Anthropomorphic Robot Hand with Hydrostatic Cluster Actuator and Detachable Passive Wire Mechanism

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Abstract—Anthropomorphic robot hand has been an interest of researchers to investigate principle and to realize dexterous manipulation. However, designing such a hand had been a challenge due to their large degree of freedom and limited payload. Those challenges result in lack of actuator power, lack of durability, and poor maintainability. To overcome such issues of anthropomorphic robot hand, we proposed novel mechanism of robot hand with detachable passive wire mechanism and hydrostatic actuator cluster. In this paper, basic concept of the proposed hand, hydrostatic actuator and hand development, and basic experiments with the developed hand is explained.

I. INTRODUCTION

Anthropomorphic robot hand has been an interest of researchers to investigate principle and to realize dexterous manipulation. However, development of such hands were challenge because it is required to fit large number of degree of freedom, that is almost comparable to degree of freedom of the rest of the body, into a space of a single hand.

To design such mechanism, either distribution or miniaturization of actuator is necessary. Following approaches were taken as attempts to solve this issue.

1) Tendon drive of finger joints[1], [2], [3]
2) Miniaturization of actuators[4], [5], [6]
3) Fluid actuator approach[7], [8], [9]

The advantage of first group is that it can use large output motors that would not fit into fingers. That means they can integrate large number of degree of freedom (DOF), thus more dexterity with same actuator power output. However, this method often suffers from the mechanical complexity to put the wires through the wrist. Conduit tubes are often used for wires to reduce the complexity, but they increase the transmission friction significantly. Also, they have issue in maintainability because wires break due to the fatigue.

Second group mostly use gear drives placed in finger joints those are connected to miniature motors mounted in the finger. However, usage of gear drives cause loss of backdrivability and lack of durability. Also, grasping force exerted by miniature motors is often small. Thus those hands have tendency of being weak and fragile.

Third group places fluid actuators in the finger joints and pressure generators in the forearm or in the palm. It has same advantage as the first group in a way that it has possibility of using large speed and torque motors. It also has additional advantages as follows: backdrivability (with appropriate design[9]), low mechanical complexity, and high shock resistance. But they have issue in placement of tubes connecting actuator components.

In this paper, we propose hybrid approach of first group and third group. Hydrostatic actuators are used to provide backdrivability, torque sensing capability, and high shock resistance. Those actuators are clustered to reduce mechanical complexity and increase modularity. Low friction wire transmission is used to transmit the torque produced by hydrostatic actuators without losing backdrivability. Issue on maintainability is resolved by introducing detachable architecture of wire transmission; in case of failure, the transmission can be replace with ease.

This paper is organized as follows. In next section, basic concept of the hand is described. In section 3, details on development of hydrostatic actuator cluster is explained. In section 4, details on proposed wire transmission architecture is explained. In section 5, experiments with the developed hand are performed. The section 6 is the conclusion.
II. STRUCTURE OF ROBOT HAND

In our previous study [9], we used EHA (Electro-Hydrostatic Actuator) as the actuator of the finger joint for improvement of backdrivability and durability. We placed vane motors in finger joints and placed hydraulic pump in the forearm. With use of EHA, we gained backdrivability and structural robustness. This structure had advantages in mechanical simplicity and actuator modularity. However there were issues as listed.

1) Flying tubes connecting vane motors and pumps were obstacle in manipulation tasks.
2) Connecting tubes must be flexible to allow vane motors to move, but they limited operating pressure. Usage of low pressure increased volume and weight of actuators. Additionally, EHAs in the hand were not equipped with charge circuitry and pressure relief circuitry which limited maximum output power of the actuators. These facts motivated us to use EHAs as actuators, but use rigid connections between vane motors and pumps.

In this research, we place whole EHA in palm of the robot hand. By having actuators nearer to the extremity than the wrist, we can reduce the mechanical complexity significantly. We designed a hydrostatic actuator cluster with all active components of the hand integrated. The hand portion consists of only passive wire transmissions and linkages. We designed the actuator cluster for the hand, but this cluster is modular and can be used for other applications as well. This modular design method simplifies the design process significantly by isolating two components interfaced by specifications[10].

Torque generated by the EHA should be transmitted with as small friction as possible to retain high backdrivability. We designed wire transmission without conduit tubes to minimize transmission friction. However, wire transmissions have fate of failure due to fatigue of wire. For this reason, the hand was designed that the passive wire transmission can be detached for replacement easily. Fingers are also designed to follow the modular design philosophy. To eliminate the possible backlash at the coupling connecting actuator cluster and wire mechanism, we developed backlash-less coupling mechanism that is explained in section 4. We aligned all couplings in single plane, so the attachment and detachment can be performed in single action.

From the weight and size point of view, fewer DOF (degree of freedom) as possible is desirable. We chose 4 fingers and 11 joints - 8 DOF (degree of freedom) as shown in Fig. 1 as minimum DOF that can realize realistic manipulation tasks. With this configuration, we can realize most of grasp patterns proposed by Cutkosky [11] as shown in Fig. 2.

III. HYDROSTATIC ACTUATOR CLUSTER

Advantages of EHA are backdrivability, durability, and design flexibility [9], [12]. Backdrivability is caused by low transmission friction. EHA or hydraulic actuators in general are significantly durable than gear drive systems because the force transmission is done with surface, where gear drive systems transmit force by small area, essentially a line. Usually axis arrangements of motor and output of gear drives are constrained to either parallel or perpendicular. In hydraulic systems, axis arrangements can be chosen arbitrarily by using bent tube to connect pumps and hydraulic motors. However, EHA had disadvantage of having a tendency of being heavier than gear driven systems. This disadvantage can be resolved by using higher operating pressure. By using higher pressure, both pump and hydraulic motor can be built smaller, thus lighter.

To increase the operating pressure of EHA, a rigid manifold was used for connection between pumps and vane motors. It does not mean the loss of the design flexibility because we can still design actuators with arbitrary arrangement of pump and hydraulic motor. These EHAs were assembled as a block, or a cluster, to reduce unnecessary structure to hold actuators together. By clustering actuators, we could have single pressure source and line to provide charge pressure, and single line to drain relief valve outlet as shown in Fig. 3. Charge pressure is important in closed hydraulic systems to avoid cavitations [13]. Relief valves are also integrated in the system to release the pressure to drain and protect the system when the system encounters unexpected high pressure as in the case of impact. The relief valve was designed to crack at the pressure of 5(MPa): it is expected to operate only in emergency case. Operating pressure and output torque were simulated in design phase with the method proposed in [12].

To maximize reduction ratio in limited actuator volume, single vane hydraulic motors and trochoid pumps were used. Vane motors were assembled in staggered arrangement as shown in Fig. 4 to minimize actuator cluster size. Two of the rows shown in Fig. 4 were used to build actuator cluster with 8 DOF. Additionally, the actuator cluster is equipped with a charge pump. Fig. 5 shows the CAD model of designed actuator cluster.

IV. MECHANISM OF ROBOT HAND

The hand part consists of passive wire transmission mechanism. The requirement for the mechanisms are as follows: High rigidity, Low friction, and Modularity.
To realize such a mechanism with wire, there are several types of wire transmissions commonly used. Three major types are $N$, $N+1$, and $2N$ types. $N$ type wire transmission use $N$ actuators to drive $N$ joints. This is simplest configuration, but requires tensioners to give wires pretension. $N+1$ type uses $N+1$ actuators to drive $N$ joints. This is minimum configuration to actively control wire pretension. $2N$ type uses $2N$ actuators to drive $N$ joints. This is called antagonistic drive. With this configuration, pretension of individual wire can be controlled independently.

For following reasons, we decided to use $N$ type wire transmission mechanism for driving finger joints.

1) Hand must be light and small, so minimum number of actuators are desirable.

2) With the usage of $N+1$ and $2N$ wire transmission, wires will derail from pulleys when the system is not powered due to the backdrivability of EHAs.

Pretension of the wires are controlled with tensioners placed adequately. Although constructing whole wire transmission only with pulleys increases mechanical complexity, conduit tubes were not used because of their friction.

All fingers including thumb were designed identical. The structure of wire transmission is shown in Fig. 6. This type of wire routing was chosen to keep the length of the wires constant regardless of the joint angles; this eliminates necessity of complicated tensioner mechanisms with preloaded springs. With this design, just by locking pulleys of unnecessary DOF, fingers operate as shown in Fig. 1. Movable range of all finger joints were chosen as $0 \sim 90$ (deg).

Relationship between EHA position ($\theta_i, i = 0, 1, 2$) and finger joint positions ($q_i, i = 0, 1, 2, 3$) can be expressed as (1) and (2), where $\theta = [\theta_0, \theta_1, \theta_2]^T$ and $q = [q_0, q_1, q_2]^T$. $s_i$ and $t_i$ are reduction ratios noted in Fig. 6. $q_0$ is the position of MP2, $q_1$ is the position of MP1, $q_2$ is the position of PIP, and $q_3$ is the position of DIP respectively. $q_3$ is omitted in (1) and (2) because $q_2 = q_3$ or $s_4 = 1$.

$$q = A\theta \quad (1)$$
TABLE II

<table>
<thead>
<tr>
<th>Joint</th>
<th>MP2</th>
<th>MP1</th>
<th>PIP</th>
<th>DIP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque (Nm)</td>
<td>1.7</td>
<td>0.68</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>

A = \[
\begin{bmatrix}
    t_0 & 0 & 0 \\
    t_0s_1 & t_1s_1 & 0 \\
    t_0(s_1-s_2)s_3 & t_1s_1s_3 & -t_2s_2s_3
\end{bmatrix}
\]

\tag{2}

To have maximum torque at the joints, torque optimization is necessary. We take this mapping $\theta \mapsto q$ as $f$, thus $q = f(\theta)$. If we put the moving range of finger joints as $W_q \subset \mathbb{R}^3$, the problem of torque optimization becomes a problem of finding $f^{-1}(W_q)$ under mechanical constraints of $s_i$ and $t_i$. This problem is a non-linear optimization problem, but by introducing additional constraint $s_1 = s_2$, this optimization problem can be solved analytically. Table II shows the optimized pulley reduction ratio with this additional constraint for the case of designed hand.

By using the virtual work principle, torque at the finger joint $\tau_q$ can be estimated from $\tau_\theta$ as:

$$
\tau_q = A^{-T} \tau_\theta
\tag{3}
$$

From this relation, maximum single joint torque at finger joint was calculated as in Table III. Considering the coupling, maximum finger tip force in fully stretched posture is 2.9(N) when all loads are supported by actuator torque. If the dorsiflexion was mechanically locked, maximum finger tip force becomes 10(N) in same posture. Length of the finger sections are as follows: proximal phalanx, 45(mm); middle phalanx, 35(mm); and distal phalanx, 28(mm).

Connection between passive wire hand and actuator cluster is done through cross-shaped wedge couplings which are shown in Fig. 5 and Fig. 7. Couplings are designed to provide axial preload with the springs in the couplings to eliminate possible backlash. Amount of preload $f_p$ is selected so the axial force produced from transmitting torque due to the wedge shape $f_r$ never exceeds $f_p$.

Fig. 8 shows outlook of developed hand assembly. Fig. 9 shows the detached state of the hand. Table IV shows the size and weight of the system.

V. Experiments

A. Torque-Speed Characteristics of EHA

To evaluate the performance of developed actuators, measurement of T-N (Torque-Speed) characteristics was performed. This was performed by providing constant voltage to the pump motor(electric motor) and constant torque to the vane motor (hydraulic motor), speed of the vane motor was
measured by link side encoder. Applied torque was measured simultaneously with load cell. Measurements were performed for different torque to acquire the characteristic curve.

Fig. 10 shows the least-square fitted measured value imposed on the designed curve. From this evaluation, stall torque at motor’s rated voltage was 1.17(Nm) and no-load speed of the EHA as 106(RPM), where designed value of the stall torque was 1.7(Nm) and no-load speed was 60(RPM). This difference is expected to come from difference in designed gap amount and actual gap amount of hydraulic components, because the amount of leakage is proportional to cube of the gap amount which have significant impact on actuator performance.

B. Backdrivability of EHA

One of the important basic feature of EHA is backdrivability of the system. In hydraulic systems, two definition of backdrivability are necessary to describe backdrivability[12]. The output backdriving is the state that the output axis is driven by external force. This term does not take in account of input, or pump axis state. Total backdriving is the state that the input axis is driven by external force. Backdrivability is defined as an ability to operate in backdriving state.

Backdrivability was measured by applying quasi-static torque to the vane motor axis through load cell while measuring speed of output and input axis encoders. Fig. 11 and Fig. 12 shows state of output backdriving and total backdriving respectively. From these figures, both output and total backdrivability were confirmed. Minimum output backdriving torque was 0.02(Nm) (1.7% of maximum torque) and minimum stable total backdriving torque was 0.4 (Nm) (34% of maximum torque). This result implies that stable position based impedance control can be used and the controller would respond with the small torque of 0.02(Nm).

C. Torque Sensing of EHA

In developed system, torque acting on EHA can be sensed using integrated pressure sensors. Fig. 13 shows the relationship between pressure and applied torque. Hysteresis is observed from the data which is caused mainly by friction of vane motor output axis oil seal. Amount of maximum hysteresis in this experiment was 46(mNm) (4%) and maximum estimation error was 15% of full scale. The nonlinearity of the result comes from nonlinearity of the oil seal friction.

D. Motion Test of Developed Hand

To confirm basic operation of the hand, finger joints were position controlled with PD controllers and encoders on the output axes of EHAs. Finger motion was preformed by tracking predefined trajectory commanded from the host controller. Fig. 14 shows the time series snapshot of the finger motion.
VI. CONCLUSIONS

Listed below are the conclusions of this paper.

1) Proposed modular structure of the anthropomorphic hand with hydrostatic actuator cluster and detachable passive wire mechanism to realize robust, force sensitive, and easy-to-maintenance robot hand.

2) Proposed design method for high density hydraulic actuator cluster with all necessary active components. Actuator cluster is modular and can be used for generic purpose. Designed cluster is equipped with 8 axes and produces maximum torque of 1.17(Nm) and maximum speed of 106(RPM). From the experiment, output backdriving torque was 0.02(Nm). Torque sensing with built-in pressure was performed with error of 15% F.S. The result implies that the actuator can be controlled with stable position based impedance controller with minimum response torque of 0.02(mNm) with built in sensors.

3) Proposed modular finger structure with N type wire transmission mechanism. Also proposed torque optimization scheme for this design. Designed finger joint produces 1.7 and 0.68, 0.28, and 0.28(Nm) at MP2, MP1, PIP, and DIP joints respectively when EHA produces 1.7(Nm). Proposed configuration can realize major grasp patterns of Cutkosky [11].

4) Finger operation in actual hand was performed to confirm position controllability of the hand.

REFERENCES