Artificial Finger Consisting of Closed Linkages and Single Planetary Gear System: an Approach to Grasp Stabilizing with Distal Hyperextension Joint

Yuma Eto, Koichi Koganezawa and Yoshihiro Kai

June 3, 2024

Artificial finger consisting of closed linkages and Single Planetary Gear System: an approach to grasp stabilizing with a distal hyperextension joint

Y. Eto*, K. Koganezawa#, Y. Kai†

*Ph.D Course, Graduate School of Science and Technology Tokai University, 4-1-1 Kitakaname, 259-1292, Hiratsuka, Japan, 3ctad003@cc.u-tokai.ac.jp

#Institute of Sports Medical Science Tokai University, kogane@tsc.u-tokai.ac.jp

†Mechanical Systems Engineering, Tokai University, kai@tokai.ac.jp

Abstract

The authors have developed a five-finger robot hand [1-4]. Figure. 1 shows the structure used in four fingers (index, mid, medicinal, and little). It has two serially connected closed four-bar linkages and a Single Planetary Gear System (SPGS). It is a two-degree-of-freedom (2-DOF) mechanical system that drives actively and passively. It constitutes a variable stiffness mechanism that achieves sensorless shape-fitting motion (envelope grasping) when grasping an object of unknown shape. This mechanism gains robustness on harsh environmental usages since no electric or electronic devices are embedded in the finger part. However, the mechanism of such an under-actuation system requires stability in its motion, specifically, stable object grasping or pinching. It must be achieved on a mechanical basis, not by control maneuver.

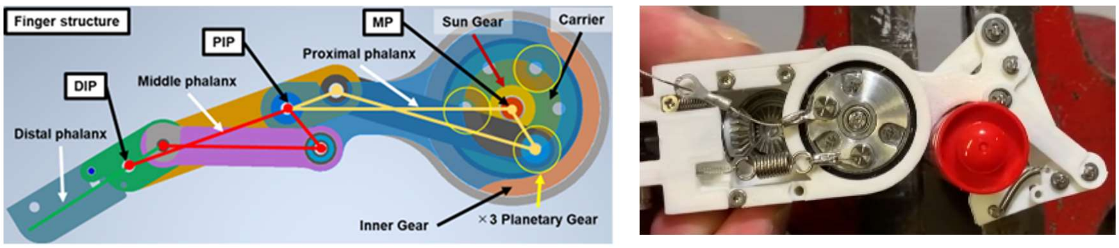
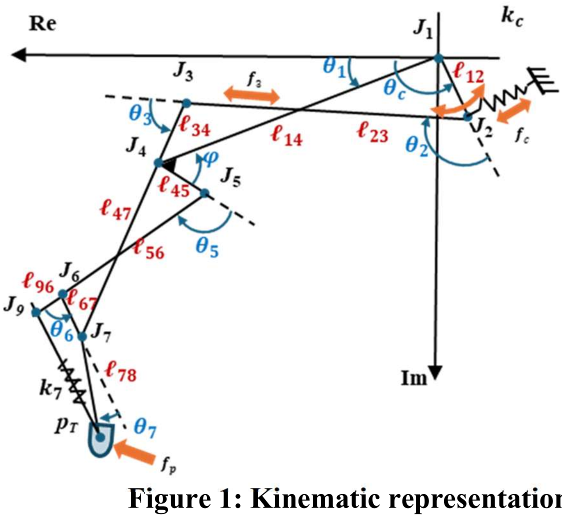


Figure 2: Finger mechanism



θ_s : Rotation angle of the sun gear.

θ_c : Rotation angle of the carrier that is passively determined by an external load.

$\theta_2 \cdots \theta_5$: Dependent angles that are passively determined by kinematic constraints and kinetic constraints.

$$\theta_1 = \frac{-Z_s}{Z_i}\theta_s + \frac{Z_s+Z_i}{Z_i}\ \theta_c$$

Z_s=tooth number of the sun gear, Z_i=tooth number of the inner gear

φ : A constant degree.

P_T : The tip position being prescribed. $\boldsymbol{P_T} = P_{Tr} + iP_{Ti}$

f_p : The tip force vector. $\boldsymbol{f_p} = f_{pr} + if_{pi}$

Figure 1: Kinematic representation of the finger having a Hyperextension joint.

Recently, we developed a new finger mechanism with a Hyperextension joint at the fingertip aiming to stabilize the pinching motion passively. This joint has a linear compression spring. This abstract just shows the mathematical formulation of the finger mechanism to compute its static motion and force that the fingertip applies to an external object. The analysis will be reported in the presentation.

Figure .2 shows the kinematic representation of the finger mechanism. We determine unknown 9 variables $\theta_c, \theta_2, \theta_3, \theta_5, \theta_6, \theta_7, f_3, f_{pr}, f_{pi}$ under solar gear rotation θ_s being given and the tip position $P_{Tr} + iP_{Ti}$ being prescribed.

$$\begin{aligned}
&\boldsymbol{J_1} = \{0,0\}, \boldsymbol{J_2} = \boldsymbol{\ell_{12}} e^{i\theta_c}, \boldsymbol{J_3} = \boldsymbol{J_2} + \boldsymbol{\ell_{23}} e^{i(\theta_c+\theta_2)}, \boldsymbol{J_4} = \boldsymbol{\ell_{14}} e^{i\theta_1} = \boldsymbol{J_3} + \boldsymbol{\ell_{34}} e^{i(\theta_c+\theta_2+\theta_3)} \\
&\boldsymbol{J_5} = \boldsymbol{J_4} + \boldsymbol{\ell_{45}} e^{i(\theta_1+\pi-\varphi)}, \boldsymbol{J_6} = \boldsymbol{J_5} + \boldsymbol{\ell_{56}} e^{i(\theta_1+\pi-\varphi+\theta_5)}, \\
&\boldsymbol{J_7} = \boldsymbol{J_4} + \boldsymbol{\ell_{47}} e^{i(\theta_c+\theta_2+\theta_3)} = \boldsymbol{J_6} + \boldsymbol{\ell_{67}} e^{i(\theta_1+\pi-\varphi+\theta_5+\theta_6)} \\
&\boldsymbol{P_T} = \boldsymbol{J_6} + \boldsymbol{\ell_{78}} e^{i(\theta_1+\pi-\varphi+\theta_5+\theta_6+\theta_7)}, \boldsymbol{J_9} = \boldsymbol{J_6} + \boldsymbol{\ell_{96}} e^{i(\theta_1+\pi-\varphi+\theta_5)}
\end{aligned} \tag{1}$$

First, we derive the kinematic constraints. Two joints J_4 and J_7 have two passes to reach their positions due to closed linkages. It gives us the first to fourth constraint equation.

$$\begin{aligned} \boldsymbol{c_1} + \boldsymbol{i}\boldsymbol{c_2} &\equiv \boldsymbol{\ell_1} e^{i\theta_1} - \left(\boldsymbol{J_3} + \boldsymbol{\ell_4} e^{i(\theta_c+\theta_2+\theta_3)}\right) = \boldsymbol{0} \\ \boldsymbol{c_3} + \boldsymbol{i}\boldsymbol{c_4} &\equiv \left(\boldsymbol{J_3} + (\boldsymbol{\ell_4} + \boldsymbol{\ell_5}) e^{i(\theta_c+\theta_2+\theta_3)}\right) - \left(\boldsymbol{J_6} + e^{i(\theta_1+\pi-\varphi+\theta_5+\theta_6)}\right) = \boldsymbol{0} \end{aligned} \tag{2}$$

Second, we derive the kinetic constraints. Let f_3 be the internal force vector acting on the link $J_2 - J_1$. Then, $\boldsymbol{f_3}$ is expressed by $\boldsymbol{f_3} = pf_3(\boldsymbol{J_3} - \boldsymbol{J_2})/\ell_3$, where pf_3 is the force value. The sum of the force vectors acting at the J_2 is in parallel to the vector $J_2 - J_1$ on an equilibrium state, which provides a constraint described by outer product of $f_3 + f_C$ and $J_2 - J_1$ being zero.

$$\boldsymbol{c_5} = \left(\boldsymbol{f_3} + \boldsymbol{f_c}\right) \times (\boldsymbol{J_2} - \boldsymbol{J_1}) \tag{3}$$

, where, the operator "×" is defined as $\boldsymbol{p} \times \boldsymbol{q} = p_r q_i - p_i q_r$ for $\boldsymbol{p} = p_r + \boldsymbol{i} p_i$ and $\boldsymbol{q} = q_r + \boldsymbol{i} q_i$.
Let f_7 be the force vector acting on the spring link $J_c - J_2$. Then, $\boldsymbol{f_7}$ is expressed by $\boldsymbol{f_7} = pf_7(\boldsymbol{J_c} - \boldsymbol{J_2})/\ell_{c2}$ ($\ell_{c2} = spling\ link\ length$), where pf_7 is the force value. The sum of the force vectors acting at the $\boldsymbol{J_7}$ is in parallel to the vector $\boldsymbol{J_7} - \boldsymbol{P_T}$ on an equilibrium state, which provides a constraint described by outer product of $\boldsymbol{f_7} + \boldsymbol{f_p}$ and $\boldsymbol{J_7} - \boldsymbol{P_T}$ being zero.

$$\boldsymbol{c_6} = \left(\boldsymbol{f_7} + \boldsymbol{f_p}\right) \times (\boldsymbol{J_7} - \boldsymbol{P_T}) \tag{4}$$

The fact that the torque acting at $\boldsymbol{J_4}$ is zero provides us another constraint,

$$\boldsymbol{c_7} = \boldsymbol{f_3} \times (\boldsymbol{J_4} - \boldsymbol{J_3}) + (\boldsymbol{f_7} + \boldsymbol{f_p}) \times (\boldsymbol{J_4} - \boldsymbol{P_T}) \tag{5}$$

A prescribed tip position $\widehat{\boldsymbol{P}}_T = \widehat{P}_{Tr} + i\widehat{P}_{Ti}$ gives us the following two constraint equations,

$$\boldsymbol{c_8} + \boldsymbol{i}\boldsymbol{c_9} = \widehat{\boldsymbol{P}}_{\boldsymbol{Tr}} + \boldsymbol{i}\widehat{\boldsymbol{P}}_{\boldsymbol{Ti}} - \left(\boldsymbol{J_6} + \boldsymbol{\ell_{78}} e^{i(\theta_1+\pi-\varphi+\theta_5+\theta_6+\theta_7)}\right) = \boldsymbol{0} \tag{6}$$

The set of infinitesimal variation of nine constraint equations ;
$\Delta\boldsymbol{c} = (\Delta c_1\ \Delta c_2\ \Delta c_3\ \Delta c_4\ \Delta c_5\ \Delta c_6\ \Delta c_7\ \Delta c_8\ \Delta c_9)$, should also hold zero vector during motion ($\Delta\boldsymbol{c} = \boldsymbol{0}_9$). In addition, we find solutions of nine variables ($\boldsymbol{\theta_c}, \boldsymbol{\theta_2}, \boldsymbol{\theta_3}, \boldsymbol{\theta_5}, \boldsymbol{\theta_6}, \boldsymbol{\theta_7}, \boldsymbol{f_3}, \boldsymbol{f_{pr}}, \boldsymbol{f_{pi}}$) by repeatedly executing the Newton-Raphson method under nine constraint equations being sustained.

$$\boldsymbol{\varphi_1} \to \boldsymbol{\theta_s}, \boldsymbol{\varphi_2} \to \boldsymbol{\theta_c}, \boldsymbol{\varphi_3} \to \boldsymbol{\theta_1}, \boldsymbol{\varphi_4} \to \boldsymbol{\theta_2}, \boldsymbol{\varphi_5} \to \boldsymbol{\theta_3}, \boldsymbol{\varphi_6} \to \boldsymbol{\theta_4}, \boldsymbol{\varphi_7} \to \boldsymbol{f_{pr}}, \boldsymbol{\varphi_8} \to \boldsymbol{f_{pi}} \tag{10}$$

$$\Delta\boldsymbol{c} = \frac{\partial \boldsymbol{c}}{\partial \boldsymbol{\varphi}} \Delta\boldsymbol{\varphi} + \frac{\partial \boldsymbol{c}}{\partial \boldsymbol{\theta_s}} \Delta\boldsymbol{\theta_s} = \begin{pmatrix} \partial c_1/\partial\varphi_1 & \cdots & \partial c_1/\partial\varphi_9 \\ \vdots & \ddots & \vdots \\ \partial c_9/\partial\varphi_1 & \cdots & \partial c_9/\partial\varphi_9 \end{pmatrix} \Delta\boldsymbol{\varphi} + \frac{\partial \boldsymbol{c}}{\partial \boldsymbol{\theta_s}} \Delta\boldsymbol{\theta_s} = \boldsymbol{\Lambda}\Delta\boldsymbol{\varphi} + \boldsymbol{\alpha}\Delta\boldsymbol{\theta_s} = \boldsymbol{0} \tag{11}$$

$$\Delta\boldsymbol{\varphi} = -\boldsymbol{\Lambda}^{-1}\boldsymbol{\alpha}\Delta\boldsymbol{\theta_s} \tag{12}$$

$$\boldsymbol{\varphi_k} = \boldsymbol{\varphi_{k-1}} + \Delta\boldsymbol{\varphi}\ , \boldsymbol{k} = \boldsymbol{1}, \boldsymbol{2}, \boldsymbol{3} \cdots \tag{13}$$

$$\boldsymbol{\varphi_{k,j}} = \boldsymbol{\varphi_{k,j-1}} - \boldsymbol{\Lambda}^{-1}\boldsymbol{c},\ \boldsymbol{j} = \boldsymbol{1}, \boldsymbol{2}, \cdots \tag{14}$$

where, k is an iteration number. The numerical errors generated by the linear approximation will be compensated by employing the Newton-Raphson convergency procedure in the cycle.

We analyze the finger motion and the reaction force of the fingertip in this way. At this point, we analyze how the force produced at the fingertips varies due to sun gear rotation input and how the hyperextension of the fingertips affects on. This abstract shows a new finger structure and the mathematical basis of the analysis. We will show the simulation results at the time of presentation.

References

[1] Eto, Y.; Koganezawa, K.; Kai, Y.: Five-Finger Robot Hand Aimed for a Multi-DOF Prosthetic Hand. Proceedings of the 39th Annual Conference of the Robotics Society of Japan, 3C2-04, September 2023. In Japanese.

[2] Eto, Y.; Akiyoshi, K.; Koganezawa, K.: Modular Artificial fingers with Variable Stiffness Mechanism using Single & Double Planetary Gear Systems and an application to 3 fingers robot hand. Proceedings of the 7th International Conference on Advanced Mechatronics (RSJ2021), Online (Host Aichi, Japan), July 2021.

[3] Koganezawa, K.; Ito, A.: Artificial Hand with Stiffness Adjuster. Proceedings of 2014 IEEE International Conference on Intelligent Robots and Systems (IROS), Chicago, USA,2014.

[4] Eto, Y.; Koganezawa, K.: A Mechanism for Artificial Finger Based on the Double Planetary Gear System -Kinematics and Kinetics Study-. Proceedings of International Symposium on System Integration (SII2022), Narvik, Norway, January 2022.