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A Robot Hand Driven By Hydraulic Cluster Actuators

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Abstract— **To enable a humanoid robot to use its hand in the whole body motions, such as hanging, climbing or using a ladder, we developed a robot hand driven by a powerful but backdrivable cluster EHA. A miniature crescent trochoid pump with high discharging pressure was developed. The design of a direct casted cylinder manifold with low hydraulic friction is also presented. Results of basic experiments such as maximum output force, speed, position and force controllability and backdrivability are shown in the end of this paper. A movie of grasping demonstration is also attached.**

I. INTRODUCTION

Robot hands of a humanoid robot play the most important role in the interaction with the environment. In addition to the tasks such as grasping or handling, they need to support the whole body weight to realize motions such as hanging or using a ladder. When the robot is going to fall down, the hands need to contact the ground earlier than the torso or head to avoid their damage. To fulfill these needs, the actuator of the hand need to be both powerful and backdrivable.

Backdrivability plays an important role to prevent the hardware to be damaged by unpredicted collision with the environment. Compliance controlled but mechanically stiff hands cannot be compliant against impact force due to latency of the sensors and controllers. To acquire backdrivability, several robots introduced series elastic actuator [1],[2]. It is difficult, however, to properly design the property of the elastic elements and dump the oscillation. Tsagarakis et al. [2] showed a systematic method to tune the elasticity. Some actuators can change their stiffness [3],[4].

Actuators with gear transmissions such as harmonic drives, which support the force with small surface, are easy to break with large external force. Hydraulic actuator, on the other hand, supports the force by large surface so it is relatively strong[5][6][7]. A lot of hydraulic robots use servo valve hydraulics: all actuators are connected to a single central pump through pressure-resistant hoses. Servo valves between the actuators and the pump intentionally generate pressure loss to input desired pressure to the actuator to control its output force.

There is another kind of hydraulic system called EHA(Electro-Hydrostatic Actuator)[8], which has the same number of pumps with actuators. The hydraulic circuit of EHA is closed and independent with each other. No valves are needed to control the actuator so it can reduce the hydraulic friction and improve its backdrivability. It is also advantageous in maintenance because of its modularity. Due to its high backdrivability and force sensitivity, it have been adopted in knee joints of a humanoid robot[9], wearable robot[10], and anthropomorphic robot hand[11],[12]. In previous research, trochoid pumps and rotational vane hydraulic motors were used to realize highly backdrivable system. The problem was that since trochoid pumps have large internal leakage, they are not suited for high pressure. Vane motors can be compactly packed in a rotational joints, but it is difficult of seal the vane tip to prevent internal oil leakage, which decreases its output force.

we develop a new cluster EHA for tendon driven robot hand that has larger power and degree of freedom, while keeping its size compact. The actuator drives the low-friction tendon driven hand developed by Treratanakulwong et al.[13]. The combination of high pressure crescent trochoid pumps and casted cylinder manifold realized a small size, powerful, and backdrivable cluster actuator unit.

II. HYDRAULIC CLUSTER ACTUATORS

The actuator is designed to drive the hand developed by Treratanakulwong et al.[13]. The hand has 11 dof with 12 active tendons. The one redundant tendon is for the thumb extension, while other fingers use elastic bands to realize it. Therefore, the actuator should have 14 dof in total including two dof for the wrist. Its whole size need to be compact and light enough to be packed in forearm. The maximum output force is aimed to exceed 300 N each, which we regard as enough to enable a human weight robot to hang with his two hands. Since the hand requires 28 mm actuator stroke, we set its stroke to 31 mm, taking account of the inaccuracy of the tendon length. For dynamic task, we assumed that the actuator should be fast enough to enable the hand to be closed in less than 0.5 seconds.

To reduce hydraulic friction, the flow channel should be short, thick and straight. Therefore, we directly connect the input and output port of both pump and cylinder without hose or pipe. Mechanical friction also need to be small to improve its backdrivability. Pressure sensors should be attached on the cylinder to measure its output force. Cavitation, which occurs when the oil has lower pressure than atmosphere, badly impairs actuator's controllability and damages the hardware. To avoid it, the system need to be constantly pressurized[8]. We distribute pressure from a single accumulator to all axes. A coil spring is installed in one of the cylinders to use it as an accumulator. The hydraulic circuit of the actuator is shown in Fig.1. The whole actuator cluster weighs 2.3 kg including motors, sensors and hydraulic but not motor drivers. Fourteen MAXON EC16 motors were attached to the actuator which

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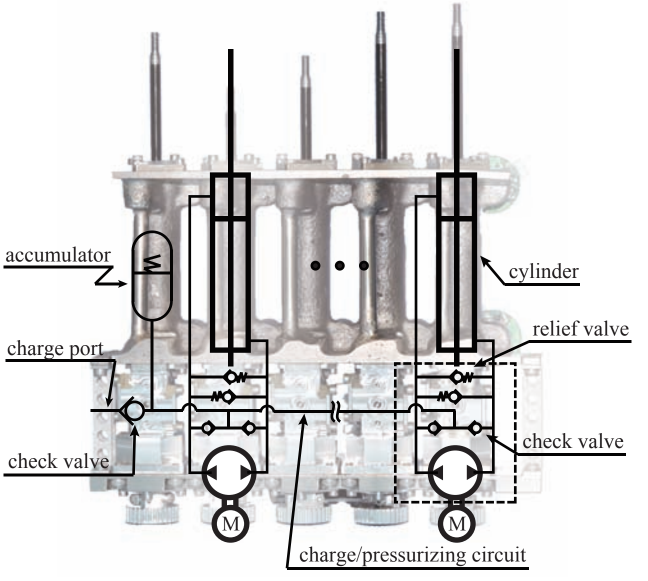

Fig. 1. Hydraulic Circuit of the Actuator Cluster. The main hydraulic circuit of each axis is independent with each other. The high pressure side and low pressure side are connected by relief valve to relief abnormally high differential pressure. The both sides are connected with the accumulator through check valves to avoid cavitation. The accumulator is commonly used for all axis.

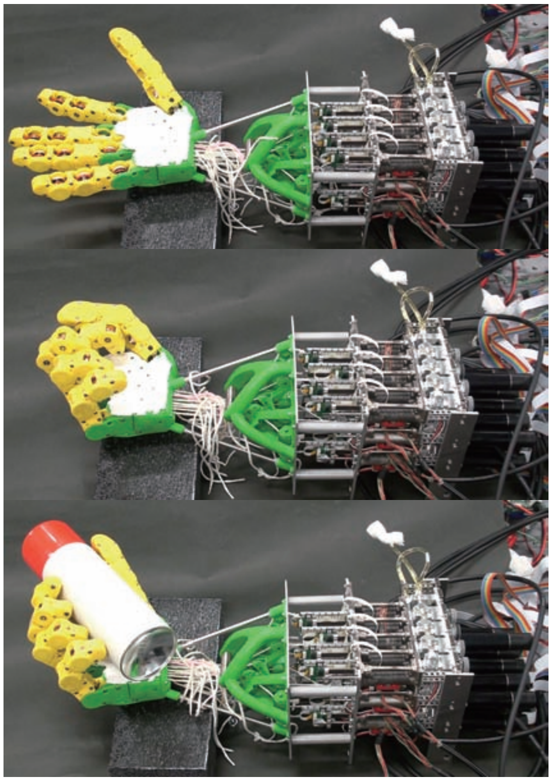

Fig. 2. Picture of the Actuator Connected with the Hand.

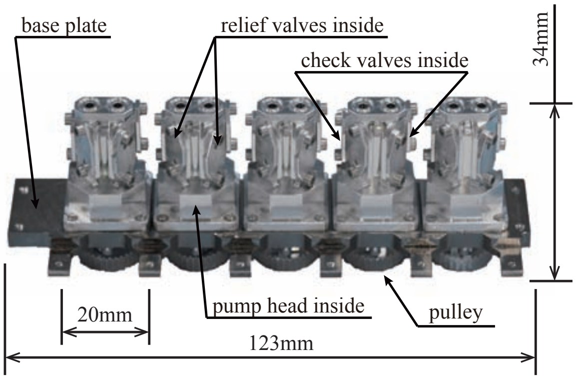

Fig. 3. Picture of a Five-pumps Cluster.

weights 0.8 kg in total. The actuator cluster can be packed in a 100 × 125 × 220 mm box. The property is shown in TABLE.III. A picture of the actuator with the hand[13] is shown in fig.2. The graping demonstration is shown in the attached video. In the demonstration, the actuator is force controlled so that the object does not drop when the author shake the whole arm.

III. TROCHOID PUMP WITH CRESCENT SEPARATOR

To fulfill the need of compact size and large output, the pump need high output pressure. A large factor that lower the output pressure is internal leakage. Due to the generated pressure, the oil leaks back from high pressure side to low side through small gaps inside the pump. The key is how to reduce the internal leakage, and the leakage is proportional to the cube of the internal gap. To totally remove internal leakage, contact seal is needed, which has large friction. This makes it reasonable to make the gap of the pump as small as possible but still keep it to have no direct contact.

Crescent trochoid pump was chosen since it has smaller internal leakage than trochoid pumps, lower rotational friction than piston pumps or ordinary crescent pumps with involute shaped teeth, and it is compact compared with its discharging volume.

Compactness and light weight is the key to introduce hydraulics into a robot. Merging multiple parts into a single manifold employing 5-axes CNC machining, casting, and 3D-printing techniques, is a solution. We can reduce O-rings, which need proper housing to ensure their sealing property, consuming non-negligible space especially in small size hydraulics. We can also reduce screws which are needed to support the large force generated by the pressure. Two check valves (to initially charge the oil, and after that connected to the accumulator to avoid cavitation), and two relief valves (to relief abnormally high pressure) are integrated into a single pump casing. The base plate shown in the figure is shared by five pumps in the cluster, in other words, five of this part are merged and machined as a single part and all other components are mounted on the basement, therefore put the pumps as close as possible. Fig.3 shows a picture of the five pumps cluster.

TABLE I

PROPERTY OF THE CYLINDER

pump output volume [mm^3/rev]	6.3
cylinder type	double rod
cylinder bore [mm]	9
piston rod diameter [mm]	3
full stroke [mm]	31

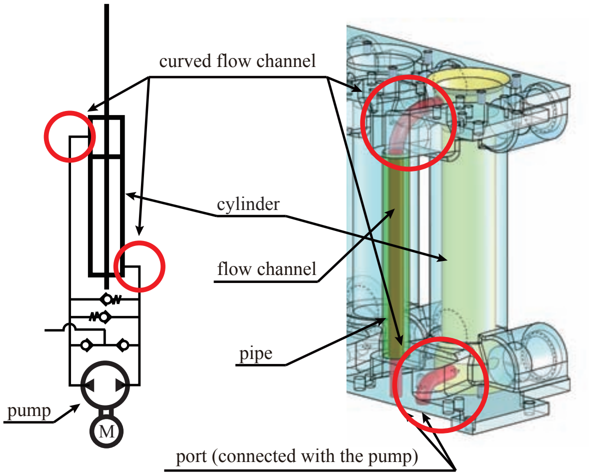

Fig. 4. The Cylinder Manifolds are Casted to Shape Curved Flow Channels. The direct casting technique enables curved flow channels, which have less hydraulic friction than right-angle corner.

IV. CASTED CLUSTER CYLINDERS

Hydraulic cylinder is adopted as the actuator since it is more suitable for large output. It has simple tubular shape sliding surface so that it is easy to implement oil seal to prevent internal leakage. Its long and thin shape is more suitable to be packed in the forearm, while the vane motors are easy to be directly packed in the joints. Double rod cylinder is more suitable for small size and backdrivable EHA since the total volume of the hydraulic circuit does not change according to the piston position. TABLE.I shows the property of the cylinder.

As in pumps, five cylinders are also merged as a single piece. The whole actuator cluster consists of three assemblies of the five axes. The cylinder manifold is manufactured by direct casting technique. In direct casting, the plaster mold is printed by a three-dimensional printer. This makes it easy to cast a complex shape with short time and low price. With this technique, we could shape curved flow channels (see Fig.4), which have much less hydraulic friction compare with right-angle corners. Since casting cannot realize thin and long pipe, a pipe is welded to the manifold for the long and straight part of the flow channel. A cylinder manifold is shown in Fig.5.

Two pressure sensors per each cylinder is fixed on the cylinder to measure the differential pressure to estimate the force. Both the piston rod and the inner surface of the cylinder is coated by nickel-PTFE plating. to reduce the friction. The position of the piston is measured by a magnetic linear encoder fixed on the end of the piston rod with a linear guide to keep the sensor in a same distance with the scale.

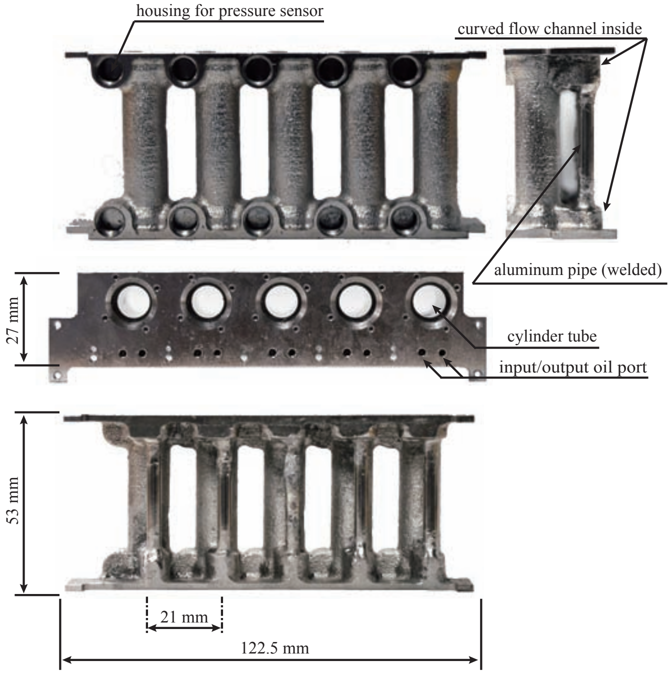

Fig. 5. Single Cylinder Manifold. The direct casting technique enables complex modeling that realizes light weight and strong structure. It also enables smoothly curved flow channel that reduces flow resistance.

V. EXPERIMENTS

To evaluate basic abilities of the actuator, the following experiments were conducted. Since the developed actuator focuses on large output force, its maximum output was measured first. To check whether the hand can be closed in the desired time 0.5 s, we measured the time a piston need to move from one side to the other. Its position and force controllability were also evaluated, while we put more importance on its force controllability since the main task of the hand is to grasp and hold the target or environment. Finally, its backdrivability, which mostly differs the actuator from the other ones, was measured.

A. Maximum output force and moving speed

The maximum output force of the actuator was evaluated. The force gauge and the actuator was set vertically to cancel the weight of the hook. The force gauge was pulled by the actuator through a tendon which is the same with the one used for the hand. Eleven axis are tested and their result is shown in Fig.6. The X-axis shows the time and the Y-axis shows their force. As the graph shows, the largest force was 264 N and the lowest was 118 N. The average was 197 N. The pressure sensors showed that the average output pressure of the pumps was around 3.5 MPa.

The difference of the force comes from the difference of the output pressure of the pumps. To compensate the inaccuracy due to manufacturing and inner gap of the bearings that support the rotors, shims were added by hand to adjust

TABLE II

MAXIMUM OUTPUT FORCE AND MINIMUM TIME TO MOVE THE FULL STROKE.

average output [N]	197
maximum output [N]	264
minimum output [N]	118
average max pump pressure [MPa]	3.5
average time for full stroke move [ms]	407
shortest time for full stroke move [ms]	340
longest time for full stroke move [ms]	480

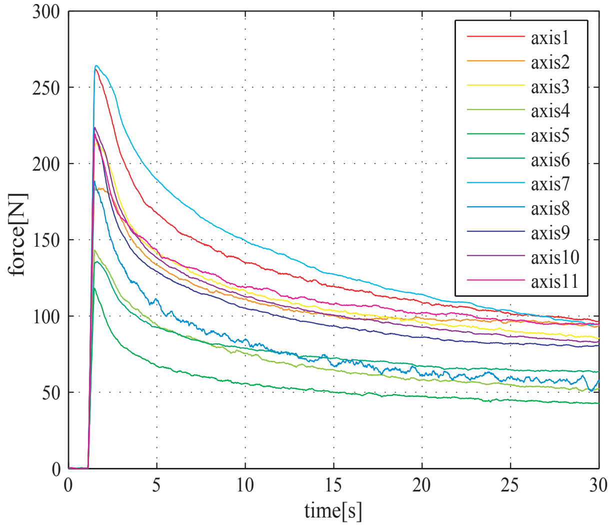

Fig. 6. Maximum output force of 11 cylinders and their change with the time.

the side gap of the rotors. Inaccuracy of the adjustment causes large internal leakage to decrease the pressure, since the leakage is proportional to the cube of the gap[12]. It may also cause unnecessary contact between the rotors and pump casing to have large friction and heat. The drop of the force comes from the temperature increase of the oil. Since the piston pulls the fixed force gauge, its doing no work. Therefore, all energy input form the motor is converted to the heat and increase the oil temperature. This reduces the viscosity of the oil, which means larger internal leakage and smaller force.

Since the difference of the output force comes from the assembling process of the pump, once we properly tune the pump, it will constantly output high pressure. Fig.7 shows 4 results of a single axis (axis-8) and we can see that the output force does not differ much across trials.

The time to move the pistons from one side to another were measured. No additional load were attached to pistons. They took 407 ms in average, which means the hand can be closed in less than the desired time 0.5 s. Their deviation was smaller than the force, since the difference of the internal leakage has less effect in low pressure condition. The result is summarized in TABLE.II.

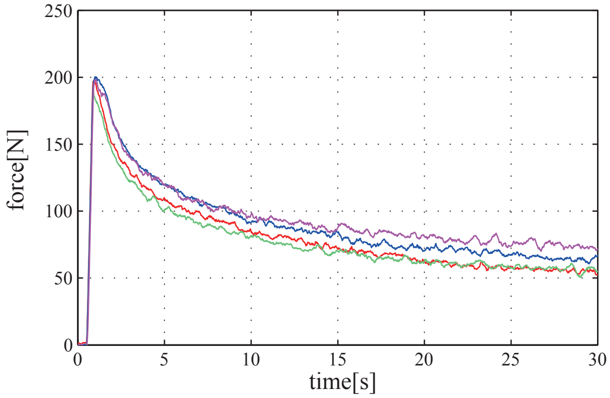

Fig. 7. Multiple data of the maximum force experiment of a single axis. The graph shows that the maximum force does not vary much across the trials.

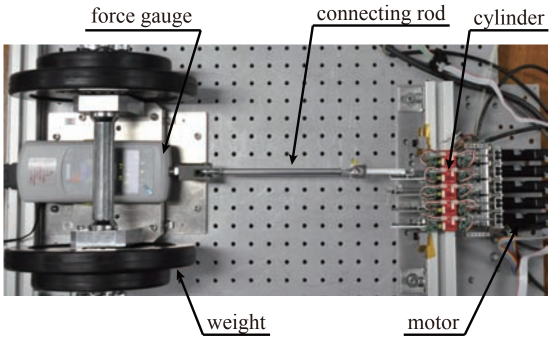

Fig. 8. Setup of the Experiment for Frequency Response. The load on the rail is actuated by the cylinder horizontally. The moving part weights 20 kg in total.

B. *Step and Frequency Responses*

The closed loop step response and frequency response of the piston position was measured using a setup shown in Fig.8. To cancel the effect of gravity, the cylinder was placed horizontally. The moving part was supported by linear guide. It weights 20 kg including the force sensor. Reference position was given to the controller and motor current was PI controlled according to the position error. Control frequency was 2 kHz. The P-gain was 2.15×10^{-5} A/mm and the I gain was 2.02×10^{-7} A/mm.

Fig.9 shows the step response. X-axis represents the time and Y represents the position. The red line shows the reference and the blue line shows the real position. As the graph shows, its position accuracy is not high. EHA has low friction in the force transmission process from the motor to the piston. The problem is that it has large sliding friction in the force transmission between the piston and the environment, due to the oil seal for the piston and piston rod.

Fig.10 shows the bode plot of its frequency response. Sine-wave reference position was input to the controller and the relation of reference and measured position was evaluated. As the graph shows, the cut-off frequency is around 2 Hz.

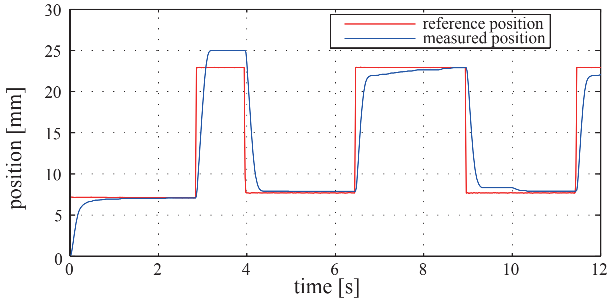

Fig. 9. Step Response of the Piston Position.

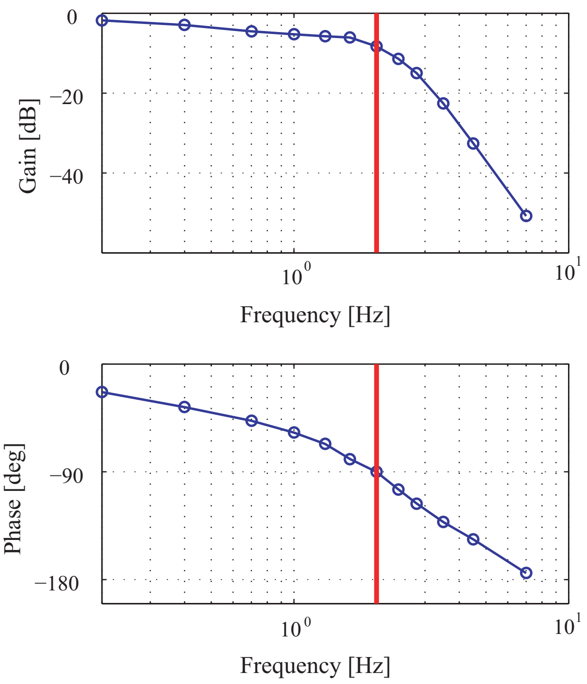

Fig. 10. Frequency Response of the Piston Position.

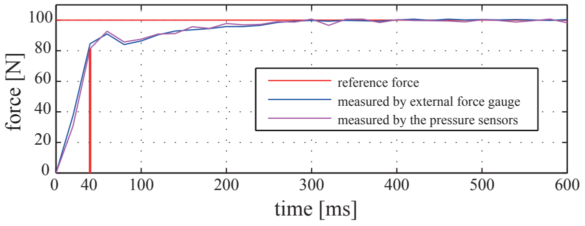

Fig. 11. Step Response of the Output Force.

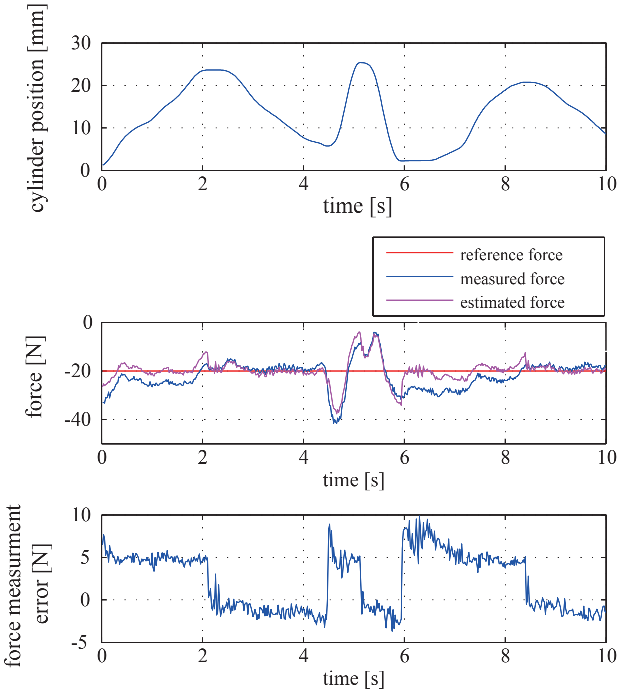

Fig. 12. Piston Position, Output Force and the Error between Measured Force and Estimated Force from the Pressure: the output was PI controlled to keep the same force and the output was backdriven by human hand.

C. Force Control by Current Control

To evaluate the actuator's response to force control, step reference force was input to the controller and the motor current was PI controlled. The controller used the differential pressure measured by the pressure sensors to estimate the force for the feedback control, while the value of the force gauge was used to evaluate it. The experiment was done with the same setup of the previous one, but this time the moving weight was fixed to the basement. Fig.11 shows the result. As the graph shows, the output reached the reference in 0.3 s. To reach 80 % of the reference, it only took less than 40 ms. One weak point of EHA, compared with the ordinary servo valve hydraulics, is that it has slower force output response. This is because it need to drive the pump rotor to get output force, while the valve type only need to move the valves, which has much less inertia. However, the experiment shows that the developed actuator can be fast enough for practical use.

In next experiment, the reference was fixed to -20 N. The output was backdriven by human hand and its output was measured. Fig.12 shows the result: the first graph shows the piston position and the time; the second one shows the measured force and reference force; the last one shows the error between measured force and the force estimated from the pressure sensors. The output kept in ± 20 N range from the reference, which is 10 %@of the average maximum output. Since the pressure sensors cannot measure the friction of the oil seal for the piston rod, there exists error between real output and estimated output from the sensors. The experiment shows that the error changes with the moving direction and speed, but keep less than 10 N, which is 5% of the average maximum output.

D. Backdrivability

To evaluate its backdrivability, the piston rod was backdriven with force up to 100 N. Fig.13 shows the relationship between backdriven speed and force. The graph shows that there is a constant viscosity of about 4 Ns/mm viscosity, which comes form the internal leakage in the pump. Total

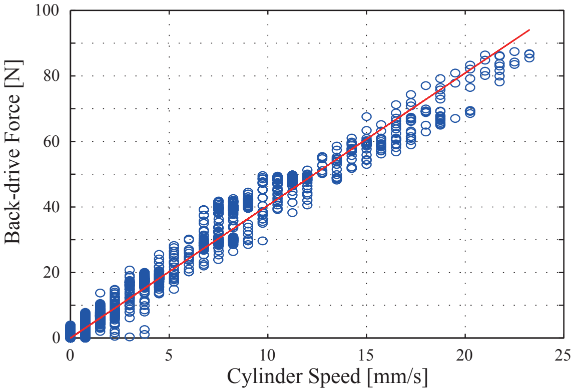

Fig. 13. Relationship between Backdriven Speed and Force.

TABLE III

COMPARISON OF THE ACTUATORS

	developed	previous design
Weight (including hydraulic)[g]	2300	
Dry Weight [g]		1900
Size(W×D×H) [mm]	123×100×220	134×116×123
Number of DOF	14	8
Volume per Axis [cm^3]	193	239
Weight per Axis [g]	164	238
Maximum Force [N]	260	60
Time to Close hand [s]	0.34	0.14

backdrivability was not confirmed in this experiment. Since the developed hydraulic system is a reducer that transform rotational movement of the motor into linear movement, we can define its "lead screw pitch". Its pitch is 42 μm/rev including the pulley coupling between the motor and the pump, which has 32/12 reduction ratio. Currently, the 42 μm/rev pitch seems to be too small to enable total backdrivability. However, its 4 Ns/mm viscosity is still enough to keep the actuator and the hand from being damaged due to unpredicted contacts with the environment.

VI. DISCUSSION

The experiments above show that the developed actuator can output more than 260 N force and can move its 31 mm full stroke in 0.34 s. We need to compare this with another EHA hand[12] with ordinary trochoid pump and vane motor. Since the vane motor has rotational output, we introduce a moment arm that converts the 90 deg movement (the moving range of the vane motor) into 31 mm linear tendon movement to compare the force and speed. TABLE.III shows the comparison of the actuators. The table shows that we made the actuator 20 % smaller, more than 31 % lighter (per axis) and outputs 4.5 times larger force. Its weak point is that it got 3 times slower and lost total backdrivability, but it is still fast enough for grasping tasks and its output backdrivability will protect the system from damage.

Since the hand[13] is still a prototype made with ABS plastic, grasping test with the maximum actuator output is not possible. Thus, we estimate it from its pulley diameter - 10 mm. With 260 N tendon force, the joint will exert 1.3 N/m. The distance between the finger tip and MCP joint is around 100 mm, which means the finger tip force will be 13 N. Made with aluminum, the hand will be 950 g thus the hand and actuator will weight around 3.3 kg in total, which is almost the same with [12].

VII. CONCLUSION

In this paper, we proposed a robot hand driven by cluster EHA. The main focus is on the design of the actuator. The conclusion is as follow:

1) Proposed a hand system that have 11 DOF, 1.3 N/m torque in each joint, 3.3 kg weight, and can be closed in less than 0.4 s.
2) Proposed design method that integrate multiple part into single manifold to build light, compact and powerful cluster EHA. The combination of low internal leakage crescent trochoid pump, 5-axis machined pump casing integrated with valve housing, and direct casted cylinder manifold enable EHA that is 20 % smaller, more than 31 % lighter (per axis) and outputs 4.5 times larger force compared with the old design.

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