Structure Design Fused with Electronic Devices of Holonic Manipulator*

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A holonic manipulator has many electronic devices such as control computers and sensors among its local mechanical components. This kind of manipulator design has three major advantages: reduction of wire harness between devices, high software productivity, and fault tolerability of the system. In this paper, we first represent two actually developed holonic manipulators. Then we compose a simple structural model of the manipulator focusing particularly on the constituent component mass so that the efficiency ratio of payload mass to total manipulator mass can be analyzed. This efficiency ratio exhibits a saturated increase consistent with the payload mass, which is due to DC servomotor mass/power characteristics and mechanical structure mass/stress characteristics. For the improvement of the efficiency ratio, the fused structure design has been employed mainly between heat sinks or support members of the computer and mechanical structure. The achieved improvement is estimated with the model using a mass fusion function.

Key Words: Mechatronics, Robotics, Control Device, Manipulator, Fused Structure Design, Payload-Deadload Ratio

1. Introduction

The present robot manipulator system is composed of elements of two kinds. One is a mechanical element which forms robot mechanisms such as a structural member, a joint mechanism, or a power generation and transmission mechanism. The other is an electronic component such as a motor drive controller of a joint, a controller of a sensor attached to various parts, or a computer that generally manages these devices. The two kinds of elements are designed independently before they are connected to each other by wiring when the robot is finally assembled.

One of the problems with this conventional design is the connection wirings when we are to equip a robot with additional intelligence. In order for a robot to become more intelligent, it is necessary for it to

process a large quantity of information about its environment as well as itself. It is also imperative for the robot to exercise more degrees of freedom in control than with which it is equipped at present, including more precise control of its fingers so as to accomplish more precise manipulation of objects. This requires that various sensors and motors be equipped in large numbers at each part of the robot, especially at the hand. Thus, the wirings needed to connect the parts with their controllers will become quite substantial. Since securing the reliability of many connectors is difficult to accomplish, maintainability certainly deteriorates in accordance with the increase in wire junctions. Naturally, reliability of the robot system decreases because most system failures occur at connections between parts. Moreover, it is required that robot control incorporates the rigidity and weight of wiring when the amount of wiring increases significantly. However, since the modeling of a wire harness is not necessarily easy to complete, precise motion trajectory of the robot cannot be achieved.

The authors are developing a holonic manipulator which has many small computers embedded in each part of the mechanical structure to solve the problems

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that arise in the realization of an intelligent robot^{(1),(2)}. Most of the wirings that result from present structural design where a mechanical element and a electronic element are divided completely are notably reduced by being localized by the design developed here. The wiring traversing a movable part of a joint is limited to a multiplexed communication network and a power line which connect embedded computers. In this article, we first describe two design instances of the holonic manipulator which is equipped with computers at every joint part. By embedding electronic parts, the possibility arises that the mass (weight) ratio of maximum payload to total manipulator mass may decrease. We then estimate the ratio improvement expected by this design of fused parts based on the structural model of the manipulator.

Table 1 Specifications of manipulator No. 1

Mechanical configuration	Articulated-type manipulator
Degrees of freedom	6 (R-P-R-P-R-P)
Gripper mechanism	Two-fingered hand (1 d.o.f)
Max. load	Approximately 0.5kg
Joint driving mechanism	DC servomotor+reduction gears
Controller	Joint embedded controller
	• i8751 (8bit CPU, 4KB EPROM)
	• 10bit A/D converter
Control modes	Three modes of position, velocity and dynamic control
Controller connection	Bus network
Communication speed	125Kbps
Command transmission	Asynchronous message of packets

Fig. 1 Structure of manipulator No. 1

2. Structural Design of Holonic Manipulator

2.1 Design of holonic manipulator No. 1

Figure 1 shows the structure of holonic manipulator No. 1, and its specifications are listed in Table 1. Manipulator No. 1 has six-degree-of-freedom (d.o.f.) rotating joints and one d.o.f. hand. Each joint and the hand are equipped with its own embedded control computer. The computer not only executes the joint servo autonomously as a complete unit, but plays a slavish part of the total arm trajectory control according to the messages arriving through the communication network. This characteristic of the joint element is the source of its name 'holonic'.

Connection wirings between joints are reduced to seven at most, including power lines, by linking them to a communication network which has bus topology. The wires originating from each joint denoted in Fig. 2 are such connection wirings which comprise two motor power lines, two shared power lines for the control computer and sensors, and three communication lines.

A computer embedded in each part has the minimum composition for joint control, which includes a single-chip CPU, an A/D converter, and its power supply integrated in a $38 \times 68 \text{ mm}^2$ board. A motor drive amplifier is also embedded in the joint to form a simple bridge circuit by discrete transistors, which switches the power output according to a PWM signal from the CPU.

Table 2 shows the constitutional mass of the manipulator. The maximum ratio of the embedded electronic part mass to the whole joint mass reaches 35 % at the first joint. This implies that the ratio has already required such intensive consideration at the time of design that the electronic part mass cannot be ignored, although the embedded electronic parts are not very numerous in this design instance.

2.2 Design of holonic manipulator No. 2

The structure of manipulator No. 2 is shown in Figs. 3 and 4, and its specifications are listed in Table

Fig. 2 Decomposed joints of manipulator No. 1

3. The embedded computer of manipulator No. 2 is designed to have an extremely large computational capacity for real-time solution of manipulator dynamics. Since the mass and the volume of the computer must be augmented in accordance with the capacity increase, the computer parts and mechanical parts are designed from the beginning as a fused form

Table 2 Constitutional mass of manipulator No. 1

	Total mass [g]	Mechanical parts[g]		Electronic parts[g]			Ratio of electronic parts [%]
		Structure	Motor	CPU board	Potenti- ometer	Amplifier	
Hand	578	397	80	71	13	17	17.5
Joint #1	563	234	130	59	13	127	35.3
Joint #2	780	423	130	59	13	155	29.1
Joint #3	1370	753	420	65	13	119	14.4
Joint #4	1600	959	420	65	13	143	13.8
Joint #5	4155	2639	1100	64	13	340	10.0
Joint #6	7765	6299	1100	63	13	290	4.7
Total	16811	11704	3380	446	91	1191	10.3

Table 3 Specifications of manipulator No. 2

Mechanical configuration	Articulated type manipulator
Degrees of freedom	4 (R-P-R-P)
Gripper mechanism	Three-fingered hand (6 d.o.f)
Max. load	Approximately 0.5kg
Joint driving mechanism	DC servomotor + harmonic drive
Controller	Joint embedded controller
	<ul style="list-style-type: none"> • i8097(16bit CPU, A/D converter) × 2 • Serial communication ASIC × 2 • ROM 8KB × 2, RAM 16KB × 2 • Shared memory 512 words
	Sensor controller at hand location
	• i8751(8bit CPU, 4KB EPROM)
Controller configuration	Fused structure with mechanical parts
Control modes	Position, velocity, and realtime dynamic control
Controller connection	Loop network (Joint/Hand part)
	Point-to-point full duplex (Sensor part)
Communication speed	4Mbps (Loop part)
Command transmission	Asynchronous message of packets

to compensate for this augmentation. The embedded computer is composed of four hybrid ICs (made of $50 \times 75 \times 1 \text{ mm}^3$ ceramic board) as shown in Fig. 5: two CPU boards, a ROM board, and a shared memory board. They are put together, respectively, with a duralumin structural support member (Fig. 6) which also functions as a heat sink. They are then connected by two FPC (flexible printed circuit) boards at 50 lead wires attached on both sides after being piled up as shown in Fig. 7. A motor drive amplifier is also embedded in the structure after fabrication into a hybrid IC (made of $38 \times 55 \times 1 \text{ mm}^3$ aluminum board). This bulk of the computer part occupies the primary ratio of manipulator volume and forms a contour line of the manipulator.

The embedded computers at the joints and hand, each of which has two CPUs, are connected to each other by a loop network. This network is actually composed of a serial concatenation of small loops, each of which contains four adjacent CPUs, since the

Fig. 3 Manipulator No. 2

Fig. 4 Structure of manipulator No. 2

two CPUs in one joint utilize a shared memory to communicate with each other. The communication among CPUs is executed by selecting the shortest path in the network. The number of connection wirings between the joints is ten at most : six for a round trip of the communication line and four for two systems of the power line as in manipulator No. 1. The effect of wire reduction is notable since more than 80 proximity sensors are equipped at the fingertips and palm, in addition to the motors and potentiometers for the six degrees of freedom of the three fingers of the hand.

Fig. 5 Embedded computer of manipulator No. 2

Fig. 6 CPU board

Fig. 7 Structure of an embedded computer and an amplifier (heat sink omitted)

Table 4 shows the constitutional mass of manipulator No. 2. Manipulator No. 2 has some parts that cannot be classified definitely, as in the case of manipulator No. 1, owing to its fused structure design. These parts correspond to support members which also serve as a computer board or as a heat sink of an amplifier. They are included in the mechanical part mass in Table 4. In the table, therefore, the ratio of pure electronic parts is given only for reference. Although the hand has a massive amount of additional mechanical parts in the fingers, the ratio of pure electronic parts already amounts to about 27 % of the largest figure at the hand since it is furnished with many sensors.

3. Design Evaluation by Structural Model

3.1 Structural model of holonic manipulator

We describe the structure of the holonic manipulator mentioned in the previous section by a simplified model (Fig. 8). The nomenclature is as follows :

M_0 : payload mass including a hand kg

M_i : total mass of the i -th joint kg

Mm_i : motor mass of the i -th joint kg

Ms_i : structural member mass of the i -th joint kg

Me_i : electronic part mass of the i -th joint kg

Mh_i : heat sink mass of a motor drive amplifier of the i -th joint kg

P_i : motor output power of the i -th joint W

T_i : joint torque of the i -th joint Nm

V_d : payload velocity m/s²

$\dot{V}_d$: payload acceleration m/s²

l : length of the link m

The manipulator is modeled by joints with a centralized mass and links which have the same length and negligible mass. The centralized total mass

Table 4 Constitutional mass of manipulator No. 2

	Total mass [g]	Mechanical parts[g]		Pure electronic parts[g]			(cf.) Ratio of pure electronic parts [%]
		Structure	Motor	CPU Board	Potentiometer etc.	Amplifier	
Hand	750	339	210	80	(Sensor) 71 30	20	26.8
Joint #1	745	508	130	80	13	14	14.4
Joint #2	780	548	130	80	13	14	13.8
Joint #3	1340	813	420	80	13	14	8.0
Joint #4	1680	1153	420	80	13	14	6.4
Total	5295	3361	1310	400	153	76	11.9

Fig. 8 Structural model of holonic manipulator

M_i of the joints is the sum of four kinds of masses of the constitutional part: $M_i = Mm_i + Ms_i + Me_i + Mh_i$. Each mass of the constitutional part is estimated with the following assumptions.

(1) Motor mass Mm_i — The mass Mm_i of the DC servomotor is considered to have a nearly proportional relation to its power P_i according to a survey of market products⁽³⁾. We use the next empirical formula derived from our survey to obtain the motor mass:

$$Mm_i = 0.0501 \cdot P_i^{0.88}$$

(2) Motor power P_i — Motor power is determined by the power to be applied to a payload. Where angular velocity and angular acceleration of the i -th joint are denoted as ω_i and $\dot{\omega}_i$, respectively, the required power to drive only M_0 is the following:

$$P_{i0} = M_0 \cdot \dot{V}_d \cdot V_d \\ = M_0 \cdot (il)^2 \cdot \dot{\omega}_i \cdot \omega_i$$

The power P_i is given by the next formula, where the joint i drives all the centralized masses located in one direction of the hand when all the joints are extended.

$$P_i = \sum_{j=1}^i M_{i-j} \cdot (jl)^2 \cdot \dot{\omega}_i \cdot \omega_i \\ = \dot{V}_d V_d / i^2 \cdot \sum_{j=1}^i M_{i-j} \cdot j^2$$

(3) Joint torque — Joint torque is calculated by the next formula with motor power P_i and angular velocity ω_i of the joint:

$$T_i = P_i / \omega_i = P_i \cdot i \cdot l / V_d$$

(4) Joint structural member and reduction gear mass — The mass of a joint structural member and a reduction gear of a motor are estimated together since they cannot be definitely discriminated from each other. In the strength design of a reduction gear shaft based on the maximum shearing stress estimation, the diameter d of a shaft is calculated by the next formula, where τ denotes permissible shearing stress and Te represents an equivalent torsional moment:

$$d = (16 \cdot Te_i / (\pi \tau))^{1/3}$$

If the structural member is evaluated from only shaft material, its mass is given as

$$Ms_i \sim d^2 \cdot l \sim Te_i^{2/3} \cdot l$$

Moreover, if bending stress imposed on the member is evaluated, we also obtain the same result. The cogwheels which occupy a large proportion of the reduction gear mass have a proportional relationship between their mass and driving torque, according to the market data⁽³⁾: $Ms_i \sim Te_i^{1.0}$. Since this gives an appropriate value so that the power of Te_i selected as the mean value, we estimate structural mass by the next formula, where r is a proportional constant:

$$Ms_i = r \cdot Te_i^{0.833} \cdot l$$

(5) Motor drive amplifier heat sink mass — Calorific value to be radiated is proportional to the

power consumption of a joint. Moreover, heat radiation capacity is also nearly proportional to the mass of a heat sink. Thus, the mass is obtained by the next formula, where s is a proportional constant:

$$Mh_i = s \cdot P_i$$

Proportional constants of r and s are determined as $r=1.3$ and $s=0.022$ according to actual measurement on the prototypes. Each joint mass estimated based on these formulae is shown in Fig. 9 with real measured values of manipulators No. 1 and No. 2. The data used in the estimation are the following: payload of 1.0 [kg], payload velocity of 0.5 [m/s], payload acceleration of 9.81 [m/s²], link length l of 0.135 [m] (which is the mean value between l s of manipulators No. 1 and No. 2), and electronic part mass of 0.8 [kg/joint] (which is equivalent to that of manipulator No. 1). The joints of No. 1 through No. 4 exhibit proper accordance with actual measured data in Fig. 9. The fact that the actual joints No. 5 and No. 6 of manipulator No. 1 show larger values than the model results from two design considerations. One is that the actual link length of these portions is much longer than the mean value used in the model on account of total geometrical balance design of the manipulator, and the other is that design strength is overestimated toward the safety side so as not to reduce the mass. On the other hand, the curve of the model must indicate larger values if the model utilizes the actual data of manipulator No. 2 which has a longer link length of 0.15 [m] and the bigger electronic part mass of 0.2 [kg]. However, the mass of manipulator No. 2 is almost held at the same value as that of manipulator No. 1, which is derived from the effect of mass reduction by the fused design described above. This point is discussed again in section 3.3.

3.2 Ratio of payload mass to manipulator mass

The ratio of payload mass to manipulator mass of the above model is shown in Fig. 10 which has the two parameters of payload mass and link length. The ratio

Fig. 9 Mass of the joints

of payload mass to manipulator mass, which indicates its efficiency as a transfer machine, increases in accordance with augment of payload, and the increase rate has a tendency for saturation. This reflects a non-linear relationship between the desired output and the mass increase rate of structural members with a motor. It is concluded from the figure that payload should be appropriately large if no severe limitation to the total mass increase is imposed, since sufficient efficiency cannot be achieved if the payload is too small. It is also found that the efficiency can be easily improved if the movable region of the manipulator allows for abatement because it is almost inversely proportional to the link length. The ratio has a value of 0.107 in the case of the model data shown above. In addition, the required payload velocity and acceleration are constant in this figure. If these values are changed in proportion to the link length, the curves will expand upwards and downwards from the referenced curve of the link length fixed in the center. However, in that case, the general tendency that the curves show is identical to that in this figure.

3.3 Improvement of mass ratio by fused design

The mass ratio related above can be improved by a fused design that merges structural members with electronic parts such as a computer and a heat sink of a motor drive amplifier. The quantity of the improvement can be estimated by applying the fused design of manipulator No. 2 to the model.

Here, we calculate the mass M_c of the part which is designed from two parts of mass M_a and M_b ($M_a \leq M_b$) in a fused manner by the next formula:

$$M_c = (M_a + M_b) \cdot F_u(M_a/M_b, \nu),$$

where F_u is a fusion function that removes the common part between M_a and M_b by the rate ν . The function is defined as

$$F_u(r, \nu) = (1 + r \cdot (1 - \nu)) / (1 + r), \quad 0 < r \leq 1,$$

Fig. 10 Ratio of payload mass to manipulator mass

where ν is a fusion rate which is defined as $0 \leq \nu \leq 1$. If $\nu = 1$, then the maximum mass M_a is reduced.

In the design of manipulator No. 2, support members of a computer which work also as a heat sink, and an amplifier heat sink are designed in this fused manner with the joint support members. The computer mass, that is, approximately 0.2 [kg] for one joint, can provide half of itself as structural members of the link. The amplifier heat sink can provide almost all of its mass. When these masses are fused with M_{si} , the total mass is calculated by the next formula:

$$M_i = Mm_i + Me_i \cdot 0.5 + (Mh_i + Me_i \cdot 0.5 + M_{si}) \cdot F_u((Mh_i + Me_i \cdot 0.5) / M_{si}, \nu).$$

The ratio of payload mass to manipulator mass estimated by the formula is shown in Fig. 11, where payload mass and fusion rate ν are the parameters. The link length is 0.15 [m] and computer mass is 0.2 [kg]. The mass ratio is augmented by the fused design at the rate of from 25 % to 40 %, and the increase rate is more significant for the lighter payload to promote efficiency improvement. In the case of manipulator No. 2, whose payload mass is 1.0 [kg], the mass ratio is raised from 8.1 % to 10.4 %, which corresponds to the manipulator mass reduction of 12% from 12.3 [kg] to 9.6 [kg].

Figure 12 shows the total mass of each joint. The mass difference between joints No. 1 and No. 2 of manipulator No. 2 is smaller than that of the model since the two joints are designed in almost the same configuration. However, it is observed that the manipulator mass is reduced to nearly the fusion rate of $\nu = 1.0$ on an average.

4. Conclusions

In this paper, we demonstrated embodiment examples of a holonic manipulator which has a control computer within every joint and within the hand in order to equip a robot manipulator with higher

Fig. 11 Effect of mass ratio improvement by the fused design

Fig. 12 Joint mass reduction by the fused design

intelligence. Moreover, we estimated the fused design

of electronic parts focusing on the efficiency of payload-deadload mass ratio by a simplified structural model of the manipulator. Consequently, it is presumed that the efficiency has been improved by 2.3 % and the total mass has been reduced by approximately 12 %.

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