A Hierarchical Planning Strategy for Robotic Arms Based on Movement Rules of Human Arms*

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***Abstract* —In this paper, a motion framework of robotic arms for generating human-like movements is presented. Because of the limitation of the pages, this paper puts the emphasis on Hierarchical Planning Strategy (HPS) in motion framework. The HPS which decomposes the complete arm movements into a set of different motion processes corresponding to different states of motion is proposed according to the movement rules of human arms, and then the distance condition and the orientation condition are obtained. Meanwhile, the arm models in different planning hierarchies are built and the corresponding Human Performance Measures (HPM) are obtained. Finally, the efficiency of the HPS has been verified by comparing the experiments with the actual movements of human arms.**

Ⅰ. INTRODUCTION

The prediction of arm postures involving multidisciplinary knowledge in ergonomics, robotics and psychophysics has always been a focus and also a difficulty in researches on humanoid manipulators. It has captured scholars' interests of making manipulators act automatically as humans do. Human-like motion can give people a sense of security and comfort and enhance the efficiency. The assistive robots such as the wearable exoskeleton robot can support or enhance natural body movements for the disabled people. Generating human-like natural movements becomes even more important to the assistive robots, which affects the treatment outcomes. Accurate prediction method of arm postures can improve human-like motion, at present, the researches on the prediction of arm postures mainly focus on two aspects: states and processes. Researchers focusing on the former study some special moments (such as the initial moment or the final moment) and think the models and motion states of arms are the same in the entire movement. Those studying the latter consider the entire movement as a whole. A lot of achievements have been obtained in the researches on states in both ergonomics and robotics [1]-[4]. As to the researches on processes, [5] observed that lower arm pronation was preferred to orient the hand compared to arm pivoting and that wrist angles were small and near the wrist neutral position after grasping, and [6] obtained the same results in experiments. There are some further researches on the basis of this [7]-[8]. It can be found through the researches on processes that the motion states of human arms change during the movement and that the entire movement may be a set of different motion processes.

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The purposes of previous researches on processes are mostly to simplify models of human arms or to satisfy some special calculating method but not to seek the fundamental internal mechanism of human arm movement. Most researches are experience-based judgments without theoretical foundations and no systems are formed. By observing the states of moving human arms, we propose several movement assumptions of human arms. On the basis of the assumptions, we systematically analyze the arm postures in motion and propose the Hierarchical Planning Strategy according to the movement rules of human arms. Furthermore, an intelligent decision based on the HPS is constructed to select the planning method for robotic arms and the motion framework of robotic arms is built. In this paper, we focus on the HPS, and other parts will be showed in the next paper.

Ⅱ. THE MOTION FRAMEWORK OF ROBOTIC ARMS

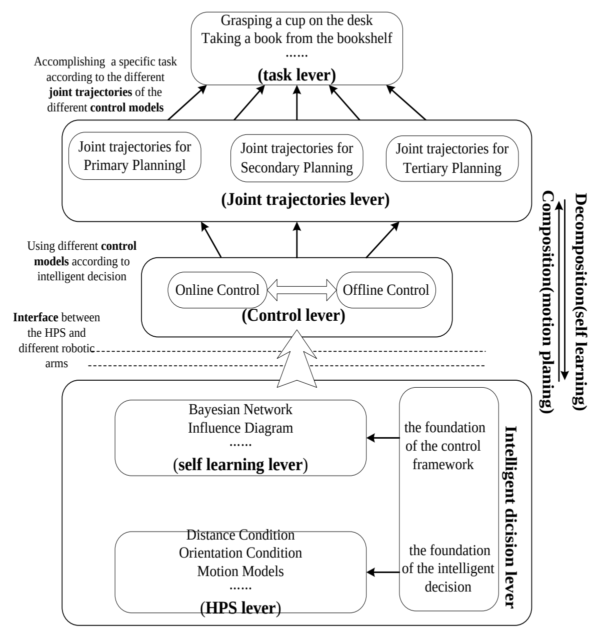


Fig.1. The motion framework.

This section offers a brief overview of the motion framework. In Fig.1, the motion framework can be divided into four levels: task level, joint trajectories level, control level and intelligent decision level. The intelligent decision level is the foundation of the motion framework and the HPS is the foundation of the intelligent decision level. Through the interface between the intelligent decision level and different manipulator platforms, the joint trajectories of a certain platform can be generated to accomplish required tasks, which realizes the universality of this method. Understandably, the down-top process from the intelligent decision level to the task level is a motion planning process for a specific task and the top-down process from the task level to the intelligent level is a self-learning process for a manipulator platform. For example, if we want to accomplish a task of grasping a cup on the desk, before the task, the intelligent decision level makes an analysis for it and connects the manipulator platform through the interface. Then we choose the control model in the control level and plan the joint trajectories in the joint trajectories level based on the intelligent decision. So if we want to give the anthropopathic arm ability to complete a task, we should comprehend the task firstly and then reconstitute the motion process.

III. A HIERARCHICAL PLANNING STRATEGY

A. Brief Introduction of the Hierarchical Planning Strategy

From the analysis of the experimental researches we have done, it can be known that the motion state of human arms changes during the movement and different motion processes correspond to different motion states. Only accurate models of arm movement are built, can arm posture be predicted accurately. Based on the research on movement rules of human arms, a HPS is proposed for robotic arms as shown in Fig.2. We abide by the hypothesis about "*Target Arm Pose (TAP)*" that Xie [9] has raised, that is, we assume that humans have pre-determined images of their final arm poses in their minds before their arms move. The subsequent arm motion can be interpreted as a series of unconscious movements to reach the TAP. On the basis of the hypothesis, the initial state C_{start} and the final state C_{goal} can be known, and the processing state C_{proc} can be calculated in real time.

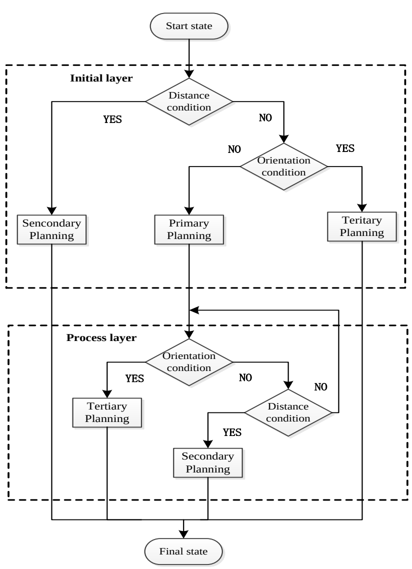


Fig.2. The flow chart of the HPS.

In the flow chart of the HPS, there are two trigger conditions (distance condition and orientation condition) dividing the complete movement into different motion processes and three kind of planning hierarchies (Primary Planning, Secondary Planning and Tertiary Planning). The specific procedure of the HPS is as follows:

a) The initial state C_{start} (θ_{start}, P_{start}, R_{start}) and the final state C_{goal} (θ_{goal}, P_{goal}, R_{goal}) of the manipulator have been known, and the processing state C_{proc} (θ_{proc}, P_{proc}, R_{proc}) can be calculated in real time. θ (q_1,q_2…q_n), P (x, y ,z) and R (n, o, a) represent joint angles, end position and end orientation of the manipulator respectively.

b) Before the movement, we need decide the motion state according to the initial state as shown in the initial layer. When the distance error $\Delta P = P_{goal} - P_{start} \le \Delta E_P$, the distance condition is satisfied and the Secondary Planning is used until the end of the movement. If not, we use the orientation condition. When the orientation error $\Delta R = R_{goal} - R_{start} \le \Delta E_R$, the orientation condition is satisfied and the Tertiary Planning is used until the end of the movement.

c) When $\Delta R > \Delta E_R$, the orientation condition isn't satisfied. In this case, the Primary Planning is used to move the manipulator from the initial state, the processing state is calculated and updated in real time and the movement accesses to the process layer.

d) In the process layer, the method we use to decide the motion state of the manipulator is the same with that in the initial layer. We use the processing state C_{proc} instead of the initial state C_{start} to calculate the trigger conditions and the motion state of the manipulator changes when the planning hierarchy changes. The only one we should notice is that in the process layer, we ensure that the processing state C_{proc} is calculated and updated in real time so that the motion state of the manipulator can change on time.

e) Finally, through the Secondary or the Tertiary planning, the final state is reached, that is, $C_{\text{proc}}=C_{\text{goal}}$.

We find that the initial layer and the process layer are almost the same except for the first trigger condition: the initial layer is the distance condition but the process layer is the orientation condition. The initial layer applies to the situation that the target object is near the end effector of the manipulator before the movement. So the distance condition is the first priority in the initial layer. After the initial layer, the movement accesses to the process layer which mainly decides the motion state of manipulator in the movement. At this time, the orientation condition is the first priority.

B. The Trigger Conditions of the HPS

In the HPS, the trigger conditions (distance condition and orientation condition) divide the complete movement into different motion processes. Different motion processes correspond to different states of motion in which models of human arms and approaches to predict arm posture are both different. Thus, accurate conditions are particularly important.

Distance condition: End velocity of the human arm has been studied a lot in many subjects such as biomechanics and some results [10]-[12] have been achieved. Here we use them for reference. The wrist movement time is:

$$t_{wrist} = \frac{\left\|\theta_{goal|wrist}\right\| - \left\|\theta_{start|wrist}\right\|}{\left\|\dot{\theta}_{wrist}\right\|} \quad (1)$$

where $\theta_{\text{start|wrist}}$ and $\theta_{\text{goal|wrist}}$ represent the wrist joint angles in the initial and final state respectively, and $\dot{\theta}_{wrist}$ represents generalized velocity of wrist joint angles. We use the norm of the vectors to approximate the time.

If we set the end generalized velocity to V_e, the wrist movement distance (distance condition) is

$$\Delta E_P = S_{wrist} = V_e t_{\text{wrist}} \quad (2)$$

It can be seen that the distance condition is mainly decided by the velocity of the wrist joint angle $\dot{\theta}_{wrist}$ and the end generalized velocity V_e. As inputs, $\dot{\theta}_{wrist}$ and V_e are selected reasonably to get the distance condition.

Orientation condition: Both online and offline, the end orientation R_{proc} can be updated timely, and the difference between the end orientation R_{proc} and the final end orientation R_{goal} is calculated. We obtain the orientation condition ΔE_R through the experiments. As the Tertiary Planning of the HPS is a special process of the human arm movement, we design the experiment as follows: the experimental process is a grasping process performed by different experimenters. The initial state is to raise the arm laterally and horizontally; the target object is in front of the experimenter's chest; the entire movement is completed in one horizon. We normalize the placement of the target object (the distance between the target and the chest) and select a set of data to be benchmark data as follows:

$$St = \frac{r_s}{l_s} \quad (3)$$

where r_s represents the distance between the target and the chest in the benchmark data, and l_s represents the arm length of the experimenter in the benchmark data.

For other experimenters, the position of the target object is

$$r = St \bullet l \quad (4)$$

The orientation error of the wrist is as follows:

$$\Delta R_{ex} = R_{end} - R_{expro} \quad (5)$$

where R_{expro} is the end orientation when the wrist joint angles change significantly in the experiment. Based on the variation trend, we analyze the experimental data and obtain the orientation condition:

$$\Delta E_R = n \bullet \Delta R_{\text{ex}} \quad (6)$$

where n is weight coefficient.

C. Different Motion States

Distance condition and orientation condition divide the movement into different motion processes corresponding to different motion states. In the HPS, each planning hierarchy has its own feature:

The Primary Planning: the motion model is similar to the reaching movement without considering the wrist orientation. In this paper, we adopt the reaching movement model which Xie presented [13]. We use the minimum Total Potential Energy (TPE) including Gravitational Potential Energy (GPE) and Elastic Potential Energy (EPE) to explain how human choose the natural arm postures in reaching tasks and the TPE is defined as:

$$f_{\text{TPE}} = f_{\text{GPE}} + f_{\text{EPE}} \quad (7)$$

So the HPM for Primary Planning Hp is defined as follows:

$$H_{\text{P}} = m_u g h_u + m_l g h_l + \frac{1}{2} k (\pi - \phi)^2 \quad (8)$$

where H_{P} represents the minimum Total Potential Energy including Gravitational Potential Energy and Elastic Potential Energy. m_{u} and m_{l} are the masses of upper and lower arms; h_{u} and h_{l} are the heights of the center of mass. ϕ is the Elbow Swivel Angle and k is the stiffness of the torsion spring. Details about this model can be found in Xie [13].

The Secondary Planning: This process is a grasping movement considering the orientations. In biophysics, "reaching movement" is guided by upper arm while lower arm plays a dominant role in "grasping movement". We analyze the arm movement in Secondary Planning through the experiments and find that the lower arm has more exercise and lower inertia than upper arm, which abide by the minimal effort criterion. So we use the minimum mobile distance of elbow as the optimization function. Given the initial position (x_0, y_0, z_0) and final position (x_e, y_e, z_e) of elbow, the optimization function can be written as follows:

$$\min s = \sqrt{(x_e - x_0)^2 + (y_e - y_0)^2 + (z_e - z_0)^2} \quad (9)$$

So the HPM for Secondary Planning H_{S} is defined as follows:

$$H_{\text{S}} = \frac{t}{t_{ts}} k_1 s + \frac{t_{ts} - t}{t_{ts}} k_2 f_{TPE}(q_{j=1,2,3,4}) \quad (10)$$

where t and t_{ts} represent the motion time and final time respectively; k_1 and k_2 are weight coefficients.

The Tertiary Planning: the wrist orientation will remain unchanged or change slightly and doesn't affect the arm posture. So we utilize this feature for the motion planning in Tertiary Planning. The minimum joint displacement of wrist can be as the optimization function:

$$\min q = \sum_{i=5}^{7} r_i (q_{ti} - q_i)^2 \quad (11)$$

Then the HPM for Tertiary Planning H_{T} is defined as follows:

$$H_{\text{T}} = \frac{t}{t_{tt}} k_1 q + \frac{t_{tt} - t}{t_{tt}} k_2 f_{TPE}(q_{j=1,2,3,4}) \quad (12)$$

where q_{ti} and q_{i} represent the initial and final joint angels respectively; t and t_{tt} represent the motion time and final time respectively; k_1, k_2 and r_{i} are weight coefficients.

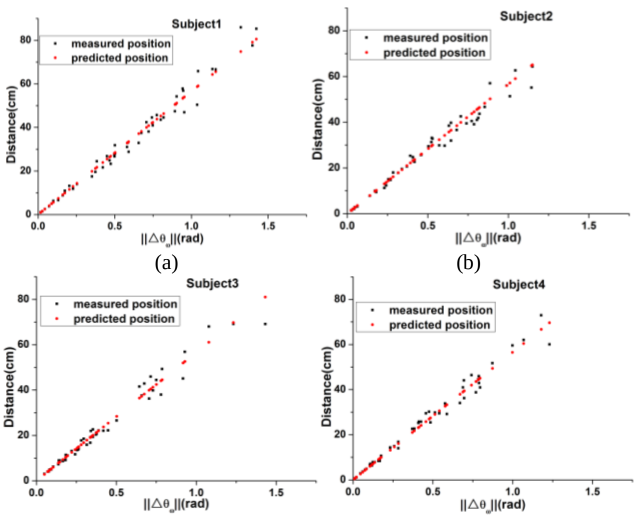
Ⅴ. EXPERIMENT

Individuals are different from each other for various reasons. Our purpose is to analyze and study the human arm movement on the basis of "common standards" which are movement rules that most people satisfy within the error range. Four experimenters were asked to reach 48 different target points with arbitrary final arm orientations from the initial state of dropping arms naturally. Then we use the

HPS to predict the human arm postures in different target positions and verify the efficiency of the strategy by comparing with the acquired data from the motion capture system.

(a) (b)

Fig.3. (a) Represents of the 48 target points on three parallel grids. The distance between the neighboring points is 10 cm. (b) Illustration of the human reaching movement experiment. Subjects reach the points with random end orientations.



(c) (d)

Fig.4. (a)-(d) represents the distance from the end position to the target position when the motion state changes during the actual movement and the distance predicted by the HPS, plotted by the difference between the initial wrist joint angles and the final wrist joint angles at different target points on the horizontal axis.

TABLE Ⅰ
THE HEIGHT AND MASS OF FIVE SUBJECTS

Subject	1	2	3	4
Height (cm)	174	170	177	184
Mass (kg)	65	52	81	82
Relative deviation	6.94%	6.76%	7.56%	7.70%
Variance	5.2399	4.4062	5.7733	6.8125

According to the analysis of experimental data, we find that the relative deviation between measured position and predicted position is less than 8%, which is an acceptable result in consideration of the experimental system error and inevitable human causes. The stable variation of the error (the difference between the measured values and the predicted values) shown from the variance further verifies the rationality and accuracy of the HPS. It is found that the relation between the changes of the motion state and the changes of the end orientation is an approximately linear relation, and our future research will focus on the influence of different configurations on the experimental results.

Ⅵ. CONCLUSIONS AND PROSPECTS

Different from traditional static prediction methods, we study the moving human arm postures. We propose a Hierarchical Plan Strategy decomposing the movement into a set of different states of motion in multiple processes and obtain the distance condition and the orientation condition. The corresponding arm models and Human Performance Measures have been built to generate the joint trajectories. Eventually the accuracy of the Hierarchical Planning Strategy has been verified through experiments. Because of the limitation of the pages, other parts of motion framework will be introduced systematically in the next paper.

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