Design for a 5-DOF Cable-Driven Anthropomorphic Arm

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Abstract

In this paper, a motion control approach for a 5-DOF cable-driven manipulator is designed, and the mechanical structure design of this anthropomorphic-arm is introduced. For the 5-DOF manipulator, a hybrid algorithm is proposed to make the trajectory tracing of the manipulator in task space with high accuracy; the goals of the first phase of the robot arm have been meet. Although the method of motion control is limited in the current state, it serves as a strong foundation on which to test the performance and interface of the electronic components. The coupling cable lengths among the different joint modules are analyzed in detail.

Keywords: *5-DOF, Design, Anthropomorphic Arm.*

1. Introduction

Recently, a research effort has been made over the past few years to model and control flexible structures and, in particular, flexible arms. Many papers on the control of flexible arms with fixed or variable payloads at the tip have been reported. A 5-DOF anthropomorphic-arm is a kind of typical redundant robot [1]. However, the actuators of a conventional robot are all installed on the joints, which not only increase the inertia and weight of robot, but also reduce its load capacity. Meanwhile, this type of design is also unsuitable for high speed motion and rapid response of a robot. Therefore, Cable-driven method brings a new idea to overcome the defect from conventional robot for its motion performance [2-4].

The regional and international competitions began to appear during 1950s that gave people a lot of fun, playing rules, rank are not resolved yet. The game is one that anyone can take participate in, regardless of age, sex, weight or experience, so that arm wrestling robots for entertainment are easily to be popularized. Several arm wrestling robots have been developed in recent years. In the 1990s, Taihei built an arm wrestling robot, whose driving mechanism is electric drive. In 2002, a system that enables players to arm wrestling via a force-position I/O device was built by Kunihiko Kano, their main topic is force testing, but the operation is complex and test results are low accuracy, so it did not have wide application. After two years, Kekuk University in Korea developed an intelligent arm wrestling robot [5] for senior, which is used to help them keep physical and mental health in order to lessen social welfare cost.

Parallel mechanisms have been widely examined in terms of its theory and applications. Its main attractions are its low structural weight, very high rigidity, and very high accuracy in positioning. However, its major drawback is its limited workspace. Cable-driven mechanisms have also been examined in terms of its theory and applications. These mechanisms have very low structure weight because the actuators are not moved and can be located away from the mechanism. The cable-driven concept has been applied to both serial and parallel mechanisms, however, for the cable-driven serial mechanisms, it encounters difficulties in guiding the cables around the joints and while for cable-driven parallel mechanisms, it still encounters the drawback of limited workspace [6, 7].

This paper details the design and development of the arm and hand assembly within the first phase. The arm and hand, henceforth referred to as arm, are designed to meet the following requirements. First, it must have the ability to grasp an object and place it in a different location. Second, it must be similar in scale to that of a human arm and be able to replicate similar motions. The final design should be made with standard components, such that it could be easily reproduced and mirrored to create left and right versions. Finally, the arm should be easily mounted to the mobile base [8-10].

This project involves using an existing head and neck and modifying an existing mobile base. The arm, however, is designed and built from scratch. For this reason, the majority of work on the arm in the first phase revolves around its mechanical design and construction [11].

2. Mechanism Design

A 5-DOF robot prototype, as shown in Fig. l, similar to human arm, the 5-axis motion of the robot includes three horizontal axis and a vertical axis of rotary motion, plus a hundred and eighty degree rotation of the pinch. The robot can carry out self-motion around the shoulder-wrist line; hence it fits for flexible operation under complex environment. To realize the force-closure of the manipulator, the redundant force is obligatory, because cables can only be pulled unilaterally. In order to realize an n-DOF motion, at least n+1 cable is needed as actuating elements [12, 13]. To use six cables to drive sphere joint, this paper proposes an approach to drive sphere joint by four cables.

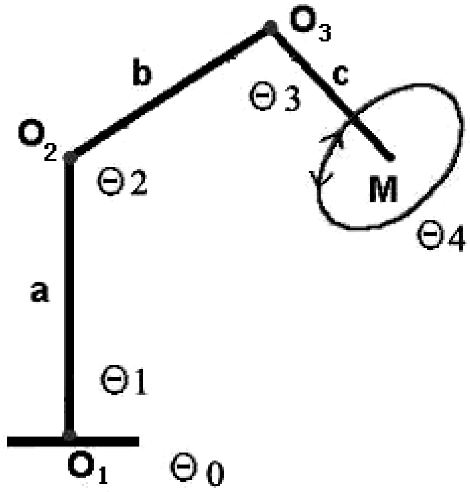

Fig. 1 5-DOF Robot.

By using two cables, the elbow joint realizes 1-DOF rotation. As shown in Fig. 2, to eliminate the motion influence from the elbow joint to the wrist joint, the oriented pulley should be installed on the rotation center of the elbow joint. Meanwhile, the actuating cables should pass along the axial core of the rotary wheel. Thus the cables will only have curving change, whereas the cable length will not be affected by elbow joint.

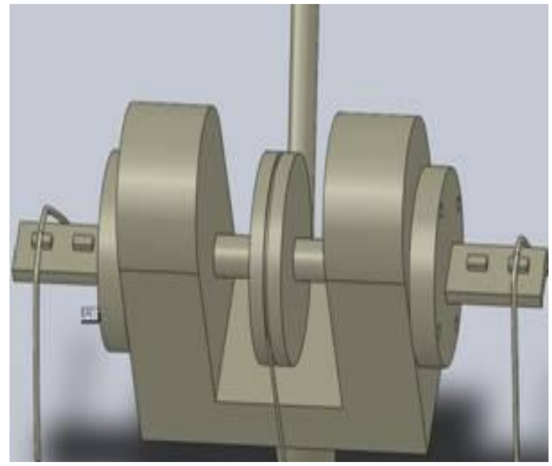

Fig. 2 Elbow joint driven by cables.

3. Solution of Joint Angles

It is difficult to directly solve the cable lengths from the pose of the end-efiactor, thus we propose an approach to find joint angles of the manipulator first, and then to find the cable lengths through analyzing the geometry relationship between cable lengths and joint angles.

According to the workspace analysis, the motion ranges of joint angles q_1, q_2, q_3 have influences to each other; joint angles q_4 and q_5 have such influences also. In order to improve fault-tolerance ability of the manipulator, here we propose an approach to avoid such situation through joint rate redistribution.

Assuming the dimensions of task space and joint space are m and n respectively, here we also define that the number of locked joints for failures is n_f, the number of joints with joint rate saturations is n_s, and the number of joints with normal work ability is n_g respectively. The joint rate redistribution can be included: According to the practical working ability of every joint, individual joint rate can be redistributed to ensure the trajectory of the end-effector being unchanged. Normally the velocity of end-effector is described by the hybrid velocity of a rigid body, as expressed below:

$$V_n^h = \binom{p_n}{w_n^s} \tag{1}$$

Where $P_n' \in R$ represents the instantaneous linear velocity, and w_n^s represents the instantaneous angular velocity, both are viewed in the base frame. So, the relationship between the velocity of the end-effetor and joint rates can be expressed as:

$$V_n^h = j_n^h(q)q' \tag{2}$$

Where $j_n^h = [\begin{matrix} I & p_n \\ 0 & I \end{matrix}]$, $J_n^s \in R^{4\times n}$, J_n^h represents the hybrid Jocobian matrix of the manipulator, $J_n^s \in R^{4\times n}$ is termed as the spatial Jocobian of the manipulator, where matrix $J_n^s(q) = [(\frac{\partial T_{0,n}}{\partial_{q_1}} T_{0,n}{}^{-1})^V \ldots (\frac{\partial T_{0,n}}{\partial_{q_n}} T_{0,n}{}^{-1})^V]$ so that the joint rates can be obtained according to Eq.(2):

$$q' = (J_w^h)^+ V_n^h + K_{mom}(I - (J_n^h)^+ J_n^h)[\nabla H(q)] \tag{3}$$

Where K_{mom} is the coefficient of homogeneous solution, $\nabla H(q)$ is the gradient vector of kinematic performance criterion H(q), $(J_w^h)^+$ is the weighted pseudoinverse of the Jacobian matrix, it can be given by

$$(\tilde{J}_n^h)^+ = w^{-1}(J_n^h)^t (J_n^h w^{-1}(J_n^h)^t)^{-1} \tag{4}$$

Where $W \in R^{n\times n}$ is a symmetric positive-definite matrix, and is referred to as a weighted matrix .Usually it is a diagonal matrix:

$$W=\text{diag}\,[w_1, w_2,\ldots, w_n] \tag{5}$$

with its i^{th} entry given as:

$$W_i = 1 + \left|\frac{\partial H(q)}{\partial q_i}\right|, \text{ i=1, 2, 4….n} \tag{6}$$

From Eq. (4), the contribution from the i^{th} joint to the pose of end-effector is relevant to the i^{th} column of J_n^h only. If the i^{th} joint is locked with rate q_1^f=0 because of failure, r the i^{th} joint rate is commanded to run with rate that is higher than its saturation rate q_1^s, in these cases, the contribution difference, $J_i^h(q_1 - q_1^s - q_1^f)$, should be ensure the end-effector to move compensated by other joints to along predetermined trajectory.

If there are f failure joints, and s saturation joints, thus the contribution of n_g normal joints to the end-effector should be revised as following

$$\tilde{V}_n^h = V_n^h - \sum_{j=n_{f1}}^{nf_f + n_{st}} J_j^k q_j'^s \tag{7}$$

Where j=n_{f1}, n_{f2}, n_{f3},…, n_{ff} refers to the index of the i^{th} failure joint, while n_{si} (i=1, 2, 3,…, s) refers to the index of the i^{th} saturation joint.

For calculating simplicity, assuming only the i^{th} joint is locked because of reaching its joint angle limit, thus:

$$\tilde{q}' = [q_1', q_2', q_3',\ldots, q_5'] \tag{8}$$

$$\tilde{J}_n^h = [J_1^h, J_2^h,\ldots, J_5^h] \tag{9}$$

Then we have

$$V_n^h = \tilde{J}_n^h \tilde{q}' \tag{10}$$

$$\tilde{q}' = (\tilde{J}_w)^+ V_n^h + K_{mom}(I - (\tilde{J}_n^h)^+ \tilde{J}_n^h)[\nabla \tilde{H}(q)] \tag{11}$$

Where

$$(\tilde{J}_w^h)^+ = \tilde{W}^{-1}(\tilde{J}_n^h)^T (\tilde{J}_n^h \tilde{W}^{-1}(\tilde{J}_n^h)^T)^{-1} \tag{12}$$

$$\tilde{W} = diag[w_1, w_2,\ldots, w_{i-1}, w_{i+1},\ldots w_5] \tag{13}$$

Where $I \in R^{n\times n}$ is the identity matrix, $\nabla \tilde{H}(q)$ is the remainder parts of ∇H after its i^{th} entry is extracted.

Consider t_0 as the interpolation period, G_k as the pose of the end-effector for k^{th} interpolation, and q_i (i=1, 2…5) as the individual joint angle. If the pose of the end-effector is G_{k+1} for $(k+1)^{th}$ interpolation, will be changed as:

$$G_{k+1} = e^{\tilde{s}_1 q_1} e^{\tilde{s}_2 q_2} e^{\tilde{s}_3 q_3} e^{\tilde{s}_4 q_4} e^{\tilde{s}_5 q_5} G_k \tag{14}$$

The process to find the inverse solution of the given pose G_{k+1} can be shown as following:

Firstly, solving joint angel q_i for special joint

After finding out the joint rate q_i^k for the k^{th} interpolation through Eq. (3) the joint angle for the$(k+1)^{th}$ interpolation can be obtained shown as following:

$$q_3^{k+1} = q_3^k + q_3^k t_0 \tag{15}$$

Fix the joint q_i to convert the manipulator from redundant to non-redundant to solve other joint angles.

Secondly, solving q_1 and q_2 with Eq. (2).

Since q_i have been solved relating to q_1 and q_2. Take a point P_1 on the axis s_1, we have $e^{s_1 q_1} P_1 = P_1$, then q_1, q_2 can be solved via Eq. (2).

Finally, solving q_4, q_5 by Eq. (1) and Eq. (2).

Since q_1, q_2, q_3 are known, let:

$$G_{k+1}{}' = e^{\tilde{s}_1 q_1} e^{\tilde{s}_2 q_2} e^{\tilde{s}_3 q_3} G_{k+1} G_k^{-1} \quad (16)$$

So that we can rearrange Eq. (14).

$$e^{\tilde{s}_4 q_4} e^{\tilde{s}_5 q_5} = G_{k+1}{}' \quad (17)$$

Take a point p_5 that is on the axis of s_5 but not on the axess s_3, s_4, For $e^{s_5 q_5} P_5 = P_5$ right multiply p_5 on both sides of the Eq. (17), then:

$$e^{\tilde{s}_3 q_3} e^{\tilde{s}_4 q_4} P_5 = G_{k+1}{}' P_5 \quad (18)$$

Take a point P, on the axis s_3, we can get q_3, q_4 via Eq. (2). Further q_5 can be obtained via Eq. (1).

Then, all joint angles, from q_1 to q_5, have been determined. Totally there are eight group possible solutions that come from multiple solutions. Usually, we can choose a group solution with minimum norm of joint rates to make the inverse solution is in the same trajectory group with its initial solution.

4. Coupling influences Among Joints

Because the actuating motor of each joint is installed on the base, every cable that actuates the corresponding joint should reach the base along the anthropomorphic-arm. Hence, the lengths of cables passing the shoulder joint will also be changed when the shoulder joint moves. The coupling influences from shoulder to the wrist and the elbow joint should be compensated to ensure the cable lengths of elbow and wrist correct.

As presented in this paper, the cables drawn from the elbow and wrist joints pass the moving platform P_1, P_2, P_3, P_4 of the shoulder join; P_5, P_6, P_7, P_8, P_9, P_{10} is respectively the connecting points for the six cables to pass moving platform of shoulder joint; B_5, B_6, B_7, B_8, B_9, B_{10} is respectively the connecting points for the six cables to pass fixed platform of shoulder joint. They are all distributed symmetrically.

Since the orientation matrix of the shoulder joint, ${}^A R_p$ can be solved from the paper, so that the cable length change, because of the coupling from the shoulder to the elbow and wrist joint, can be obtained by

$$\Delta l_1' = [\![{}^B B_i - {}^B R_p \cdot {}^P P_i]\!] l_i' \text{ (i=5, 6,…, 10)} \quad (19)$$

where ${}^P P_i$ and ${}^B B_i$ is the coordinates of point P_i in the frame P and the point B_i in frame B respectively.

5 .Drive motor and ancillary equipment selection

The low-power servo motor in drive motor will reduce the weight of the drive system. Using the direct control of the micro motor, meet the basic control requirements, at the same time, Design and implementation are relatively simple. Manipulator rod parameters are shown in Fig. 3. In order to facilitate the presentation, deputy campaign numbered from 0-3, Adjacent the spacing of the motor rotary shaft is in turn defined as i0 to i3, in which i3 including the execution unit.

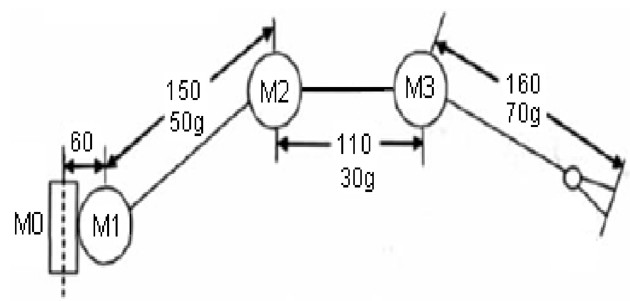

Fig. 3. Schematic manipulator rod parameters

Based on the manipulator rod Parameters, calculating the joint maximum drive torque required, then selecting the appropriate gearbox torque and efficiency. Ultimately determine the appropriate drive motor, and choose the matching code disc.

6. Conclusions

A 5-DOF Cable-Driven Anthropomorphic Arm is designed in this paper, and the mechanism design for this cable driven anthropomorphic-arm is analyzed. It proposes a hybrid inverse kinematic algorithm to combine both gradient project method and Paden-Kahan Subproblem. Therefore the optimization in redundancy solution can be realized with high trajectory tracing accuracy. Overall, the goals of the first phase of the robot arm have been meet. Although the method of motion control is limited in the current state, it serves as a strong foundation on which to test the performance and interface of the electronic components. The forward kinematic equations have been developed and the process has been well documented for future research with this robot.

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