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ANALYSIS OF THE GRASP PLANNING METHOD FOR MANIPULATION OF BH-4 DEXTEROUS HAND

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ABSTRACT

The paper presents method for planning robotic dexterous hand grasping task using example of the Beihang University's BH-4 dexterous hand. The grasping planning method is devised through modeling and simulation and experimentally verified using physical prototype. The paper presents the method for forward and inverse kinematic solutions of the BH-4 robot 4-DOF finger, including transformation matrix between the palm coordinate system and the finger base coordinate system. In addition, the method of the idiographic manipulation is presented using example of ball grasping. The simulation results and physical experiment verify that the inverse kinematic solution is correct, and kinematic grasping and operating planning is valid and feasible. Finally, the experiment with the complex system integrated robot arm with dexterous hand is carried out. Experimental result shows that the more complicated grasping task can be done by a dexterous hand integrated in the robot arm system.

Keyword: Dexterous hand; Grasping planning; Kinematic analysis; Virtual prototyping.

INTRODUCTION

The robotic dexterous hand can be effectively used to aid or replace humans in numerous difficult to work or outright dangerous areas, e.g. aeronautic and astronautic applications, and nuclear power plant environment. A number of dexterous hands (e.g. UATH/MIT hand and DLR hand) have been designed and associated research work presented [1, 2, 3, 4]. Although extensive work has been performed on dexterous hands, still one of the major issues related to dexterous hand is operation planning in avoidance of the interference among fingers and palm. Some work have been done for the problem to choose precision fingertip grasps [5, 6]. Also Miller and Knoop use grasping simulator GraspIt! to test and evaluate each grasp generated by a set of rules [7].

This paper presents method for planning robotic dexterous hand grasping and operating task using example of the Beihang University's BH-4 dexterous hand. The method of the manipulation is presented along with example of ball grasping and manipulation. By combining the academic analysis with virtual prototyping simulation and physical prototype experiment, the grasping planning method is carried out and verified. The grasping planning method is based on forward and inverse kinematic solutions of the 4-DOF finger. The virtual prototyping technology is applied to validate methodology using software UG and Adams. Applying the same grasp planning method, the grasp operation is carried out with physical model of dexterous hand.

GRASPING AND OPERATING PLANNING

The main problem in grasping and operation planning for robot dexterous hand is to define and determine motions of finger joints starting from initial position to grasping position, and then to operating position in which the object is manipulated. In order to solve this problem, important thing is to change curve motion of the finger tip described in Cartesian space, obtained by grasping and operation planning, into the angular motions of finger joints. This can be accomplished with forward and inverse kinematic analysis.

Kinematic Analysis

The location of the centers of the semi-balls (such as O_4 shown in Fig.1) at the ends of the fingers in the palm coordinate system and the angular rotations of the joints are determined by the idiographic grasping and operating task. The kinematic sketch of BH-4 robot 4-DOF finger is shown as Figure 1. The coordinate systems $O_iX_iY_iZ_i$ (i=0,1,……4) are fixed on the part i. Where, a_j (j=2,……4) are the structural parameters of the finger mechanism (the lengths of links), and θ_k (k=1,……4) are relative angles of the finger mechanism.

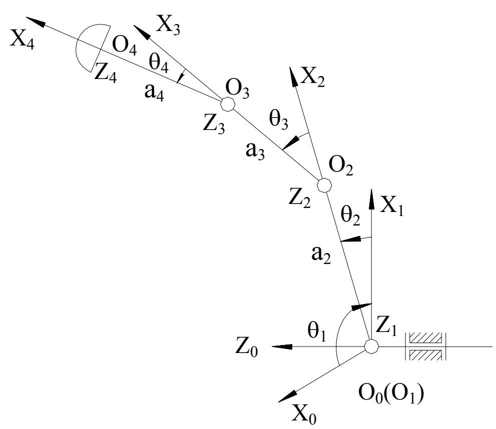


Fig.1 KINEMATIC SKETCH OF FINGER MECHANISM

The position (p_x,p_y,p_z) of the center O_4 of the semi-ball at the end of the finger can be described in the base coordinate system $O_0X_0Y_0Z_0$ as a function of the rotation angles θ_k.

$$p_x = [a_4\cos(\theta_2+\theta_3+\theta_4) + a_3\cos(\theta_2+\theta_3) + a_2\cos\theta_2]\cos\theta_1 \qquad (1)$$

$$p_y = [a_4\cos(\theta_2+\theta_3+\theta_4) + a_3\cos(\theta_2+\theta_3) + a_2\cos\theta_2]\sin\theta_1 \qquad (2)$$

$$p_Z = a_4\sin(\theta_2+\theta_3+\theta_4) + a_3\sin(\theta_2+\theta_3) + a_2\sin\theta_2 \qquad (3)$$

Combining equation (1) and (2), one obtains

$$\theta_1 = arctg\,\frac{p_y}{p_x} \qquad (4)$$

Simulating the coupling relationship between the links of the human finger, the coupling relationship between θ_3 and θ_4 is defined as

$$\theta_4 = \frac{2}{3}\theta_3 \qquad (5)$$

The equation for angle θ_3 can be described as follows

$$\frac{1}{a_2}\cos\left(\frac{2}{3}\theta_3\right) + \frac{1}{a_3}\cos\left(\frac{5}{3}\theta_3\right) + \frac{1}{a_4}\cos\theta_3 - \frac{p_{xy}^2 + p_z^2 - a_2^2 - a_3^2 - a_4^2}{2a_2a_3a_4} = 0 \qquad (6)$$

Where, $p_{xy} = \dfrac{p_x}{\cos\theta_1} = \dfrac{p_y}{\sin\theta_1}$.

The value of angle θ_3 can be determined by solving equation (6) using numerical methods. Further, the value of angle θ_4 can be obtained as $\theta_4 = \frac{2}{3}\theta_3$.

Finally, the expression for angle θ_2 is

$$\theta_2 = arctg\,\frac{A}{M\sqrt{B^2+C^2-A^2}} - arctg\,\frac{B}{C} \qquad (7)$$

Where, $A=p_z$, $B=a_4\sin(\theta_3+\theta_4)+a_3\sin\theta_3$,

$C=a_4\cos(\theta_3+\theta_4)+a_3\cos\theta_3+a_2$, M=1 or M= -1.

The proper value of parameter M is determined by the structure of the dexterous hand and position of the finger in the grasping process.

Applying inverse kinematic method to the finger mechanism mentioned above, the values of angles θ_k (k=1,……4) can be obtained in the case when the position (p_x,p_y,p_z) of the center O_4 of semi-ball is known.

The kinematic sketch of the dexterous hand is shown as Fig.2.

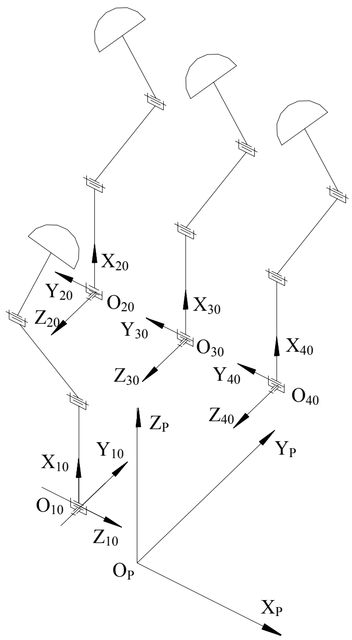


Fig.2 KINEMATIC SKETCH OF BH-4 DEXTEROUS HAND

The coordinate system $O_{i0}X_{i0}Y_{i0}Z_{i0}$(i=1,……4) is the base coordinate system of the i^th^ finger. The coordinate system $O_PX_PY_PZ_P$ is palm coordinate system.

The position and orientation of the base coordinate system $O_{i0}X_{i0}Y_{i0}Z_{i0}$ of i^th^ finger relative to palm coordinate system $O_PX_PY_PZ_P$ can be described with transform matrix $\boldsymbol{T}_i^P$,

$$\boldsymbol{T}_i^P = \begin{bmatrix} \boldsymbol{R}_{iP} & \boldsymbol{r}_i^P \\ 0 & 1 \end{bmatrix} \qquad (8)$$

Where, $\boldsymbol{R}_{iP}$ is the orientation cosine matrix of the base coordinate system $O_{i0}X_{i0}Y_{i0}Z_{i0}$ relative to palm coordinate system $O_PX_PY_PZ_P$, r_i^P is position vector of the origin point O_{i0} of the base coordinate system $O_{i0}X_{i0}Y_{i0}Z_{i0}$ in the palm coordinate system $O_PX_PY_PZ_P$. $\boldsymbol{R}_{iP}$ and $\boldsymbol{r}_i^P$ can be easily obtained from the relationships among the coordinate systems shown in Fig. 2.

When the position of a point is described as $r_P = [x_P \quad y_P \quad z_P]^T$ in palm coordinate system $O_PX_PY_PZ_P$, and the position of the same point is described as $r_i = [x_i \quad y_i \quad z_i]^T$ in base coordinate system $O_{i0}X_{i0}Y_{i0}Z_{i0}$, the relationship between $\boldsymbol{r}_P$ and $\boldsymbol{r}_i$ can be described as

$$\begin{bmatrix} r_i \\ 1 \end{bmatrix} = (\mathbf{T}_i^P)^{-1} \begin{bmatrix} r_P \\ 1 \end{bmatrix} \qquad (9)$$

Grasp and Operation Process

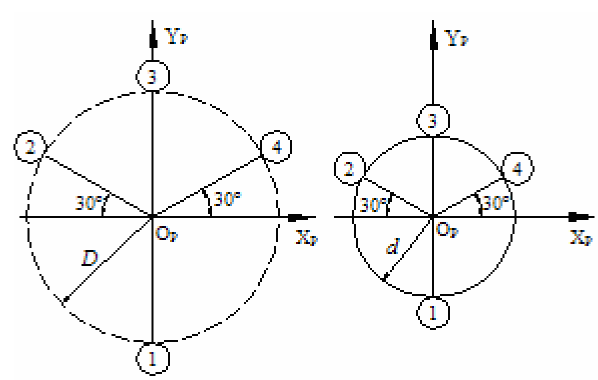
The whole grasping and operating process is decomposed into a sequence which starts at initial state and ends at end state, and then the motion planning is carried out for changing the sequence into ideal motion trajectory for the fingers. The entire grasping and operating process is defined as four sub-processes. The 1^st^ sub-process is from initial position to pre-grasping position. The 2^nd^ is from pre-grasping position to grasped position. The 3^rd^ is from grasped position to operated position. The 4^th^ is from operated position to initial position. Here, first three sub-processes are discussed separately.

The grasping and operating planning method which is called "Experience Method" brought forward by Cutkosky [8] is used for the grasping and operating planning of the BH-4 dexterous hand which has four fingers. The initial position of a finger is defined as the position in which the finger is fully extended and in vertical position. According to the grasping taxonomy brought forward by Cutkosky, the 14^th^ grasping type of the "Precision" grasping model is adapted in this paper, as this position and orientation is also commonly used in human hand and can fit the most needs of grasping and operating tasks. In addition, this type of the position and orientation has strong adaptability to the profile of spherical object.

Grasp planning

Assuming that grasping is planar, it means that the positions of the centers of semi-balls at the ends of the four fingers are in the same plane when the hand is in the pre-grasping position. The locations of the ball centers in the palm coordinate system are shown in Fig.3. Fig.3(a) shows that the hand is in pre-grasping position, and Fig.3(b) shows that the hand is in grasped position.

The motion of every finger in the 1^st^ sub-process is defined in the joint space. The position of the center of semi-ball in the base coordinate system can be obtained using equation (9), in conjunction with the position which the ball center reaches in the palm coordinate system, shown in Fig.3(a). Applying the inverse kinematics analysis equations (4)-(7), the angles of the joints in pre-grasping position can be determined. Finally by interpolation operating in the joint space, the fingers can be driven by the angular motion command obtained above.



(a) PRE-GRASPING POSITION (b) GRASPED POSITION
Fig.3 DISTRIBUTIONS OF BALL CENTERS OF FINGERS

The motion of the finger moving in the 2nd sub-process is defined in the Cartesian space. The purpose of doing this is to make the tip of the finger move along the designed track and avoid the interference among the fingers and the palm. In this sub-process, the track of the tip of the finger is first interpolated in the Cartesian space, and then the increment values of the joints corresponding to the increments of track interpolation are calculated.

Operation Planning

After the ball is grasped by the robot dexterous hand, some dexterous operations (such as rotating and translating the object) usually need to be done out according to desired operation requirements. It is assumed that the operation is accomplished by a compound motion which consists of translation and rotation. Compound motion can be described by translation along with the base point with rotation around the base point. For the given operating task, in order to determine the motions of the fingers of robot dexterous hand, the relationship between the object and the fingers should be established. For the small displacements, the position of the contact point between the object and the hand is supposed to be unchanged during operation process. The relationship between the object and the finger is described in Fig.4. Point A is the contact point on the finger tip. Point B is the base point, and O_{io} and O_p are the origin points of the base coordinate system of the i^{th} finger and palm coordinate system.

The translation is defined as parallel motion along three axes of the coordinate system of the palm $O_PX_PY_PZ_P$. The displacement of the reference point on the object can be described as $[dx, dy, dz]^T$. The rotation is defined as the synthesis of three rotations around three axis of the coordinate system $O_PX_PY_PZ_P$. The order of the rotations is as follows: first rotation about x axes for θ_x, then rotation about y axes for θ_y, finally rotation about z axes for θ_z. The corresponding transformation matrix is

$$T = Tran(dx\ dy\ dz)Rot(z,\theta_z)Rot(y,\theta_y)Rot(x,\theta_x)$$
$$= \begin{bmatrix} c_z c_y & -s_z c_x - c_z s_y s_x & -s_z s_x + c_z s_y c_x & dx \\ c_z c_y & c_z c_x - s_z s_y s_x & c_z s_x + s_z s_y c_x & dy \\ -s_y & c_y c_x & c_y c_x & dz \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (10)$$

where, $s_j=\sin\theta_j$, $c_j=\cos\theta_j$.

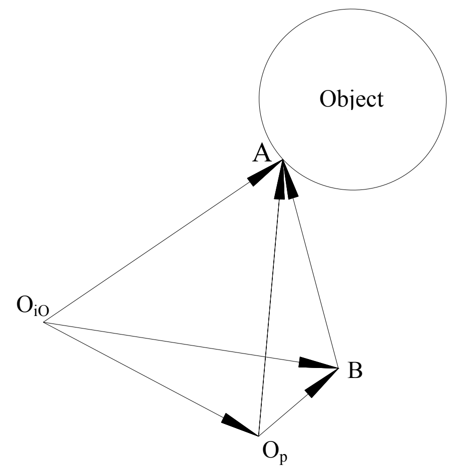


Fig.4 TRANSFORM OF COMPOUND MOTION

The position vector of the center of the semi-ball of the i^{th} finger is defined as $\boldsymbol{r}_{i0}$ when the object is grasped, and the position vector of the center the semi-ball of the i^{th} finger after the object is operated is $\boldsymbol{r}_i$, then the relationship between $\boldsymbol{r}_i$ and $\boldsymbol{r}_{i0}$ is

$$\begin{bmatrix} \boldsymbol{r}_i \\ 1 \end{bmatrix} = T \begin{bmatrix} \boldsymbol{r}_{i0} \\ 1 \end{bmatrix} \quad (11)$$

The trajectory of the tip of the finger moving from the grasping position $\boldsymbol{r}_{i0}$ to the operating position $\boldsymbol{r}_i$ is first interpolated in Cartesian space, and then the increment values of the joints corresponding to the increments of trajectory interpolation is calculated. Finally the joints can be driven according to these increments for the ball centers to move and reach the grasped position in the Cartesian space according to the designed moving track. Hence, the 3rd sub-process has been accomplished.

The 4th sub-process, is trivial and will not be derived here. Thus, the full grasping and operation process is accomplished.

VIRTUAL PROTOTYPING AND SIMULATION

The model of dexterous hand has been developed and computer simulation performed to validate accuracy of grasp and operation planning. The approach allows for visual analysis of the system motions in order to avoid interferences among the fingers and object.

Creation of Virtual Prototyping

The virtual prototyping model of robot dexterous hand is created in several steps. The first step is to create the solid model of the hand (UG was used in this application). The second step is to transfer the solid model from UG environment into Adams (Automatic Dynamic Analysis of Mechanism System) environment. The last step is to define the restrictions among the parts. The virtual model of the dexterous hand is shown as Fig.5.

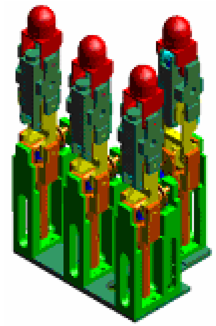


Fig.5 VIRTUAL PROTOTYPING OF BH-4

The position of the hand shown in Fig. 5 is initial position.

Simulation of Virtual Prototyping

The motion interpolation is carried out in joint space according to data obtained during the grasp and operation planning. The contact forces among fingers are measured and used as indication of interference between the fingers. If the interference among the fingers occurs, the pre-grasping position and grasped position of the four fingers have to be reset, and motion trajectory of the tips of the fingers should be planned again, and simulation of the virtual model should be reinitiated. The final rotational angles of joints of the fingers are obtained by repeating the process until no interference occurs. The pre-grasping position and grasped position of the hand obtained by simulation are shown in Fig.6 and Fig.7 respectively.

Fig.6 PRE-GRASPING POSITION

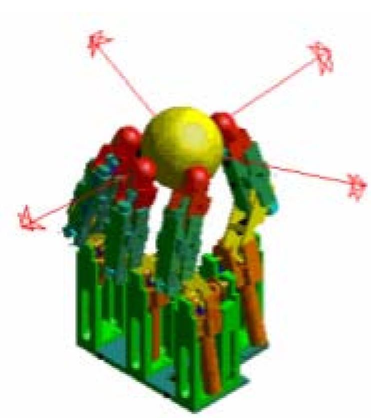


Fig.7 GRASPED POSITION

The simulation results show that the method used for analytical analysis and the results of the grasping and operation planning are all correct and feasible and can be used in the grasping and operation experiments of the physical model.

GRASP AND OPERATION EXPERIMENT

The physical grasping and operating experiments are carried out according to the data obtained from the grasping and operation planning and simulation. The initial, pre-grasping, and grasped positions of the physical prototype are shown as Fig.8, Fig.9 and Fig.10 respectively.

Fig.8 INITIAL POSIRION

Fig.9 PRE-GRASPING POSITION

Fig.10 GRASPED POSITION

The physical experiment validates the method and verifies the results of the analytical analysis and the simulation.

The experiment with the complex system integrated robot arm with dexterous hand is carried out by controlling the robot arm and dexterous hand respectively. The experiment process is shown as Fig.11.

Fig.11 EXPERIMENT OF INTEGRATION SYSTEM

The experimental results show that more complicated grasping task can be done by a dexterous hand integrated in the robot arm system.

CONCLUSIONS

The paper presents method for planning robotic dexterous hand grasping task. The method is verified on Beihang University's BH-4 dexterous hand. The grasping planning method is developed through modeling and simulation and experimentally verified using physical prototype. In addition, the method of the idiographic manipulation is presented using example of ball grasping. It is shown that in order to successfully accomplish a grasping and operation task, it is necessary to make appropriate planning. The grasping and operation planning study process indicates that the research method combining analytical analysis, virtual simulation and physical experiment is available and efficient and can guarantee the work to be done safely and successfully.

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