the pitch and roll motion is proper modeling of the friction between the foot and the floor. Analyzing the data generated so far showed that at the time instance the heel of the stance foot came off the ground the stance foot started sliding in forward direction as well. The cause was a wrong implementation of the friction model as shown by [1]. It was not dependent on the actual normal load and moreover computed in the wrong way. The friction model is replaced by the model shown in (3.3) which was proposed by [27]. This function has the big advantage that it is continuous and therefore does not slow down simulations as was the case with a proper implementation of the old model. The values of $\beta_x$ and $\beta_y$ determine the width of the nearly linear regime around $\dot{x} \approx 0$ and $\dot{y} \approx 0$ respectively. The value for the friction coefficient $\mu$ is for the moment fixed at a value of 2 which is the average of common static and dynamic friction coefficients for contact between rubber and dry concrete [20]. The real value is of course heavily depending on the type of rubber and the floor material and needs to be verified during future projects. If the friction coefficient appears to be significantly depending on the sliding velocity and the influence is clearly visible in the sliding velocities expected in the set-up, it is useful to split up the friction coefficient in (3.3) in a coulomb and viscous part, as shown in (3.4).
\[ F_{w,x} = \left( \frac{2}{1 + e^{-\beta x}} - 1 \right) \mu F_n \quad \text{[N]} \quad (3.3a) \]
\[ F_{w,y} = \left( \frac{2}{1 + e^{-\beta y}} - 1 \right) \mu F_n \quad \text{[N]} \quad (3.3b) \]

\[ F_{w,x} = \left( \frac{2}{1 + e^{-\beta x}} - 1 \right) \left( \mu_c F_n + \mu_c \dot{x} F_n \right) \quad \text{[N]} \quad (3.4a) \]
\[ F_{w,y} = \left( \frac{2}{1 + e^{-\beta y}} - 1 \right) \left( \mu_c F_n + \mu_c \dot{y} F_n \right) \quad \text{[N]} \quad (3.4b) \]

Left ankle roll (\( \theta_{12} \))

Right ankle roll (\( \theta_1 \))

Figure 3.12: Comparison of trajectories based on the inverted pendulum model and based on data recorded from humans.

### 3.2.2 Unactuated toe joint rotation

The rotation of the unactuated toe joint plays an important role in the duration of ground contact. This determines on its turn if the position of the ZMP stays within the PoS or moves out which could give a wrong indication of a stable or unstable gait. The stiction parameters chosen by [1] appears to be too high such that the joint does not move, even if the forces applied by the weight of AAU-BOT1 on the spring are large. A solution to this problem is decreasing the stiction parameter by multiplication with a factor of 0.9. The unactuated toe now rotates freely, which means that the angle of the joint is not limited as is the case in the real set-up. The most straightforward way to impose this mechanical constraint is applying an additional spring-damper structure only acting if the toe passes the 0 rad angle and penetrates the foot. This method works in the sense that it indeed stops the toe if the damping constant and spring constant are chosen appropriately. However it also involves a large drawback. The high spring stiffness causes a very high frequent oscillation of the toe.
hitting the virtual spring over and over again. By consequence of the high oscillations the simulation is no longer solvable and the part that is solvable takes approximately $10^{-100}$ times longer than before. So another approach is required in order to solve this problem. The movement of the toe is only present in some particular phases of the stride where for other phases the rotation of the toe joint is simply 0. This knowledge can be used to reduce the stiction only during the phases the toe is supposed to rotate with respect to the foot. Elaboration of this method gives rise to four different cases, distinguishable by the ground normal force acting on each heel and toe. The different cases are shown in Figures 3.13a-3.13d and from now on denoted with case A, B, C and D. Case A is the case where only the toe is in contact with the ground and the heel is already lifted off. This case occurs at the end of the DSP for the leg that is swinging forward in the next SSP. In this situation there are only normal forces experienced on the toe and the stiction is supposed to be low in order to facilitate the rotation of the toes. Case B is a case where the foot has just fully lost ground contact. At the instance it fully loses ground contact the toe will be pulled back to zero position by the spring. Once being in zero position, the virtual spring-damper structure will decelerate it and will cause the oscillating behavior. Braking the rotation of the toe takes however always approximately the same amount of time and after this amount of time, the spring and damper are disabled and the stiction is increased again. If the foot makes ground contact again, it will be in case C. The heel is here in contact with the ground and the toe not, which means that the stiction can still have a high value. In case D, the foot is eventually in contact with the ground with both the heel and the toe. This means that the toe has to be in zero position and therefore the stiction value can be high in this phase as well and the virtual spring-damper structure will be disabled too. This method removes a significant part of the high frequent oscillations and enables solving the simulation. However simulations are still significantly slower in comparison to the duration before modifications with respect to the stiction parameter of the toe joint. The rapid accelerator mode of Simulink is proposed as a work around for this problem, speeding up simulations significantly on the cost of a larger compilation time and a disabled SimMechanics visualization feature. Overall, simulations are much faster in this simulation mode, although simulations clearly speed up at times where the toe is fixed and slow down at time instances where the oscillation are present.

All modifications described so far, are recapitulated in Appendix E in order to give a clear overview of the modifications implemented during this project and to make sure that it is possible to benefit from this in future projects.

### 3.2.3 Torso mass

As mentioned earlier, the current mass of the torso and both arms is not large in comparison to the mass of the limbs below the overall CoM. This section shows the results of experiments with an additional mass, of varying weight, placed at the top of the torso in order to determine whether an additional mass indeed makes it easier to influence the roll and pitch motion by changes in the waist roll and pitch trajectories. This is investigated since the torso is designed for placing batteries too, that are currently not installed. The weight of the torso and arms in humans is in general larger than 50% of the total body weight, according to [3]. For AAU-BOT1, the total body weight is approximately 67 kg where the weight of the torso and both arms is 13.4 kg, which is 20% of the total body weight. The additional mass, $m_a \in \{5, 10, 15\}$ kg, is assumed to be a solid and uniform cube made of steel with a density of $7.8 \cdot 10^3$ kg m$^{-3}$. Figure 3.14 shows the position of the additional mass, which is indicated by the red cube. The inertia tensor $I \in \mathbb{R}^{3\times3}$ for a cube with uniform density and sides of length $l$ rotating around its center of mass is given by (3.5), derived with use of [12].
Case A: Heel is lifted from the ground while the toe has still ground contact.

Case B: The full foot is lifted off the ground and the toe is moved to zero position by the spring.

Case C: The heel makes ground contact after the swing phase while the toe is still lifted.

Case D: The full foot, so heel and toe, are in contact with the ground.

Figure 3.13: The four different cases of ground contact.

\[ I = \frac{1}{6} m a I^2 \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{[kgm}^2\text{]} \quad (3.5) \]

The waist roll joint, i.e. \( \theta_{15} \), is now forced to follow a certain sinusoidal trajectory in case of no additional weight and with the different additional weights. Note that this trajectory is just chosen like this in order to monitor the possible effect of the additional mass on for example the GCoM. The influence of the additional weight is now evaluated based on the change in the location of the GCoM and ZMP in comparison to the situation were the roll angle of the waist roll joint is kept at approximately 0 rad. Moreover, the velocity of the pelvis is considered too. The applied trajectory is depicted in Figure 3.15.
Adding additional mass to the torso, preferably at a large distance from the waist roll and pitch joints, does indeed influence the capability for making corrections in the position of the ZMP and GCoM location. Moreover it can be used to influence the velocity of the pelvis which could be useful to increase forward pelvis velocity at the end of the DSP. The position of the GCoM in y-direction, the ZMP in y-direction, the pelvis velocity in y-direction and the current required by the waist roll joint ($\theta_{15}$) are shown in Figure 3.16a, 3.16b, 3.16c, 3.16d respectively. The position of the ZMP is not very much influenced by the additional mass and the movement of the torso. Nevertheless the GCoM position is influenced much more and in this perspective it is useful to add at least some additional weight. This enables influencing the GCoM position in order to influence the stability by making smaller motions in comparison to a situation with no additional mass in the torso. Moreover the pelvis velocity is influenced by the addition of some weight and the rotation of the waist roll joint. In this way, the additional weight enables also to influence the pelvis velocity and to counteract an excessive increase of the velocity in y-direction due the push-off. Regarding the pelvis velocity and the current required to make the desired motion in the waist roll joint, it is at least questionable if it is useful to add much weight, for example 15 kg or add just some weight, for example 5 kg. The result of this consideration depends also on the purpose of the torso movement. A heavy additional weight can be beneficial in case it should take over the roll motion currently carried out by the ankle roll joint to stabilize the sideways movement. But if it is just used to make small corrections on the other hand, so on top of the roll motion in the ankle joints, a lighter weight will be beneficial. This lighter weight can be accelerated faster, and hence corrections are faster. The most important note at this point is that the waist roll joint has a nominal current of only 1.2 A, which might be limiting the possibilities in the actual setup.

### 3.3 Final simulation results

This section contains the final results and a review of these results. Figure D.2 in Appendix D depicts snapshots of the current gait, taken every 0.1 s. Figure 3.17 shows the position of the GCoM and the ZMP as function of time and it is clear that during the first step, so during the first 0.5 s, the ZMP stays within the PoS and the GCoM is in front of the toe tip for some amount of time. Moreover the duration of the first step is approximately equal to the target value of 0.49 s, although the second step still takes too much time, as is visible in Figure 3.18. Tracking of the joint angles is
Figure 3.16: Results of simulations with varying values for \( m_a \) and a sinusoidal roll angle for the waist roll joint, \( \theta_{15} \).
relatively accurate and seems at least to be accurate enough, although the saturation limits which were set at twice the nominal current are for some of the joints exceeded for some period of time. Especially the pitch joints of the knee and hip are exceeding these limits by a factor between 1.5 and 2. Saturation limits at only twice the nominal current are however quite conservative, since higher peak loads are permitted for a short amount of time. Nevertheless, this might still cause problems in the future and might hence require a slower gait in order to reduce required accelerations. The velocity of the pelvis in \(x\)-direction is now quite repetitive and no longer decreasing during the first \(\text{DSP}\) as shown in Figure 3.19. One final note is the scaling which seems to be required for the ankle roll trajectories. The results significantly improved in terms of stability once the magnitude of the ankle roll trajectories derived from data captured from humans was decreased by scaling with a factor of 0.6. Noteworthy is the fact that this gives the same maximum amplitude as for the trajectories obtained from solving the differential equation for the inverted pendulum model with a desired \(y\)-position of the \(\text{ZMP}\). All these observations show that the gait is not far from being stable. The modifications proposed are indeed improving the results and enabling \textit{AAU-BOT1} to come closer to a stable dynamic walk.

Figure 3.17: The position of the \(\text{GCoM}, \text{ZMP}\) and the outline of the first stance foot during the final simulation.
Figure 3.18: $k$-values for both feet as function of time. A $k$-value larger than 0 indicates ground contact.

Figure 3.19: Velocity of the pelvis as function of time.
Chapter 4

Conclusions and discussion

This chapter contains a summary of the most important conclusions and finally a short discussion about possible subjects for additional research in the future. Reference trajectories are derived in several different ways and the trajectories derived from data captured from humans walking obviously give the biggest chance for an anthropomorphic gait that is stable. For this reason these trajectories are taken as starting point for simulations. This shows that it is possible to obtain a gait that is dynamic and close to stable by applying these joint trajectories with minor modifications. Online trajectory updates of the ankle pitch joints enable a proper push-off at the end of the DSP. Moreover the influence of gait initiation is ruled out by a proper initiation process to enable research on the stability of the true gait only. The model contained stiffness and damping coefficients that are very low in comparison to real values for real floor surfaces. Moreover the friction model for friction between the foot sole and the floor was implemented in a wrong way. This is solved by implementing a new, continuous friction function describing the same behavior. The dynamic model of AAU-BOT1 moreover suffered from a very high stiction coefficient for the passive toe joints. This was disabling a rotation of the toes with respect to their foot, which was on its turn influencing the way of walking and also stability. This issue is resolved by decreasing the stiction in phases where the toe rotation is of importance and by introducing a virtual spring-damper structure to account for the mechanical constraint in the physical set-up. Adding an additional mass is shown to be useful in order to make corrections in the CoM position and to influence for example the pelvis velocity. The amount of mass that is added heavily influences the required actuation power and moreover whether the current actuator is suited or not. A relatively small mass of 5 kg has already a large influence in comparison to the situation without additional mass. Finally, the ZMP stays within the PoS and the GCoM is in front of the toe tip during the first step. Moreover the duration of the first step is approximately equal to the target value of 0.49 s, although the second step still takes too much time. There is however still a challenge as the actuators are loaded quite heavily and are close to, or for some time even, saturated.

4.1 Recommendations and future research

Future participants of the larger project can benefit especially from the bugs identified in the dynamic model and the way they are solved and have moreover trajectories for some of the joints that are already enabling AAU-BOT1 to perform a stable first step. Moreover, these trajectories seem to be close to trajectories that enable AAU-BOT1 to perform a stable gait. Future research is at least required in the topic of gait initiation and termination as this is an essential part in order to make the transformation between simulations and experiments with the actual set-up. Besides, the saturation limits that are violated for some of the joints require more research on how to perform
a slower gait and in what way the gait characteristics of humans change with step frequency and walking velocity. Another solution could also be replacing some of the actuators.


Bibliography


Appendix A

The dynamic model of AAU-BOT1

This appendix contains figures showing the dynamic model in more detail and moreover clearly showing the complexity of the model. Figure A.3 shows the big picture, where Figure A.1 shows the implementation of the left toe and Figure A.2 shows the implementation of the mechanical constraint on the rotation range on the toe joint. The left toe is chosen to show here, since the model of the toe is modified substantially in this project. The mechanical constraint, shown in Figure A.1 is for example introduced here and was not implemented earlier. Note that all other parts of the model, i.e. all other limbs, have the same kind of structures under their mask and are as complex as the left foot and toe.

Figure A.1: Scheme of the left toe.
Figure A.2: Scheme of the implementation of the mechanical constraint on the range of the toe joint.
Figure A.3: The main components of the dynamic model. Note that each limb is assembled of other Simulink schemes.
Appendix B

Conversion cartesian coordinates to joint angles

This appendix describes how the trajectories for the hip and ankle designed in the cartesian coordinate space are transformed into relative joint angles in order to generate trajectories based on predefined points defined in the task space. Figure B.1 gives an overview of all angles and distances used in the derivation of the relative joint angles where basic goniometric relations are used like the law of cosines and Pythagorean theorem. The shank is represented by the line indicated with $L_1$ and the thigh is indicated by the line with label $L_2$. Note that the angles indicated with $\theta_i$ indicate the subscript of the corresponding joint in the right leg although these equations hold as well for the joints in the left leg.

![Figure B.1: Parameters used in the derivation of the joint angles](image)

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\[ \Delta x = x_{\text{hip}} - x_{\text{ankle}} \quad \text{[m]} \quad (B.1) \]
\[ \Delta z = z_{\text{hip}} - z_{\text{ankle}} \quad \text{[m]} \quad (B.2) \]
\[ a = \sqrt{\Delta x^2 + \Delta z^2} \quad \text{[m]} \quad (B.3) \]
\[ \cos \alpha = \frac{L_1^2 + L_2^2 - a^2}{2L_1L_2} \quad \text{[rad]} \quad (B.4) \]
\[ \cos \beta = \frac{L_1^2 + a^2 - L_2^2}{2L_1a} \quad \text{[rad]} \quad (B.5) \]
\[ \tan \gamma = \frac{\Delta x}{\Delta z} \quad \text{[rad]} \quad (B.6) \]
\[ \delta = \frac{\pi}{2} - \beta - \gamma \quad \text{[rad]} \quad (B.7) \]
\[ \theta_4 = - \left( (\pi - \alpha - \beta) + \lambda - \frac{\pi}{2} \right) \quad \text{[rad]} \quad (B.8) \]

Finally the obtained angles are converted to relative angles, as the joint angles in the model and the real setup are defined as relative angles. Moreover the \( x \)-position and the \( z \)-position of the knee joint is determined. This is done in the following way:

\[ \theta_2 = \delta - \frac{\pi}{2} \quad \text{[rad]} \quad (B.9) \]
\[ \theta_3 = \pi - \alpha \quad \text{[rad]} \quad (B.10) \]
\[ x_{\text{knee}} = x_{\text{hip}} + L_2 \sin (-\theta) \quad \text{[m]} \quad (B.11) \]
\[ z_{\text{knee}} = z_{\text{hip}} - L_2 \cos (-\theta) \quad \text{[m]} \quad (B.12) \]
Appendix C

ZMP based upper body trajectory

This appendix describes in more detail how the trajectory for the full upper body and for the torso are derived. The equation of motion proposed in [16] is verified and moreover the assumptions made by them are verified. The most important assumptions are that no external forces and moments are acting on the robot considered. This means that a badly chosen initial position and velocity of the upper body could cause it to fall backwards instead of being in balance. In practice this does most likely not occur as a torque can be applied by the actuators to prevent it. However, it is something to take into account when applying this method here. Another assumption is made with respect to the motion of the full upper body in $z$-direction. Since it is assumed that the full upper body stays in position, the velocity and acceleration are equated to zero. In a later stage in this derivation, this is altered in order to simulate with the desired leg and hip trajectories where there actually is a relatively small hip motion in $z$-direction.

The momentum equilibrium is shown in (C.1), where the external forces and the acceleration of the full upper body in $z$-direction are still present. The notation is equal to the notation in [16] and Figure C.1 shows the main parameters and variables. The bodies referred to by generalized coordinates $q_1$ to $q_7$ are the right foot, right shank, right thigh, left thigh, left shank, left foot and full upper body respectively.

\[
\sum_{i=1}^{7} m_i (\ddot{z}_i - g_z) x_i - \sum_{i=1}^{7} m_i (\ddot{x}_i - g_x) z_i + x_{zmp} \left( - \sum_{i=1}^{7} m_i (\ddot{z}_i - g_z) + \sum_k F_{z,k} \right) = 0 \quad [Nm]
\] (C.1)

For a first approximation of the real solution, the velocity and acceleration of the full upper body is first equated to zero which reduces the complexity of (C.1) in terms of coupling. Before solving an important feature is added in order to express $z_7$ in terms of $x_7$ which reduces the number of unknowns and prevents the need for introducing another assumption. The CoM of the full upper body is composed of the CoM of the waist and pelvis and of the CoM of the torso, including both arms. In the remainder of the derivation the torso is indicated with subscript $t$, the combination of pelvis and waist with subscript $pw$ and the full upper body with subscript $7$. The full upper body CoM is expressed as function of the upper body components and reads as shown in (C.2) which is with respect to the center between both hip yaw joints.

\[
\overline{\text{COM}}_7 = \frac{1}{m_7} \left( m_t \overline{\text{COM}}_t + m_{pw} \overline{\text{COM}}_{pw} \right) \quad [m]
\] (C.2)
Moreover there is a geometrical relation between the $x$ and $z$-position of the CoM of the torso with respect to the waist pitch joint, which yields as shown in (C.3), where $x_t$ is with respect to the waist pitch joint and $z_t$ with respect to the pelvis yaw joint. This relation is also shown in Figure C.2. Note that it is assumed that there is no roll angle applied to the waist roll joint as (C.2) is not valid in that case.

$$z_t = \sqrt{|\text{COM}_{t,\text{waist pitch joint}}|^2 - x_t^2 + 0.15} \quad [\text{m}] \quad (C.3)$$

The momentum equation is solved for $x_7$ while meeting the geometrical relation (C.3) by substitution of (C.3) and (C.2) into (C.1). Finally, some post-processing is required to convert the results to the desired pitch angle of the torso. This is done by means of (C.2) and (C.3). Important is to note the fact that there exists a small angle between the torso and $\text{COM}_{t,\text{waist pitch joint}}$ due to the fact that the CoM of the torso is not perfectly aligned at the center of the torso. This is corrected resulting in the expression for the torso angle as shown in (C.4).

$$\theta_{14} = -\left(\tan^{-1}\left(\frac{x_t}{z_t}\right) - \tan^{-1}\left(\frac{\text{COM}_{t,x}}{\text{COM}_{t,z}}\right)\right) \quad [\text{rad}] \quad (C.4)$$
Figure C.2: Geometrical relation between the $x$ and $z$-position of the CoM of the torso
Appendix D

Snapshots illustrating the gait

This appendix shows snapshots of the gait performed by **AAU-BOT1** in order to illustrate the motion it performs and to make it easier to follow the reasoning in the report. Figure D.1 shows the gait during one of the first successful steps where Figure D.2 shows the gait during the final simulation.
(a) Pose of **AAU-BOT1** after 0.0s.

(b) Pose of **AAU-BOT1** after 0.1s.

(c) Pose of **AAU-BOT1** after 0.2s.

(d) Pose of **AAU-BOT1** after 0.3s.

(e) Pose of **AAU-BOT1** after 0.4s.

(f) Pose of **AAU-BOT1** after 0.5s.

Figure D.1: Snapshots from a simulation with proper pushoff and fixed toe.
Figure D.2: Snapshots from the final simulation.
Appendix E

Model and library modifications

This appendix describes which parts of the simulation model are modified and for what purpose. Moreover the library is updated with some new and modified blocks which is also described in this appendix. The new updated library is called "aaubot1_library_v2.mdl" and contains the blocks from the previous library too.

E.1 Dynamic simulation model related issues

All modifications described in this section concern modifications of the dynamic simulation model of AAU-BOT1 and the modified dynamic simulation model is part of the library and called AAU-BOT1 simulator version 2.

Ground Normal Force computation

The computation of the $GRF$ was implemented by [1] in a way where it was computed before checking if ground contact actually existed. This is changed in order to limit the amount of computations as much as possible. The computation of the ground normal force is only performed in case there exists ground contact, otherwise, its value is simply set to 0. This feature is also implemented in the new ground model block in the updated library, called Ground model v2.

Ground Friction computation

The computation of the friction at the contact between the sole of a foot and the floor was implemented in the wrong way. The friction force was not depending on the normal load, but consisted solely of a contribution of the viscous effect. This is changed in order to model the coulomb and viscous effects. The function is moreover replaced by a continuous function describing the same behavior. This is computationally more attractive as it affects the variable sample time most likely a lot less. The friction coefficient is at this moment estimated from a contact between rubber and dry concrete. It is therefore recommended that the real friction parameters are measured in experiments by future projects. The modified friction function is only evaluated if there is contact between the floor and the foot in order to minimize the number of calculations and to speed up simulations. This feature is also implemented in the new ground model block in the updated library, called Ground model v2.
Ground stiffness and damping parameters

The ground stiffness and damping parameters were model parameters chosen by [1]. During the current research both the stiffness and damping appeared to be chosen rather low in comparison to values found in reports of research on human hopping and walking. The original values caused problems like penetration of the foot into the ground surface and did not allow for fast changes in for example the roll angle of the ankle joint to obtain a stable sideways motion. For these reasons, the damping and stiffness parameters are increased by a factor 10. This modification is included in model_parameters_version_2.m. This script replaces the script model_parameters.m.

Connection between pelvis and world coordinate frame

The connection between the pelvis and the world coordinate frame was previously implemented by a 6[DoF] joint. This however did not allow for imposing initial conditions on the rotation of the pelvis with respect to the fixed world coordinate frame and only allowed for displacements along the three main axes. This is solved by replacing the 6[DoF] joint by a so-called custom joint where translations along the three main axes and rotations around the three main axes are allowed.

Initial Conditions

Initial conditions are included for all joints that have time varying joint angles at this time. This enables to start a simulation as if AAU-BOT1 is performing this gait already in order to omit the influence of the gait initiation process. The initial conditions are determined automatically from the trajectories that are loaded as spline-structures.

E.2 Data post-processing issues

FTS data post-processing

Post-processing of data from an FTS was implemented in the previous project in order to correct for a bias. An additional FTS post-processing block is added to the library which does not perform this bias correction as this is not required in simulation. Moreover it contains a transformation from the SimMechanics coordinate frame to the coordinate frame used in this report and also used by [1]. The block taking care of the coordinate frame conversion is called Frame conversion FTS SIMULATION and the block not correcting for the bias is called Foot ZMP Estimator SIMULATION.

IMU data post-processing

Post-processing of the data from the IMU in simulation is necessary as it is given in the SimMechanics coordinate frame which differs from the coordinate frame used in all other library blocks and used in this report. The updated library contains an additional block called Frame conversion IMU SIMULATION, where this correction is implemented.

Forward Kinematics

The Forward Kinematics block implemented by [1] was no longer compatible with the output of the block accounting for the frame conversion of the IMU data. The IMU data was previously by the forward kinematics block converted from a quaternion to a rotation matrix, where the output of the coordinate frame conversion is already a rotation matrix. For this reason a second version of the Forward Kinematics is added to the new library, called Forward kinematics SIMULATION, which can be used in combination with the frame conversion block.
Forwarding data to visualizer

Forwarding data to the Palantir visualization tool was implemented by means of the library block called To visualizer. The IP-address of the laptop where the visualizer is running has however changed and is now 172.26.12.147. This is updated and the new block is called To visualizer v2.