Trajectory planning based on hand operation for the un-redundant arm of service robot

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Abstract: - Any unfamiliar motions of the arm for service robot will make people anxious and human-like arm motion may be a solution. A virtual prototype of service robot with dual 6DOF (Degree of Freedom) arms named FISR (Family Intelligent Service Robot) has been developed. The application of service robot is not only performing human-like arm motion but also focusing on the hand operation such as grasping an object. So based on hand operation a formulation of elbow elevation angle is constructed to plan human-like arm motion for FISR. Furthermore a strategy about how to grasp a convex object is proposed.

Key-Words: - Elbow elevation angle, human-like trajectory, hand operation, un-redundant arm, service robot

1 Introduction

The research on the effect of manipulator motion on human psychology in last several years shows that people who staying near a manipulator will feel nervous if manipulator motions are not familiar to them[1]-[10]. It is a necessary for service robot using human-like arm motion when working with human. [11]- [20]-

T.Asfour et al.[21] proposed an approach to generate human-like arm motion using mathematical representation with 7DOF arm. Seungsu Kim et al.[22] developed an approach of using Response Surface Methodology to calculate the elbow elevation angle from human motion for a robot with 6DOF per-arm. Nancy S.Pollard et al.[23] realize a humanoid robot that consist of only an upper body adapting pre-recorded human motion and trajectory. Nakaoka et al.[24] explored a procedure to make a humanoid robot(HRP-1S) imitate a Japanese folk dance captured by a motion capture system. J.F.Soechting et al. [25] concluded that the Donder' law is not hold for pointing movements of the human arm which means the elbow elevation angle is not determined by the wrist location only.

A 6DOF manipulator is popular in industry, so it will be widely used as the arm of service robot. It is not applicable for only realizing the arm motion human-like, but ignoring its hand operational functions. It hasn't been studied yet about how to synthesize both of these two requirements in a 6DOF arm of service robot. In order to study it a mobile service robot with two

6DOF arms named FISR has been developing in our lab. Its DOF configuration is based on the angle defining the posture of the human arm.[26] In this paper a formulation of elbow elevation angle is constructed for FISR based on the inverse kinematics equations and the qualitative relationship between the palm direction and the elbow elevation angle. A strategy on how to determine an arm motion to grasp a convex object is proposed. A simulation of FISR using its right hand to grasp a box with human-like arm motion is presented in the end.

2 Derivation of Human-like Arm trajectory

2.1 Angles defining the posture of human arm

Based on the results in [26], a sketch map of human right arm is depicted in Figure 1. We define v to be the angle between the perpendicular P to the plane of the arm and the horizontal plane. An equation can be derived: $\sin v = \sin\alpha \sin\zeta$, the parameter v is elbow elevation angle for a given hand location and the result of that elbow angle ϕ depends only on the hand location.

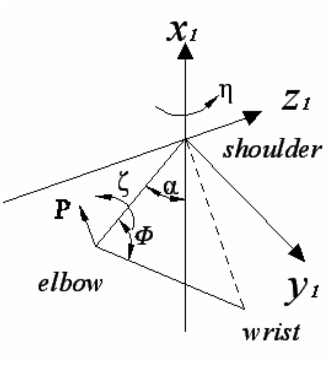

Fig.1 Angles defining human arm posture

2.2 Forward kinematics of FISR

Each arm of FISR has 6DOF revolute joints with a gripper and the body uses 3 Omni-wheels. The Denavit-Hartenberg (D-H) convention and methodology are used in this section to derive its kinematics. The coordinate frame assignment and the D-H parameters are depicted in Figure 2 and listed in Table 1 respectively, where (x_0, y_0, z_0) represents the local coordinate frame at the body, (x_1, y_1, z_1) to (x_6, y_6, z_6) represent the local coordinate frames at the six joints respectively, $(x_h, y_h, z_h)$is local coordinate frames at the hand, the α, γ, θ are the rotation angles about x, y, and z respectively. The description of the coordinate transformation from frame i to i+1 is given by:

${}^{i}T_{i+1}$ = Rot(y_i , γ_i)Trans(y_i , d_i) Rot(x_{i+1} , α_{i+1})Trans(x_{i+1} , a_{i+1})Rot(z_{i+1} , θ_{i+1}) , $i = 0,1...n$ s and c mean mathematical symbols $\sin$ and $\cos$ in the formulations respectively.

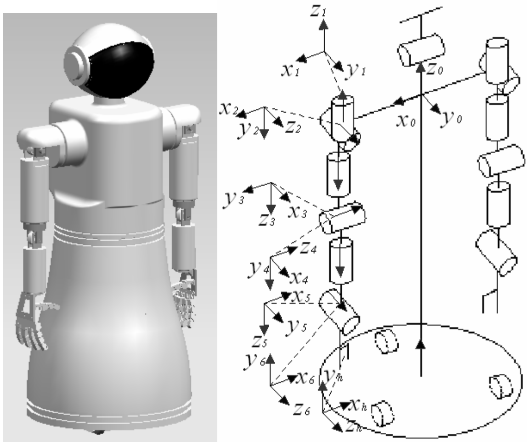

Fig.2 DOF configuration of FISR

Table 1 D-H parameters for FISR

Link	θ	$d(mm)$	$a(mm)$	γ	α
1	θ_1	0	$a_1 =$ 300	0°	0°
2	θ_2	0	0	0°	-90°
3	θ_3	$d_2 =$ 268	0	-90°	-90°
4	θ_4	0	0	0°	90°
5	θ_5	$d_4 =$ 158	0	-90°	-90°
6	θ_6	0	0	0°	-90°

According to [26] and [27] we can define the range of the parameters $\theta_1 \sim \theta_6$ represented in Table.2 which are in the range of rotation angle for human arm joints. It also can be generated an equation $\sin v = -\sin\theta_2 \cos\theta_3$ based on the forward kinematics of FISR.

Table 2 Joints angle range

Link/Joints	θ	Range	
1/0-1	θ_1	-50°~0°	0°~130°
2/1-2	θ_2	-1°~-90°	-1°~-120°
3/2-3	θ_3	-90°~90°	
4/3-4	θ_4	0°~-150°	
5/4-5	θ_5	-80°~80°	
6/5-6	θ_6	-70°~80°	

2.3 Human-like elbow elevation angle

In order to make the arm motion human-like based on hand operation, it is necessary to use 4 joints on the shoulder and elbow to control arm posture which includes the elbow elevation angle.

$$\begin{bmatrix} R_6 & P_6 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} n_{6x} & o_{6x} & a_{6x} & p_{6x} \\ n_{6y} & o_{6y} & a_{6y} & p_{6y} \\ n_{6z} & o_{6z} & a_{6z} & p_{6z} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$ and

$$\begin{bmatrix} R_h & P_h \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} n_{hx} & o_{hx} & a_{hx} & p_{hx} \\ n_{hy} & o_{hy} & a_{hy} & p_{hy} \\ n_{hz} & o_{hz} & a_{hz} & p_{hz} \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

represent the posture of wrist and hand at the coordinate frame of (x_0, y_0, z_0) respectively. The following equation can be derived: $\begin{bmatrix} R_6 & P_6 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} R_h & P_h \\ 0 & 1 \end{bmatrix} \left({}^6T_h\right)^{-1}$.

Let's define $f = \sin v = -s\theta_2 c\theta_3$.So there is an equation. The following formulations can be generated:

$$\begin{aligned} &p_{6x} \\ &= 300 - 158(c\theta_1 c\theta_2 s\theta_3 - s\theta_1 c\theta_3)s\theta_4 \\ &-158c\theta_1 s\theta_2 c\theta_4 - 268c\theta_1 s\theta_2 \end{aligned} \tag{1}$$

$$\begin{aligned} &p_{6y} \\ &= -158(s\theta_1 c\theta_2 s\theta_3 + c\theta_1 c\theta_3)s\theta_4 \\ &-158s\theta_1 s\theta_2 c\theta_4 - 268s\theta_1 s\theta_2 \end{aligned} \tag{2}$$

$$\begin{aligned} &p_{6z} \\ &= 158s\theta_2 s\theta_3 s\theta_4 - 158c\theta_2 c\theta_4 - 268c\theta_2 \end{aligned} \tag{3}$$

$$f = -s\theta_2 c\theta_3 \tag{4}$$

According to the cosine theorem the formulation can be obtained:

$$\begin{aligned} &(p_{6x} - 300)^2 + p^2{}_{6y} + p^2{}_{6z} \\ &= 158^2 + 268^2 - 2 * 158 * 268c(\pi + \theta_4) \end{aligned} \tag{5}$$

The solution for θ_4 is as follows.

$$\theta_4 = \arccos\frac{D}{-2*158*268} - \pi$$

$$D = \left(p_{6x}-300\right)^2 + p^2{}_{6y} + p^2{}_{6z} - 158^2 - 268^2 \tag{6}$$

If $s\theta_4 = 0$, the solution for θ_2 can be resulted from (3)

$$\theta_2 = -\arccos\left(\frac{p_{6z}}{-426}\right) \tag{7}$$

If $s\theta_4 \neq 0$, the following formulation can be derived from (3) and (4):

$$0 = \left(\left(158c\theta_4 + 268\right)^2 + \left(158s\theta_4\right)^2\right)c\theta_2{}^2 + 2p_{6z}\left(158c\theta_4 + 268\right)c\theta_2 + \left(158s\theta_4\right)^2 f^2 + p_{6z}{}^2 - \left(158s\theta_4\right)^2 \tag{8}$$

In order to ensure the formulation (8) has solutions, the following equation should be satisfied.

$$\Delta = -4*\left(158s\theta_4\right)^2 \cdot \left(\left(268^2 + 2*268*158c\theta_4 + 158^2\right)\left(f^2-1\right) + p_{6z}{}^2\right) \tag{9}$$

There is relationship between the elbow elevation angle and the palm direction. [27] [28] It can be intuitively noticed that when the palm direction is upward vertically the elbow elevation angle is usually close to zero, but it will become larger gradually during the palm direction transits from the upward vertically to the downward vertically. So a factor $1-e^{n_{6z}-1}$ is used here to indicate the relationship between the palm direction and the elbow elevation angle. Although it is difficult to represent the relationship of these two angles precisely, since there are many personalities in arm motion, its qualitative representation is enough to make the arm motion of FISR human-like. The equation of (9) will be satisfied if the following formulation exists.

$$f = \sqrt{(1-d)\left(1-e^{n_{6z}-1}\right)}$$

$$d = \frac{p_{6z}{}^2}{268^2 + 2*268*158c\theta_4 + 158^2} \tag{10}$$

Then we can get another solution for θ_2, and solutions for other joints in the arm.

2.4 A strategy for grasping a convex object

Grasping an object is an important function for service robot. If the center of coordinate frame $\left(x_h, y_h, z_h\right)$ is in an object, it can be believed that the object can be grasped. In order to plan a motion of grasping an object, an initial posture of $\left(x_h, y_h, z_h\right)$ for the hand to grasp the object should be chosen. Then the joints angle can be derived from the inverse kinematics of the arm. Based on the forward kinematics, a hand posture can be derived then. If it doesn't equal the initial posture, there must be a rotation on the axes of x_h in the initial posture and the angle can be represented as α. Let's rotate the coordinate frame of initial posture on its axes of x_h for $\frac{\alpha}{2}$, and the result can be used as the initial posture for the next iterative calculation. The iterative computing will stop until the rotation α is in the range of the threshold or there are too many iterative times. The initial value of α is zero, and its threshold is 0.2 in this paper. The posture of $\left(x_6, y_6, z_6\right)$ can be determined by $\begin{bmatrix} R_6 & P_6 \\ 0 & 1 \end{bmatrix}$

$$= \begin{bmatrix} R_h & P_h \\ 0 & 1 \end{bmatrix} Rot\left(x_h, \frac{\alpha}{2} \right) Trans(y_h, 100).$$

After the posture of the hand to grasp an object is determined, the trajectory of its transiting from the current location to the final location can be planed. The distance and the posture of the wrist from the current location to the final location are denoted as D_i and ΔR_i, let's suppose $\frac{\Delta R_i}{\Delta R_0} = \frac{D_i}{D_0}$.

3 Simulation and Discussions

A simulation of grasping a box is implemented with the right hand to illustrate how to pick up an object with human-like motion for the un-redundant arm of FISR. There is a box 60mm long and wide, 110mm high mounted upon a horizontal table. Suppose the center of initial posture of $(x_h \quad y_h \quad z_h)$ is at the center of the box and the x_h perpendicular to a plane of the box. Its initial posture of the hand is $\begin{bmatrix} -0.707 & 0.707 & 0 & 30.0 \\ -0.707 & -0.707 & 0 & 300.0 \\ 0 & 0 & 1 & -250.0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$ at the coordinate frame (x_0, y_0, z_0). So the initial wrist posture of $(x_6 \quad y_6 \quad z_6)$ is $\begin{bmatrix} -0.707 & 0.707 & 0 & 100.7 \\ -0.707 & -0.707 & 0 & 229.3 \\ 0 & 0 & 1 & -250.0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$.

The strategy on how to determine a hand posture to pick up a box is presented. The desired posture for $(x_h \quad y_h \quad z_h)$ in the final has rotated 13.1^{o} clockwise on the axes x_h relative to the initial posture.

Suppose the current posture of the arm for FISR is as depicted in Figure 2 whose joints angle are $\theta_1 = 0^\circ$, $\theta_2 = -1^\circ$, $\theta_3 = 0^\circ$, $\theta_4 = 0^\circ$, $\theta_5 = 0^\circ, \theta_6 = 0^\circ$, and the trajectory of wrist to transit from the current location to the final location is a straight line. The solutions of the parameters in the motion for grasping the box are presented in Figure 3 and listed in Table.3.

The first drawing in Figure 3 is the solutions of six joints in the motion of grasping the box. The second drawing is the value of elbow elevation angle in the motion. It is obviously that when the hand is raised more quickly than the elbow, the elbow elevation angle is becoming larger for the perpendicular to the plane constructed with points shoulder, wrist and elbow rotated from vertical direction to horizontal direction. The transition of elbow elevation angle is similar to human arm motion in this operation. In the last drawing '*', 'o' and '• ' represent the location of elbow, wrist and hand at the coordinate frame of (x_0, y_0, z_0) respectively. In simulations the manipulator transformed from the posture of hanging vertically to almost rising horizontal. The wrist moved backward first and then forward when the robot bent its arm and put its hand on the table. The results demonstrate the strategy to plan a human-like motion with the un-redundant arm to grasp a convex object is effective.

Table 3 The parameters in iterative process

Times	(x_6, y_6, z_6)	α	$\alpha/2$	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	f
1	(100.7,229.3,-250)	19.8	9.9	110.6	-41.9	23.1	-46.8	47.2	-19.5	0.614
2	(99.6,230.4,-232.8)	4.7	2.35	108.4	-43.0	22.0	-53.3	46.2	-22.6	0.632
3	(99.1,230.9,-228.8)	1.2	0.6	108.1	-43.3	21.9	-54.5	46.1	-23.1	0.637
4	(98.9,231.1,-227.8)	0.4	0.2	108.0	-43.4	21.9	-54.7	46.0	-23.2	0.638
5	(98.9,231.1,-227.4)	0.1	0.05	108.0	-43.5	21.9	-54.8	46.0	-23.3	0.638

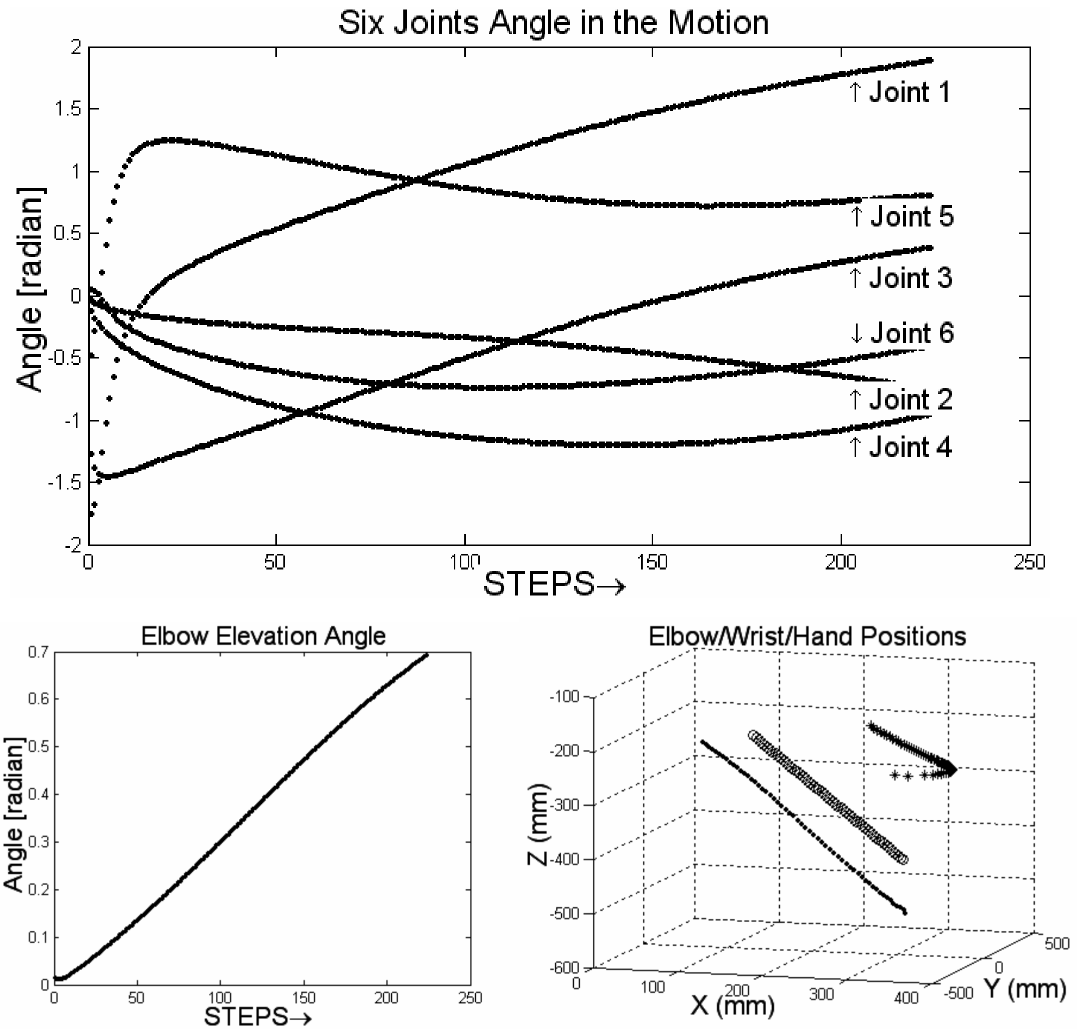

Fig.3 Solutions of the parameters in motion

4 Conclusion

It is the first approach of planning human-like motion based on hand operation for the un-redundant arm of FISR. A strategy on how to determine a posture of the hand to grasp a convex object and plan the human-like arm motion is proposed. Although a 6-DOF manipulator can be yielded an effective posture for grasping an object in Cartesian coordinate. But in order to grasp an object in real world will not using only one posture. So if a posture can grasp the object and it is human-like will be much better than a normal posture only satisfies the grasping function. The approach is one attempt for realizing this dream. The method can be applied in other service robot using 6DOF arm to realizing hand operation with human-like arm motion. Furthermore it can also be applied in the 7-freedom manipulator which can grasp objects with many kinds of postures.

5 Acknowledgments

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Appendix

The following formulations focus on the solutions of θ_2 will always exist on equation (8).

According to the equation (9), the following formulations can be derived.

$$\left(268^2 + 2*268*158c\theta_4 + 158^2\right)\left(f^2 - 1\right) + {p_{2z}}^2 \le 0 \qquad \text{(A)}$$

$$c\theta_2 = \frac{F}{E} \qquad \text{(B)}$$

$$F = -p_{2z}\left(158c\theta_4 + 268\right) \pm 158\left|s\theta_4\right| \cdot \sqrt{-\left(E^2\left(f^2 - 1\right) + {p_{2z}}^2\right)}$$

$$E = 268^2 + 2*268*158c\theta_4 + 158^2$$

$$\frac{F}{E} \le \frac{G}{E} \qquad \text{(C)}$$

$$F = -p_{2z}\left(158c\theta_4 + 268\right) \pm 158\left|s\theta_4\right|\sqrt{E^2 - {p_{2z}}^2}$$

For $\theta_4 \in [0, \pi]$ and $f \in [-1, 1]$

$$\frac{G}{E} \le \frac{H}{E} \qquad \text{(D)}$$

$$H = -\left(158c\theta_4 + 268\right)s\alpha - 158s\theta_4 c\alpha$$

For $p_{2z} \ge 0$ and $\alpha \in \left[0, \pi/2\right]$

$$c\alpha = \frac{\sqrt{E^2 - {p_{2z}}^2}}{E}$$

$$s\alpha = \frac{p_{2z}}{E}$$

$$I = E^2 - H^2$$

$$I \ge J$$

$$\begin{aligned} J &= 2 \cdot 268 \cdot 158c\theta_4 \\ &+ 2 \cdot 268 \cdot 158\left|c\alpha\right| \cdot \left|c\left(\theta_4 + \alpha\right)\right| \\ &- 2 \cdot 268 \cdot 158 s\alpha s\left(\theta_4 + \alpha\right) \end{aligned}$$

If $c\left(\theta_4 + \alpha\right) > 0$, so $\theta_4 + \alpha \in \left(0, \pi/2\right)$,

$$\begin{aligned} J &= 2*268*158c\theta_4 + 2*158*268c\left(\theta_4 + 2\alpha\right) \\ &= 2*268*158\left(c\theta_4 + c\left(\theta_4 + 2\alpha\right)\right) \end{aligned}$$

Because $\theta_4 \in [0, \pi]$, $\alpha \in \left[0, \pi/2\right]$, $\theta_4 + \alpha \in \left(0, \pi/2\right)$, so $\theta_4 \in \left[0, \pi/2\right]$.

If $\theta_4 + 2\alpha \in \left[0, \pi/2\right]$, we can derived that $\theta_4 \in \left[0, \pi/2\right]$ and $\theta_4 \le \theta_4 + 2\alpha$, so $J \ge 0$.

If $\theta_4 + 2\alpha \in \left[\pi/2, \pi\right]$, we can derived that $\pi - \left(\theta_4 + 2\alpha\right) \in \left[0, \pi/2\right]$, $-c\left(\theta_4 + 2\alpha\right) = c\left(\pi - \left(\theta_4 + 2\alpha\right)\right) \ge 0$, and because $\pi-(2\theta_4+2\alpha)\geq 0$,

$\pi-(\theta_4+2\alpha)\geq\theta_4, \theta_4\in\left[0,\pi/2\right].$

So $c\theta_4\geq\left|c(\theta_4+2\alpha)\right|$, so $J\geq 0$

So the solutions are in the range of $[-1,1]$.

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