Design and Control of a Novel Compact Dexterous Hand

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Abstract

This paper presents a novel design of a compact dexterous hand which could be mounted on robot arm ends directly with high adaptation. Actuated by one motor and multiple clutches, the hand has three fingers, 7 DOF and 9 active joints. The hand mechanism and its kinematics analysis are described in detail. Due to the specialty of the hand mechanism, an asynchronous time-sharing control method is proposed for the joint control. Some simulation results are given to show the control validity of this hand.

Keywords: compact dexterous hand, single motor actuation, passive joint, asynchronous time-sharing control

1. Introduction

Although many dexterous hands [1],[2],[3],[4],[5],[6] have been developed and much research work has been done on hand grasp and manipulation theory, hand kinematics, hand dynamics, the progress in hand mechanism remains slow. Most current dexterous hands have bulky actuation parts and can't be mounted directly to the ends of robot arms, while those portable ones may not be flexible enough to handle different operation requirements.

In traditional hand design, multiple motors are usually adopted and lengthy tendons are used for motion transmission. For example, The Utah/MIT hand with 16 DOF deploys 32 pneumatic actuators in a remote actuator pack and uses polymeric tendons and pulley to transmit the power. The Standford/JPL dexterous hand with 9 DOF deploys 12 electric motors as actuators in remote site and uses teflon coated cable to transmit motion.

This solution, however, has some major problems:

- Remotely placed heavy and bulky control parts make the hand less adaptive to be mounted on different robot arms or bodies when necessary.
- The more lengthy tendons are used, the more damping and friction are introduced, which will lead to both force and position error.
- Researchers also point out that the control system of the dexterous hand with multiple motor actuation will be very complex because of the large number of motors and the actuation system coupling [7].
- Multiple motors incur high cost of implementation.

Mechanism breakthroughs are seen in three significant famous compact hands in the history of hand development. Using direct driven technology, The compact Belgrade hand has only 4 DOF. It emphasizes more on local autonomy during grasping than on maximizing dexterity. The BarrettHand uses TorqueSwitch to control two joints with only one motor. However it is more like an intelligent gripper than a dexterous hand because only 4 axis can move at the same time and can't achieve most dexterous manipulations. DLR Hand introduces small specially designed linear actuators inside the finger digits to achieve direct joint drive, however, this design has limitation on the size of fingers to some extent.

Therefore, to design a really compact hand with high dexterity has always been a big challenge since the emergence of robotics. In this paper, the mechanism of the compact dexterous hand is described before the proposed control method of finger joints is presented. Some simulation results and conclusions are given at the end.

2. Mechanism of the Novel Compact Dexterous Hand

In our laboratory, a dexterous hand prototype has been previously developed with single motor actuation technology [8] (Figure 1).

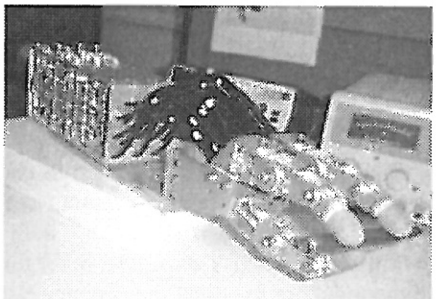

Figure 1. Hand prototype with single motor actuation

However it uses tendons to transfer the remote motion to each finger and has a bulky size too. Based on this model, our research focuses on compact design by integrating the actuation and control part with finger as a whole. The benefits of this integration are apparent: first the tendon overheads for long distance motion transmission are cut off; Secondly, additional special support parts used to attach bulky hand on the robot arm or body are not needed so that the hand has high adaptability to various robot applications.

2.1. Optimization of the Number of DOF

Generally speaking, the more flexibility the hand requires, the more DOF are needed and the more complex the hand is. A human hand has over 25 DOF and each finger has 4 DOF. Fortunately, most tasks themselves limit the number of DOF. That is, for a certain manipulation, not all DOF are required and some only function to facilitate the completion of the task. In short, for compact design purpose, the highest priority should be given to optimize the number of DOF while maintaining most static and dynamic characteristics of human hands and manipulations. The thumb, middle, and index fingers compose the basic configuration of our dexterous hand. Three fingers of human hand have totally 12 DOF, but two observations prompt us to reduce the number of DOF from 12 to 7.

The first observation is that there is certain relationship between the rotation of the tip digit and that of the middle digit. In natural movement, the middle joint and the tip joint always rotate together. One can't move just one of them but keep the other stationary without external force or internal force constrain. As shown Figure 2, when one rotates the middle joint of each finger in a natural way, the tip joint will follows its movement naturally and vice versus. Based on this observation, in our design, the tip joint is made passive to the middle joint in our hand design. In this way, 3 control DOF are omitted while one finger still has 3 active pitch joints and is more anthropomorphic.

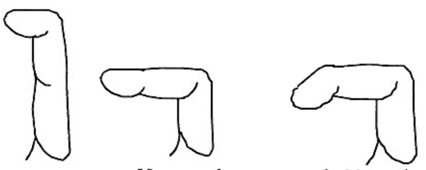

Figure 2. Human finger behavior

The second observation is that although each human finger has a yaw joint for lateral movement at the end of proximal digit, one seldom, if not totally, uses this joint for object translation along Y axis. The main functions of the yaw movement are to adjust the distance between the index and the middle finger and to help to rotate object around Z axis more conveniently. Hence for compact purpose, the yaw joints of both index and middle fingers are given up but that of the thumb is kept.

2.2. Compact Hand Model

Since our index and middle fingers have only two pitch DOF, they are driven by worm gears directly at the finger ends. The worms connect with the output shafts of the clutches protruding out of the cylindric actuation box attached behind the fingers. In this manner, we cut off the lengthy tendons or cables. There are two advantages by using worm and worm gear. First it can achieve a large motion transmission ratio while occupying the smallest space; the other is its self-block attribute (not backdrivable). This attribute provide us essential function to manipulate objects using clutches. When manipulating an object and one finger is required not to move and the clutches of the finger are powered off, the finger will not loose contact with the object but maintain the contact by receiving passive contact force exerted by other fingers.

Thin stranded steel ropes are used to transfer motion between finger joints, from finger ends to middle joints and tip joints. The finger motion transmission is illustrated in Figure 3.

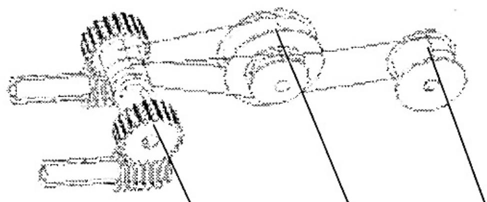

Figure 3. Finger joint actuation

To simplify mechanical design, the thumb finger has only one yaw joint at the finger base and no passive joint at the fingertip. The yaw joint is directly driven by the worm, in the meantime the middle joint and tip joint are independently driven by steel ropes which route over the base yaw joint to avoid jam with the yaw joint.

The thumb finger is located exactly at the middle place opposite to the index and middle fingers, but the thumb tip can choose to approach each finger. The base, middle and tip digits of each finger are human scale, having a scale of 1:0.666:0.444 [5](Table 1). At each active joint (except the tip joint of the index and middle fingers), a tiny potentiometer is installed to provide position feedback.

Item	Dimension
Finger tip digit	24 mm
Finger middle digit	36 mm
Finger base digit	55 mm
Actuation box diameter	104 mm
Actuation box length	92 mm

Table 1: Basic mechanical data of the hand

One motor and 7 clutches serve as the main actuation part. All the clutches and motor are integrated within a cylinder box, which mainly includes three parts: one DC servo motor with encoder, motion distribution part and 7 clutches. A torque dc servo motor with digital encoder is used. The motor's output is distributed to 7 input shafts of the clutches with a star configuration evenly. The output shafts of clutches directly drive the worm gears at each finger base. The bilateral clutches are the key components of our hand and their sizes comprise most volume of the actuating part. The special designed compact clutch mainly consists of an input shaft, an output shaft, an armature, two coils and two rotors which are connected to a pulley and a spurgear respectively. The armature always rotates with the input shaft. Once one coil is powered on, the armature will be attracted to corresponding rotor and make the rotor rotates too. According to the pulley and spurgear, different direction of rotation is achieved and transmitted to the output shaft. The whole clutch size is constrained in space of 35x25x70 mm.

Shown in Figure 4 is the proposed compact dexterous hand.

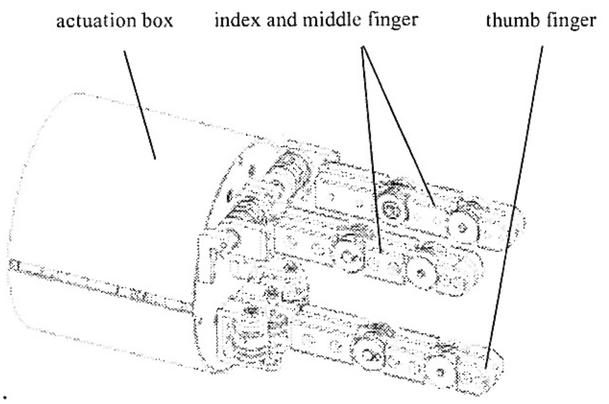

Figure 4. Compact dexterous hand model

3. Hand Kinematics

Since index and middle finger have identical kinematics, only index and thumb finger's kinematics are presented here. Define $\{T_i\}$ and $\{B_i\}$ are frames attached to the finger tip and finger base respectively as shown in Figure 5. The absolute control angles for index and thumb finger are α_i, β_i and $\gamma_m, \alpha_m, \beta_m$, the corresponding relative joint angles are $\theta_{i1}, \theta_{i2}, \theta_{i3}$ and $\theta_{m1}, \theta_{m2}, \theta_{m3}$. Finger lengths are denoted as l_{nk}, n={i,m} and k={1,2,3}.

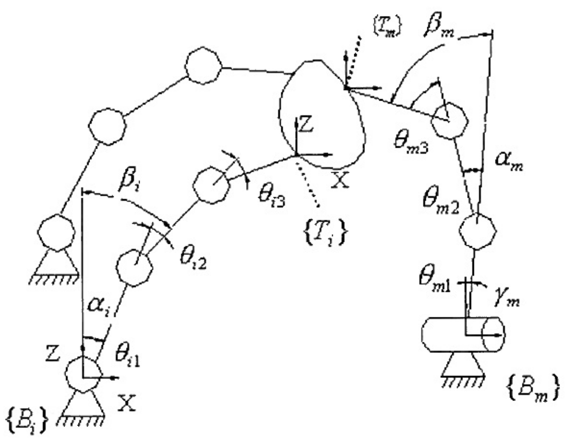

Figure 5. Kinematics model of the hand

To solve the forward kinematics of the hand, two special relationships, which are determined by the unique mechanism of the hand, should be noticed firstly. The first one is that the tip joint is passive to the middle joint for the index and middle fingers. The second one is that the middle joint and the base joint are both independently controlled. Rotation of one of them will not change the orientation of the digit controlled by the other joint, which is different from the nature of human hand. These two relationships can be expressed in matrices in (1) and (2).

$$\begin{bmatrix}\theta_{i1}\\ \theta_{i2}\\ \theta_{i3}\end{bmatrix}=\begin{bmatrix}1 & 0 & 0\\ -1 & 1 & 0\\ 0 & 1/2 & 0\end{bmatrix}\begin{bmatrix}\alpha_i\\ \beta_i\\ 0\end{bmatrix} \tag{1}$$

$$\begin{bmatrix}\theta_{m1}\\ \theta_{m2}\\ \theta_{m3}\end{bmatrix}=\begin{bmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & -1 & 1\end{bmatrix}\begin{bmatrix}\gamma_m\\ \alpha_m\\ \beta_m\end{bmatrix} \tag{2}$$

Based on the above relationships, the forward transformation matrices of the index and thumb fingers can be easily deduced in (3) and (4).

$$A_{B_i}^{T_i}=\begin{bmatrix}\cos\frac{3}{2}\beta_i & 0 & \sin\frac{3}{2}\beta_i & l_{i3}\sin\frac{3}{2}\beta_i+l_{i2}\sin\beta_i+l_{i1}\sin\alpha_i\\ 0 & 1 & 0 & 0\\ -\sin\frac{3}{2}\beta_i & 0 & \cos\frac{3}{2}\beta_i & l_{i3}\cos\frac{3}{2}\beta_i+l_{i2}\cos\beta_i+l_{i1}\cos\alpha_i\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{3}$$

$$A_{B_m}^{T_m}=\begin{bmatrix}\cos\beta_m & 0 & \sin\beta_m & -l_{m3}\sin\beta_m-l_{m2}\sin\alpha_m\\ -\sin\gamma_m\sin\beta_m & \cos\gamma_m & -\cos\gamma_m\cos\beta_m & -l_{m3}\sin\gamma_m\cos\beta_m-l_{m2}\cos\alpha_m\sin\gamma_m-l_{m1}\sin\gamma_m\\ \cos\gamma_m\sin\beta_m & \sin\gamma_m & \cos\gamma_m\cos\beta_m & l_{m3}\cos\gamma_m\cos\beta_m+l_{m2}\cos\alpha_m\cos\gamma_m+l_{m1}\cos\gamma_m\\ 0 & 0 & 0 & 1\end{bmatrix} \tag{4}$$

4. Finger Joint Control

Fundamental control issue for dexterous hand is finger joint control, that is the basis of hand moving, grasping and manipulating. Previous researchers have proposed a control scheme similar to PWM in motor control for single motor actuation technology. In this method, the angular position θ and velocity ω are determined by:

$$\begin{cases} \omega = \lambda\omega_0 \\ \theta = \lambda\omega_0 t \end{cases} \quad (5)$$

where λ is the engaging time ratio of clutches, t is the operation time and ω_0 is the constant motor speed.

However, this method assumes an ideal condition: the mechanical clutches could work in frequency as high as electronic components, which is impossible apparently. Therefore this method can only work at very low speed situation. Furthermore, because of the on-off nonlinear characteristics of the clutches, the control of the dynamic behavior of the hand will be very difficult.

Due to the special feature of our hand mechanism, asynchronous time-sharing control, which controls the length of time slice for each clutch to realize individual joint velocity and position controllability, is introduced to overcome the non-linearity of clutches.

Within this control scheme, the trajectories of joint angular position and the velocity profile are constrained both by specific motion task and time-sharing driving mechanism. One finger's trajectory is interpolated by the finger's different joints' action. Figure 6 shows a typical joint position and velocity trajectory of one finger, which has two joints.

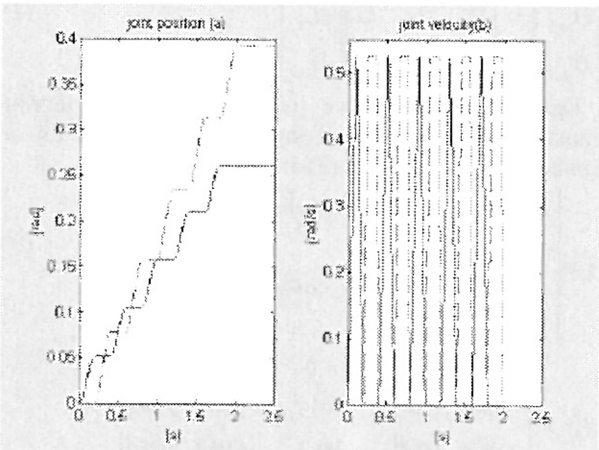

Figure 6. Typical joint angular position (a) and trapezoid velocity (b) (solid: joint 1, dash: joint 2)

The finger joint model is shown in Figure 7. Considering the finger kinematics and dynamics, the model is similar to the common multi-joint manipulator. The difference is that the motor is not mounted on the joint any longer, the joints' motion is dependent on the status of clutches.

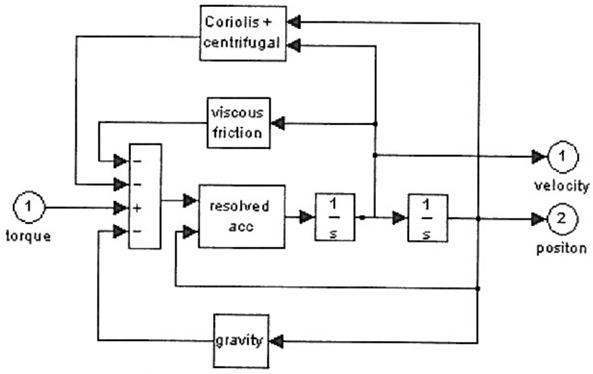

Figure 7. Block diagram of finger model

For the real hand control, the joint torque compensation is calculated by central processor according to the objective trajectory and then loaded to the servo controller for controlling the motion. As in Figure 8., the compensation torque is added to drive the hand motion feed forwardly.

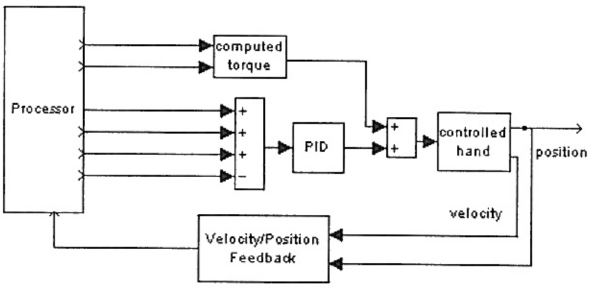

Figure 8. Block diagram of feed forward compensation for dexterous hand motion control

5. Simulation Results

This section presents some simulation results. The critical results are the control of joint torque and the precision of joint position. Since all the joints of three fingers are controlled by single motor through multiple clutches and special mechanical transmission, the control time slice for each joint is an important parameter. By tuning this parameter and adopting joint space control with feed forward computed torque compensation, the joint performances of one finger with different width of time slice are presented in Figure 9 and 10. It assumes that the finger has two joints and joint motion is from [0 0] to $[\pi/12 \quad \pi/8]$ with payload 0.1kg at the fingertip.

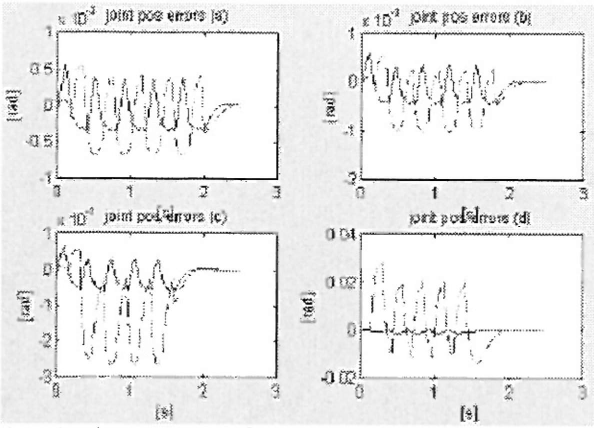

Figure 9. Joint position error for different control time slice (a) 0.20 (b) 0.18 (c) 0.16 (d) 0.14 second, (solid: joint 1, dash: joint 2)

As shown in Figure 9, the joint position error increases much with the decrease of slice width. Obviously, without enough time for switching, the control system will have no enough time to response, which will affect the smoothness of output position seriously.

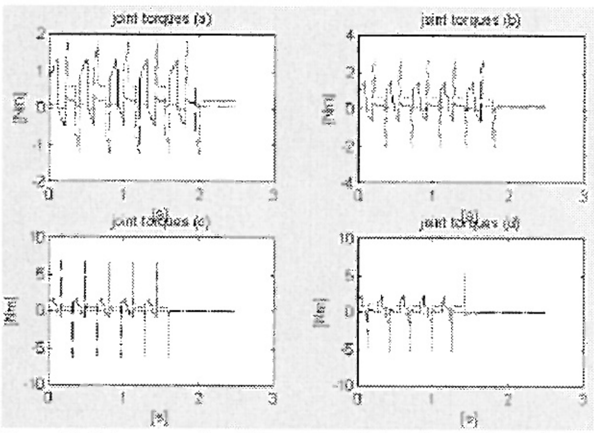

Figure 10. Joint torque for different control time slice (a) 0.20 (b) 0.18 (c) 0.16 (d) 0.14 second, slice (solid: joint 1, dash: joint 2)

As shown in Figure 10, the joint torque will increase if the driving system switch too fast. The consistent results in the above two figures show that an ideal response can be achieved by choosing suitable control time slice (for example 0.2s). The simulation results preliminarily prove the validity of the proposed hand design.

6. Conclusions

A novel compact dexterous hand is newly developed in this paper. The main objective is achieved by adopting one motor actuation and optimized and integrated mechanism. The novel design makes our dexterous hand have the following characteristics: 1) Single motor actuation; 2) Passive joints for the index and middle finger; 3) Compact integration of the actuation part and the fingers; 4) 7 DOF; 5) low cost. Asynchronous time-sharing method is proposed to control the finger joint. Future works include extensive experimental prove of the validity of the proposed control and evaluation of the performance of this compact dexterous hand.

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