A Study on Robust Control of a Three-Finger Hand with 15 D.O.F

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Abstract: The focus of this paper is to design a flexible three fingered hand system with 15 D.O.F for dynamic manipulation with an intelligent controller, and to build a useful database for dynamic manipulation based on the experimental results. The weight of the hand module is only 0.6 kg, but flexible motion and powerful grasping are possible. To achieve such a dynamic motion in a robotic hand, we have developed a flexible fingered hand with a control system incorporating image recognition system in which we deal with the problems of not only accuracy and range of motion but also the flexibility of hand.

Keywords: Robot Hand, Intelligent Controller, Multifingered Hand.

I. INTRODUCTION

Recently several hands have been developed in which actuators are placed directly in each finger link. Several human-like robotic hands have been developed with this approach. These robotic hands have many degrees of freedoms to achieve the dexterous grasp of a human hand, but power and speed are not enough to achieve dynamic manipulation. General Hand is lightweight and powerful, but the number of degrees of freedom is not enough to achieve precise motion.

In order to develop a dexterous and skillful artificial hand, such as a human hand, various types of multifingered hands have been researched. Such hands were designed with attention to range of motion and accuracy, and less attention to speed of motion.

Examples of this dynamic change are ""pushing"", ""hitting"", ""throwing"", ""catching"", etc. A human takes advantage of such dynamic motion for mani - pulation. This is one of the reasons that a human manipulation is more dexterous and flexible than a robotic hand.

There has been considerable theoretical work on a multifingered hand addressed to: grasp stability, force analysis, and dynamic control. But in most of this research static or quasi-static movement was assumed, and there has been little work on dynamic manipulation.

Various types of robotic hands have been developed. In most hands a wire driven mechanism is used with control through high-power actuators that are placed outside of the main body of the hand. But the mechanism is complicated and the total system is big and heavy.

On the other hand, in dynamic manipulation, transitions in the contact condition often occur when the fingers let a target go, or the fingers touch a target. It is difficult to observe a target only using force and tactile sense; vision plays an important role in this case. To observe a moving object in realtime, a flexible vision system in which the sampling rate is more than 1.2 kHz is effective. Several types of vision chips have been developed, and this technique was applied to a sensory motor fusion system, and to produce high speed grasping.

In this paper we describe a newly developed intelligent flexible hand system and its application to a catching task. The hand has 10 joints and 3 fingers. A newly developed small harmonic drive gear and a high power mini actuator are fitted in each finger link, and a strain gauge sensor is in each joint.

II. FLEXIBLE HAND SYSTEM DESIGN

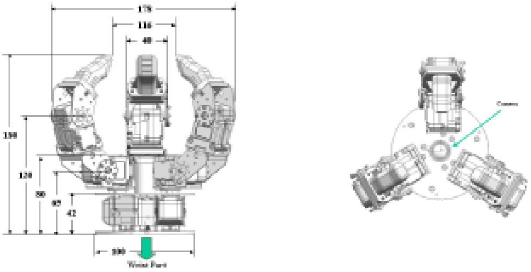
The mechanism of a flexible hand gripper requires the mass of the hand should be as low as possible. It is highly desirable that the hand weigh less than 1kg. Furthermore the low mass of the finger mechanism is desirable not only to achieve flexible motion but also for stable control.

Our philosophy about dynamic manipulation is maximization of the power and minimization of the mechanism. In particular three factors are important: (1) light weight, (2) high speed and high acceleration, (3) accuracy.

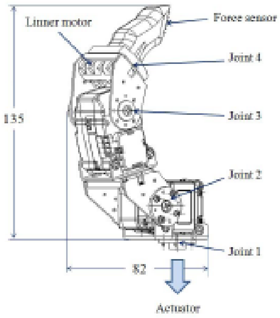
Fig. 1 shows the mechanical design of the hand, and Fig. 2 shows a scene of the Gripper control. It has three fingers, and we call the fingers ""left finger", ""index finger"" and ""right finger"" looking from the left side. We call the joints of each finger as joint 1; joint 2, joint 3, and Joint 4 (were represented in the Fig. 1).

To achieve the light mechanism, we reduced the number of joints and fingers as much as possible. We used three fingers, which is the minimum number to achieve a stable grasp.

The index finger has 3 degrees of freedom, and the other fingers have 3 D.O.F, so that the hand has 15 D.O.F total. In general a hand needs 9 D.O.F to move a target to any position and orientation. But in our hand 1 D.O.F of the index finger is omitted, and the wrist joint of the manipulator takes its place.



(a) Front view (b) Top view



(c) The structure of a finger

Fig. 1: The specification of Hand Fingers

The fingers are arranged so as to grasp both circular and prismatic objects. Both left and right thumbs play the role of the “"thumb”" of a human hand. Each thumb has only 3 D.O.F, which is less than the 5 D.O.F of a human thumb, but various types of grasping can be achieved because the joint can move in a wide range.

In order to achieve “"lightning”" high acceleration, we have developed a new actuator that allows a large current flow for a short time.

The design is based on the new concept that maximum output should be improved rather than rate output. As a result this actuator can generate maximum power only for a short period of time, but the power output is high, to prevent the actuator from overheating, the amount of current is controlled by software in realtime.

The finger has strain gauges at the inter-phalange and metacarpal-phalange joints for force control. In addition a 6-axis force/torque sensor and a tactile sensor will be mounted on each fingertip.

The flexible motion imposes a heavy load on the finger mechanism. For this reason a simple mechanism should be used for reduction gear, transmission, etc. In most traditional hand systems a wire-driven mechanism is used. But this is not suitable for a lightweight mechanism, because it is large and complicated.

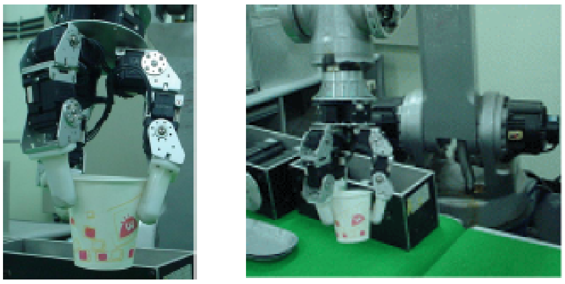


Fig. 2: Scene of the hand gripper control

In our hand a newly developed small harmonic drive gear and a high-power mini actuator are fitted in each finger link. A harmonic drive gear has desirable properties for control such as no backlash and a high reduction rate.

As the transmission mechanism between actuator and joint, we adopt a bevel gear. This is because the axis of the actuator should be orthogonal to the axis of the joint, and a bevel gear is simple and strong enough to achieve flexible rotation. Normally a bevel gear has a large amount of backlash. To reduce backlash the bevel gear was processed precisely, and derris coated on the surface.

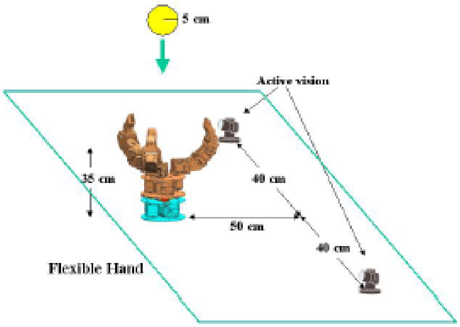


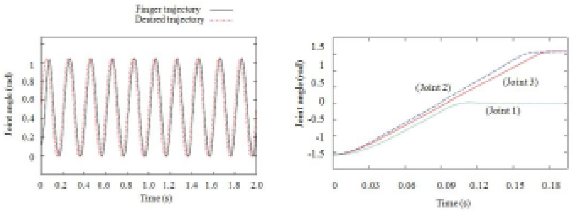
Fig. 3: Visual feedback control system

We added dual vision to the hand system, as shown in Fig. 3. Vision is with a massive parallel vision system called column-parallel high-speed vision system. It has 128 × 128 photo detectors with an all pixel parallel processing array based on vision chip architecture and an exclusive summation circuit for calculating moment values. Because the visual processing is executed in parallel in the processing array, flexible visual processing (moment detection, segmentation, etc.) is achieved within 1ms.

Early image processing is performed in order to achieve segmentation of the image, extraction of the target area, and computation of the image moments. From these data, the position of the target is computed.

Each vision sensor is mounted on an active vision, as shown in Fig. 3. Because the joint angle sensor has high resolution, high resolution of 3D position sensing is achieved by fusing image information with joint angle information. The information acquired by the vision system is sent to the hand actuator at the rate of 1.2 kHz, which is the same rate as the joint angle sensor and the joint torque sensor.

Each joint is controlled by PD feedback. Fig. 4(a) shows the time response of the joint 2 to a 20 Hz sine wave input, which shows that the finger tracks the 20Hz wave with no discernible delay. Fig. 4(b) shows the time response to a step input, which shows that the Joint 2 closed an angle of 180 deg within about 0.15s. The Joint 3 closed this same angle in about 0.18s, and the joint 1 closed an angle of 90 deg within about 0.11s.



(a) Sine wave (b) Step

Fig. 4: Result of Performance

III. PERFORMANCE TEST

The main advantage of a multi fingered hand is that it can grasp various objects by changing its shape. Several classifications of grasping have been proposed. In this proposal various grasps are classified into three large categories: a power grasp that passively resists arbitrary external forces exerted on the object, a precise grasp to manipulate the object, and an intermediate grasping which some fingers are used for a power grasp and the other fingers are used for a precise grasp.

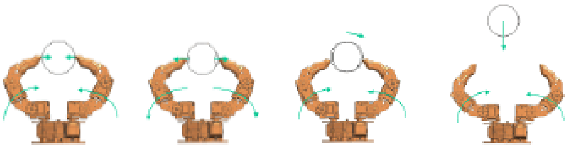
We achieved these typical grasp types in our developed hand. Fig. 5 shows the results. It is not always necessary that all types of grasping be achieved, but it is most useful to achieve dexterous manipulation.

Catching is one of the most important tasks for dynamic manipulation. In this section catching is shown using our flexible hand with a visual feedback controller.

To simplify the problem, suppose that the target and the hand are on a 2 dimensional plane, the target is a sphere, and two fingers catch the target. From various experimental trials, we have decided on the catching strategy shown in Fig. 6.

Fig. 5: Grasping examinations

The fingertips impact the target, and the target is moved to a stable grasp position. Finally two fingers catch the target, and the impact from both sides' stops the falling motion of the target.



(a) Holding (b) Rebounding (c) Locking (d) Approaching

Fig. 6. Catching strategy

To simplify the problem we assume that the inter-phalange joint is always controlled at 90deg. In Fig.7, $q_0 \in \mathbb{Q}^2$ is the target position, $q_i \in \mathbb{Q}^2$ is the i-th tip position, $e_{i1} \in \mathbb{Q}^2$ and $e_{i2} \in \mathbb{Q}^2$ are the unit vectors fixed on the finger link, $Q \in \mathbb{Q}$ is a target radius, and $\theta_i \in \mathbb{Q}$ represents the angle of the metacarpal-phalange joint of the i-th finger.

With two fingertips the optimal grasp points are both sides of the sphere: $q_0 \pm Qe_x$, where e_x is the x-axis unit vector. In order to bring the tip close to the point in the approaching phase, we define the following virtual constraints:

$$[(-1)^i Q_0 e_x + q_0 - q_i]\, e^T_{i1} = 0, \qquad (i = 1,2). \qquad (1)$$

This means that the fingertips are always directed to the optimal grasp points, and it is regarded as the process to make a "virtual wall" along the trajectories of both fingertips. If the speed of fingertip is fast enough to track the target, the target falls along the virtual wall. For this reason, the locking and holding phases are also achieved.

Because e_{i1}, e_{i2}, and q_i are a function of the joint angle θ_i, Eqn. (1) is rewritten as

$$f_i(\theta_i, q_0) = 0, \qquad (i = 1, 2), \qquad (2)$$

where f_i represents a nonlinear function. The desired trajectory of metacarpal-phalange joint $q_{di} \in \mathbb{Q}$ is given as the solution of Eqn.2. It is written as

$$\theta_{d_i} = g_i(q_0), \qquad (i = 1, 2), \qquad (3)$$

where g_i is the implicit function of f_i.

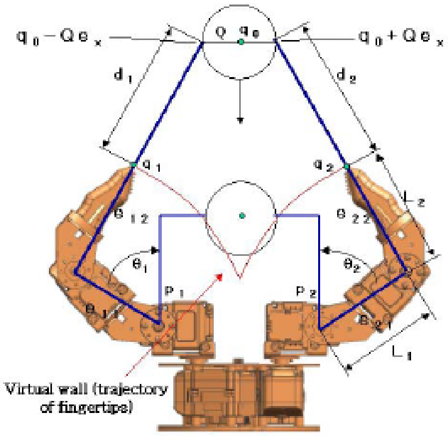


Fig. 7. Catching algorithm

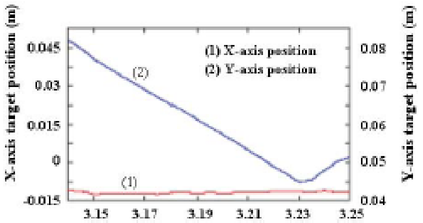


Fig. 8. Time response: target position

As a result, the control method is written as

$$\tau_i = K_p\left[g_i(q_0) - \theta_i\right] - K_d\dot{\theta}_i, \quad (i= 1, 2). \qquad (4)$$

where τ_i is the command torque of the metacarpophalangeal joint, and K_p and K_d are appropriate scalars. Because the finger mechanism is light and the output of the actuator is high power, the inertia of the link almost can be ignored, and the PD feedback control achieves good performance.

In the rebounding phase, it is desirable that the movement of the fingertips caused by the rebound is small enough. To solve this problem, the gain K_p is increased temporary in the moment both fingertips touch the target.

We used a rubber ball with radius of 5cm as a target, and we dropped it from about 1.2m in height. The speed of the falling ball is about 5.9m/s just before it hits the ground.

The catching task for the ball is:

- Approaching (0÷40ms)
- Locking (40÷50ms)
- Rebounding (50÷60ms)
- Holding (60ms÷).

Fig. 8 shows the changes in the target position q_0, and Fig. 9 shows the changes in the distance d_1 and d_2. The success rate was more than 95% and tolerance of position error of the target was about ±1.5cm from the center of the palm.

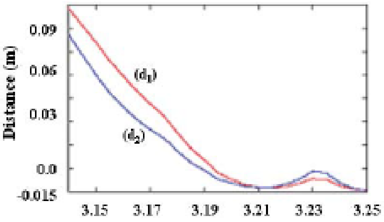


Fig. 9. Time response: distance

Several types of failure modes were observed. The direction of a bounced ball depends on the coefficient of friction and restitution. It is difficult to know the accurate values of these parameters, but the errors in their measurement may be ignored if the speed of the fingertip is fast enough.

IV. CONCLUSION

We have described a lightweight flexible hand with 15 D.O.F, and the associated visual feedback control. We are now developing a flexible manipulation system, which consists of a dual flexible multi-fingered hand-arm system, and a dual active vision system. In the future this new hand-arm system will be used for tasks.

The need for a robotic hand that works in the real world is growing. And such a system should be able to adapt to changes in environment. We think that the concept of a flexible hand system with realtime control implementation will become an important issue in robotic research.

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