Conceptual Design of 3 Independent Motor Actuation Transmission Systems for Low-Cost Anthropomorphic Prosthetic Hand

Anggriyawan Putranto, Ilham Priadythama, Susy Susmartini, and Pringgo W. Laksono

***Abstract*—This paper presents a transmission mechanism design for anthropomorphic prosthetic hand which enables it to do both power and precision grip. The fingers and thumb is pull type with 1 DOF and they must be adaptive towards object's contour. In the other hand, transmission system must be small enough to be placed in metacarpal. To solve any physical and technical contradiction problem, we used TRIZ methodology. The result is 3 independent motor actuation transmission systems, each for thumb, pointing finger, and the unity of middle-ring-little finger. Every independent system using bolt-nut as reducer and tension spring as adaptive component. This configuration enables the hand to do 5 of 6 basic models of human grasping.**

***Index Terms*—Transmission, anthropomorphic, prosthetic hand.**

I. Introduction

Prosthetic hand is a replacement tool for the role of the human hand. Prosthetic hand, especially the anthropomorphic one, is expected to be seen like the real hand as well as can perform as normal hand. Because of its vital role, the prosthetic hand has been being developed until now. Nowadays, there are a lot of researches in prosthetic hand development. In Laboratory of Product Planning and Design (LPPD), Sebelas Maret University, some researches has conducted and focused on low cost anthropomorphic prosthetic hand to respond the need of affordable prosthetic hand in Indonesia.

Previously, there were two researches which strongly correspond with the affordable anthropomorphic prosthetic hand. Firstly, TBM Hand [1], a prosthetic hand for children, proposed a comprehensive mechanical design of passive adaptive mechanism. It provides grasping functionality without any sensors and computers. The hand only has one actuator for a simultaneous five fingers actuation. Because of its actuation system, TBM Hand is only suitable for power grip movement and has difficulties to do precision grip such as tip, palmar, and lateral. Nevertheless, its adaptive components can ensure good contact to the grasping object.

Another research was LARM Hand [2], a robotic hand with optimized 1-DOF anthropomorphic finger which ensures a more natural grasping motion. Its design is simpler than the finger of TBM Hand. LARM Hand is equipped with one actuator per finger of total three fingers. With 1 motor in each finger, LARM Hand is potentially capable to do both the power grip and precision grip. However, the design is not adaptive and has a weakness in its cross links of its finger’s four bar linkage system, since it is the sleekest and endure compressive load during grasping (potentially buckle when the material is soft such as plastic). LARM uses Aluminum Alloy for its finger material and the size is bigger than human hand, making the buckling issue is not clearly appeared.

In LPPD, there have been developed design concepts of 1-DOF anthropomorphic prosthetic fingers and thumb. Opposite to the LARM Hand system, its cross links bear tensile load to ensure its buckling free structure. The design also has been optimized toward human finger’s movement and size [3] and [4]. To accomplish prototype stage, there is a need to develop a transmission system. The transmission mechanism of anthropomorphic prosthetic hand is very specific and no one has design it through a structured framework.

Poonekar has conducted research on prosthetic hand in India and concluded that the prosthetic hand must have 13 criteria [5]; *low cost, locally available, capable of manual fabrication, considerate of local climate and working conditions, durable, simple to repair, simple to process using local production capability, reproducible by local personnel, technically functional, biomechanically appropriate, as lightweight as possible, adequately cosmetic, and psychosocially acceptable*. Some of these criteria can be directly influence by a transmission system design. Therefore this study aims to produce a transmission mechanism design for low-cost anthropomorphic prosthetic hand which is considering those criteria and adaptive and able to perform activities in both power and precision grip. The transmission system carries many criteria derived from its overall package, such as affordability, functionality, light weight, etc. Consequently, it will carry its complexity as well. This paper used TRIZ method (Theory of Inventive Problem Solving) to resolve this issue in order to develop a preliminary conceptual transmission design.

II. Theory

A. Type of Grasp

The main function of an anthropomorphic prosthetic hand is performing grip movement as the human hand. Basically, the grip movement can be divided into two types those are power and precision grip. Then based on the object that interacts, grip movement can be divided into six types of movement those are cylindrical, tip, hook, palmar, spherical

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and lateral [6].

In cylindrical/spherical, all fingers and metacarpal grasping around a cylindrical/spherical object such as a bottle/tennis ball. While in hook, fingers move to grip object such as hold without the involvement of the thumb. The next type, tip, is a movement by the thumb and pointing fingers to pinch small objects such as a seed. Similar with tip, palmar is a pinching movement, but it requires more straight thumb and pointing finger such as holding a pencil. The last, the lateral, the thumb is abducted and move to hold flat and thin object as a sheet of paper. Fig. 1 illustrates fingers and thumb movement for each grasping type [7].

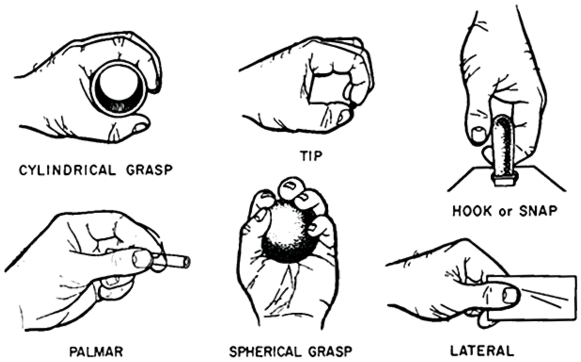

Fig. 1. Typical human grasping.

B. TBM Hand

TBM Hand is a prosthetic hand which is designed specifically for children, developed in Toronto, Ontario, Canada. The hand only uses one actuator for a simultaneous five fingers actuation. TBM Hand able to perform passive adaptive grasp, that is the ability of the fingers to conform to the shape of an object held within the hand. This passive design is simple and effective, not requiring sensors or electronic processing. Because of its actuation system, TBM Hand is only suitable for power grip movement. Fig. 2 shows the TBM Hand from the dorsal side, with fingers in the extended position and the thumb abducted (rotated out to the side position).

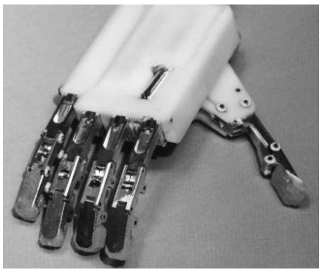

Fig. 2. TBM Hand, dorsal view.

C. LARM Hand

This is a robotic hand which is build with three optimized 1-DOF anthropomorphic finger (Fig. 3). It was developed by University of Cassino, Italia. Its design is simpler than the finger of TBM Hand. LARM Hand is equipped with one actuator per finger of total three fingers. The dimensional design of a finger driving mechanism has been formulated as a multi-objective optimization problem by using evaluation criteria for fundamental characteristics that are associated with finger motion, grasping equilibrium, and force transmission. With 1 motor in each finger, LARM Hand is potentially capable to do both the power grip and precision grip. However, the design is not adaptive and has a weakness in cross links of its finger four bar linkage system. Since it is sleek and endure compressive load during grasping, it potentially buckle, especially when soft material is used.

Fig. 3. A prototype of three-fingered LARM hand with 1-DOF anthropomorphic fingers of human sizes.

D. LPPD UNS Hand

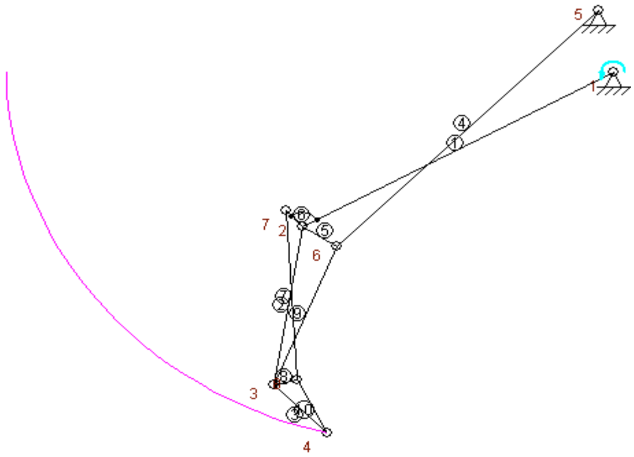

Fig. 4. The optimized driving mechanism of pointing finger.

Design concepts of 1-DOF anthropomorphic prosthetic fingers and thumb have been developed in Laboratory of Product Planning and Design, Universitas Sebelas Maret. Its driving mechanism uses the pull system to minimize buckling, opposite to the LARM Hand system. Design of anthropomorphic fingers were optimized based on similarity movement and total length of the fingers when holding the cylindrical objects with maximum grasping size (diameter) of Indonesian hand. Fig. 4 shows the driving mechanism of pointing finger after optimization.

E. TRIZ (Theory of Inventive Problem Solving)

TRIZ was put forward by former a Soviet Union scientist, Altshuller, who after studying almost 400,000 patents, deemed it was possible to turn this theory into a systematic method [8]. TRIZ method is often used in several studies on the development design of product. A design based on TRIZ aspires to permit and solve the contradiction, creating a system in which the improvement of one characteristic is not accompanied by deterioration of others [9].

III. METHODS

As illustrated in Fig. 5, the early stage of this research is **problem identification**. Through this stage, the problem can be explored and well understood. This stage includes many literature studies (patent, article, design, etc.). From this stage, we can get a grand strategy for the mechanism. Next stages will be explained as follows:

A. Problem modeling and analysis

Modeling and analyzing the relationship between functions to define technical requirements.

B. Contradiction analysis

Defining contradictions as "improving and worsening features" caused by requirement fulfillment and translate them in to "problem parameters" as provided by TRIZ.

C. Contradiction elimination

Eliminating occurred contradictions by "40 inventive principles" provided by TRIZ as the solution.

D. Solution evaluation

Evaluating and proposing concepts as translation of TRIZ solutions in to more technical, rational, and comprehensive solutions.

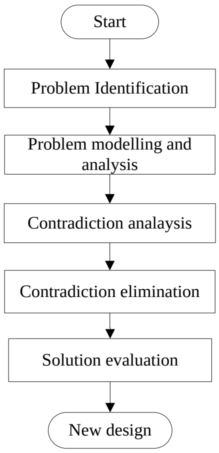

Fig. 5. Research Methodology (Adopted from TRIZ).

IV. RESULTS

A. Grand Strategy

The adaptive transmission mechanism adopts the design of TBM Hand. To increase the variety of grasp movement, then the design of transmission using 3 motors as actuators with 1 motor on the thumb, 1 motor on the pointing fingers and 1 motor on the unity of middle-ring-little finger.

TABLE I: NUMBER OF ACTUATOR

Actuator	Grasping Model					
	Cylindrical	Spherical	Hook	Tip	Lateral	Palmar
1 motor	Yes	Yes	No	No	Yes	No
2 motor	Yes	Yes	Yes	No	Yes	No
3 motor	Yes	Yes	Yes	Yes	Yes	No
4 motor	Yes	Yes	Yes	Yes	Yes	No
5 motor	Yes	Yes	Yes	Yes	Yes	No

TABLE II: ACTUATOR ACTIVATION STRATEGY

Grasping Model	Actuator		
	Thumb	Pointing	Middle – Ring - Little
Cylindrical	On	On	On
Spherical	On	On	On
Hook	Off	On	On
Tip	On	On	On/Off
Lateral	On*	On	On
Palmar	N/A	N/A	N/A

*) Abducted

By using 3 motors, the transmission is expected to perform 5 of 6 variations grasp movements (Table I). And the default position of the thumb is opposite with the other fingers. The following table shows the status of the actuators when performing several variations of movement;

Table II shows that the design strategy of this transmission cannot perform only for palmar since this movement type need more than 1 DOF for the thumb and pointing finger.

B. Technical Requirement

The technical requirements are derived from combination of Poonekar's criteria and functional analysis diagram. This strategy (Fig. 6) is applied considering the transmission system must fulfill not only its technical requirements but also the prosthetic general package features.

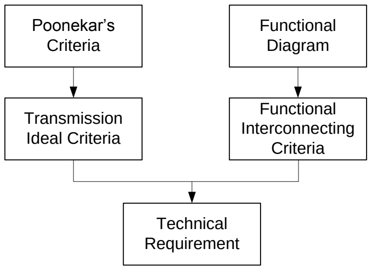

Fig. 6. Technical requirement strategy.

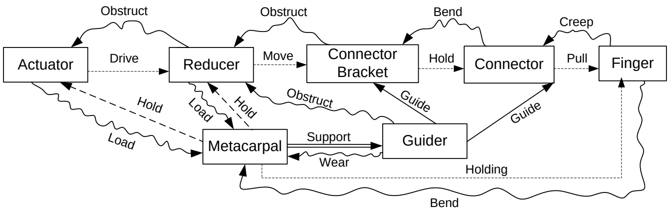

Fig. 7. Functional analysis diagram of elements.

Fig. 7 shows the relationship between function of each elements. The results of technical requirements for each element are described in Table III.

TABLE III: TECHNICAL REQUIREMENTS

Parts	Technical Requirements
Actuators	Strong enough to move finger *** Light weight ** Compact size *** Low wattage **
Reducers	High reducing ratio * Not fail due to high torque *** Easily attach to the actuator shaft * Highly efficient *** Simple design ** Light weight **
Connector Brackets	Distribute the force evenly * Not fail due to dynamic loads *** Simple design ** Light weight **
Connectors	Flexible for full flexion/extension * Maintain strong gripping ** High elastic endurance *** Compact size **
Guiders	Provide linear movement stability * Highly efficient **
Metacarpal base	Not fail during operation *** Light weight ** Rigid (minimum deformation) *

*) Requirement from the functional analysis diagram of elements
**) Requirement from Poonekar's criteria
***) Requirement from both source

TABLE IV: SOLUTION TABLE

Parts	Technical Requirements	Improving Feature	Worsening Feature	Inventive Principles	Solution Interpretation
Actuators	Strong enough to move finger	Mechanical power (21)	Weight (2)	Move object (17)	Choose small motor available on the market with good torque to wattage ratio, move motors as close as possible to the fingers
	Light weight	Weight (2)	Mechanical power (21)	Optimize (15)	
	Compact size	Space requirement (6)	Mechanical power (21)	Reorient object (17)	
	Low wattage	Wattage (21)	Magnet size (6)	Move object (17)	
Reducers	High reducing ratio	Reduction rate (39)	Space requirement (6)	Reorient object (17)	Choose screw or other parallel tooth type reducers equipped with press fitted shaft coupling
	Not fail due to high torque	Elements strength (14)	Elements size (6)	Pass through (7)	
	Easily attach to the actuator shaft	Adaptability (35)	Number of part (36)	Press fit (15)	
	Highly efficient	Friction (22)	Precision (29)	n/a	
	Simple design	Complexity (36)	Reduction rate (39)	Reorient object (17)	
	Light weight	Weight (1)	Elements durability (15)	Parallel object (5)	
Connector Brackets	Distribute the force evenly	Balance (13)	Shape complexity (12)	Asymmetry (4)	Choose asymmetric plate, attached to connectors with a certain angle and then added a spring to the screw shaft
	Not fail due to dynamic loads	Elements strength (14)	Weight (1)	Antiweight (8)	
	Simple design	Complexity (36)	Balance (13)	Reorient object (17)	
	Light weight	Weight (2)	Elements strength (14)	Prearrange (10)	
Connectors	Flexible for full flexion/extension	Adaptability (35)	Grasping force (10)	Optimize (15)	Choose a high elastic material which has been optimized for its all parameters and adaptable restrain for its ends
	Maintain strong gripping	Grasping force (10)	Adaptability (35)	Optimize (15)	
	High elastic endurance	Durability (15)	Weight (1)	Parallel object (5)	
	Compact size	Size (7)	Durability (15)	More flexibilty (35)	
Guiders	Provide linear movement stability	Stability (13)	Complexity (36)	Taking out (2)	If the other elements already stable, guiders may be eliminated
	Highly efficient	Friction (22)	Precision (29)	n/a	
Metacarpal base	Not fail during operation	Elements strength (14)	Weight (2)	Composite (40)	Choose simple plate metacarpal design and improve its strength using composite material
	Light weight	Weight (2)	Elements strength (14)	Taking out (2)	
	Rigid (minimum deformation)	Stability (13)	Weight (2)	Composite (40)	

C. TRIZ Solution Evaluation

Table IV shows the results of contradiction problems translated into 39 problem parameters. The obtained solutions were derived from contradiction table provided by TRIZ with 40 inventive principles as the solution guidance. The solution for actuator was choosing a small common motor available on the market with good torque to wattage ratio. After several observations, a standard motor, FA-130RA-18100 from Mabuchi Motor Co., Ltd [10] was chosen. The motors must be placed as close as possible to the fingers and fixed tightly to the metacarpal. A screw type reducer was chosen for reducing the speed and increasing the torque. The screw diameter must be small enough to ensure its light weight and low friction characteristics. The one of the screw end was then connected to the motor shaft with a press fitted coupling. A nylon material was chosen for this coupling since it has good strength and flexibility. Another end of the screw is attached to a nut which mounted on the bracket. For the connector bracket, the obtained solution was flat/grooved plates. This bracket was compact but can accommodate many element constrains by the asymmetric constraint arrangement. Spacing areas between brackets and motors were equipped with an anti-weight helical spring which is enclosing the screw shaft to create anti-weight effect. For the connector, a high elastic material which has been optimized for its all parameters (strength, elongation, stiffness, cross sectional area, etc.) was chosen. The two potential candidates are polyurethane and nylon. Each of these connectors may be attached to the bracket with a small axle as an adaptable "easy attachment" constrain. Specifically for the guider, if the other elements already stable, the guiders may be eliminated. For example, a direct contact of bracket and metacarpal has stabilized the motion. This strategy allows the system to be more simple and light weight. Finally for the metacarpal, the solution was choosing a single layer thin plate and improve its strength by laminate it with other stronger thin material. As mentioned in previous study, PVC was chosen as the main prosthetic finger material [11]. Therefore, it is potential as metacarpal's material too since it is cheap, strong, and light weight. However, thin PVC (≤ 2 mm thickness) is not stiff enough considering to its function. A metal laminator such as thin aluminum sheet will be required to increase its stiffness.

D. Conceptual Design

After all the solutions for each element obtained, the design of 3 independent motor actuation transmissions system can be conceptualized (Fig. 8). The thumb is using similar system which is applied for pointing finger, but with twisted bracket orientation. After some sketching works, we tried to visualize the 3D design using SolidWorks™ (Fig. 9 and Fig. 10). An anti-weight spring must be developed with a precise free length which lies between full flexion and full extension spring space. During flexion, spring will turn into a compression spring and turn into a tension spring when extension. This is a simple innovative element which helps the motor to initiate flexion/extension movement against friction and inertial loads and expected can cause smoother grasping movement.

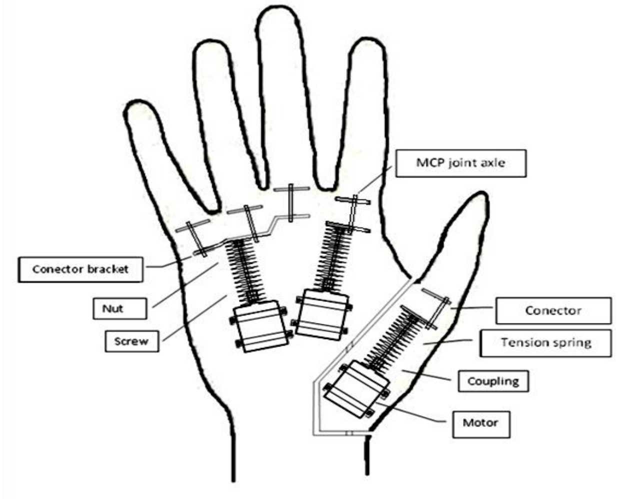

Fig. 8. Conceptual design of 3 independent motor actuation transmissions system.

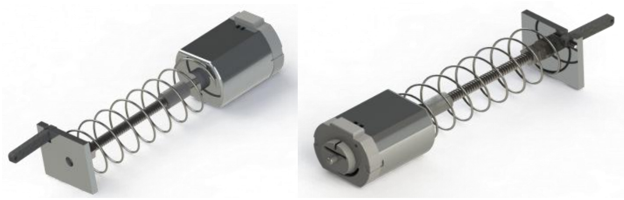

Fig. 9. 3D visualization of the transmission for pointing finger and thumb.

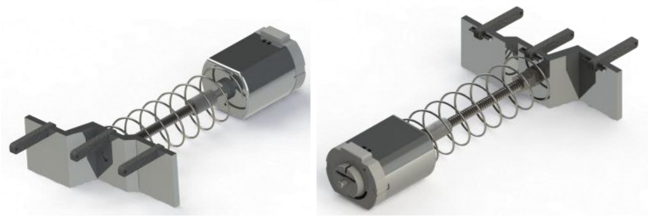

Fig. 10. 3D visualization of transmissions for middle–ring–little finger.

V. Conclusion

This research has produced a conceptual design of adaptive transmission mechanism system for LPPD UNS Hand using TRIZ. In this research, TRIZ has identified 23 technical contradictions and successfully resolved 21 of them. This transmission will be equipped with 3 motors so that it can perform both power grip and precision grip. This transmission mechanism is expected to be able to perform 5 of the 6 basic grasping movements.

References

[1] N. Dechev, W. L. Cleghorn, and S. Naumann, "Multiple finger, passive adaptive grasp prosthetic hand," *Mechanism and Machine Theory*, vol. 36, no. 10, pp. 1157-1173, 2001.

[2] N. E. N. Rodriguez, G. Carbone, and M. Ceccarelli, "Optimal design of driving mechanism in a 1-DOF anthropomorphic finger," *Mechanism and Machine Theory*, vol. 41, no. 8, pp. 897-911, 2006.

[3] D. Kuncara, I. Priadythama, and S. Susmartini, "The optimum design of 1 DOF anthropomorphic prosthetic finger with human finger movement similarity criterion (Desain optimum prosthetic jari tangan anthropomorphic 1-DOF dengan kriteria kemiripan gerakan jari tangan manusia)," presented at Seminar National Ergonomics, Bandung, Indonesia, November 13-14, 2012.

[4] T. Prasetyo, S. Susmartini, and I. Priadythama, "Optimum design of 1-DOF anthropomorphic thumb considering grasping motion for Indonesian low-cost prosthetic hand," presented at 6th International Seminar on Industrial Engineering and Management, Batam, Indonesia, February 12-14, 2013.

[5] D. Cummings, "Prosthetic in the developing world: A review of the literature," *Prosthetics and Orthotics International*, vol. 20, pp. 51-60, 1996.

[6] J. Z. Zheng, S. D. L. Rosa, and A. M. Dollar, "An investigation of grasp type and frequency in daily household and machine shop tasks," in *Proc. IEEE International Conference on Robotics and Automation*, 2011, pp. 4169-4175.

[7] N. Fukaya, S. Toyama, T. Asfour, and R. Dillmann, "Design of a Humanoid Hand for Human Friendly Robotics Applications," in *Proc. Human Friendly Mechatronics: Selected Papers of The International Conference on Machine Automation ICMA2000*, Elsivier, 2001, ch. 6, pp. 273-278.

[8] K. Yang and B. S. El-Haik, *Design for Six Sigma: A Roadmap For Product Development*, 2nd Ed, The McGraw-Hill Companies Inc., 2009, ch. 9, pp. 281-352.

[9] S. D. Savransky, *Engineering of creativity*, Boca Raton, FL: CRC Press, 2000, ch. 4, pp. 59-69.

[10] Mabuchi Motor Co., Ltd. (2012). Metal Brush Motor FA-130RA. *Mabuchi e-catalogue*. [Online]. Available: http://www.mabuchi-motor.co.jp/cgi-bin/catalog/e_catalog.cgi?CAT_ID=fa_130ra

[11] F. Purnamasari, I. Priadythama, and S. Susmartini, "Material selection strategy in low cost anthropomorphic prosthetic hand design (Strategi pemilihan material dalam desain low cost anthropomorphic prosthetic hand)," presented at 7th National Industrial Engineering Conference, Surabaya, Indonesia, October 10, 2013.

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