NAO Humanoid Robot Motion Planning Based on its own Kinematics

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***Abstract*—In this paper, an approach to whole body motion planning for humanoid robots using only onboard sensing is presented. Reliable and accurate motion sequence of motions for humanoid robots operating in complex indoor environments is a prerequisite for robots to fulfill high-level task. The design of complex dynamic motions is achievable only through the use of robot kinematics, which is an application of geometry to the study of arbitrary robotic chains. A sequence of actions for avoiding obstacles including, step over actions, as well as step onto/down actions is presented. As demonstrated in simulation as well as real world experiments with NAO humanoid the validity of the approach is examined and evaluated.**

I. INTRODUCTION

Humanoid robots have become popular research platforms in robotics and artificial intelligence, as they offer new perspectives compared to wheeled vehicles. 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 [1], [2].

Autonomous obstacle avoidance by stepping over, onto/down the obstacle with humanoid robots is a challenging task, since humanoids typically execute motion commands only inaccurately [1], [2], [3]. 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 [4].

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 [2], [5]. 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 [2], [6].

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 [2], [7], [8].

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 [7]. 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 [7].

The relationship between forward and inverse kinematics is illustrated in fig. 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 [1].

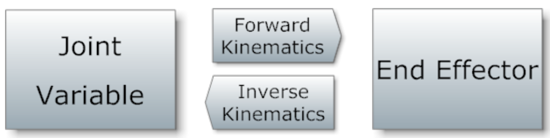


Fig. 1: The schematic representation of forward and inverse kinematics

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 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 [1]. The main goal of whole body balancing motion is to generate and stabilize consistent motions and adapt robot's behavior to the current situation [9].

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 in a 3D environment. Relying only on the robot's onboard sensors, joint encoders, an efficient whole body motions planning perform safe motions to robustly navigate in challenging scenes containing obstacles on the ground. Our approach determines the appropriate motion that consists of a sequence of actions according to the detected obstacle using monocular camera. As demonstrated in practical experiments with a NAO humanoid, our system leads to robust whole body movements in cluttered, multi-level environments containing objects of various shapes and sizes.

The remainder of this paper is structured as follows: related work is discussed in the Section II. Section III describes the humanoid robot and the 3D environment used for experimentation. Section IV illustrates the robustness and accuracy of our motion planning approach in experiments. Finally, Section V concludes the paper.

II. RELATED WORK

Humanoid motion planning has been studied intensively in the last few years. For instance [2] 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 [10] also investigated a dynamic pattern generator that provides dynamically feasible humanoid motion including both locomotion and task execution such as object transportation or manipulation. While [11] 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's 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 [12]. 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 [13]. The authors in [3] 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 [14] a detailed description of a walking algorithm is presented. This algorithm was designed for 3D simulation of locomotion and path planning of humanoid robots and was implemented on the NAO humanoid. The authors in [15] 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.

III. ACTION SET FOR NAO

In this section, the action set for the NAO humanoid (see fig. 2) that is used during the experimental evaluation is described.

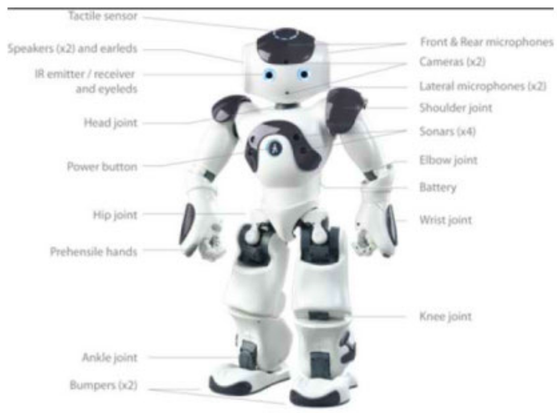


Fig. 2: Aldebaran NAO H25

A. NAO Robot Platform

NAO is a small-sized humanoid developed by Aldebaran Robotics [9]. It is 58 cm in height; 5.2kg weighs and has 25 degrees of freedom. 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 fig. 3 [9], [2].

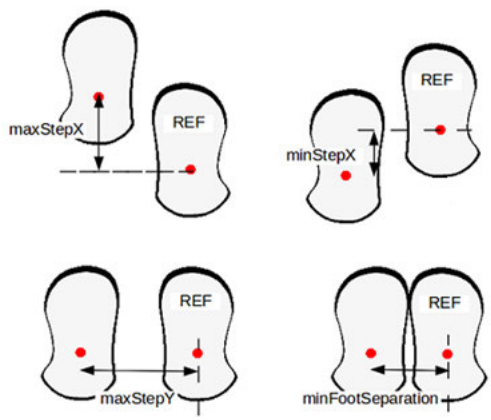
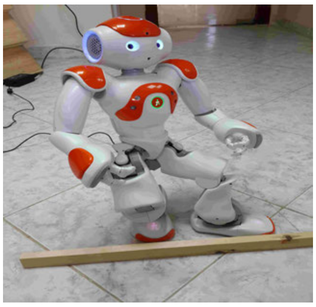


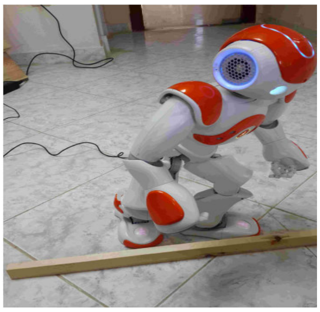
Fig. 3: Clip with maximum outreach [9].

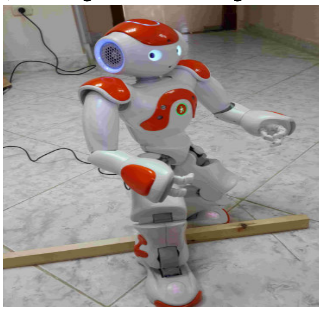
B. Motion Design

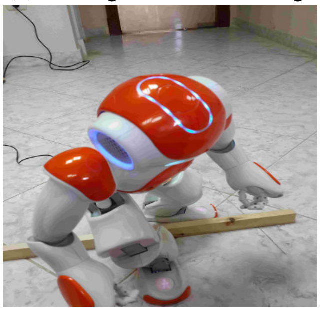
A kinesthetic teaching is applied to enable the robot to overcome these limitations. Here, Choregraphe [16], a graphical tool developed by Aldebaran Robotics, and python programming language are used to program the NAO H25 humanoid. A special motion design, inspired from [2] and [17], is presented which allows the robot to step onto or step over/down an obstacle according to the shape of the obstacle. In the designed motion, the feet are placed at an angle of 60°, which is the basis for the other actions. Then the robot will move its balance to that leg L1 (the leg with the angle 60°) and move the other leg L2 freely; after that the balance is moved to L2 and L1 moves to be beside L2 and then the balancing is made on both legs as shown in fig. 4.

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 motion of the step on/down actions is similar to the step over motion but the swing foot is placed at a different height.


(a) Placing left foot at angle 60°


(b) Moving balance to left leg


(c) Step over obstacle


(d) Balance on right leg

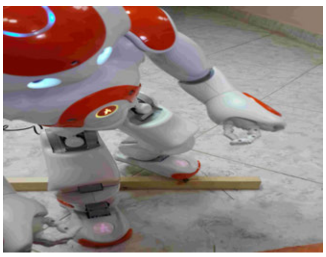
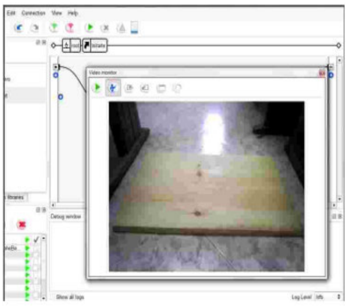
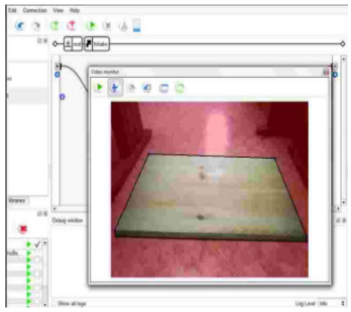

(e) Moving left leg

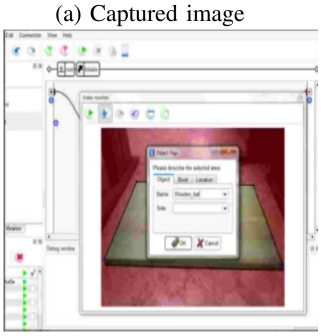
Fig. 4: Designed motion step

C. 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 [16]. After the images are learned and stored in the database of NAO, the object recognition module should be tested to assure that the robot is able to identify the correct object when recognized in the environment. During the learning phase (see fig. 5), once the image is captured using NAO's cameras as in fig. 5a, the perimeter of the object of the captured image is manually determined as shown in fig. 5b. After that a name is assigned to the determined object as shown in fig. 5c. Then a message appear to show the success (see fig. 5d)or fail (see fig. 6) of the process of learning, then the image is stored in NAO's database. Once all images are stored into NAO's database, NAO will be able to perform object recognition as shown in fig. 7.


(a) Captured image


(b) Object determination


(c) Naming object

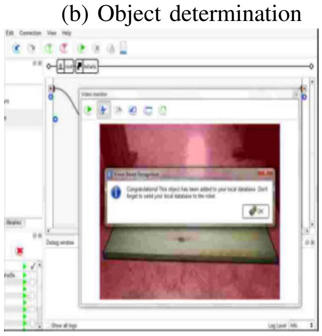

(d) Object learned result

Fig. 5: Object learning phase

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 [9]. Every detected key-point in the current image is matched with only one learned key-point in the database. If scores 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

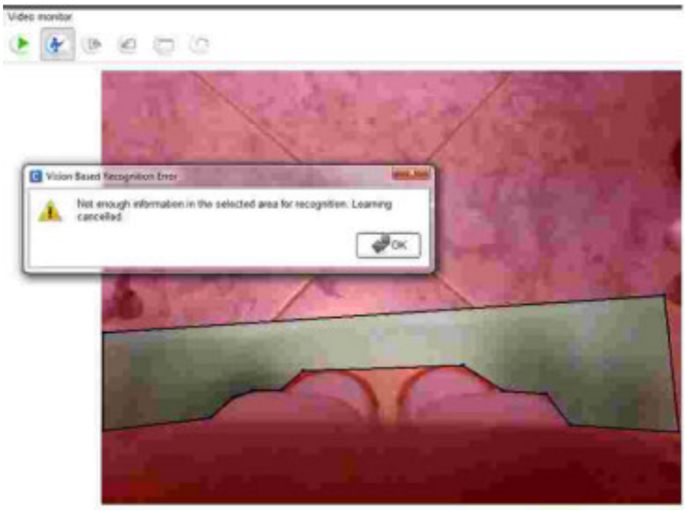


Fig. 6: Example of wrong learning

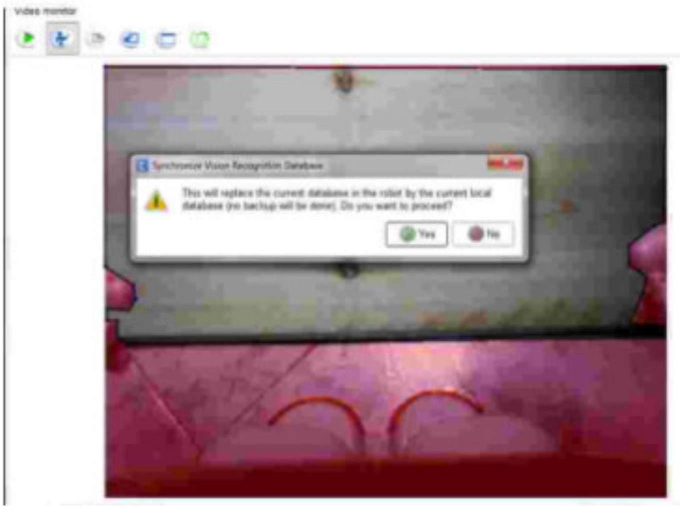


Fig. 7: Uploading learned image to NAO Database

its detection rate [8].

IV. 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 by 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 [1], [7]. Our whole body balancing motion is designed using NAO own kinematics to control directly its effectors in the Cartesian space using an inverse kinematics solver. We use the Generalized Inverse Kinematics which 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 balance, keeping a foot fixed, etc.

Afterwards, the capabilities of our motion system are demonstrated in a series of real world experiments. All experiments were carried out with NAO H25 humanoid robot. In the experiments presented, the robot moves 3 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 3 steps forward. In the case there is an obstacle recognized the robot had to execute stable whole body motions in order to deal with it.

The experiments carried out for robot stepping over a wooden bar of width of 40 cm, height of 3.5 cm, and depth of 2 cm shown in fig. 8; steeping onto a wooden bar of width of 40 cm, height of 2 cm and depth of 40 cm shown in fig. 9; and stepping down from that bar to the ground shown in fig. 10. All figures show still frames of a video sequence where our robot successfully steps over, onto, and down the wooden bar. The algorithm implemented is the same for all motions; the only exception is the height of its leg. As 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, the robot will step on/down that bar and will move its leg on/down it. Also, the execution time of all motions is quite similar, as it takes 45 seconds form the robot to perform step over motion and 42 seconds to perform step onto/down motion.

We perform a quantitative evaluation of our approach for accurate step over, onto/down an obstacle. The success rate of executing these actions is evaluated using only the onboard sensors; the robot is able to step over, onto/down the wooden bar six 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 fails to override the obstacle and sometimes falls.

The robot may also fail to override the obstacle if the distance between its feet and the object isn't appropriate. As the robot's camera has a limitation in providing depth information, the distance between the robot's feet and the obstacle isn't known. In the case the obstacle is located at a distance smaller than a suitable margin to the robot, the robot will hit the obstacle while moving its leg which leads to a change in the 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 bar which also 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 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 will fall. Another case, if the time of execution is too long, to allow the robot to finish the action it is preforming,

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

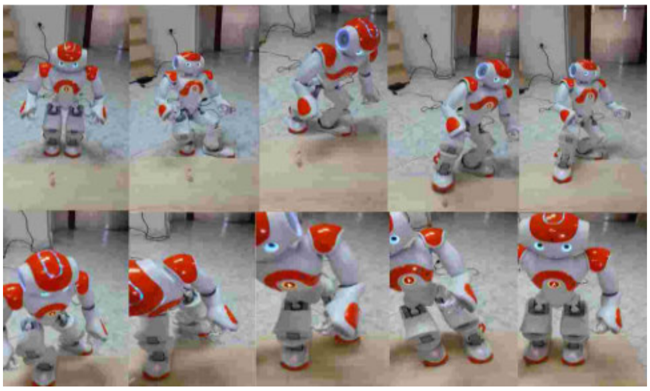


Fig. 9: NAO stepping on a wooden obstacle of height 2 cm and depth 40 cm using planned whole body motion

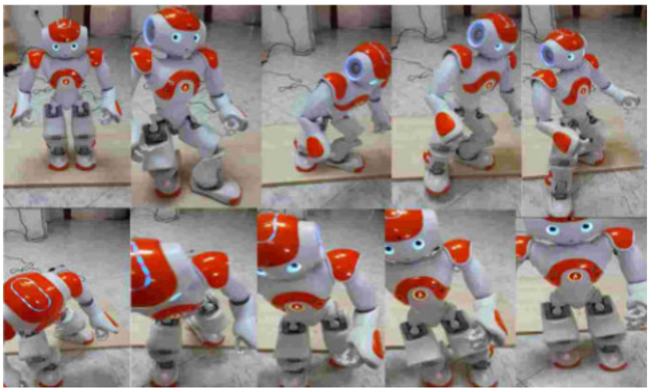


Fig. 10: NAO stepping down from a wooden obstacle of height 2 cm and depth 40 cm using planned whole body motion

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.

V. 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. Our system includes recognizing objects stored into the NAO's database using NAO's camera. Based on the recognized object the robot executes specific motions to deal with the obstacle recognized. The robot can't execute these motions seven time consequently because the heating of the joints. 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. The robot's camera has a limitation that it can't provide the distance between the robot and the obstacle; to overcome this limitation two images can be captured by moving the robot head's yaw angle in order to obtain a stereo image. As demonstrated in 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.

VI. Future Work

After verifying the validity of the designed whole body motion for NAO humanoid robot to perform complex motions. A lot of work remains to be done in order to achieve high degree of robustness and automation. First, evaluating the performance of the motion if the feet are placed at an angle of 30° instead of 60°, and see the robot capabilities to perform complex motions. Second, reducing the time spent in a critical position in order to decrease the heating rate of the joints. Third, trying to perform more motions like climbing the stairs up or down, climbing ramp of 20 inclination up or down using the designed sequence of motions.

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