Backdrivable Mechanism for Artificial Finger

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Abstract: This paper shows mechanisms for artificial finger based on the originally developed mechanism called “double planetary gear system” (DPGS). Using the DPGS as a transmitter provides an under-actuated system for driving three joints of a finger with back-drivability that is crucial characteristics for fingers as an end-effector when it interacts with external environment. The DPGS provides not only back-drivable and under-actuated flexion-extension of the three joints of a finger, but also adduction-abduction of the MP joint. Proposed finger mechanism is inherently safe due to being back-drivable with no electric device or sensor in the finger part. They are also rigorously solvable in kinematics and kinetics as shown in this paper.

Keywords: Robotics, Artificial finger, Backdrivability, Inherently safe, synergetic motion

1. INTRODUCTION

Artificial finger has been strenuously studied in recent two decades since an anthropomorphic robot or spacecraft manipulator requires end-effectors to achieve dexterous task. However it is tremendously difficult to develop a hand having multiple fingers with a lot of DOF, which is feasible and practical not only on a mechanical point of view but also on their control. Some studies have been pursued to produce a hand of which fingers have full of DOF; each one is controlled by tiny DC-motor assembled in the finger(Kawasaki(1999), Namiki (2004)) or by a remote control via wires (Salisbury (1983), Maekawa (1992), Lovchik (1999)). This approach is interested in developing a research platform to study various control methods of multi-DOF hand when it handles objects, but it may not be oriented for practical usage as a hand for anthropomorphic robots or forearm prostheses.

In the meanwhile practical usage for robot hands or forearm prostheses requires reducing DOF. There have been some studies to control three joints of one finger (MP, PIP, DIP joints) by one motor via pulleys and wire (Lee (1994), Harada) or closed linkage system. It is a matter of course that the motion of the finger developed in these studies is restricted in one typical motion such as open-and-grip.

The study of this paper aims to develop finger mechanisms and a hand with multiple-fingers that can achieve dexterous handling tasks while sustaining feasibility for practical usage. The author considers an artificial finger or hand should have following properties to take into consideration for practical usage.

Back-drivability (BD): The hand with multiple fingers is an end-effector that always interacts with external environment, of which effect to the fingers is usually not expected to be predictable. This fact requires a hand to have some “resiliency” to the external interaction, which is interpreted as “back-drivability” of the joints of the hand in the technical point of view. This property has been pursued in some studies to develop tendon-driven hand (Lee (1994), Harada).

Inherently safe design (ISD): This property is much related to the BD in the meaning that the hand never harmful to external environment (especially to human). In addition to the BD, ISD requires some items to a controller of the fingers as follows.

(a) Any electric/electronic devices or sensors should not be equipped in the finger part. Because of the trait of the fingers as an end-effector, it has to cope with severe external environments to be possible, such as electromagnetic or radio-active fields.

(b) According to (a) the controller cannot much rely on the feedback from sensors such as tactile or pressure sensors.

ISD does not completely deny using the sensory feedback, which might be helpful to accomplish some dexterous and precise motion of the hand if a measure against noise is satisfactory. Therefore ISD requires that some primitive motions of the fingers should be provided without sensory feedback, in other words, mechanically, but it allows using the sensory feedback as subsidiary measures.

All-in-one design (AOD): All of the actuators should be mounted in a hand (distal to the wrist). A lot of works have equipped the actuators at the place away from the hand (Salisbury (1983), Maekawa (1992), Lovchik (1999)), the forearm part for example, and taken the wire driven as a force/torque transmission. But it will hamper to compose a wrist joint that has three DOF if trying to mimic a human. Moreover the wire-driven have some drawbacks; friction loss, control delay, unpredictable non-linear behaviour due to the friction and the elastic element of the wire, all of which make the control precision worse. The place for mounting the actuator is therefore severely restricted due to AOD and ISD requirements. Only the palm is remained for it. Therefore the AOD requires reducing the number of actuators as many as possible by employing some under-actuation mechanical systems.
Simple Control (SC): The control of the multiple fingers of the hand should be as simple as possible. This requirement will be achieved along with pursuing the above BD and ISD properties. BD will reduce the control burden to determine the fingers’ shape when they interact with external objects. ISD also provides the simple control that does not much rely on the sensory feedback.

Hence the purpose of the study is to develop a finger and a hand with multiple fingers that meet or have a potential to meet the above properties, BD, ISD, AOD and SC.

The authors have already proposed and developed a mechanism as one resolution for achieving all of the above requirements (Koganezawa(2004)). The mechanism is composed of the planetary gear system and the compound closed linkage system as shown in Fig.1. This mechanism can be fundamentally driven by only one motor, in which three joints of one finger automatically and mechanically fit the shape of the object when it grips the object with basically no sensory feedback in the control loop. The key point of this mechanism is that it enables to amalgamate an active driving and a passive driving for achieving the synergic gripping motion.

In this paper a successively developed mechanism is proposed. It completely succeeds the synergistic gripping motion of the former mechanism and also provides the adduction/abduction of the MP joint.

This paper is organized as follows. In the subsequent section, the newly invented mechanism called DPGS (Double Planetary Gear System) is introduced followed by the details of how to attain the synergistic gripping motion and the adduction/abduction. The mechanism for gripping/pinching force is also described. Its kinematics and kinetics are described in the third sections. The kinetics for handling the pinching object by two fingers is successively described followed by the simulation and experimental results. Some conclusive remarks are shown in the last section.

2. STRUCTURE OF THE FINGER

We have been developing an advanced mechanism that covers all of the functions the former mechanism (Fig.1) has and has one more DOF; abduction/adduction of the MP joint [10]. It mainly consists of two parts: the double planetary gear system (DPGS) and the compound four-bar linkages as shown in Fig.1. The appearance of the assembled finger is shown in Fig.2.

2.1 DPGS

Fig.3 describes the structure of the DPGS. It consists of one inner gear in which two sets of a solar gear and three planetary gears are embedded face to face. The left-hand and the right-hand solar gears are driven by individual motors.
Planetary gears located around each solar gear rotate on their own axes and transmit the rotation torque to the inner gear, or take an orbital rotation around the solar gear accompanied by rotating an individual carrier.

2.2 Abduction/adduction of the MP joint by DPGS

Abduction/adduction of the MP joint is carried out as follows. A link 2-p (see Fig.5) is connected to the axle of one planetary gear on the carrier. The rotation of the left and right hand side solar gears in opposite direction gives rise to the orbital rotation of the planetary gears (the rotation of the carriers), which is also opposite between the left-hand side and the right-hand side. Then the link 2-p of both sides moves forward and backward as shown in the right-hand figure in Fig.5, which induces the abduction/adduction of the MP joint.

2.3 Synergic gripping motion

The new mechanism can achieve the completely identical gripping motion to the former mechanism. Three joints of one finger (DIP, PIP and MP joints) concurrently grip the object if both sides of the solar gears are rotated in the same direction, which provides the synergic motion likewise as schematically shown in Fig.6.

The spring pulls the carrier of the planetary gears of which force is strong enough to sustain the weight of the finger and not to have the carrier rotate under no external force lording to the finger (a).

The clock-wise rotation of the solar gear gives rise to the counter clock-wise rotation of the inner gear via the rotation of the planetary gears on their axes (b).

Once the motion of the link 1 is hampered by touching the object and the rotation of the inner gear is stopped, further clock-wise rotation of the solar gears give rise to the orbital rotation of the planetary gears around the solar gear accompanied by the rotation of the carrier. The rotation of the carrier push the link 2 forward, which leads the wrapping motion of the object by the link 3, 4 and 5 (c).

It is noteworthy that the line of motions described above can be carried out only by one-way rotation of the solar gears with no sensory feedback. Therefore this mechanism will meet the entire requirement of BD, ISD, AOD and SC defined in the former section.

Fig.7 shows the actual gripping motion of the finger. All of the gripping motions are achieved under the identical driving; both sides of solar gears are rotated with a constant torque,
with which synergic flexion of MP, PIP and DIP joints are induced according to the shape of objects.

2.4 Gripping/Pinching force controller

The back-drivability of the finger system is attained through the passive motion of the spring as shown in Fig.6. In lieu of linear springs like those illustrated in Fig.6, we use flat-spiral-springs (FSS, hereafter) in order to make the prime mover part (the boxed portion in Fig.2) as small as possible. The carrier is directly connected to the outer terminal of FSS with gears as shown in Fig.8. On the other hand, the central core of the FSS is directly connected to a DC-motor (hereafter we call it as “carrier motor”) to control its twisting angle. The DPGS has two carriers on the left- and right-hand sides. Therefore two sets of the FSS and the carrier motor are equipped in the prime mover part. During the gripping experiments shown in Fig.7 we did not use the carrier motors; they kept on holding their initial angle under switched-off due to their high speed reduction ratio of the reduction gear. In this state, the torsion angle of the FSS is passively determined according to the shape of the object. This is a back-drivability. However the gripping force loading on the object differs with the shape of it. Hence the carrier motor has a role to control the gripping or pinching force by setting the twisting angle of the FSS. The gripping/pinching force can be measured by measuring the twisting angle of the FSS, which means the FSS has a role as a force sensor. This fact much contributes to the ISD requirement as defined in the introduction.

3 KINEMATICS AND KINETICS

3.1 Jacobian

According to the assignment of the joint angles and the links shown in Fig.9, we can derive the kinematics and the kinetics of the finger. We have two solar gears angles $\theta_{S1}, \theta_{S2}$, two carrier angles $\theta_{P1}, \theta_{P2}$ and one inner gear angle $\theta_{I}$ in the DPGS. They have the mutual relations

$$\begin{bmatrix}
\Delta \theta_{S1} \\
\Delta \theta_{S2} \\
\Delta \theta_{P1} \\
\Delta \theta_{P2} \\
\Delta \theta_{R1} \\
\Delta \theta_{R2} \\
\Delta \theta_{R3} \\
\Delta \theta_{R4}
\end{bmatrix} = A \begin{bmatrix}
\Delta \theta_{S1} \\
\Delta \theta_{S2} \\
\Delta \theta_{P1} \\
\Delta \theta_{P2} \\
\Delta \theta_{R1} \\
\Delta \theta_{R2} \\
\Delta \theta_{R3} \\
\Delta \theta_{R4}
\end{bmatrix}$$

where, $\rho_{Si} = Z_{i} / Z_{S}$ with $Z_{S}$ and $Z_{i}$ being the numbers of teeth of the solar gear and the inner gear respectively.

Next we find the following eight kinematical constraints existing in the closed link system,

$$f_{c1} = J_{61_{x}} - J_{62_{x}} = 0, \quad f_{c2} = J_{61_{y}} - J_{62_{y}} = 0, \quad f_{c3} = J_{61_{x}} - J_{62_{x}} = 0, \quad f_{c4} = J_{61_{y}} - J_{62_{y}} = 0, \quad f_{c5} = J_{61_{y}} - J_{63_{y}} = 0, \quad f_{c6} = J_{61_{y}} - J_{63_{y}} = 0, \quad f_{c7} = J_{61_{x}} - J_{62_{x}} = 0, \quad f_{c8} = J_{61_{x}} - J_{62_{x}} = 0$$

Partial differentiation with respect to angular variables provides the following equation to derive the infinitesimal variations of 8 dependent variables $\theta_{i} = [\theta_{1}, \theta_{2}, \theta_{3}, \theta_{4}, \theta_{5}, \theta_{6}, \theta_{7}, \theta_{8}]^{T}$,

$$\Delta \theta_{j} = -B^{T}C^{T}d^{T} = \begin{bmatrix}
\Delta \theta_{S1} \\
\Delta \theta_{S2} \\
\Delta \theta_{P1} \\
\Delta \theta_{P2} \\
\Delta \theta_{R1} \\
\Delta \theta_{R2} \\
\Delta \theta_{R3} \\
\Delta \theta_{R4}
\end{bmatrix}$$

where, $B = \partial \mathbf{f}_{c} / \partial \mathbf{\theta}_{j} \in \mathbb{R}^{8 \times 8}$ and $C = \partial \mathbf{f}_{c} / \partial \mathbf{\theta}_{in} \in \mathbb{R}^{8 \times 3}$ with $\mathbf{f}_{c} = \{ f_{ci} | i = 1, \cdots , 8 \}$ and $\mathbf{\theta}_{in} = [\theta_{1}, \theta_{2}, \theta_{3}, \theta_{4}, \theta_{5}, \theta_{6}, \theta_{7}, \theta_{8}]^{T}$.

At the same time the infinitesimal variation of the fingertip position $\mathbf{J}_{in} = [J_{10_{x}}, J_{10_{y}}, J_{10_{z}}]^{T}$, will be,
\[ \Delta J_{10} = (E - DB^2C)A[\Delta \theta_{31} \Delta \theta_{32} \Delta \theta_{31} \theta_{32}]^T \]

with \( D = \partial J_{10} / \partial \theta_{3i} \in \mathbb{R}^{3x3} \), \( E = \partial J_{10} / \partial \theta_{ind} \in \mathbb{R}^{3x3} \) and the Jacobian \( A = (E - DB^2C)A \in \mathbb{R}^{3x3}. \)

Once the Jacobian is identified we can establish the kinetics that relates the force at the fingertip \( (J_9) \) \( \mathbf{f} = \begin{bmatrix} f_x & f_y & f_z \end{bmatrix}^T \) and the torque of the solar gear and the carrier of the planetary gears \( \boldsymbol{\tau} = \begin{bmatrix} \tau_{31} & \tau_{32} & \tau_{31} & \tau_{32} \end{bmatrix} \) as based on the virtual work principle,

\[ \boldsymbol{\tau} = \Lambda^T \mathbf{f} \quad (4) \]

Fig.10 shows the kinematical motion of the finger. Fig.10 (a) is the result when two solar gears rotate in the same direction and Fig.10 (b) is those for the opposite direction. Both results are assumed that the carriers do not rotate due to the FSS. As shown, the solar gears’ rotation in the same direction gives rise to the synergetic flexion of MP, PIP and DIP joints. On the other hand their rotation in the opposite direction gives rise to the abduction/adduction of the MP joint about \( \pm 25^\circ \) that is almost the same range as those of a human finger.

**3.2 Pinching force control**

The developed finger mechanism allows us to scheme a very simple control when the two fingers pinch an object and handle it. Basically the solar motor that directly drives the solar gear has a role to handle the object position, while the carrier motor (see Fig.8) that twists the FSS has a role to adjust the force exerted at the finger tip, although they are not rigorously discriminated.

![Fig.10  Kinematical simulation of the finger](image)

(a) Finger motion when two solar gears rotate in the same direction

(b) Finger motion when two solar gears rotate in the opposite direction

![Fig.11  Kinetic simulation of the object lifting-up by two fingers](image)

(a) No FSS control (b) FSS control

Fig.11 is the simulation result of lifting up the object by two fingers. The input is tremendously simple; all of the solar motors (2 by 2) rotate in the same direction under the left and right fingertips obeying a holonomic constraint (the distance between them is always constant). Fig.11(a) is the case that the carrier motors hold their initial angle. In this state, the FSS are twisted because the carriers are passively rotated according to the solar gears rotation. As a result, pinching force (showing by the red arrows in Fig.11(a)) is increased. While Fig.11(b) is the case that the carrier motor is controlled as the twisting angle of the FSS stays to be constant. In this state, the pinching force (blue arrows in Fig.11(b)) also stays to be almost constant.

**4. MOTION OF THE DPGS FINGERS**

Fig.12 shows the abduction/adduction of the DPGS finger. The motion is the result of rotating the left- and right-hand solar motors in an opposite direction.

![Fig.12  Kinematical simulation of the finger](image)

Fig.13 is the experimental result of opening the screw cap. The control is totally feed-forwarded and only solar motors are used. The drive sequence is as follows.

1. All of the solar motors are rotated in the same direction for the fingertips of both fingers to touch the cap.
2. The solar motors rotate further in the same direction, which induces the passive rotation of the carrier and twists the FSS. Twisting of the FSS generates the pinching force at the fingertips.
3. The left- and the right-hand solar gears of one finger rotate in an opposite direction, which induces the adduction/abduction of a finger. The opposite directed abduction/adduction between two fingers induces to rotate the screw cap.
4. All of the solar motors rotate backward to return the initial angle.
The sequence (1) through (4) runs through several times.

Finally all of the solar motor rotates in the same direction, which induces to lift up the screw cap.

Fig.14 is the results of the pinching force control. As shown in the simulation (Fig.11), the pinching force is increased as lifting up the paper cup unless the carrier motors control the pinching force (Fig.14 (b)), which collapses the paper cup. While the lifting is succeeded without collapsing if the carrier motors rotates as the twisting angle of the FSS stays to be constant (Fig.14(a)).

5. CONCLUSION

As described above, all of the dextrous motions shown in Fig.11, 12 and 13 are achieved by tremendously simple control, which meets the SC requirement as described in the introduction. Therefore, it will be concluded that the finger mechanism will meet all of the requirements (BD, ISD, AOD and SC).

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REFERENCES


