Advanced Control of Biped Robot Motion

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Abstract—Next generation robots will be required to operate alongside people in complex environments that are primarily designed for humans. Humanoid robots present themselves as the logical choice for such tasks. In order to successfully navigate within human environments, humanoid robots require complex dynamic movements with robust balance maintenance on uneven terrain and during unexpected balance disturbances. As bipedal locomotion is one of the most challenging problems in the field of robotics today, a variety of different control approaches is being studied by researchers. This work gives a review of most frequently used methods as a starting point for future research on advanced control of biped robot motion.

Keywords—legged locomotion; balance control; humanoid walking robot; zero moment point; inverted pendulum model

I. INTRODUCTION

From the very first notion of robots introduced by Karel Čapek in the science fiction play R.U.R. in 1921, through later cinematic realizations like the 1927 Metropolis movie, people envisioned robots in humanoid form. Throughout history, people imagine and aspire to create machines that will efficiently replace them in carrying out difficult, dangerous and tedious tasks. While most robots in practical use today are designed for single or small numbers of tasks bound to a single location, great effort is being made by researchers to create versatile robots that can truly coexist and aid people in human environments. In 1973 in Waseda University, in Tokyo, Wabot-1 was built [1]. It was able to walk, to communicate with a person in Japanese and to measure distances and directions to the objects using external receptors. In 1980s Honda started experimenting with humanoid robots and by year 2000 introduced ASIMO [2], the first humanoid robot to incorporate predicted movement control, allowing for increased joint flexibility and a smoother, more human-like walking motion. Today there are many research platforms present in form of humanoid robots like ASIMO, HRP-4, HUBO, Atlas, iCub and NAO and as top level examples of today’s state of the art in humanoid robots (Fig. 1).

As humanoid robots are aimed to match and even outperform human abilities, use cases for such future robots are vast. In 2012, shortly following the Fukushima Daiichi nuclear power plant disaster, US Defense Advanced Research Projects Agency (DARPA) announced the DARPA Robotics Challenge [3], a competition focused on developing robots that can perform "complex tasks in dangerous, degraded, human-engineered environments". These robots are to be used as emergency response units in disastrous areas, where it is too dangerous or even impossible for humans to enter, to perform necessary tasks using human tools and machines while, autonomously navigating through compromised environment.

With the human population growing older, domestic and institutionalized personal assistance to sick and elderly people is becoming a field of interest for many researchers in the field of robotics. In medical research, even today, humanoid robots and AI systems are present as assistants to doctors in rehabilitation and illness diagnosis [4]. At the Faculty of Electrical Engineering and Computing, the Laboratory for Robotics and Intelligent Control Systems (LARICS) is carrying out the ADORE project, funded by the Croatian Science Foundation, in which NAO robots are used to help clinicians from the Faculty of Education and Rehabilitation Sciences diagnose autism spectrum disorders in children [5].

Funded by the European Union within the 7th Framework Program (FP7) KoroiBot project uses multidisciplinary approach in order to improve humanoid walking capabilities by human-inspired mathematical models, optimization and learning [6]. Researchers from the areas of robotics, mathematics and cognitive sciences study the way humans walk e.g. on stairs and slopes, on soft and slippery ground or over beams and seesaws, and create mathematical models to be applied in bipedal robots walking and balance control (Fig. 2).
Another FP7 European funded project Whole-body Adaptive Locomotion and Manipulation (WALK-MAN) [7] aims to develop a humanoid robot that can operate in buildings that were damaged following natural and man-made disasters. To accomplish this, robot is to be able to walk in and through cluttered spaces and maintain its balance against external disturbances, such as contact and impacts with objects or people. This should be achieved by exploiting all its limbs (hands, arms, legs, feet and trunk) to demonstrate whole-body motion dynamics and making use of surrounding workspace constraints (handrails, walls, furniture etc.). WALK-MAN will also aim to produce a European entry to the DARPA Robotic Challenge.

Bipedal locomotion is one of the most complex problems encountered today in humanoid robot design. It has been observed in animals and humans that there are several layers of control included when performing different types of motion such as walking and running. This has led to three broad approaches to locomotion [8]. Neurobiology emphasizes studies of central pattern generators (CPGs): networks of oscillators capable of generating control signals in the absence of sensory feedback. A related, reflex-driven approach concentrates on the role of proprioceptive feedback and limb coordination in shaping motion patterns. Biomechanics focus on body–limb environment dynamics where reduced biped models, such as different variants of inverted pendulum models, are used in order to simplify overall humanoid movement representation [9]. Movements of individual limbs are ignored as focus shifts to just two characteristic points, center of mass (CoM) and center of pressure (CoP) and their connection represented by a straight segment with different compression properties depending on the model used.

To achieve high levels robustness to disturbances and autonomy, humanoid robots are equipped with a multitude of different sensors which are used in fusion as feedback and predictive parameters in motion control algorithms. Inertial sensors, gyros, touch and force sensors are typically used for robots’ internal state observation while LIDAR, stereo and high resolution cameras, microphones and ultrasonic sensors are common choices for achieving environment and situation awareness of robot.

II. BIPED WALKING PRINCIPLES

Biped walking robots can broadly be divided into two groups [10]. Dynamically stable walking based on “Zero-Moment Point” (ZMP) principle, where the CoP always remains within the polygon of the stance foot, so the foot always remains firmly planted on the ground. Such principle enables the use of standard control algorithms where all DoF-s are constantly actuated through motion. It results in higher energy consumption and a somewhat unnatural sense of motion.

The Second group consists of passive-dynamic walkers and limit-cycle walkers inspired by the completely passive walkers of McGeer [11] who showed that planar walking down the slope without actuation is possible. These robots do not use full actuation of all DoF at all time and allow gravity and the dynamics to play a large part in the generation of motion, which makes them more energy efficient and natural looking in motion. However, systematic control design and systems analysis of these systems is a very challenging task.

Because of its complexity, stability analysis of biped walking can be simplified using the ZMP principle. At the cost of energy efficiency, the biped’s locomotion can be controlled to be always dynamically stable using this criterion [12]. The ZMP criterion takes the dynamical effects during walking into consideration, therefore it is an extension to the static stability criterion.

A. Biped Gait

Gait of biped walkers determines the type of movement such as walking and running. For different kinds of movement, different gaits can be defined. Generally, periodic walking gates can be divided into four different phases (see Fig. 3):

1) Double Support Phase (DSP)
   This is the phase where both feet are fully supported by the floor. Robot is statically stable.

2) Pre-Swing Phase
   In this phase the heel of the rear foot is lifting from the floor but the biped is still in double support due to the fact that the toes of this foot are still on the

3) Single Support Phase (SSP)
   The phase where only one foot is fully supported by the floor and the other foot swings forward

4) Post-Swing Phase
   In this phase the toe of the front foot is declining towards the floor. The biped is in double support because the heel of this foot is contacting the floor.

The four phases periodically repeat and each of the phase’s individual timing and duration when combined define the properties of robot movement such as speed and step length.

![Fig. 3. Gait phases of biped walker [12]](image)

III. BIPED MOTION AND BALANCE CONTROL PRINCIPLES

A. Biped stability

Biped support polygon (SP) shown in Figure 4 is a convex polygon that contains all robot contact points with the ground. SP is an important factor in stability of the robot.
A Static biped is influenced only by gravitational force so it will be statically stable as long as its ground projection of CoM stays within SP. When the robot is moving dynamic forces also influence robot stability and with higher speed their dominance prevails over the static forces. The ZMP principle takes dynamic forces, as well as static forces, into consideration. With this in mind biped gait can have two types of gait stability:

1) Statically Stable Gait
The movement or gait of a biped is called statically stable, if the projected CoM and the ZMP always remain within the SP during the entire motion or gait. This implies that if the movement is stopped, the biped will remain in a stable position. These kind of stable gaits are useful only for really slow walking velocities, which impose also low angular velocities in the joints.

2) Dynamically Stable Gait
If the ZMP resides within the SP during the gait of a biped while the projected CoM leaves the SP, then the motion or gait is called dynamically stable. The reasoning behind dynamically stable walk is that either there are enough forces and torques generated to oppose the gravitational force to prevent the biped from falling, or the time for SSP is adjusted in such a way that it is short enough to prevent gravitational forces to cause tipping over. These two factors are often used in synthesizing or generating gaits for bipedal walking machines.

B. Zero-Moment Point
For biped locomotion, ZMP is one of the most used and famous terms, it is widely known by the acronym ZMP. Originally, it was defined by M. Vukobratovic in 1972 [13].

If the load has the same sign all over the surface, it can be reduced to the resultant force \( F_p \), the point of attack of which will be in the boundaries of the foot. Let the point on the surface of the foot, where the resultant \( F_p \) passed, be denoted as the Zero-Moment Point (Fig. 5).

For simplicity, the influence of the biped is replaced with the force \( F_i \) and the torque \( M_i \) acting on a point \( A \) on the floor. The gravitational acceleration is \( g \), acting in the negative \( z \) direction. To keep the whole biped in balance: in point \( P \) the reaction force \( F_P = (F_{PX}, F_{PY}, F_{PZ}) \) and the torque \( M_P = (M_{PX}, M_{PY}, M_{PZ}) \) are acting.

The horizontal reaction force \( (F_{PX}, F_{PY}) \) is the friction force that is compensating for the horizontal components of force \( F_d \). The vertical component of the reaction torque, being \( M_{PZ} \), is balancing the vertical component of torque \( M_d \) and the torque induced by the force \( F_d \). Assuming there is no slip, the static friction is represented with \( (F_{PX}, F_{PY}) \) and \( M_{PZ} \).

To compensate for the horizontal components of \( M_d \), being \( (M_{dX}, M_{dY}) \), the point \( P \) is shifted in such a way that \( F_{PZ} \) is fully compensating for them which implies that the horizontal components of \( M_A \) are reduced to zero.

\[
M_{PX} = M_{PY} = 0 \tag{1}
\]

In case that the SP is not large enough to include the point \( P \), the force \( F_P \) will act on the foots edge and the uncompensated part of \( M_d \) and \( F_d \) will result in a rotation that will cause flipping about that edge which can result in falling.

If the forces and torques are conserved around the origin the biped will be in static equilibrium:

\[
F_p + F_d = 0 \tag{2}
\]

\[
p_{OP} \times F_p + M_d + M_{PZ} + p_{dX} \times F_d = 0 \tag{3}
\]

If the base-frame-origin \( O_{XYZ} \) is placed on the XY-plane ZMP can be calculated by:

\[
(p_{OP} \times F_p)_X + (M_d)_Y + (p_{dX} \times F_d)_X = 0 \tag{4}
\]

When the computed point \( P \), being ZMP, is within the SP, the mechanism is in dynamic equilibrium. Also at that time ZMP coincides with CoP. Moreover, if the biped robot is dynamically stable, the position of the ZMP can be calculated with the CoP, by using force sensors on the sole of the feet.

When the point \( P \) moves outside SP and stability is lost, as ZMP can only exist on the sole of the feet where friction exists, it is called Fictitious-ZMP (FZMP) or sometimes also Foot Rotation Indicator [12].

If the robot is dynamically stable ZMP coincides with CoP and can be calculated with CoP by using force sensors on the foot. If the biped is not dynamically stable the CoP can still be determined but this location does not represent the ZMP or FZMP.

The state-of-art biped walking gait pattern generators usually plan the CoG trajectory according to the given ZMP trajectory which satisfies this criterion.

C. Inverted Pendulum Mode
As humanoid robots are complex in design, many different simplified models are used to represent the robot in motion. Most common models in use today are based
on Inverted Pendulum Mode (IPM) where the body of robot is represented as a point mass at CoM which is connected to the CoP with each leg represented by a linear segment without mass (see Fig. 6). IPM is sometimes denoted as 3D-IPM to emphasize three dimensional nature of pendulum.

Fig. 6. Inverted pendulum model of NAO robot

Linear Inverted Pendulum Mode (LIPM) was first introduced by Kajita and Tani in 1991 [14]. In LIPM the connection between CoM and CoP is represented by a telescopic link in such way that dynamics of the pendulum is linearized about the upper, unstable equilibrium point. This results in CoM movement being constrained along an arbitrary defined plane which simplifies walking pattern generation as separate controllers can be designed for sagittal (XY) and lateral (YZ) planes. This method is being used by many researchers around the world since it provides a practical and relatively easy solution which allows for real-time computation of dynamically stable bipedal walking gait [15].

LIPM offers fairly easy method of ZMP calculation with a simple illustration of a problem using the cart-table model given by Kajita [16].

If \( x \)-axis is taken as walking direction and the constraint plane represented by normal vector \((k_x, k_y, -1)\) and \(z\)-axis intersection \(z_c\) (see Fig. 7) as

\[
z = k_x x + k_y y + z_c. \tag{5}\]

If the constraint plane is horizontal \((k_x = k_y = 0)\), the dynamics under the constraint control is given by:

\[
\ddot{y} = \frac{g}{z_c} y - \frac{1}{m z_c} \tau_x \tag{6}
\]

\[
\ddot{x} = \frac{g}{z_c} x - \frac{1}{m z_c} \tau_y \tag{7}
\]

where \(m\) is the mass of the pendulum, \(g\) is gravity acceleration and \(\tau_x, \tau_y\) are the torques around \(x\)-axis and \(y\)-axis respectively.

Even in the case of the sloped constraint where \(k_x, k_y \neq 0\), we can obtain the same dynamics by applying an additional constraint for the input torques:

\[
\tau_x x + \tau_y y = 0 \tag{8}
\]

As (6) and (7) are linear equations, only parameter which influences their dynamics is \(z\)-axis intersection \(z_c\) and the inclination of the plane never affects the horizontal motion.

For the LIPM with the horizontal constraint, we can calculate ZMP location \((p_x, p_y)\).

\[
p_x = -\frac{\tau_y}{mg} = x - \frac{z_c \ddot{y}}{g} \tag{9}
\]

\[
p_y = \frac{\tau_x}{mg} = y - \frac{z_c \ddot{x}}{g} \tag{10}
\]

which can then be used for walking trajectory generation.

As shown in Figure 8, Kajita also offers a simple illustration of LIPM which depicts a running cart of mass \(m\) on a pedestal table whose mass is negligible (two sets of a cart are needed on a table for the motion of \(x\) and \(y\)).

As shown in the figure, the foot of the table is too small to let the cart stay on the edge. However, if the cart accelerates with a proper rate, the table can keep upright for a while. At this moment, the ZMP exists inside of the table foot.

Couple of years after Kajita introduced the linear inverted pendulum model Park et al. came up with the Gravity-Compensated Linear Inverted Pendulum (GCLIPM) approach [17]. They claim that assumption of zero mass legs leads the swinging of each leg to act as a disturbance to the LIPM model so another mass representing the leg was added to the LIPM model. First acceleration and torque of the leg is calculated and then it is added to the existing LIPM. Separate controllers are
used for the swinging leg and for CoM which results in superior walking trajectories, especially on robots with heavy legs.

The Spring-Loaded Inverted Pendulum SLIP is a classical locomotion template that describes the center of mass behavior of diverse legged animals [19]. The SLIP represents the animal’s body as a point mass bouncing along on a single elastic leg. The Connection between CoM and CoP is represented with a spring loaded link. SLIP is more often used in four or more legged walkers which can perform gaits with flight phase in which all legs are in the air at the same time like trotting and galloping.

D. Walking pattern generation for defined ZMP trajectory

In the cart-table model cart represents trajectory of CoM of the robot and ZMP can be easily calculated from LIMP model.

Walking pattern generation is the inverse problem, where CoM trajectory is to be calculated from given ZMP trajectory, which is defined with dynamic behavior of the system. There are several approaches to address this problem.

Takanishi et al. proposed to solve this problem by using Fourier Transformation [20]. By applying the Fast Fourier Transformation (FFT) to the ZMP reference, the ZMP equations can be solved in the frequency domain. Then the inverse FFT returns the resulted CoM trajectory in time domain.

Kagami, Nishiwaki et al. proposed a method to solve this problem in the discrete time domain [21]. They showed the ZMP equation can be discretized as a trinomial expression, and it can be efficiently solved by an algorithm of $O(N)$ for the given reference data of size $N$.

Kajita et al. proposed preview control of ZMP for walking pattern generation [16]. ZMP tracking servo controller is realized using preview control theory that uses future reference of ZMP to calculate trajectory of CoM. The Advantage of this method is in the fact that it does not need to generate the whole CoM trajectory offline as previous two methods.

E. Disturbance rejection and stabilisation

Maintaining stable and balanced walk for biped robots is still a great challenge. There are several different approaches to this matter being researched today.

ZMP compensation is one of the approaches in which joint trajectories or joint torques are altered to enable the robot to react to the disturbances from the environment by keeping the ZMP within the SP. In Kim et al. [22] a constant compensation procedure is discussed. The reference angles to the ankle roll and pitch joints are changed by a constant amount when the ZMP moves out of an area in the SP. Prahlad [23] uses a compensating torque which is injected into the ankle-joint of the foot of the robot to improve stability. The value of the compensating torque is computed from the reading of the force sensors located at the four corners of each foot. With the compensation technique, the robot successfully rejected disturbances in different forms. It carried an additional weight (17% of body weight) while walking. Also, it walked up a 10° slope and walked down a 3° slope. In work of Lim et al. [24] the ZMP compensation is done by the trunk motion while walking on a flat surface.

IV. INTELIGENT CONTROL METHODS FOR BIPED LOCOMOTION

Various intelligent control system methodologies are being developed as they are proving to be very efficient for online gait and trajectory planning as well as for static and dynamic balance control. Overview of some of these methods is presented by Wongsuwarn and Laowattana [25].

A. Neural Networks

Various types of neural networks are used for gait synthesis and control design of biped and humanoid robots such as multilayer perceptrons, CMAC networks, Radial Basis Function (RBF) networks or Hopfield networks, trained by supervised or reinforcement learning unsupervised methods. Intelligent computing control technique is used by Ferreira [26]. This technique is based on support vector regression (SVR). The method uses the ZMP error and its variation as inputs, and the output is the correction of the robot's torso necessary for its sagittal balance. The SVR is trained based on simulation data and their performance is verified with a real biped robot.

B. Fuzzy Control

Fuzzy logic is used dominantly as parts of control systems on executive control level, for generating and tuning PID gains. Park [27] proposed a new control scheme for a 7 DOF biped robot based on a varying ZMP rather than a fixed ZMP. The simulation results showed that the fuzzy-logic generated moving ZMP prevented a large swing motion of the trunk and therefore significantly improved the stability of the biped robot locomotion. Li [28] proposes ZMP trajectory model with adjustable parameters to modulate the ZMP trajectory both in sagittal and lateral planes and make the ZMP trajectory more flexible. A dynamic balance control, which includes Kalman filter and the fuzzy motion controller, is also designed to keep the body balance and make the biped walking following the desired ZMP reference.

C. Hybrid Intelligent Approach

Both fuzzy and neuro control are model-free design methods. However, because a multi-DOF biped robot is a multivariable, high-order, strongly-coupled nonlinear dynamic system, it is difficult to get fuzzy control rules by using human expert-based or supervised neural network by using numerical data methods. Thus, Hybrid intelligent methods find the place in the research of gait synthesis as well as control of biped and humanoid robots. Bebek et al. [29] worked on an online Fuzzy controller as 3-layer neural network where parameters were adapted via back propagation. Simulation techniques were employed for a 12 DOF biped robot. The proposed adaptive method for one of the many parameters of the walk pattern was tested successfully. Wongsuwarn, et al. [30] implemented a Neuro-fuzzy algorithm to generate the desired ZMP trajectory depending on the body posture. The proposed method is demonstrated in a 7-DOF biped robot. Park, et
al. [31] presented an adaptive neuro-fuzzy inference system ANFIS modeling of the ZMP trajectory of biped walking robot. The simulation results also showed that the ZMP generated using the ANFIS could improve the stability of the biped walking robot.

V. THE NAO ROBOT

NAO is an autonomous programmable humanoid robot developed by Aldebaran Robotics. It is mainly used for research and education purposes in academic institutions worldwide. In 2007 NAO replaced Sony's robot dog Aibo as the robot used in the RoboCup Standard Platform League (SPL), an international robot soccer competition. By the end of 2014, over 5000 NAO robots were in use with educational and research institutions in 70 countries [32].

In December 2011, Aldebaran Robotics released the NAO Next Gen, featuring hardware and software enhancements such as HD cameras, improved robustness, anti-collision systems and a faster walking speed. LARICS is equipped with six NAO Next Gen robots, which have already been used in several projects such as the before mentioned ADORE.

A. Physical configuration and actuation

NAO robot shown in Figure 9 is a 58 cm tall and 5.2 kg heavy humanoid robot with 25 degrees of freedom (DoF), 5 in each leg, 5 in each arm, 1 in each hand, 2 for the head and 1 in the hip which is shared between both legs [33]. Robot joints are actuated using brush DC coreless electric motors with magnetic rotary encoders for position feedback, powered by Lithium-Ion battery which provides autonomy of 60 to 90 minutes, depending of usage intensity. Smart Stiffness is a unique feature of NAO which automatically adapts the power needed by the motors during the movements of the robot which results in better use of the drive components as well as energy savings for the battery. It also features Anti Self collision and Fall Manager for protection against physical damage to the robot in case of falling.

B. Sensors

NAO is equipped with an inertial measurement unit (IMU) composed of an accelerometer and gyro, along with four ultrasonic sensors for obstacle detection. The detection range is 1 cm to 3 meters. Each foot is outfitted with a bumper and four pressure sensors, while hands and head have capacitive tactile sensors. Two high definition cameras in the head are used for computer vision, including facial and shape recognition. The first camera, located on NAO’s forehead, scans the horizon, while the second located at mouth level scans the immediate surroundings. Four directional microphones located on the head can be used for voice and speech recognition as well as for sound source localization. NAO communicates using a text-to-speech voice synthesizer in 9 different languages through two speakers located on its head.

C. Processing units and software

NAO uses two processing units. The First one is located in the chest area and is used for inertial sensor processing. The Second one is an Intel ATOM 1.6ghz CPU located in the head, that runs an Open NAO Linux kernel, based on the Gentoo distribution, and supports Aldebaran’s proprietary middleware NAOqi which allows for easy programming through Choregraphe software using C++, Python, Java, MATLAB, Urbi, C and .Net.

D. Connectivity

NAO supports Wi-Fi and Ethernet network communication protocols. In addition, infrared transceivers in his eyes allow connection to objects in the environment. They have 3 different purposes:

- use NAO as a remote control
- set NAO to receive orders from a remote control
- make several NAOs communicate together

NAO is compatible with the IEEE 802.11b/g/n Wi-Fi standard and can be used on both WPA and WEP networks, making it possible to connect him to most home and office networks. NAO's OS supports both Ethernet and Wi-Fi connections and requires no Wi-Fi setup other than entering the password.

E. Motion

NAO implements the following motion behaviors and algorithms. Implemented motion can be adjusted and improved by controlling different motion parameters such as step length and height, CoM position etc.

1) Omnidirectional walking

NAO's walking uses a simple dynamic model (linear inverse pendulum) and quadratic programming. It is stabilized using feedback from joint sensors. This makes walking robust and resistant to small disturbances, and torso oscillations in the frontal and lateral planes are absorbed. NAO can walk on a variety of floor surfaces, such as carpeted, tiled, and wooden floors. NAO can transition between these surfaces while walking.

2) Whole body motion

NAO's motion module is based on generalized inverse kinematics, which handles Cartesian coordinates, joint control, balance, redundancy, and task priority. This

Fig. 9. NAO H25 joints and sensors
means that when asking NAO to extend its arm, it bends over because its arms and leg joints are taken into account. NAO will stop its movement to maintain balance.

3) Fall Manager
The Fall Manager protects NAO when it falls. Its main function is to detect when NAO’s center of mass (CoM) shifts outside the support polygon. The support polygon is determined by the position of the foot or feet in contact with the ground. When a fall is detected, all motion tasks are killed and, depending on the direction, NAO’s arms assume protective positioning, the CoM is lowered, and robot stiffness is reduced to zero.

VI. CHALLENGES
Factory implemented walking algorithms in NAO robot demonstrate certain shortcomings when it comes to speed, stability and outside or inside disturbance handling.

Several researchers have already made improvements to the factory algorithms. RoboCup STL, due to the dynamic nature of the competition, has yielded several upgrades to NAO robot motion. Xue et al. [34] uses ZMP trajectory represented by a cubic polynomial to connect the goal state (the position and the velocity of the CoG) to the previous one in only one step to achieve fast omnidirectional walk with maximum forward speed of around 0.33 m/s on a flat surface. Team HTWK from RoboCup STL achieved a forward speed of 0.32 m/s based on a machine learning approach [35]. They used closed-loop walking motions evolved through a genetic algorithm, which was fast but lacked omnidirectional walking important in RoboCup competition. Team Dortmund using pre calculated trajectories optimized with algorithms of computational intelligence was able to reach walking speeds of up to 0.44 m/s, which exceeds the theoretical maximum walking speed given by Aldebaran in an earlier specification by almost 50% [36]. To avoid regular recalibration and repeated parameter optimization later they switched to walking engine capable of generating online dynamically stable walking patterns with the use of sensor feedback which also showed better resistance to external disturbances.

Most high-level tasks of autonomous robots require that the robot is able to localize itself in the environment, detect obstacles, and avoid collisions with them by keeping track of their locations and planning collision-free paths around them. Maier, et al. [37] presents an integrated approach for robot localization, obstacle mapping, and path planning in 3D environments based on data of an onboard consumer level depth camera mounted on the NAO head (Fig. 10). The increased weight due to the mounted camera destabilized the walking behavior of the robot and therefore thin plastic sheets were added to the robot’s feet to increase the friction. However, overall stability was still decreased.

Juršević [39] shows that a NAO robot with added unbalanced mass in form of Microsoft Kinect attached to its head deviates from the given trajectory and is unable to walk in straight line. It also exhibits large oscillations in the frontal plane which compromises overall stability of the robot. By manually adjusting gait and leaning parameters, while also raising height of inverted pendulum, a more stable and straight walk is established.

This internal disturbance created by added unbalanced weight could be mitigated by intelligent optimization of NAO motion parameters or by using some of presented advanced control mechanisms. For example, ZMP compensation done by Prahlad [23] where weight disturbance in sagittal plane was handled by adding compensating torque in ankles solves similar problem. Intelligent control methods using neuro [26] or fuzzy [28] controller can be used to stabilize trunk motion of biped robots while walking. Hybrid approach utilizing neuro-fuzzy [31] also showed that the ZMP generated using the ANFIS could improve the stability of the biped walking robot. Further research of this problem will focus on implementing and testing dynamic parameter adaptation algorithm which ought to minimize unbalanced load disturbance by adjusting gait parameters in real time using onboard sensor data.

References


