Humanoid Robot Torso Motion Planning Based on Manipulator Pose Dexterity Index

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Abstract. Humanoid robot operation task is mainly executed with arm-torso system. The torso system can effectively increase humanoid robot arm operation range and vision range of the humanoid robot, but it also increases the difficulty of the humanoid robot motion planning. Humanoid robot torso increases humanoid robot arm operation range by changing the pose of the robot arm base and it also reconstruct humanoid robot arm workspace pose dexterity. Humanoid robot torso position is optimized with manipulator pose dexterity in different humanoid robot arm sub-workspace. For different operation tasks, the indicators to be considered for the position of the torso joint include: whether the robot arm can grasp the target position, whether the specified motion trajectory can be reached, and whether it has higher dexterity in specified motion trajectory. In this paper, we consider higher manipulator pose dexterity sub-workspace is better operation position, and we introduce a scheme to optimize torso joint position.

1. Introduction
Humans learn to grasp object when they grow up, they grasp object in dexterous orientation with motion of torso and manipulator subconsciously. And also we can know which place is easy to reach and which are difficult to approach, it seems that we have a map/model of our arm’s capabilities and dexterity. To a human robot, a similar map of manipulator capability and dexterity is meaningful [1]. The information can be used in robot design stage to extend its workspace or maximize robot dexterous region of workspace, and it could apply in humanoid torso motion planning.
There are many different manipulator dexterity description index, such as, Klelin et al, [2] use ratio of maximum Jacobian matrix singular value and minimum Jacobian matrix singular value as condition number to optimize manipulator joint angles. When the condition number has an optimal value of 1, the configuration has been termed isotropic. With the goal to obtain a global isotropy design parameter, Stocco et al. [3] optimized the ratio of the maximum and the condition number in whole workspace to obtain a global version of the condition number. Yoshikawa et al. [4] quantify the ease of arbitrarily changing the position and orientation of the end-effector with manipulability ellipsoid. Zacharias et al. emphasized the importance of being able to easily find robot target configurations that solve the subtask and facilitate the subsequent process of finding paths in a task planning process in paper [5]. Then they proposed a capability map to analysis manipulator workspace [1]. They focus on manipulator directional structures, by positioning of the torso, manipulator could reach target in...
highest reachability index. Also, A pose dexterity map is created with pose dexterity index in our previous article [6]. The basic function of the humanoid robot motion planning is to allocate the system motion resources, coordinate the resource allocation with time and space, form the optimal or better motion output, and realize the input task [7]. The basic operational task form of the robot can be divided into two types: continuous trajectory tracking and realization of discrete directional target constraint tasks. The continuous trajectory tracking problem needs to solve the inverse solution planning problem, while the other one needs to plan the smooth continuous joint motion trajectory that satisfies the discrete position constraint in the feasible variable space. The two types of tasks are different, but in the same way, the smooth joint continuous trajectory of the time base is required as the motion output or task realization method. The trajectory planning for redundant manipulators is mainly dominated by the former, while the other one is mostly used for large-scale mobile trajectory planning of mobile platforms.

In the multi-degree-of-freedom robot system motion planning, redundant degree of freedom or the solution is not unique, the unique solution must be determined by the performance index function optimization. The weighted sum mode combination performance index function to achieve multi-objective decision-making to obtain a unique solution, which is the most common multi-objective decision-making method. However, the application of weighting and performance functions is inherently flawed [8], because the objective functions have the effect of each other[9]. This makes the adjustment strategy of the weight parameter design one of the determinants of the performance of the weighted objective function algorithm. When the combined objective function needs to be two, the adjustment weight strategy is simple, but when the combined objective function needs to be three or more The incompatibility caused by different unit dimensions, different rate of change, and different ranges of values of the objective function [10] makes it difficult to design a weight adjustment strategy with unclear physical meaning. In this paper, a torso motion planning method with manipulator dexterity index is proposed to optimize humanoid torso trajectory. The remainder of this paper is organized as follows. Section II details our HIT humanoid robot. In section III, the dexterity map with different pose dexterity index range is proposed. In section IV, high pose dexterity index zone transform with torso movement, section V humanoid robot torso position optimized with manipulator pose dexterity index data, section VI introduces experiment to verify the proposed algorithm and section VII concludes this paper.

2. Robot systems
HIT humanoid robot, as shown in Figure 1, is designed with “from up to down” sequence and consists of an anthropomorphic upper body which is mounted on a wheeled mobile robot. The upper body carries a 3-DOF binocular head [11], two extremities, each of them consists a 7-DOF humanoid arm [12] and a 15-DOF five-fingered dexterous hand [13], and a torso with two joints [14]. The wheeled mobile robot is employed as a first solution to provide mobility to robot when main focus of design was on the stable operation of upper body, future developments will concentrate on a new lower limbs of mobility. The initial specifications for design of the robot is to be a versatile platform for research on replicating human in special environments. Therefore, it should have an anthropomorphic kinematic configuration for research on bi-manual grasping in addition of a human-like appearance. More detail is presented in [15].

3. The dexterity map with different pose dexterity index range
Humans grasp an object most in a dexterous orientation when they could reach the object in many orientations, it facilitates the following operations and in case of some unexpected matters. The same operation criterion is in point for HIT humanoid robot, whose design is oriented at human model. In general, each manipulator has different orientation dexterity in smaller subspace due to its configuration and D-H parameters. We show that manipulator capabilities result in end-effector pose dexterity specific to sub-workspace regions and those structures can be expressed in a visualization
map. First, we defined manipulator pose dexterity in sub-workspace with sum of feasible arm angle in different orientations. In the second step, manipulator pose dexterity map with different pose dexterity index range is generated with the data. Right arm of HIT humanoid robot is employed as an example.

### 3.1. The pose dexterity index generated

$R(p_{i,j,k})$ represents quantity of reachable orientations in each sub-workspace center. In paper [16], Zacharias assign a measure called the reachability index $D$ to characterize the workspace. But to a redundant manipulator as used in our humanoid robot, the reachability index $D$ can not represent manipulator dexterity in region enclosed by sub-workspace. In this paper, we consider feasible arm angle range as a significant value to refer redundant manipulator dexterity, the pose dexterity index $D_{\text{redundant}}$ in each sub-workspace is defined by,

$$D_{\text{redundant}} = \sum_{m=1}^{n_p} \sum_{n=1}^{n_{\theta}} (\Psi \times \text{Reachable}(T_{r,j,k,m,n})) / (2\pi \times n_p \times n_{\theta})$$

(1)

Where, $\text{Reachable}(T_{r,j,k,m,n}) = \begin{cases} 1 & \text{if pose can be reached} \\ 0 & \text{otherwise} \end{cases}$.

### 3.2. Sub-workspace zone with different pose dexterity index range

According to the dexterity of the workspace of the robot arm, the robot workspace is divided into different dexterity workspace areas. As can be calculated with equation (1), the position of the humanoid robot workspace is from 0 to 19.41. The workspace of the robot arm is divided into 4 layers according to the dexterity, and the dexterity of each layer is gradually increased, which means that the mechanical arm has better operability in the workspace of this layer. Sub-workspace that yield different dexterity ranges for the robot arms are shown in figure 2.

In figure 2, light black part in the figure is the complete workspace of the robot arm, and the red part is the sub-workspace area where the mechanical arm is dexterity in different positions. At this time, the sub-workspace area defining the robot arm position dexterity $D_{r}>13$ is a high-dexterity workspace of the robot arm. When the humanoid robot arm moves in the workspace region, the humanoid robot arm has better dexterity.
Figure 2. Sub-workspace zone with different pose dexterity index range

4. High pose dexterity index zone transform with torso movement

One of the main goals of the humanoid robot torso motion is to assist the robotic arm to complete the operational tasks, providing a more dexterous workspace for the robotic arm in specific operational tasks. When the operation target is outside the workspace of humanoid robot arm, the arm movement of the robot arm envelops the operation target by the movement of the humanoid torso, so that the robot arm can reach the position of operation target; When the operation target is in the low-index workspace of the robot arm, the humanoid arm cannot realize complicated operation, the movement of humanoid robot torso makes the robot arm high-dexterity workspace envelop operation target, thereby achieving dexterous operation of the operation target.

When the humanoid robot moves torso joint, the pedestal posture of the humanoid robot arm changes accordingly, resulting in a change in the dexterity of the workspace of the humanoid robot arm, as shown in figure 3. As can be seen from the illustration, the movement of the torso joint of humanoid robot has a significant influence in high-dexterity workspace distribution. For different dexterous operational task requirements, the manipulator torso joint angle should be changed to achieve the operability of humanoid arm to improve position of operation target, thereby completing the specified operation task.

Figure 3. Example of high pose dexterity index zone transform with torso movement

5. Humanoid robot torso position optimized with manipulator pose dexterity index data

During the operation of the humanoid robot, due to the different relative positions of the base of the robot arm and operation target, the operation target in the dexterity workspace of humanoid robot arm. In order to realize dexterous operation when the robot arm is close to the operation target, this paper through changing position of humanoid robot arm base by the movement of the torso, thereby changing the relative positional relationship between the operation target and the base of humanoid robot arm, so that the dexterity workspace area of humanoid robot arm completely envelops the operation target.

In order to optimize the position of the torso joint, torso joint movement range is first divided equally into m×n group, and then torso joint angle group of the robot dexterous operation space is fully
enveloped under different torso joint angle conditions. The minimum torso joint movement angle is selected as optimal torso joint position. The specific optimization flow is introducing in Table 1.

6. Experiments

6.1. Torso-arm grasp scenario for HIT humanoid robot
In this section, one application scenarios are verified with manipulator pose dexterity map. For example, in figure 4, target bottle is in lower dexterity index region of manipulator workspace, the bottle can be overlaid with the region of the pose dexterity map where the dexterity index is highest by moving humanoid robot torso. Which means manipulator could grasp the target with more alternatives. Thus torso motion could be planning with manipulator pose dexterity map to optimally reach objects.

Table 1. Torso position optimized with pose dexterity index

| Algorithm 1: Torso position optimized with pose dexterity index |
|---------------------------------------------------------------|
| **Initial** | P_{target} \leftarrow Vision_{system} |
| | $\theta_w (\theta_1, \theta_2) \in \mathbb{R}^{m \times n}$ \leftarrow Torso_Discretization |
| for $k = 1$ to $m \times n$ do |
| | $T_k \leftarrow Function_{Trans}(\theta_{wk})$ |
| | $P_k \leftarrow Function_{Inverse}(T_k)$ |
| | if $P_k \in D_{High}$ do |
| | $\theta_{opt} = \theta_{wk}$ |
| | end if |
| end for |
| $\theta_{opt} \leftarrow Function_{min}(\theta_{opt})$ |

Figure 4. Target grasp scenario for HIT humanoid robot
When the operation target is in the unobtrusive/non-dexterity grasping state in the erect state of the torso joint, after the movement of the torso joint, the operation target can be in the dexterity grasping range of the mechanical arm, and the coordinated movement of torso can achieve effective grasping of the operation target. The initial position of the experimental operation target sets $p_{target} = [1.00 \ 0 \ 0.85]$. Through the inverse kinematics calculation, it can be seen that the operation
target is out of humanoid arm workspace with rigid torso, that is, under the condition of the torso joint upright, the humanoid robot can not achieve effective operation of the target. Therefore, it is necessary to move torso joint to finish grasping task.

6.2. Torso position optimized with pose dexterity index distribution

The torso joint angle optimization was performed according to the torso joint optimization method proposed in the section. Firstly, the torso joint angle range $[-90^\circ~90^\circ; -45^\circ~135^\circ]$ is divided into $37 \times 19$ group joint angle with equal intervals $\Delta \theta_w = 5^\circ$. Then, the equivalent position $p'_\text{target}$ of the target initial position under the condition of torso joint upright with different sets of torso joint group is calculated by inverse kinematics of humanoid robot. Finally, pose dexterity index in sub-workspace of the humanoid robot can be obtained by the equivalent position. The pose dexterity index with different torso joint angles group $\theta_w$ are shown in figure 5.

![Figure 5. Pose dexterity index distribution of operation platform with dynamic torso](image1)

The white point in the figure is the pose dexterity index of arm at the target initial position $p_{\text{target}}$ under straight up torso condition. It can be seen from the figure 6 that when the torso is upright, the end of the humanoid arm cannot reach the target initial position at any angle. The torso joint angle of the inverse kinematics of the mechanical arm is basically distributed in the direction of the left and/or forward tilt of the torso, and it can be seen that the left turn and the forward until it has ability to increase dexterity index of target initial position. The same effect. by moving torso, the pose dexterity index of humanoid arm at initial position can be increased, and the circle is centered on the white point to obtain the nearest joint angle of dexterity index of different positions. Determine torso joint angle group $\theta_w = [15^\circ; 75^\circ]$ for the grasp task.

![Figure 6. Torso position optimized with manipulator pose dexterity index distribution](image2)

7. Conclusion

Structure is indeed present in a manipulator's workspace and can be captured in the form of a map. We develop the representation called manipulator pose dexterity map to capture the manipulator dexterity in its workspace. The manipulator pose dexterity can be computed offline for a specific manipulator. The map is anchored manipulator base and shift position when humanoid torso moves. When target is
out of manipulation workspace with rigid torso, optimizing torso position to accomplish task. And manipulator pose dexterity is used to optimize torso position with minimum energy. With the optimized torso joints angle, humanoid robots could use it to enhance humanoid arm manipulation ability. The ungraspable target with rigid torso can be reached with optimized torso joints angle. In further work, optimized torso joints combine with optimized manipulator joints to drive humanoid robot to accomplish task.

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