Complex Motion Planning for NAO Humanoid Robot

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Abstract: In this paper, we introduce an integrated approach that enables a humanoid robot to plan and robustly execute whole body motions including stepping over, climbing up or down obstacles as well as climbing up straight staircase using only onboard sensing. Reliable and accurate sequence of motions for humanoid robots operating in complex indoor environments is a prerequisite for robots to fulfill high level tasks. The design of complex dynamic motions is achievable only through the use of robot kinematics. Based on the recognized object from the robot database, using the robot camera, a sequence of actions for avoiding that object is executed. As demonstrated in simulation as well as real world experiments with NAO humanoid, NAO can reliably execute robustly whole body movements in cluttered, multi-level environments containing objects of various shapes and sizes.

1 INTRODUCTION

Robots have always been a subject of curiosity for both generalists and technologists alike. Humanoids, robots with multiple degrees of freedom, have become popular research platforms as they are considered to be the future of robotics. The human like design and locomotion allow humanoid robots to perform complex motions. This includes balancing, walking, access different types of terrain, standing up, step over or onto obstacles, reaching destinations only accessible by stairs or narrow passages, and to navigate through cluttered environments without colliding with objects. These abilities would make humanoid robots ideal assistants to humans, for instance in housekeeping or disaster management (Graf et al., 2009; Maier et al., 2013).

Autonomous obstacle avoidance by stepping over, onto/down the obstacle, climbing stairs with humanoid robots is a challenging task, since humanoids typically execute motion commands only inaccurately (Graf et al., 2009; Maier et al., 2013; Shamsuddin et al., 2011). This is due to the fact that humanoids possess only a rough odometry estimate; they might slip on the ground depending on the ground friction, and backlash in the joints might occur. Additionally, the observations of their small and light weighted sensors are inherently affected by noise. This all can lead to uncertain pose estimates or inaccurate motion execution (Oßwald et al., 2011).

However, there are reasons that explain why humanoid robots aren’t used frequently in practical applications. One of these reasons is that humanoids are expensive in cost, as they consist of complex pieces of hardware and are manufactured in small numbers (Maier et al., 2013). Also, many researchers apply navigation algorithms that represent a humanoid using wheels instead of legs, but the limitation of this model is that it does not respect all the navigation capabilities of humanoid robots and therefore more appropriate approaches are necessary for navigation in cluttered and multi-level scenarios (Maier et al., 2013; Hornung et al., 2010; Gouda et al., 2013).

In the beginning, humanoid robotics research focused on specific aspects like walking, but now current systems are more complex. Many humanoid robots are already equipped with full body control concepts and advanced sensors like stereo vision, laser, auditory and tactile sensor systems which is the essential condition to deal with complex problems, such as walking and grasping. Motion planning is a promising way to deal with complex problems, as planning methods allow the flexibility of different criteria satisfaction. The design of complex dynamic motions is achievable only through the use of robot kinematics, which is an analytical study of the motion of the robot manipulator (Maier et al., 2013; Kucuk and Bingul, 2006; Gienger et al., 2010).

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More specifically, robot kinematics provide the transformation from the joint space, where the kinematic chains are defined, to the Cartesian space, where the robot manipulator moves, and vice versa (Kofinas, 2012). Robot kinematics are quite useful, because it can be used for planning and executing movements, as well as calculating actuator forces and torques. Robot kinematics can be divided into forward and inverse kinematics. The forward kinematics refers to the use of the kinematics equations of the robot to compute the position of the end effector from specified values of the joint parameters (Kucuk and Bingul, 2006). On the other hand the inverse kinematics refers to the use of the kinematics equations of a robot to determine the joint parameters that provide a desired position of the end effector. It is easy to see why kinematics is required in any kind of complex motion design (Kucuk and Bingul, 2006; Kofinas, 2012).

The relationship between forward and inverse kinematics is illustrated in figure 1. Balancing methods rely on the ability to calculate the center of mass of the robot, which is constantly changing as the robot moves. Finding the center of mass is made possible only if the exact position and orientation of each part of the robot in the three dimensional space is known (Graf et al., 2009).

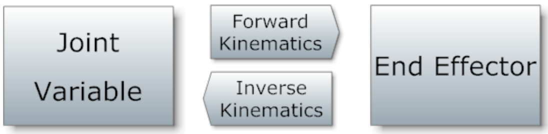


Figure 1: The schematic representation of forward and inverse kinematics.

Humanoid robots performing complex motions tasks need to plan whole body motions that satisfy a variety of constraints. As the robot must maintain its balance, self-collisions and collisions with obstacles in the environment must be avoided and, if possible, the capability of humanoid robots to step over or onto objects, navigate in multi-level environment needs to be taken into account. These constraints and the high number of degrees of freedom of the humanoid robot make whole body motion planning a challenging problem (Graf et al., 2009). The main goal of whole body balancing motion is to generate and stabilize consistent motions and adapt robot behavior to the current situation (AldebaranRobotics, 2014).

In this paper, an integrated whole body motion planning framework has been developed. The framework enables the robot to robustly execute whole body balancing sequences of actions, including stepping over and climbing up/down obstacles as well as climbing up straight staircase in a 3D environment, shown in figure 2. Relying only on the robot onboard sensors, joint encoders, an efficient whole body motions planning perform safe motions to robustly navigate in challenging scenes containing obstacles on the ground as shown in figure 2. Our approach determines the appropriate motion that consists of a sequence of actions according to the detected obstacle using monocular camera and bumper sensors. As demonstrated in practical experiments with a NAO humanoid and in a series of simulations experiments using Webots for NAO humanoid robot, which is a simulation software for modeling, programming and simulating robots (Cyberbotics, 2014), our system leads to robust whole body movements in cluttered, multi-level environments containing objects of various shapes and sizes.

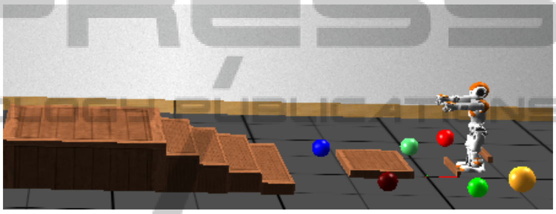


Figure 2: The simulated environment.

The remainder of this paper is structured as follows. Related work is discussed in the Section II. Section III describes the humanoid robot, also motion design and object learning phase used for experimentation are described in this section . Section IV illustrates the robustness and accuracy of our motion planning approach in experiments. Finally, Section V concludes the paper.

2 RELATED WORK

Humanoid motion planning has been studied intensively in the last few years. For instance the approach presented by (Oßwald et al., 2011) enabled an equipped NAO humanoid robot with a 2D laser range finder and a monocular camera, to autonomously climb up spiral staircases. While (Hornung et al., 2010) presented a localization method for NAO humanoid robots navigating in arbitrary complex indoor environments using only onboard sensing. Also the approach developed by (Nishiwaki et al., 2002) allowed NAO to climb single steps after manually positioning the robot in front of them without integrating any sensory information to detect the stairs. Footstep actions plan to climb staircases consisting of three steps with HRP-2 is introduced by (Chestnutt et al., 2007). While (Samakming and Srinonchat, 2008) presented a technique for climbing stair robot using image processing technique besides reducing the processing time.

While (Maier et al., 2013) designed motion, called T-step, that allows the robot to make step over actions, as well as parameterized step onto and step down actions. The authors in (Yoshida et al., 2005) investigated a dynamic pattern generator that provides dynamically feasible humanoid motion including both locomotion and task execution such as object transportation or manipulation. While (Shahbazi et al., 2012) introduced a learning approach for curvilinear bipedal walking of NAO humanoid robot using policy gradient method. Their proposed model allows for smooth walking patterns and modulation during walking in order to increase or decrease robot speed. A suitable curvilinear walk, very similar to human ordinary walking, was achieved.

Furthermore an approach to whole body motion planning with a manipulation of articulated objects such as doors and drawers is introduced in (Burget et al., 2013). Their experiments with a NAO humanoid opening a drawer, a door, and picking up an object, showed their framework ability to generate solutions to complex planning problems. A new walking algorithm implemented on NAO robot is described in (Gouaillier et al., 2010). The authors in (Shamsuddin et al., 2011) discussed the current trends in control methods of biped walks and behavior interface tools for motion control for NAO and imminent findings in both research areas.

In (Hugel and Jouandeau, 2012) a detailed description of a walking algorithm is presented. Their algorithm was designed for 3D simulation of locomotion and path planning of humanoid robots and was implemented on the NAO humanoid. The authors in (Pierris and Lagoudakis, 2009) introduced Kouretes Motion Editor (KME), which is an interactive software tool for designing complex motion patterns on robots with many degrees of freedom using intuitive means.

3 PROPOSED APPROACH

In this section, the proposed algorithm (see Algorithm 1) and action set for the NAO humanoid (see figure 3) that is used during the experimental evaluation are described.

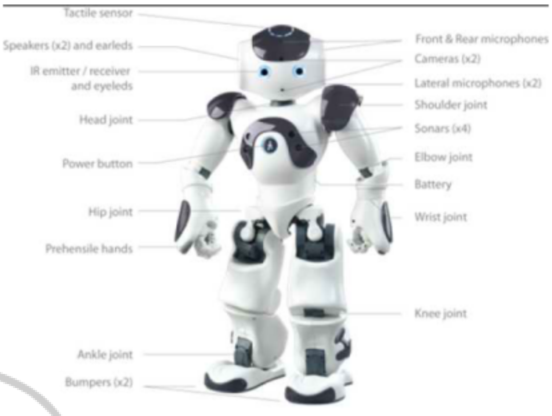


Figure 3: Aldebaran NAO H25.

Algorithm 1: Navigate through the environment.

```
1  move three steps forward
2  stop moving
3  pitch down NAO head by 30°
4  switch to NAO lower camera
5  look for obstacle
6  if obstacle found then
7      fire object recognition module
8      execute stable whole body motions
       depending on the recognized object
9  else
10     go to 1
11 end
```

3.1 NAO Robot Platform

NAO is a small sized humanoid with five kinematic chains (head, two arms, two legs) developed by Aldebaran Robotics (AldebaranRobotics, 2014), it is 58cm in height; 5.2kg weighs. In general, the robot is supposed to be fully symmetric, but interestingly, according to the manufacturer, some joints on the left side have a different range from the corresponding joints on the right side (Kofinas, 2012). Also, some joints appear to be able to move within a large range, the hardware controller of the robot prohibits access to the extremes of these ranges, because of possible collisions with NAO shell (Kofinas, 2012). NAO robot has 25 degrees of freedom (DOF), therefore it can perform several complex moves like walking, kicking a ball, standing up, etc. Kinematics are quite useful for NAO software developers, because they can be used for planning and executing such complex movements (Kofinas, 2012).

The geometric model of NAO gives the effector positions ($X = [P_x, P_y, P_z, P_{wx}, P_{xwy}, P_{wz}]$) relative to an absolute space in function of all the joint positions

($q = [q_1, \ldots, q_n]$).

$$X = f(q) \tag{1}$$

The direct kinematic model is presented in equation (2) which is the derivative of equation (1) with respect to time.

$$\dot{X} = \frac{\delta}{\delta t} f(q)\,\dot{q} = J(q)\,\dot{q} \tag{2}$$

where $J(q)$ is called the Jacobian matrix. A control on the end effector and deduction of the joint position is needed, so that the inverse kinematic model, shown in equation (3), is needed

$$\dot{q} = J^{-1}\dot{X} \tag{3}$$

In many cases, J isn't inversible directly (matrix not square), this problem is solved mathematically using Moore-Penrose pseudoinverse (AldebaranRobotics, 2014).

Aldebaran Robotics provides values of the joints in the robot documentation. The center of mass for each link/joint is represented by a point in the three dimensional space of that joint assuming a zero posture of that joint. The swing foot can be placed at most 8cm to the front and 16cm to the side and the peak elevation is 4cm using the provided walking controller. The size of the robots feet is approximately 16cm x 9cm. From these numbers, it is clear that NAO is not able to step over, onto, or down obstacles using the standard motion controller as shown in figure 4 (AldebaranRobotics, 2014; Maier et al., 2013; Kofinas, 2012).

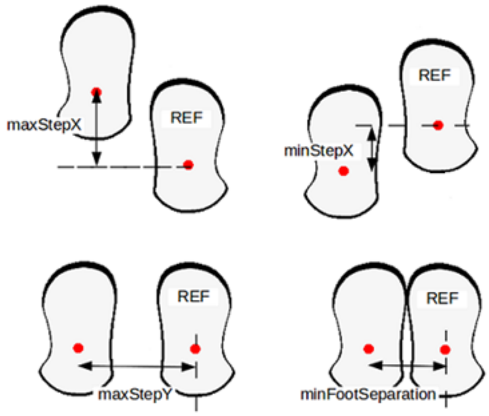


Figure 4: Clip with maximum outreach (AldebaranRobotics, 2014).

3.2 Motion Design

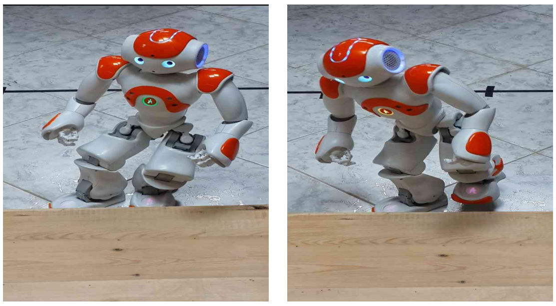
A kinesthetic teaching is applied to enable the robot to overcome these limitations. Here, Choregraphe (Pot et al., 2009), a graphical tool developed by Aldebaran Robotics, and python programming language are used to program the NAO H25 humanoid. A special motion design (described in algorithm 2), inspired from (Maier et al., 2013) and (Gouda and Gomaa, 2014), is presented which allows the robot to step over, onto/down an obstacle according to the shape of the obstacle as well as climbing up stairs. In the designed motion, the foot L_1 are placed at an angle of 30°, which is the basis for the other actions. Then the robot will move its balance to that leg L_1 (the leg with the angle 30°) and move the other leg L_2 freely; after that the balance is moved to L_2, then L_1 moves freely beside L_2 and then the balancing is made on both legs as shown in figure 5.

The motivation for using this motion action is to exploit the larger lateral foot displacement while moving forward. From this pose, the robot can perform a step over action to overcome obstacles with a height up to 4cm and width of 2cm. The motions of climbing up stairs and stepping on/down actions are similar to stepping over motion except for the swing foot placement, as it is placed closer to the stance foot and at a different height. The height is adjusted using inverse kinematics based on the recognized object.

Algorithm 2: Actuate motion.

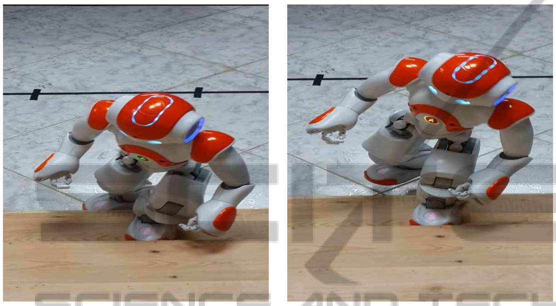
```
go to initial position
place right foot at angle 30°
move balance to right foot
let left foot move freely
if obstacle recognized is the small bar then
    move left foot forward
    set the foot height to zero, i.e., on the ground
else if obstacle recognized is the large bar then
    move left foot forward
    if robot on the ground then
        set the foot height to 2cm, i.e., onto the bar;
    else
        robot on the bar set the foot height to -2cm, i.e., down the bar;
    end
else
    the recognized object is stairs
    move left foot forward
    set the foot height to 4cm, i.e., on the stair step;
end
move balance to left foot
let right foot move freely
move right foot forward beside the left foot
```

The main differences between the designed motion and the motions described by (Maier et al., 2013)



(a) Placing right leg at 30°

(b) Balancing on right leg



(c) Balancing on left leg

(d) Moving right leg

(e) Balancing on both legs

Figure 5: Designed motion step.

and (Gouda and Gomaa, 2014) is in the robot foot angle placement. As in the designed motion the robot place its foot at an angle of 30°, this allows the robot to reach the balance state in short time and more safe. But when the angle of the robot foot placement increase, the balance state requires more time to be reached and the probability for the robot to fall increases.

3.3 Learning Objects

The robot uses its onboard sensor, the monocular camera, to recognize objects in the environment. NAO needs to learn how to recognize objects, so they can be used during navigation, by utilizing the vision monitor in Choregraphe (Pot et al., 2009). After the images are learned and stored in NAO database, the object recognition module should be tested to assure that the robot is able to identify the correct object when recognized in the environment.

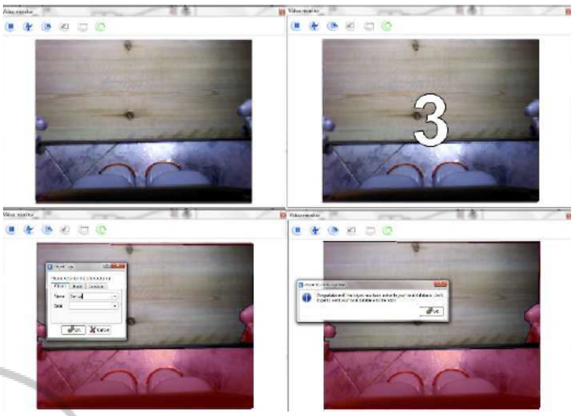


Figure 6: Object learning phase.

During the learning phase, once the image is captured using NAO cameras, the perimeter of the object of the captured image is manually determined, after that a name is assigned to the determined object, then a message appear to show the success of the process of learning, as shown in figure 6, then the image is stored in NAO database. Once all images are stored into NAO database, NAO will be able to perform object recognition. If the object marking is marked in a wrong way, the learning process will fail and the object won't be learned as illustrated in figure 7.

Figure 7: Example of wrong learning.

NAO recognition process is based on the recognition of visual key points and not on the external shape of the object, so it is able only to recognize objects that have been learned previously. The process is partially robust to distance, ranging from half and up to twice the distance used for learning, and angles up to 50° inclination for something learned facing the camera, light conditions, and rotation (AldebaranRobotics, 2014). Every detected key point in the current image is matched with only one learned key point in the database. If the score for choosing between two objects are too close, the key point will not be associated to any of them. Currently, the algorithm does not poll for several objects, learning twice the same area of an object will reduce its detection rate (AldebaranRobotics, 2014).

4 EXPERIMENTAL EVALUATION

Our approach is to make the robot perform whole body motions that enable the robot to execute complex motions such as step on/down or over the obstacle as well as climbing up stairs using monocular camera. The robot will use its camera to recognize the obstacle using the object recognition module. According to the recognized obstacle the robot will execute a sequence of actions. The design of such complex dynamic motions is achievable only through the use of robot kinematics (Graf et al., 2009; Kucuk and Bingul, 2006).

The designed whole body balancing motion uses NAO own kinematics to control directly its effectors in the Cartesian space using an inverse kinematics solver. The Generalized Inverse Kinematics is used, it deals with Cartesian and joint control, balance, redundancy and task priority. This formulation takes into account all joints of the robot in a single problem. The motion obtained guaranties several specified conditions like balancing, keeping a feet fixed, etc. Afterwards, the capabilities of the designed motion system are demonstrated in a series of simulations experiments using Webots for NAO humanoid robot, as well as real world experiments.

All experiments were carried out with NAO H25 humanoid robot. In the experiments presented, the robot moves three steps forward, then it stops moving and pitches down its head by 30° and switches to lower camera in its head in order to scan for obstacles on the ground in front of its feet. Once an obstacle is detected, the object recognition module is fired for recognition; otherwise the robot will move another three steps forward. In the case there is an obstacle recognized the robot will execute stable whole body motions in order to deal with it.

The experiments carried out for the robot stepping over a wooden bar of width of 40cm, height of 3.5cm, and depth of 2cm is shown in figure 8; stepping onto a wooden bar of width of 40cm, height of 2cm and depth of 40cm is shown in figure 9; stepping down from that bar to the ground is shown in figure 10 and climbing up straight staircase of width of 40cm, height of 4cm and depth of 20cm is shown in figure 11. All figures show still frames of a video sequence where our robot successfully steps over, onto/down the wooden bar and climbs up straight staircase.

The algorithm implemented is the same for all the motions; the only exception is the height of its leg and the place of the swing foot, as the swing foot is placed closer to the stance foot in the case of climbing stairs and step onto/down obstacles. In the case of small bar is recognized the robot will step over it and move its leg to the ground after the object. While in the case of the large bar or stairs, the robot will step on/down that bar or stairs and will move its leg on/down it. Also, the execution time of all motions is quite similar, as it takes 30 seconds form the robot to perform step over motion, 29 seconds to perform step onto/down motion and 28 seconds from the robot to climb up one stair step.

We perform a quantitative evaluation of our approach for accurate step over, onto/down an obstacle & and climbing up stairs. The success rate of executing these actions is evaluated using only the onboard sensors; In ten real world runs on our straight staircase consisting of four steps, the robot is able to successfully climbed 97% of the stairs. Only two out of 40 stair climbing actions lead to a fall. The robot also successfully step over, onto/down the wooden bar ten subsequent times on average.

Afterwards, the joints are heated by putting a force on them for an extended period of time. Joints overheating changes the joints parameters, mainly stiffness, and this affects the balance of the robot; so motions cannot be successfully executed anymore and the robot may fail to override the obstacle or may fall. The robot may also fail to override the obstacle or climb the stair if the distance between its feet and the object isn't appropriate. As the robots camera has a limitation in providing depth information, i.e. the distance between the robot feet and the obstacle isn't known.

If the obstacle is located at a distance smaller than a suitable distance to the robot, the robot will hit the obstacle while moving its leg which leads to a change in its feet angle, and so its balance will be disturbed and will fall. Another situation if the obstacle is located at a distance greater than a suitable distance the robot may put its swing foot on the obstacle which also will make a disturbance in its balance and will fall.

Another problem is in the execution time of the motion, as the robot has to have enough time to reach balance state after performing each action in the motion or it will fall. In the case of the time is too short the robot won't be able to finish the action it is performing, so balance won't be reached and the robot

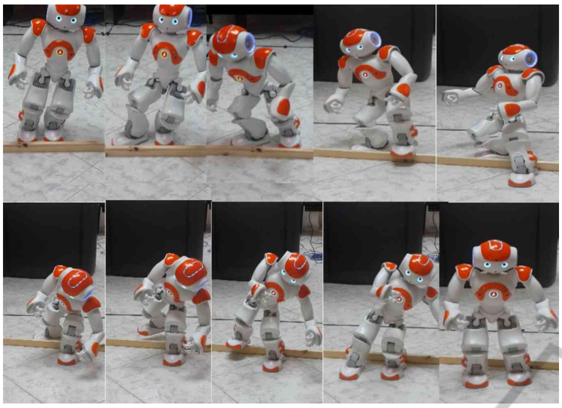


Figure 8: NAO stepping over a wooden obstacle of height 3.5cm and depth 2cm using planned whole body motion.

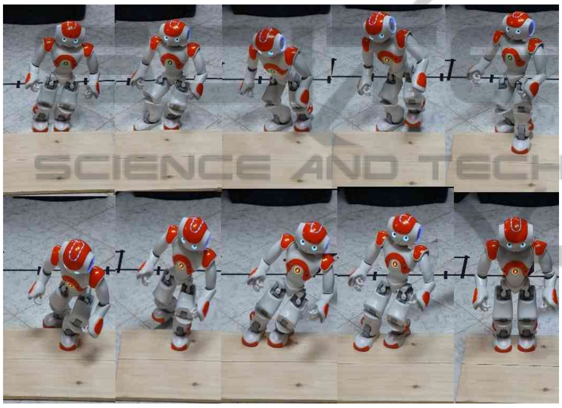


Figure 9: NAO stepping on a wooden obstacle of height 2cm and depth 40cm using planned whole body motion.

Figure 10: NAO stepping down from a wooden obstacle of height 2cm and depth 40cm using planned whole body motion.

will fall. Otherwise, if the time of motion execution is too long, to allow the robot to finish the action it is preforming, its joints will get hot quickly and may not be able to keep its balance in each position for long time so it may also fall. To overcome this problem the foot is placed at an angle of 30°, which is the basis for the other actions, that allows the robot to reach its balance state easily and in short time, so the joints are not heated rapidly.

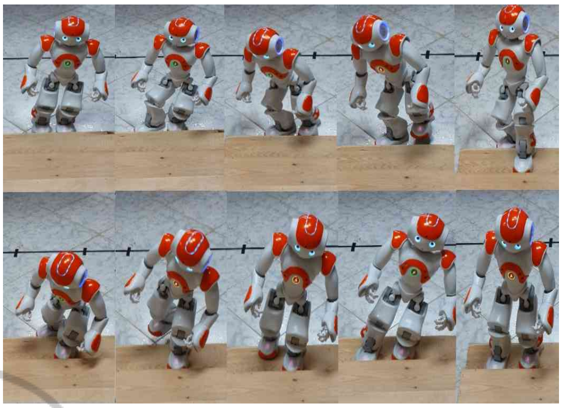


Figure 11: NAO climbing up a stair with height 4cm and depth 20cm using planned whole body motion.

These results show that our approach enables a humanoid to reliably climb up the steps of straight staircases, which are not marked to be easily visually detectable. Furthermore, avoiding colliding with ground obstacles by stepping over or onto/down it is also showed.

5 CONCLUSION

In this paper, an integrated approach that enables a humanoid robot to plan and robustly execute whole body balancing sequences of actions including stepping over and climbing up or down obstacles is introduced. Our system includes recognizing objects stored into the NAO database using NAO camera. Based on the recognized object the robot executes specific motions to deal with the recognized obstacle. The robot can execute these motions ten times consequently. It is possible to reduce the heating in the joints by reducing the time spent in critical positions or by setting stiffness to 0 after each action. In our case the heating problem is avoided by making the foot of the robot placed at an angle of 30°, which reduces the time taken by the robot to go to the balance state. The robot camera has a limitation that it can't provide the distance between the robot and the obstacle; to overcome this limitation the robot feet bumper is used. As demonstrated in both simulation experiments, using Webots for the NAO humanoid robot, and practical experiments with a NAO humanoid, our approach leads to robust whole body movements in cluttered, multi-level environments containing objects of various shapes and sizes.

In future work, we will evaluate the capabilities of the robot to perform more complex motions like climbing down the stairs, climbing up or down a ramp of 20° inclination using the designed sequence of motions.

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