12th International Conference on Electrical, Electronics and Computer Engineering (IcETRAN), Čačak, 9-12 June 2025

The methodology for the design of underactuated adaptive robotic finger for precision grasping tasks

Lazar Matijašević
Faculty of Mechanical Engineering
University of Belgrade
Belgrade, Serbia
lmatijasevic@mas.bg.ac.rs
https://orcid.org/0000-0001-9153-0303

Živana Jakovljević
Faculty of Mechanical Engineering
University of Belgrade
Belgrade, Serbia
zjakovljevic@mas.bg.ac.rs
https://orcid.org/0000-0002-7878-2909

Dušan Nedeljković
Faculty of Mechanical Engineering
University of Belgrade
Belgrade, Serbia
dnedeljkovic@mas.bg.ac.rs
https://orcid.org/0000-0001-5909-4812

Živojin Suvajac
Faculty of Mechanical Engineering
University of Belgrade
Belgrade, Serbia
zsuvajac@mas.bg.ac.rs
https://orcid.org/0009-0006-1667-2647

***Abstract* - Robotic grippers are essential components in modern automation, enabling robots to interact with and manipulate objects in various tasks. While traditional designs excel in the manipulation of identical objects in structured environments, they often lack the adaptability required for handling various objects in unstructured settings. This limitation has led to increased focus on adaptive solutions, with underactuated robotic hands emerging as a promising alternative that combines dexterity, mechanical simplicity, and cost efficiency. Unlike fully actuated hands, which are complex and expensive, underactuated designs use fewer actuators than degrees of freedom and rely on passive elements such as springs and mechanical limits for adaptation to object's shape. This paper presents the design of a two-phalanges underactuated robotic finger actuated by a four-bar linkage and gear mechanism. The finger is intended for robotic hand primarily used for precision grasping tasks. A methodology for calculating optimal linkage dimensions and mechanism for adaptability are also described, as well as the method for the analysis of grasping force during precision grasping.**

Keywords – four-bar linkage, underactuated robotic hands, precision grasping

I. Introduction

Initially industrial robotic systems were developed with the aim to help or replace human worker on production lines in doing monotonous or dangerous tasks while maintaining speed and consistency [1]. Accelerated development of robotic systems led to the implementation of these systems in other areas, such as agriculture, medicine, space exploration, research laboratories and others. Considering that industrial robots are made with the goal of mimicking and surpassing human capabilities, it is expected that the robotic systems are significantly faster than humans, have greater payload capacity and are more repeatable in doing tasks that industry imposes. In industrial processes, where there are tasks that can be completed using small number of specific tools (welding, glue application, handling of objects of same size, rough grinding and sanding, etc.), robot capabilities are way above human workers, but when it comes to tasks that involve usage of many different tools or tasks that are performed in unstructured environment, human workers' flexibility is still unmatched. Tasks such as handling and manipulation of various objects in unstructured environment require inbuilt dexterity of human hand.

This problem is even more emphasized within the mass customization production paradigm that implies production of large number of different products and imposes the need to develop a robotic system that has the ability to grasp various objects with many different customized properties including shape, material, stiffness, etc. The complex challenges imposed by mass customization can be solved in two ways. One way is to develop many different traditional gripper designs and tool-changing systems to accommodate handling a plethora of customized products [2]. Another way is to develop more dexterous robotic grippers that mimic certain properties and capabilities of human hand, and are able to adapt to different objects in unstructured environment. These dexterous robotic grippers are often referred to as robotic hands.

The development of robotic hands has been ongoing for a long time and many robotic hands have been developed. Some of them are: Utah/MIT hand [3] - tendon operated robotic hand with 16 degrees of freedom (DOFs), Keio University robotic hand [4] that is operated by ultrasonic motors and elastic elements, DLR II robotic hand with hybrid actuation [5], Shadow hand [6] with 24 DOFs operated by 20 pairs of agonist–antagonist tendons and many others. All mentioned robotic hands are fully actuated mechanisms meaning that their fingers have three phalanges and each phalanx has its own actuator. Most of these hands are tendon actuated because this design enables that all tendon actuators can be put in forearm of robotic hand reducing the overall size of fingers and palm [7]. Due to a large number of actuators and DOFs, the dexterity of fully actuated robotic hands is high and they mimic human hands capabilities to high extent. However, the control of these systems is extremely complicated. In addition, the cost of developing and manufacturing these robotic hands is high, and with so many moving parts, maintenance of these hands is also complicated and expensive. The listed drawbacks make fully actuated robotic hands insufficiently suitable for most manufacturing processes in industry.

This research was supported by the Science Fund of the Republic of Serbia, grant No. 17801, Cybersecurity of Motion Control Systems in Industry 4.0 - MCSecurity as well as by the Ministry of Science, Technological Development and Innovations of the Serbian Government under the contract No. 451-03-137/2025-03/200105.

ISBN 978-86-6200-031-6 ©2025 AM & ETRAN

Another approach in the design of adaptive and flexible robotic hands is using soft mechanisms. Soft robotic hands have shown capabilities of stable grasp of various objects despite many environmental constraints. However, the lack of robustness in construction, limited stiffness and inability to perform repeatable grasping of the same objects make these mechanisms inadequate for application in industrial manufacturing processes [8].

Considering the constraints imposed by industrial setting and limitations of above-mentioned mechanisms, the development of robotic hand with simpler design and control algorithms, while also maintaining adequate capabilities in terms of dexterity and adaptability is a crucial challenge in robotics for industrial applications within mass customization production. The utilization of underactuated mechanisms in robotic hand designs has proven to solve many of the listed challenges. One of main characteristics of these mechanisms is that they are easy to use and economically affordable. When compared with fully actuated robotic hands, the underactuated hands have fewer actuators than DOFs giving them innate ability to adapt to the object of manipulation, similar to the way in which human hand adapts its grasp mechanics according to grasped object [9-10]. In order to function properly, these mechanisms need to incorporate some passive elements like springs and mechanical limits which allow them to adapt to objects of manipulation without the need for sophisticated control algorithm.

Depending on the means of actuation, particularly on the types of transmission mechanisms used, the underactuated robotic hands can be classified into several categories [11] including mechanisms with tendon-based, linkage-based, gear-based and hybrid transmission (Fig. 1).

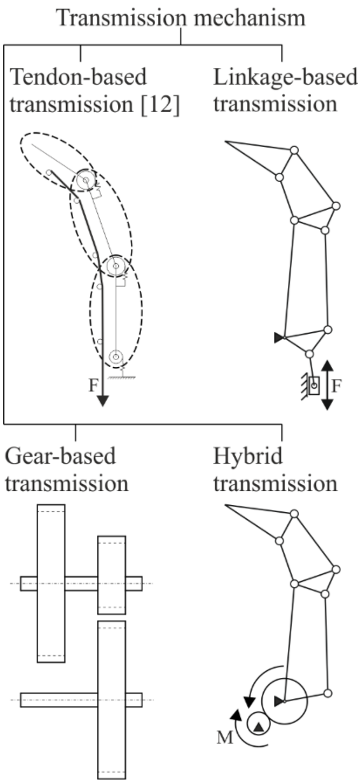

Fig. 1. Classification of underactuated robotic hands based on transmission mechanism

Gear-based transmission mechanisms have some advantages over other types of actuation, including compactness and high torque transmission, but they are much more complex and consequently they are not as frequently utilized as other three transmission mechanisms [12]. Underactuated robotic hands with tendon-based transmission mechanisms have good adaptive ability and are able to adapt well to most objects [13]. They are lightweight and those robotic hands have less inertia of their fingers because actuators are located in hand wrist and away from fingers. Giving that cables are used in transmission mechanism, grasping force is determined by both the tensile strength and the degree of tension of the cable. Because of this, underactuated robotic hands that utilize tendon-based transmission mechanisms are usually used for manipulation of lightweight objects. To enable transmission of large forces on the object of manipulation using underactuated robotic hand, rigid linkage-based transmission mechanism should be employed [14]. Because linkage-based transmission takes more space, these hands usually have smaller workspace than alternative robotic hands. These hands weigh more than tendon-based robotic hands and have much larger inertia, but are able to perform both exterior and interior stable grasp unlike tendon-based hands because lack of tension in cables, due to change of direction, prevents interior grasping. There are a lot of underactuated robotic hands that combine aforementioned transmission types in order to use best traits from each. To the best of our knowledge, the most popular approach when it comes to designing robust underactuated robotic hand capable of performing stable grasp, in research and industry setting, is the combination of gear-based and linkage-based transmission mechanisms [15-16].

This paper presents an approach for the design of an adaptive underactuated robotic finger with two phalanges for tasks of precise grasping, driven by rigid links and a gear pair. Analysis of the proposed design, as well as the methodology for calculating the lengths of the actuation mechanism's links to achieve optimal finger kinematics and force transmission will be presented. Also, methodology for grasping force calculation will be presented as well as the mechanism for adaptation, i.e., for transition from precise grasping to envelop grasping of objects of various shapes and sizes.

II. Design considerations of underactuated finger

The proposed design of underactuated finger features two phalanges that are actuated using one four-bar linkage mechanism. This four-bar linkage mechanism is used since it enables relatively simple control of robotic hand, both during grasping (closing) and releasing (opening) motion. In addition, this finger is expected to be easy to use and maintain, as well as readily and affordably rebuildable in case of damage during regular usage. The underactuated design ensures that the finger can adapt to objects of varying shapes and sizes, providing a more versatile grasping ability. Since this design is intended for the development of an underactuated robotic hand primarily aimed at precise grasping, aside from a four-bar linkage, it incorporates also a parallelogram linkage mechanism, which is used to maintain the orientation of the distal phalanx during grasping tasks.

A. Concept design

Since this robotic hand will primarily be used for precision grasping with the ability to adapt to irregularly shaped and larger objects, the design process should begin with the development of a mechanism that provides the appropriate kinematics for precise (pinch) grasping. Once the kinematic structure is defined, the actuation mechanism, based on a four-bar linkage mechanism, should be designed. Finally, passive elements that enable adaptive behavior during contact with objects should be incorporated.

The proposed concept of underactuated finger is shown in Fig. 2. It comprises of two phalanges, proximal AB and distal BB_1. In order for finger to have the ability to perform pinch grasp, distal phalanx needs to keep its orientation during grasping movement. This is achieved using parallelogram linkage $ABCA_1$ that maintains orientation of distal phalanx during movement until distal phalanx makes a contact with object of manipulation and exerts force upon it. Upon making contact with the object, the distal phalanx stops, and the grasping force increases up to a certain allowable limit, while the phalanx remains in the same orientation.

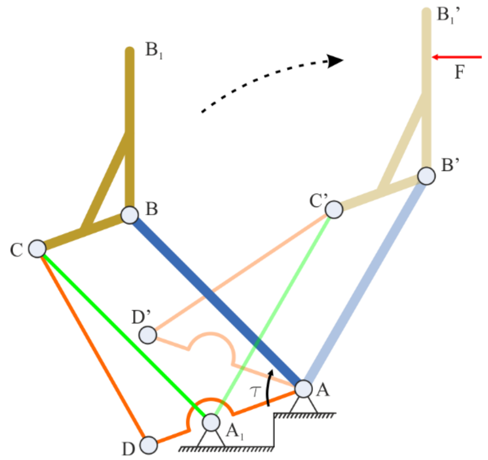

Fig. 2. The proposed concept of underactuated finger (AB – proximal phalanx, BB_1 – distal phalanx, $ABCA_1$ – parallelogram linkage for maintaining BB_1 orientation, ABCD - four-bar linkage mechanism for actuation); the position of mechanism upon making contact with object is shown in light colors

Actuation mechanism used in this concept is four-bar linkage mechanism ABCD that is used to move finger and to transmit torque τ from actuator to phalanges. Combination of parallelogram linkage and four-bar linkage mechanism moves finger and maintains orientation of distal phalanx if distal phalanx is in contact with the object. However, if the proximal phalanx contacts object first, then the finger needs to adapt to the shape of that object. In order for finger to have that adaptation ability, passive elements, such as springs, need to be incorporated.

As can be observed from Fig. 3a, if proximal phalanx during movement comes into contact with the object of manipulation, it stops moving. In this case the object is not in stable grasp and finger needs to adapt to the shape of object in order to perform stable grasp. This adaptation is performed by continuous motion of four-bar linkage mechanism ABCD and simultaneous extension of parallelogram linkage mechanism's link A_1C. Namely, link A_1C is designed as spring-loaded cylinder with spring that opposes to the extension of cylinder (Fig. 3b). If there is no force acting on proximal phalanx, the preloaded spring exerts enough force to keep cylinder retracted, the parallelogram linkage mechanism exists and it keeps constant orientation of distal phalanx.

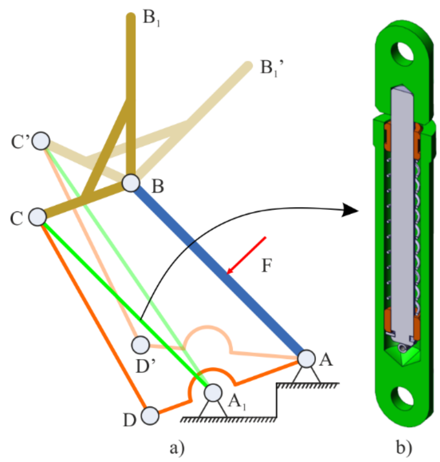

Fig. 3. Adaptation of finger to the shape of object: a) motion of mechanism in case that proximal phalanx contacts object, b) the design of link A_1C of the parallelogram linkage mechanism – spring-loaded cylinder

On the other hand, if there is a force F acting on the proximal phalanx, the proximal phalanx stops moving and link A_1C extends facilitating the movement of distal phalanx. This is the mechanism of adaptation of the proposed underactuated two-phalanges finger design.

B. The design of transmision mechanism

As described, the actuation mechanism for the proposed design is four-bar linkage mechanism and its dimensions have to be carefully determined in order for linkage to provide the desired finger motion while satisfying kinematic constraints. Prior to performing the mechanism synthesis, it is necessary to define the constraints that will guide the design. These constraints will ultimately simplify the analysis and reduce the complexity of the calculations. One of the requirements of design is that the open hand should have a finger span similar to finger span of a human hand, approximately 170 mm [18]. According to this requirement we adopt lengths of proximal and distal phalanges as 75 mm and 50 mm respectively. Also, based on the size of spring-loaded cylinder, (Fig. 3b), it is determined that output link BC of four-bar linkage mechanism should be 30 mm. Adopted dimensions are shown on Fig. 4.

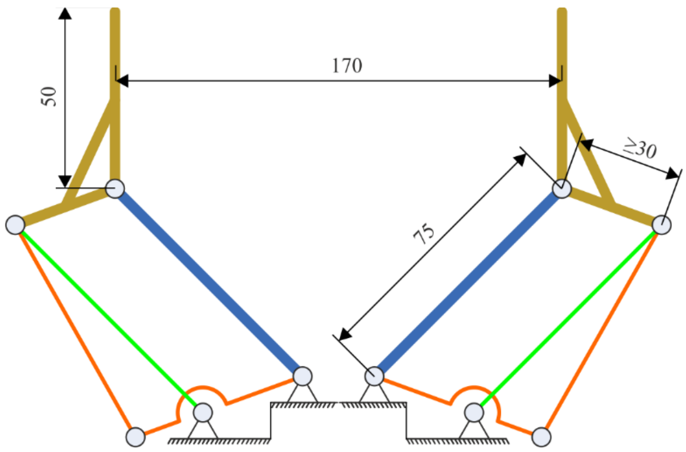

Fig. 4. Adopted dimensions of finger based on mentioned considerations

One common approach, for synthesizing four-bar linkage mechanism and make it to perform some function in constrained domain is to use Freundenstein's equation [17]. The general form of Freundenstein's equation relates the input and output angles to the link lengths of the mechanism. As shown in Fig. 5, φ_2 is input angle and φ_4 is output angle.

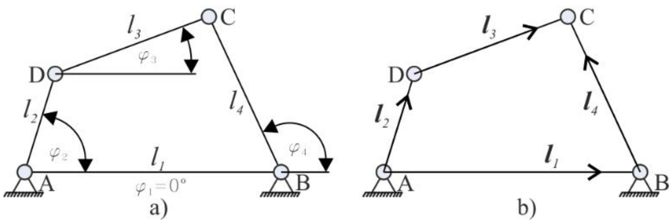

Fig. 5. Four-bar mechanism (a) and its vectorial representation (b);

Freudenstein's equation is derived from vector loop closure equation (Fig. 5b) [17]:

$$\boldsymbol{l}_2 + \boldsymbol{l}_3 - \boldsymbol{l}_4 - \boldsymbol{l}_1 = 0 \tag{1}$$

which can be written in complex form as:

$$l_2(\cos\varphi_2 + i\sin\varphi_2) + l_3(\cos\varphi_3 + i\sin\varphi_3) -$$
$$l_4(\cos\varphi_4 + i\sin\varphi_4) - l_1(\cos\varphi_1 + i\sin\varphi_1) = 0, \tag{2}$$

where φ_i, $i \in \{1, 2, 3, 4\}$ are presented in Fig. 5a. Considering that $\varphi_1=0°$, real and imaginary part of (2) can be extracted as:

$$l_2\cos\varphi_2 + l_3\cos\varphi_3 - l_4\cos\varphi_4 - l_1 = 0, \tag{3}$$

$$l_2\sin\varphi_2 + l_3\sin\varphi_3 - l_4\sin\varphi_4 = 0, \tag{4}$$

from which follows:

$$l_2^2 + l_4^2 + l_1^2 - l_3^2 + 2l_4l_1\cos\varphi_4 - 2l_1l_2\cos\varphi_2 =$$
$$2l_2l_4\cos\varphi_2\cos\varphi_4 + 2l_2l_4\sin\varphi_2\sin\varphi_4 \tag{5}$$

Finaly, application of trigonometric identities leads to:

$$\frac{l_2^2+l_4^2+l_1^2-l_3^2}{2l_2l_4} + \frac{l_1}{l_2}\cos\varphi_4 - \frac{l_1}{l_4}\cos\varphi_2 = \cos(\varphi_2 - \varphi_4) \tag{6}$$

If we introduce the following:

$$R_1 = {}^{l_1}/_{l_4}\ , \tag{7}$$

$$R_2 = {}^{l_1}/_{l_2}\ , \tag{8}$$

$$R_3 = \frac{{l_1}^2+{l_2}^2+{l_4}^2-{l_3}^2}{2l_2l_4}, \tag{9}$$

(6) becomes:

$$R_3 + R_2\cos\varphi_4 - R_1\cos\varphi_2 = \cos(\varphi_2 - \varphi_4), \tag{10}$$

which represents Freudenstein's equation. Freudenstein's equation (10) is used in the synthesis of four-bar linkages for three-position function generation. The application of (10) will be illustrated through the example of four-bar linkage transmission mechanism used in the design of underactuated finger, which is shown in Fig. 6. Given that the rotation of the distal phalanx is caused by the contact between the proximal phalanx and the object of manipulation, the proximal phalanx is assumed to be stationary in space during this phase. General form of Freundenstein's equation (10) for purpose of this paper is:

$$R_3 + R_2\cos\beta_i - R_1\cos\alpha_i = \cos(\alpha_i - \beta_i), \tag{11}$$

where i=1, 2, 3.

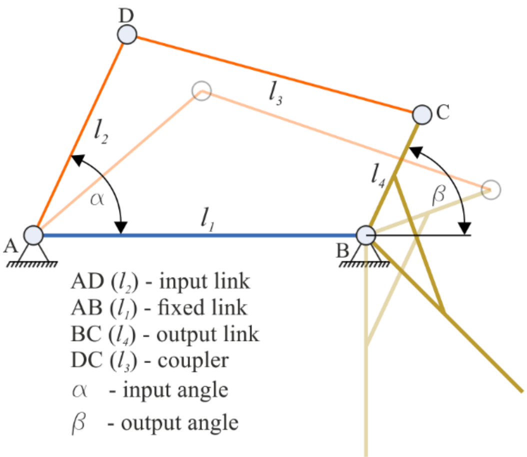

Fig. 6. Transmission mechanism; due to the contact with object, a support in point B is introduced

Since (11) has three variables, to solve this equation, three target positions of the mechanism must be defined, based on the desired pairs of input and output angles, which are shown in Table I. Substituting angle pairs into equation (11) results in a system of three nonlinear equations.

TABLE I ASSUMED PARAMETERS USED IN CALCULATION

Parameter	Value	Parameter	Value
AB	75 mm	BB_1	50 mm
α_1	65°	β_1	65°
α_2	52.193°	β_2	43°
α_3	40.66°	β_3	20°

Solving this system provides the values of the design parameters R_1, R_2 and R_3. From (7), (8) and (9) we can calculate the lengths of three links assuming the value of the length of one link. If we assume $l_1 = 1$, we can calculate remaining lengths. This is possible because the entire mechanism behaves the same even if it is scaled up or down, so after determining length of all links we can scale all links by the same value and get proper dimensions of four-bar linkage transmission mechanism. Calculated values that will be used in the design process are shown in Table II.

TABLE II CALCULATED PARAMETERS OF TRANSMISSION MECHANISM

Parameter	Value	Parameter	Value
AB (l_1)	75 mm	R_1	1.50077
AD (l_2)	49.9745 mm	R_2	2.50116
DC (l_3)	68.9740 mm	R_3	1.42278
BC (l_4)	29.9861 mm		

The calculated values are subject to change and are purely mathematical. Significant influence on them comes from the functional constraints during the design of the robotic hand, such as parts manufacturing, cost, material availability, and similar factors. Additionally, real-world factors like durability, precision, ease of assembly, and maintenance requirements also play a crucial role in the final design of the robotic gripper. This process is iterative, meaning that the calculated values serve as initial estimates. If the dimension of one link is modified, the lengths of other links must be recalculated to maintain the kinematics of the mechanism.

When designing a four-bar linkage to properly transmit input torque to the phalanges, an additional parameter needs to be considered in order for the calculated linkage to effectively transmit the input torque. This is transmission angle μ [19], which is an important parameter for the design of four-bar transmission mechanism.

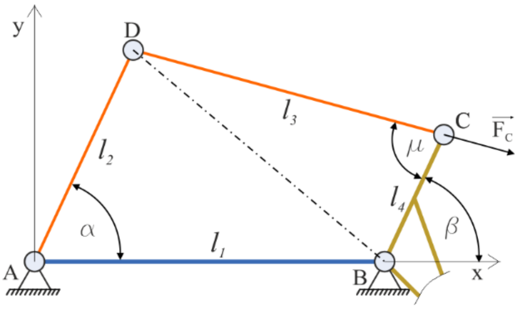

Fig. 7. Transmission angle in four-bar linkage mechanism

The transmission angle μ is defined as the angle between the coupler link l_3 and the output link l_4. This angle changes throughout the range of motion and is optimal when it is close to 90°. The recommended range for the transmission angle is between 40° and 140° (i.e., 90° ± 50°). Transmission of motion becomes impossible when the transmission angle is 0° or 180° [19]. At these angles, input force acts along the same line as the output link, creating no rotational effect and no torque can be transmitted to the output link, as the mechanism reaches its dead center position. According to Fig. 7, the transmission angle can be calculated by applying the cosine theorem to the triangles ABD and BCD, and equating the lengths of the BD for both equations. This results in the following expression:

$$\cos\mu = \frac{-l_1{}^2 - l_2{}^2 + l_3{}^2 + l_4{}^2 + 2l_1 l_2 \cos\alpha}{2l_3 l_4} \quad (12)$$

This equation is to be used alongside Freundenstein's equation to check the maximum and minimum values of transmission angle during iterative design process. Maintaining the transmission angle within its optimal range is crucial for ensuring smooth force transmission and avoiding mechanical lock-up. In the context of underactuated robotic hands, this analysis becomes especially important to guarantee reliable finger movement under load.

III. Motion and Force Analysis for Precision Grasp

The motion and force analysis for precision grasp is critical in the design of a two-finger underactuated robotic hand with two-phalanges fingers, as it ensures optimal coordination between the fingers and the object. By analyzing both the motion trajectories and the forces applied during the grasping, the hand can securely hold objects with precision without overexerting force. This analysis is vital for achieving reliable performance, particularly in delicate or changing tasks in unstructured environment.

A. *Motion analisys for precision grasp*

Finger is completing precision grasp by parallel movement of distal phalanges, of both fingers in open-close motion, which is enabled by parallelogram linkage $ABCA_1$, Fig. 3, as already mentioned. This coordinated motion of the distal phalanges ensures a stable and controlled grip.

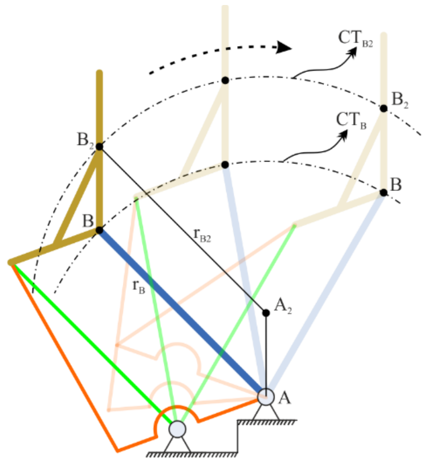

Fig. 8. Movement of finger during precision grasp

Movement of the finger during precision grasp is shown in Fig. 8. Point A is shown as the center of the circular trajectory CT_B of point B, and the length of proximal phalanx AB is the radius of that circular arc. Distal phalanx is modeled as rigid body and thanks to $ABCA_1$ parallelogram linkage, it preserves its orientation during open-close sequence of robotic hand. Thus, any point on distal phalanx, e.g., B_2, will be moving on circular trajectory around point A_2 that is in the same relative position from point A as the point B_2 is from point B (Fig. 8). We will consider point B_2 as the point of contact between distal phalanx and object of manipulation and that point will be used in force analysis.

B. *Force analysis for precision grasp*

This section introduces the model that demonstrates how the proposed finger design applies grip force to an object. Additionally, it includes the derivation of the equation for calculating the theoretical grip force using the developed finger. Analytical method [20], based on usage of principle of virtual power, is used for the force analysis of the precision grasp. The proposed method derives relationship between actuation torque and grasping force.

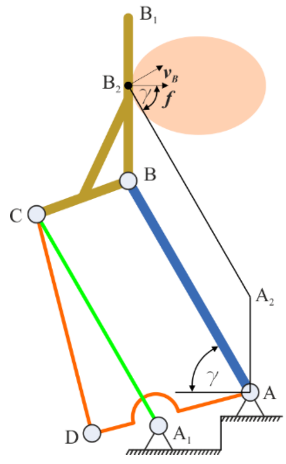

Fig. 9. Force analysis model of finger

Fig. 9 shows the model of finger that will be used in the analysis. It is assumed that distal phalanx BB_1 contacts object of manipulation in one point, represented as point B_2. Another assumption is that there is no friction force at this point of contact. Furthermore, l_{AB} denotes the distance between points A and B. Based on application of the principle of virtual work on precision grasping model, we have:

$$\boldsymbol{f} \cdot \boldsymbol{v} = \tau\dot{\gamma}, \tag{13}$$

where $\boldsymbol{f}$ is the grasp force vector applied to object of manipulation, $\boldsymbol{v}$ is the velocity vector of point B_2, τ is the actuation torque exerted on object of manipulation by input link AD and γ is open-close angle of finger measured from horizontal axis. Velocity of B_2 is tangent to circular trajectory at this point. Because the distal phalanx is a rigid body, all points on it share the same angular velocity and maintain fixed relative distances. Since point B moves along a circular path around point A, the linear velocity of the contact point B_2, which follows the same motion due to the rigid linkage, is given by the product of the link length and angular velocity:

$$v = l_{AB}\dot{\gamma}. \tag{14}$$

Based on Fig. 6, dot product $\boldsymbol{f}\cdot\boldsymbol{v}$ can be expressed as:

$$\boldsymbol{f} \cdot \boldsymbol{v} = fv\cos(90° - \gamma), \tag{15}$$

which leads to:

$$\boldsymbol{f} \cdot \boldsymbol{v} = fv\sin\gamma. \tag{16}$$

Substituting (6) and (8) in (5) we obtain:

$$f l_{AB}\dot{\gamma}\sin\gamma = \tau\dot{\gamma}. \tag{17}$$

$$f = \frac{\tau}{l_{AB}\sin\gamma} \tag{18}$$

Equation (10) represents the calculation of the grip force during precision (parallel) grasping, expressed as a function of the actuation torque. Taking into account the efficiency of the driving system, [15], the actuation torque exerted on the object by the input link AB can be expressed as:

$$\tau = \tau_m s_m s_w \eta_m \eta_w, \tag{19}$$

where τ_m is the motor output torque, s_m and s_w are the gear ratios of the motor gearbox and worm gear, respectively, and η_m and η_w represent the efficiency of the motor gearbox and worm gear, respectively.

This approach allows for flexibility in the design process, where we can either start with a desired force and select the appropriate actuator or evaluate the grasping capability of a finger where actuator is already available, ensuring the system meets the necessary performance criteria.

IV. Conclusion

This paper presented the design of a two-phalanx adaptive underactuated robotic finger that utilizes a four-bar linkage and gear-based transmission mechanism to achieve precise and synchronized phalanx motion. Since the goal is the development of an underactuated robotic finger primarily for precise grasping, it incorporates both a four-bar linkage and a parallelogram linkage mechanism to maintain the orientation of the distal phalanx during grasping tasks. By using a single actuator to drive both phalanges in a coordinated manner, the design reduces system complexity and weight, which is beneficial for integration into multi-fingered robotic hands.

Future work will focus on evaluating the performance of the finger through simulation and physical prototyping, including tests on grasping stability, force distribution, and object adaptability. The design of finger will also be used for the development of underactuated robotic hand for precise grasping that will be used for research purposes.

References

[1] B. Siciliano and O. Khatib, Springer Handbook of Robotics. Berlin/Heidelberg, Germany: Springer Science & Business Media, 2008.

[2] L. Birglen and T. Schlicht, “A statistical review of industrial robotic grippers,” Robotics and Computer-Integrated Manufacturing, vol. 49, pp. 88–97, Feb. 2018.

[3] S. C. Jacobsen, E. K. Iversen, D. Knutti, R. Johnson, and K. Biggers, “Design of the Utah/MIT dexterous hand,” in Proc. IEEE Int. Conf. Robot. Autom., pp. 1520–1532, Apr. 1986.

[4] I. Yamano and T. Maeno, “Five-fingered robot hand using ultrasonic motors and elastic elements,” in Proc. IEEE Int. Conf. Robot. Autom., pp. 2673–2678, Apr. 2005.

[5] J. Butterfass, M. Grebenstein, H. Liu, and G. Hirzinger, “DLR-hand II: Next generation of a dextrous robot hand,” in Proc. IEEE Int. Conf. Robot. Autom., vol. 1, pp. 109–114, May 2001.

[6] M. Andrychowicz, B. Baker, M. Chociej, et al., “Learning dexterous in-hand manipulation,” Int. J. Robot. Res., vol. 39, pp. 3–20, Nov. 2019.

[7] D. Yoon and Y. Choi, “Underactuated finger mechanism using contractible slider-cranks and stackable four-bar linkages,” IEEE/ASME Trans. Mechatronics, vol. 22, pp. 2046–2057, Oct. 2017.

[8] G. Ambaye, E. Boldsaikhan, and K. Krishnan, “Soft robot design, manufacturing, and operation challenges: A review,” J. Manuf. Mater. Process., vol. 8, Art. no. 79, Apr. 2024.

[9] M. Liarokapis and A. Dollar, “Deriving dexterous, in-hand manipulation primitives for adaptive robot hands,” in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., pp. 25–27, Vancouver, Canada, 24–28 Sept. 2017.

[10] L. Birglen, T. Laliberté, and C. M. Gosselin, Underactuated Robotic Hands, vol. 40, Berlin: Springer, 2008.

[11] P. Rea, “On the design of underactuated finger mechanisms for robotic hands,” Advances in Mechatronics, 2011. [Online]. Available: http://dx.doi.org/10.5772/24304. [Accessed: Apr. 21, 2025].

[12] R. Ozawa, Y. Mishima, and Y. Hirano, “Design of a transmission with gear trains for underactuated mechanisms,” IEEE Trans. Robot., vol. 32, pp. 1399–1407, Dec. 2016.

[13] K. Mitsui, R. Ozawa, and T. Kou, “An under-actuated robotic hand for multiple grasps,” in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., pp. 5475–5480, Tokyo, Japan, Nov. 2013.

[14] K. Yamaguchi, Y. Hirata, and K. Kosuge, “Underactuated robot hand for dual-arm manipulation,” in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., pp. 2937–2942, Hamburg, Germany, Sept. 2015.

[15] L. Kang, J.-T. Seo, D. Yoon, S.-H. Kim, I. H. Suh, and B.-J. Yi, “Design of a 3-DOF linkage-driven underactuated finger for multiple grasping,” in Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst., pp. 5608–5613, Macau, China, Nov. 2019.

[16] K. Telegenov, Y. Telegenov, and A. Shintemirov, “An underactuated adaptive 3D printed robotic gripper,” in Proc. 10th France-Japan/8th Europe-Asia Congr. Mecatronics (MECATRONICS 2014), pp. 110–115, Tokyo, Japan, Nov. 2014.

[17] A. Ghosal, “The Freudenstein equation - Design of four-link mechanisms,” Resonance, vol. 15, pp. 699-710, Aug. 2010

[18] A. M. Dollar and R. D. Howe, “The highly adaptive SDM hand: Design and performance evaluation,” Int. J. Robot. Res., vol. 29, pp. 585–597, 2010.

[19] S. S. Balli and S. Chand, “Transmission angle in mechanisms (Triangle in mech),” Mech. Mach. Theory, vol. 37, pp. 175–195, Feb. 2002.

[20] A. Kobayashi, K. Yamaguchi, J. Kinugawa, S. Arai, Y. Hirata, and K. Kosuge, “Analysis of precision grip force for uGRIPP (underactuated gripper for power and precision grasp),” in Proc. 2017 IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS), pp. 1937–1942, Vancouver, BC, Canada, Sept. 2017.