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A humanoid robot localization method for biped navigation in human-living environments

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***Abstract*—In real-time footstep planning for the humanoid robot, it is needed to obtain the accurate location of its foot placements. However, existing methods only needed to obtain the localization of the robot as a particle, which did not specifically consider the localization of its foot placements. This paper presents foot placement localization method for humanoid robot in human-living environments. A Kinect sensor was first used to obtain the digital map of the global environment and the position and orientation of the head of the robot was then extracted. The position and orientation of the foot placement was then calculated based on the spatial geometric relationship between the head and the target foot. The proposed method was used in the real time footstep planning in dynamic human-living environments. Experimental results validated its feasibility.**

***Keywords*—humanoid robot, biped locomotion, footstep, localization**

I. Introduction

In recent years, the problem of aging population is becoming more and more serious. How to use robots to help the elderly has become a hot spot of research. Compared to wheeled robots, humanoid robots has the ability to climb stairs and step over obstacles, thus is preferred to server elderly in human-living environment.

Locomotion planning is one of the most challenging problem to be addressed for the biped robots to accomplish high-level tasks. Regarding the complex environment and the stability problems during walking, footstep planning is not similar as the conventional path planning. Kuffner *et al*. [1]-[3] proposed a sampling-based approach for global footstep planning. Chestnut *et al*. [4] improved Kuffner *et al's* method by using a heuristic search algorithm (A*) to generate the foot sequence at the dynamically adjustable action model. Xia et al. [5]-[7] firstly introduce a randomized algorithm to footstep planning. In their algorithm, rapidly exploring random trees (RRT) algorithm is used to solve the failed planning problem in closed or narrow environments.

However, these algorithm are aimed at the static environment. In the static environment, one only needs to plan the footstep once, and does not need to update these planned footstep sequence. While in the human-living environment, as both the obstacle and target are dynamic, it is necessary to replan and update the footstep in real time. For real time footstep planning, the footstep localization which corresponds to the initial position of the footstep is needed.

For the robot localization, most existing methods [8]-[11] just involved the localization of the robot by regarding it as one point and estimate the position of the point, and did not consider the localization of footstep. This paper propose a framework for footstep localization based on a visual sensor. In the framework, a visual sensor are adopted to obtain the global map of the environment and extract the marked point set on the robot head. The extracted marked point is used to estimate the position and direction of the robot head. Then, the position of the footstep is calculated from the spatial geometric relationship between the head and foot. In the experiments, the Kinect [12] was employed as the visual sensor to obtain the global map and extract the marked point. Nao [13] was employed as the humanoid robot for physical experiments. Experimental results verified the feasibility of the proposed footstep localization method.

The remainder of this paper is organized as follows. Section II introduces the framework of footstep planning. Section III presents the framework of the footstep localization Section IV describes the localization approach. Section V gives the experimental results, and Section VI concludes this paper.

II. Introduction of footstep planning

The sampling-based footstep planner is an algorithm using a search tree to generate the footstep sequence which is based on footstep placement sampling. The work includes the following two parts:

1) Footstep placement model is a set of selected feasible footstep placements for swing foot in reachable region. The selection of gait determines the distribution of the robot footstep placements, footstep placements and gait are one-to-one relationship. In order to realize the typical gait and make the robot be able to go forward, make a turn, make a sidewards etc, we build an element step library which containing 10 element steps as the database for footstep planner (Fig. 1).

2) The search tree is expanded by footstep placements sampling, A* search is utilized to compute the foot sequence.

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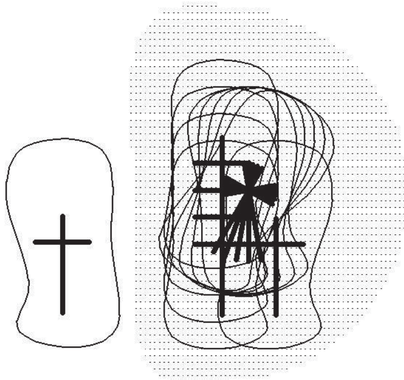

Fig. 1. Footstep placements for swing foot. Left rectangle indicates the support foot, right rectangles indicate the feasible footstep placements for the swing foot. The center of the cross in each rectangle indicate the coordinate of the footstep placement defined.

Collision checking based on the environment and possible landing footprint are the constraints for the expanding. The search tree builds from the initial footstep placement of the humanoid robot and completes until one expanding footstep placement reaches the goal region.

III. Framework of the footstep localization

A. Footstep-Gesture Transition

The planning cycle of the footstep planner is from one footstep-gesture transition to the other. Fig. 2 shows the footstep-gesture transition model while supporting foot is left and swing foot is right. The based footstep conforms to the sampled reachable region., it would require the robot to place the swing foot to the desired footstep placement. However, for continuous walking process, the steps are always changing between left and right and the control of the CoM to maintain the stability is required.

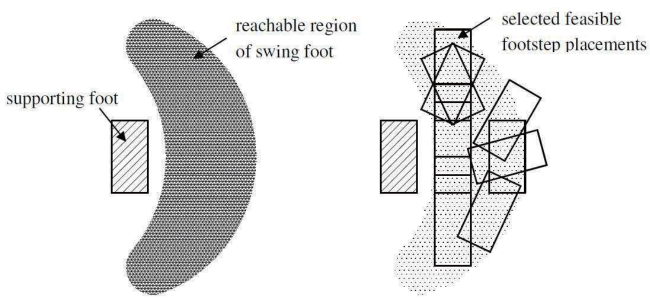

Fig. 2. Footstep transition model: left - The reachable region of the swing foot; right - a set of selected feasible footstep placements are predefined correspond to the robot stable strategy [6].

B. Footstep localization

When robots are walking in the environment, there are zones where robot feet cannot be captured by visual sensor. It is difficult to obtain the position of the footstep directly. However, the corresponding relationship of the robot head and feet are fixed at footstep-gesture transition, and the position of the head is more easily to be obtained through the visual sensor. So instead of directly estimating the position of footstep, we first estimate the position and direction of the head, and then calculate the position of the footstep. The position and direction of the head is estimated from the marked region set on the robot head. The block diagram of the proposed footstep localization is shown in Fig. 3 .

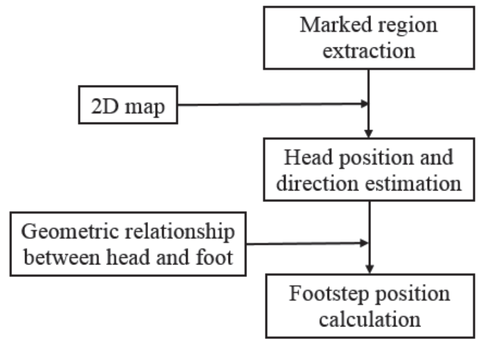

Fig. 3. Footstep localization for biped robot.

IV. Approaches

A. Calibration of Kinect

Camera calibration is a necessary step in extracting metric information from 2D images. Zhang's method has been considered as an efficient method for camera calibration [14]. Using his method, one first needs to place the checkboard plate in the area where camera can capture (Fig. 4). Assuming the plate

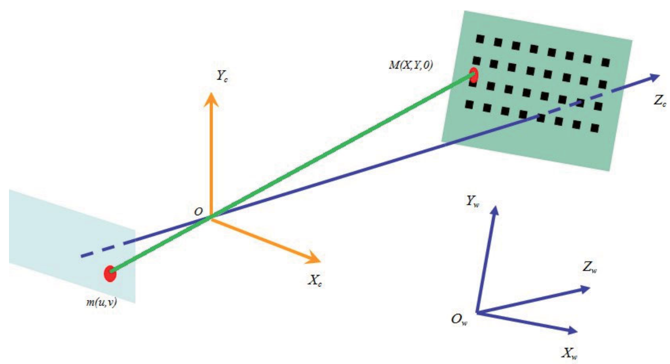

Fig. 4. Camera calibration: (*Xc*, *Yc*, *Zc*) indicate the camera coordinate, (*Xw*, *Yw*, *Zw*) indicate the world coordinate.

coordinate system in the world plane of Z=0, the relationship between the world coordinate system and the camera coordinate system can be described through the following formulas:

$$s\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = K\begin{bmatrix} r_1 & r_2 & t \end{bmatrix}\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \tag{1}$$

$$\begin{cases} H = \begin{bmatrix} h_1 & h_2 & h_3 \end{bmatrix} = \lambda K\begin{bmatrix} r_1 & r_2 & t \end{bmatrix} \\ r_1 = \frac{1}{\lambda}K^{-1}h_1, \;\; r_2 = \frac{1}{\lambda}K^{-1}h_2 \end{cases} \tag{2}$$

where K indicates the intrinsic matrix of the camera, $[X, Y, 1]^T$ is the homogeneous coordinates of points on the plate plane, $[u, v, 1]$ is the homogeneous coordinates of points on the image plane which are projection corresponding to plate plane, $[r_1,\ r_2]$ is the rotation matrix, and t is the translation vector.

According to the property of the rotation matrix, ${r_1}^T r_2$ =0 and $||r_1||$=$||r_2||$=1,each image can obtain the following two basic constraints of the intrinsic matrix:

$$\begin{cases} h_1^T K^{-T} K^{-1} h_2 = 0 \\ h_1^T K^{-T} K^{-1} h_1 = h_2^T K^{-T} K^{-1} h_2 \end{cases} \tag{3}$$

Because the camera have 5 unknown parameters, if not less than three images are used, we can obtain the only solution of K and other intrinsic parameters.

B. Position and direction estimation of the robot head

Due to the complexity of the structure of the humanoid robot, we set three marked regions on the robot head. Rectangular black zones were used as they can increase the accuracy for capturing the position of the marked region (Fig. 5).

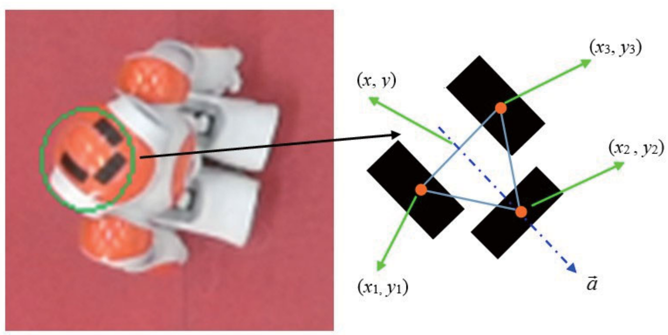

Fig. 5. Marked regions on robot.

We define that: $(x,\ y)$ indicates head position; vector indicates head direction. Three marked region are set on the robots, $(x_1,\ y_1)$, $(x_2,\ y_2)$, $(x_3,\ y_3)$ are the center of each mark which can be gained by Kinect, the relationship between the coordinates is as follows.

$$\begin{bmatrix} x \\ y \\ \vec{a} \end{bmatrix} = \begin{bmatrix} (x_1 + x_3)/2 \\ (y_1 + y_3)/2 \\ (x_2 - x,\ y_2 - y) \end{bmatrix} \tag{4}$$

$(x_1,\ y_1)$, $(x_2,\ y_2)$, and $(x_3,\ y_3)$ are estimated from the plane with a distance h (the height of the robot head) from the plane of robot foot using a single camera. Due the property of pinhole camera model, there are errors between the estimated position and the real position at the robot foot plane. It is needed to calculate the real position to eliminate the error through the following geometric relationships (Fig. 6).

$$\begin{bmatrix} x_5 \\ y_5 \\ h/H \end{bmatrix} = \begin{bmatrix} x_0 \\ y_0 \\ \frac{\sqrt{(x_5-X)^2+(y_5-Y)^2}}{\sqrt{(x_4-X)^2+(y_4-Y)^2}} \end{bmatrix} \tag{5}$$

Where h is the height of the robots head at the footstep-gesture transition, H is the height of the camera, and (X, Y) is the coordinate of the camera projected to the footstep plane. H and (X, Y) are calculated from translation vectors, intrinsic matrix and rotation matrices of the camera.

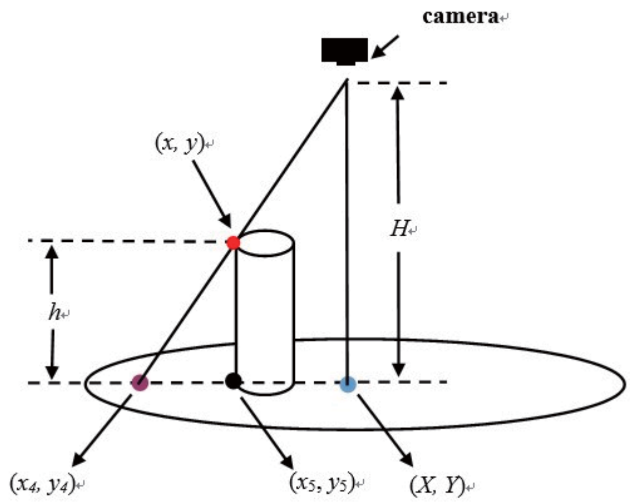

Fig. 6. Spatial geometric relationships, $(x_4,\ y_4)$ is the position of mark in 2D image, $(x,\ y,\ h)$ is the real three-dimensional position.

C. Position calculation of the footstep

Generally, there are 12 degrees of freedom (DOF) to control the biped walking of humanoid robot. Thus, we use 12 DOF to illustrate the calculation if the footstep from the head position and direction.

Fig. 7 shows the spatial structure of the 12 DOF for biped walking, where 1-12 coordinate system indicate the corresponding DOF, and 0 indicates the world coordinate system. The relationship between joints can be described by

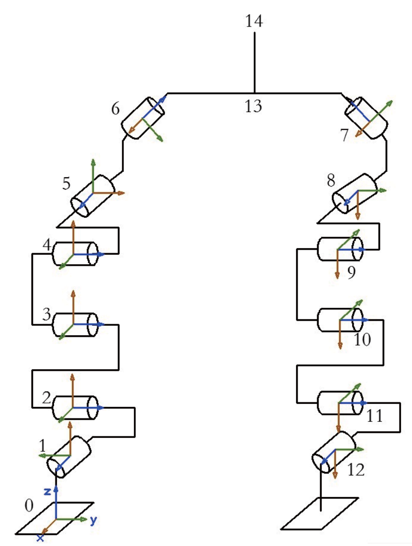

Fig. 7. The corresponding DOF of robot at the footstep-gesture transition.

G_{n_m} (rotation matrix from joint n to joint m) and L_{n_m} (transition vector from joint n to joint m), which are given as follows:

$$G = \begin{bmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad L = [\ x \quad y \quad z\ ] \tag{6}$$

where is the rotation angle, x, y and z are the translation distance in x, y and z directions respectively. The position of the footstep can be calculated from the head position and direction by using the following two equations.

$$\begin{cases} RR_{left\_foot} = L_{0\_12} + G_{0\_12}L_{12\_11} + G_{0\_11}L_{11\_10} + \\ G_{0\_10}L_{10\_9} + G_{0\_9}L_{9\_8} + G_{0\_8}L_{8\_7} + G_{0\_7}L_{7\_14} \\ R_{left\_foot} = \begin{pmatrix} x & y & h \end{pmatrix} {RR_{left\_foot}}^{-1} \\ \\ RR_{right\_foot} = L_{0\_1} + G_{0\_1}L_{1\_2} + G_{0\_2}L_{2\_3} + \\ G_{0\_3}L_{3\_4} + G_{0\_4}L_{4\_5} + G_{0\_5}L_{5\_6} + G_{0\_6}L_{6\_14} \\ R_{right\_foot} = \begin{pmatrix} x & y & h \end{pmatrix} {RR_{right\_foot}}^{-1} \end{cases} \quad (7)$$

Due to stiffness of the robot, both G and L are corrected based on the theoretical value.

V. Experiments and Results

In our experiments, an Aldebaran NAO robot with 25 degrees of freedom is used as the biped robot model and a Kinect is adopted as the visual sensor. The Kinect is used as it can generate 3D Depth Map for footstep planner and capturing the mark on the head of robot. Fig. 8 shows the virtual experimental scene set up by webots[15]. The testing scene is a 2m*2m square area, Kinect is installed onto the ceiling about 2740mm height from the floor. The camera resolution is 640*480, and the efficient area is 430*430.

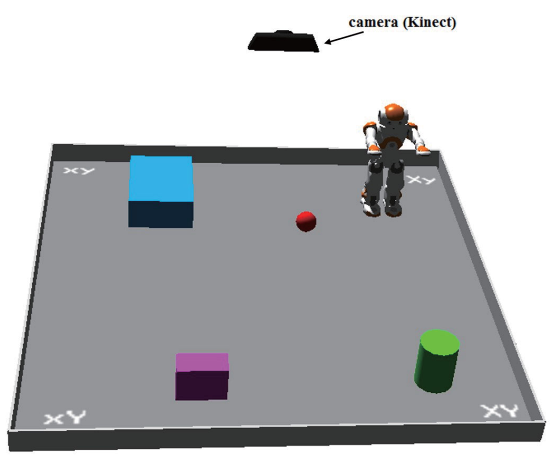

Fig. 8. A virtual scene for experimental testing. Kinect sensor is install onto the ceiling, the size of test environment is 2*2 m.

For the camera calibration, a checkerboard with 14*14 blocks (each block with a size of 50*50mm) was employed. 12 images were captured to estimate the intrinsic matrix and translation vector (Fig. 9).

Fig. 10 (a) shows physical experimental scene of the right foot support model, Fig. 10 (b) shows the extracted position of footstep.

For the quantitative error estimation of the footstep localization, 15 groups of each footstep-gesture transition were conducted. The real position and estimated position of the tested 30 groups of data were shown in Fig. 11.

When the supporting foot is left foot, the error is 16.821±11.64mm, and when the supporting foot is the right foot, the error is 15.445±9.197mm. The average error in our experiments is much better than the average error which was reduced to 73.3mm by the Kalman filter approach In [10]. Fig. 12 shows the error distribution. The average error satisfy the demand of the accuracy for footstep planning.

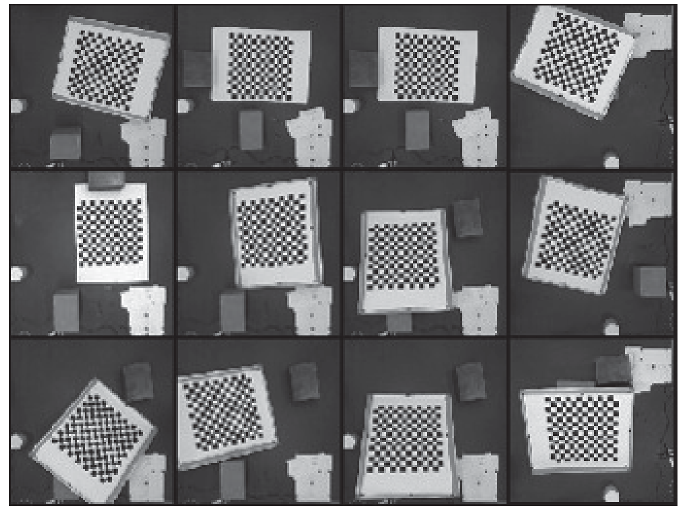

Fig. 9. The process of camera calibration, 12 images are used to calculated the camera parameters.

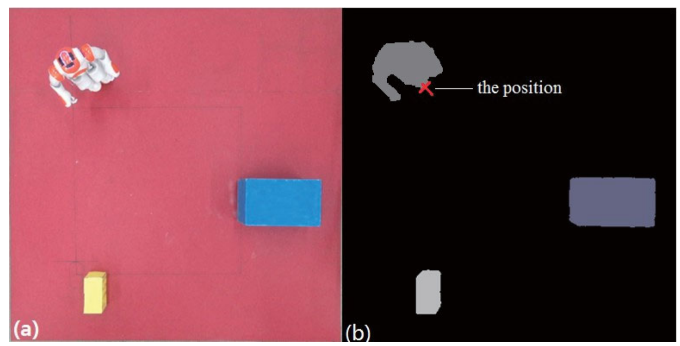

Fig. 10. (a). The experiment scene when robots support foot is right. (b). The position calculated by programs, red cross is the position.

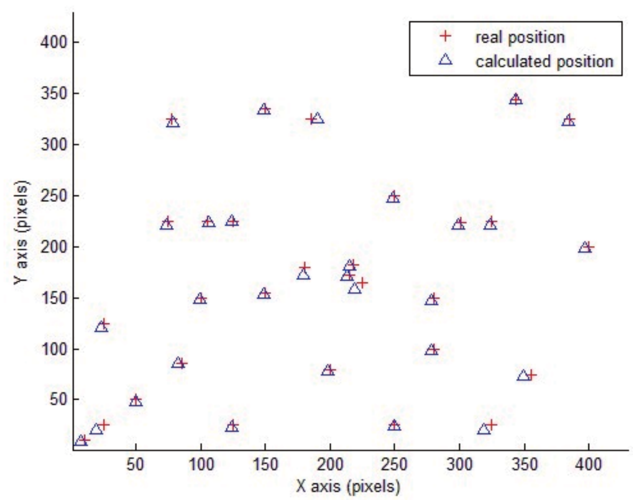

Fig. 11. The tested groups of data contain left and right model.

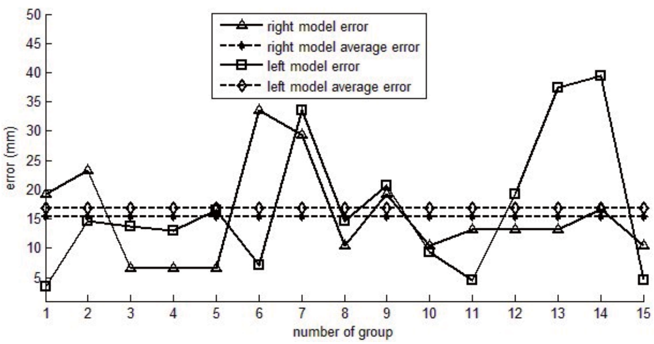

Fig. 12. Errors and average error at different supporting foot model.

We verify the feasibility of the presented localization method for biped navigation in human-living environment by the webots-based simulator. In this experiment, a red ball represented the target point, the robot would track the goal point until the robot reach it. Both the target and the obstacle (a blue box) were movable to represent the human-living environment. Fig.13 shows the procedure of the navigation. When environment changes, footstep planner will replan a new footstep sequence through using the current footstep position as the initial position which is estimated by localization. The robot will adjust the footstep sequence to reach the target. The result of the experiments proves the feasibility of the localization method.

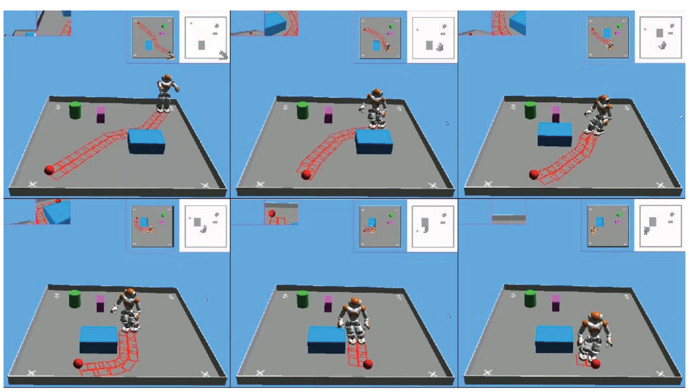

Fig. 13. The navigation procedure in webots-based simulator.

VI. Conclusion and Future Works

In the real-time footstep planning, the position and direction of the footstep is necessary. This paper presents a visual based localization method for biped robot footstep. The presented method has been tested on a physical robot platform in an experimental scene. Testing results verified that the presented method is feasible for the footstep localization of biped robot footstep planning. The localization error satisfy the demand of the accuracy for footstep planning. Future work will be focused on improving the robustness of the framework and the application of the proposed method to the footstep planning of biped robot in physical human-living environment.

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