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Design Process of Whippletree-Like Mechanism for Versatile Gripping in Arm Prosthesis

Wildan Trusaji[1], Dradjad Irianto[1], Ardianto Satriawan[2], Casi Setianingsih[3], Erza Nurtriandari[4], Rachmat Zulkarnain Goesasi[4]

[1] Faculty of Industrial Technology, Institut Teknologi Bandung, Indonesia
[2] School of Electrical Engineering and Informatics, Institut Teknologi Bandung, Indonesia
[3] School of Electrical Engineering, Telkom University, Indonesia
[4] Department of Physical Medicine and Rehabilitation, Faculty of Medicine, Universitas Padjadjaran-Dr. Hasan Sadikin General Hospital, Indonesia
trusaji@itb.ac.id

Abstract. One of the biggest challenges in arm prosthesis design is to resemble normal hand functionality. Some arm prostheses try to mimic all hand movements, while others try to produce several main hand grip patterns. We design a Versatile Gripping Technology (VGT) from a basic whippletree mechanism to produce the main hand grip pattern in an arm prosthesis. VGT development is the result of abstraction, negation, and systemic variation processes of existing solutions. To validate VGT, we test it to produce six patterns of hand grip from the Southampton Hand Assessment Procedure. VGT is capable to produce lateral, power, tip, extension, and spherical grip without changing the setting or mode of operation. In addition, VGT includes the thumb movement and it only uses one simple-shaped moving part. Thus, VGT is effective and efficient. With this result, we argue that the abstraction, negation, and systemic variation process of existing solutions can create a novel solution and it applies to another problem or domain.

Keywords: Arm Prosthesis, Versatile Gripping, Design Process.

1 Introduction

The hand mechanism is intricate and complex [1]. A normal hand and wrist can make seventeen types of movement and at least six patterns of basic grip [2], [3]. Thus, the challenge of arm prosthesis design is not only substituting the structural arrangement but also designing an intuitive control to achieve functionality.

There are two main approaches to how to design functional arm prostheses. The first is to mimic all hand movements, and the second is to emulate a variety of hand grips. Arm prostheses using the first approach usually is electronically controlled. It has multiple actuators and sensors. Hence, it is complex and unaffordable. Some design uses the second approach, and their main goal is to help users manipulate daily objects by producing several basic gripping patterns. Most prostheses embracing this approach are mechanically controlled by using a whippletree mechanism.

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This paper explains the design process of a novel whippletree mechanism that includes the thumb, has a minimum part, and is capable of versatile gripping. We called it the Versatile Gripping Technology (VGT). This paper emphasizes the design process since it is where the insight and the tacit knowledge reside [4]. This paper consists of 5 sections: (1) introduction, (2) state of the art, (3) design process, and (4) preliminary result & (5) conclusion.

2 State of The Art

2.1 Whippletree Mechanism in Everyday Life

Whippletree is a mechanism to distribute force equally through linkage. The main element of the whippletree mechanism is a pivotable bar at the center, where the force is applied from one direction at the center and the opposite direction at the tip. Figure 1 illustrates the basic element of Whippletree mechanisms.

Several whippletree mechanisms can be used simultaneously by arranging bars in series. The most common of this whippletree mechanism example is a two-horse team for pulling a carriage. In the two-horses team, 3 three bars are used to distribute a force between two horses so they can share the work evenly. This arrangement is sometimes known as doubletree. Figure 2 illustrates the schematic of the doubletree arrangement.

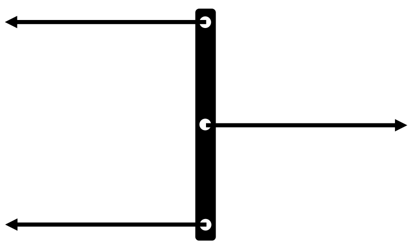

Fig. 1. Basic elements of the whippletree mechanism

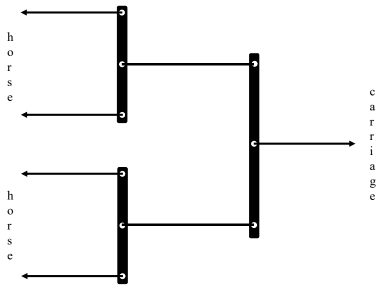

Fig. 2. Doubletree arrangement in a two-horse team

2.2 Whippletree Mechanism in Arm prosthesis

Fine-tuning every finger movement in an arm prosthesis to be capable of gripping varieties of an object is a tremendous task. Whippletree mechanism may become advantageous to solve this challenge. Instead of controlling every finger with multiple actuators, the whippletree mechanism distributes force evenly from one actuator to all fingers. Thus, the movement of fingers is mechanically controlled according to the shape of the object. This feature is achieved by regulating the force transmission into each finger based on the amount of resistance given by the object to each finger.

Groenewegen's Hand Prosthesis [5] uses a whippletree mechanism to achieve an adaptive gripping function. Instead of using bar and line, Groenewegen uses seven bars, three triangle-shaped bars, and nine pins. Those bars and pins are arranged like a double-tree arrangement. The design schematic is illustrated in figure 3.

Makerhand's arm prosthesis has a unique approach. It has only four fingers including the thumb [6]. The four fingers configuration is chosen since it is the most basic whippletree arrangement, which consists of only one bar and four lines including the actuator line. The schematic of Makerhand's whippletree mechanism is illustrated in figure 4. It is worth noting that Makerhand arm prosthesis is the winner of the CYBATHLON arm prosthesis race in 2020.

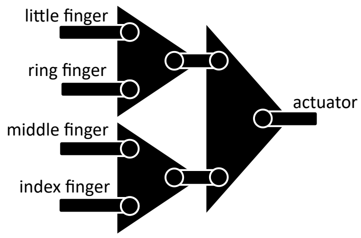

Fig. 3. Groenewegen's whippletree

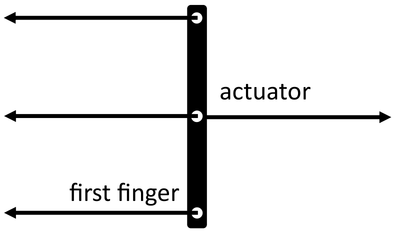

Fig. 4. Makerhand's whippletree

3 Design Process

The challenge is how to include the thumb in the mechanism since the thumb play important role in grasping [7]. To achieve that, we use three generally applicable methods from the fundamental of the Systemic Approach [8]. Those are abstraction, method of negation, and systemic variation. This section explains how we use it.

Abstraction is a cognitive process to find higher interrelationships to find an essential characteristic of a system/object [8]. In this case, we search for an underlying principle in varieties of whippletree mechanisms. We concluded that the main characteristic of the mechanism is multiple force transmissions coupled to each other by moving/pivoting objects. By this abstraction, the mechanism's main part is coupled force transmission and a moving object as a link between force transmission.

In the method of negation, a known solution is questioned, negated, or even inversed [8]. This process help designer finds alternative solutions by avoiding design fixation. Groenewegen negates the shape of the basic bar and comes with a triangle-shaped bar. Makerhand negates the amount of coupled force transmission in one bar. The bar in the basic whippletree mechanism is only coupled into two force transmissions while the bar in Makerhand is coupled into three force transmissions.

We negate several principles to develop our whippletree mechanism. In the basic whippletree mechanism, the line is relatively static, and the bar is relatively dynamic. What if we swap it so the line now is moving while the bar is standing still? Based on this negation we came up with including pulleys into the mechanism. The result is illustrated in figure 5. We feel another improvement can be made since introducing the pulley make the mechanism has more part. Thus, we change the pulley into a pin. This pin function is similar to the pulley, which is to guide the line movement. In another word, the pin acts like a tube. Figure 6 illustrates the pin base whippletree mechanism for arm prosthesis. The pin-based whippletree has fewer parts than Goenewagen and Makerhand whippletree since it only needs one bar to distribute force into four fingers

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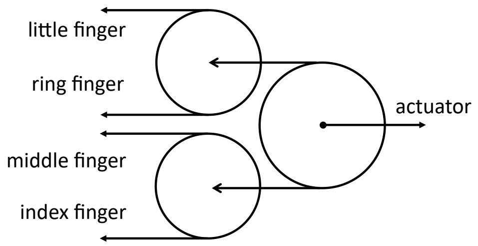

Fig. 5. Whippletree with multiple pulleys

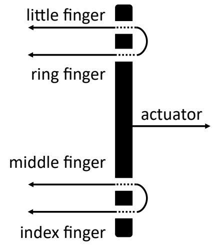

Fig. 6. Whippletree with pin

Pin-based whippletree arrangement still not met the inclusion of thumb. To solve it, we do the method of negation again. We realize all the existing arrangements only used 2-dimensional space for their movement. The question is what if we exploit 3-dimensional space. Now we have forward, backward, yaw, and pitch movement. The thumb can be included in pin-base whippletree without adding a new bar and its movement is controlled by the pitch movement of the bar. This design schematic is in figure 7.

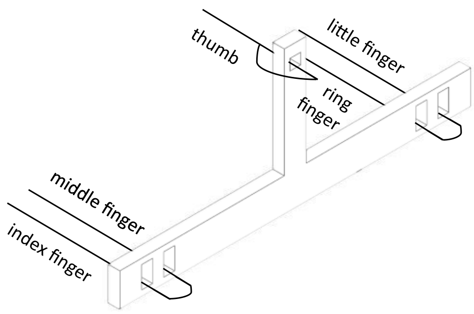

Fig. 7. Schematic of 3D pin-based whippletree mechanism

In the systemic variation, we create a general classification of solutions and generate possible solutions for each classification. We find that there are five general classifications in the whippletree mechanism; the shape of the balancer, means of force transmission, movement of linkage, dimensional space, and arrangement. All five general classifications and all possible solutions are listed in table 1.

The possible solution in each general classification can be combined into a complete mechanism. We choose a doubletree arrangement with a triangle-shaped bar, line as force transmission, pivoting bar in the first level and pin as a guide in the second level, and 3D movement. The design result is in figure 8 and the detail of the triangle-shaped balancer is in figure 9. We call this novel mechanism Versatile Gripping Technology. This technology is patent pending in Indonesian Paten Office [9]

Table 1. Result of Systemic Variation

General Classification	Possible Solution
Shape of the Balancer	Bar, Triangle
Mean of Force Transmission	Line, Bar & Pin
Movement of Linkage	Pivoting Bar, Pulley, Pin as Guide
Dimensional Space	2D, 3D
Arrangement	Singletree, Doubletree

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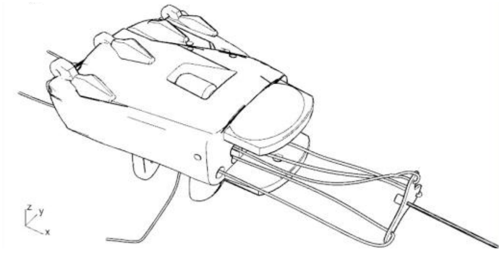

Fig. 8. Versatile Gripping Technology [9]

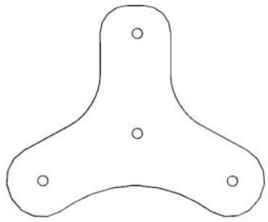

Fig. 9. The triangle shape balancer [9]

4 Preliminary Result

To validate the Versatile Gripping Technology (VGT) we adapt the Southampton Hand Assessment Procedure (SHAP) [3]. We only test the main six grips of SHAP consisting of lateral, power, tripod, tip, extension, and spherical grip with an everyday object. The VGT can produce 5 grips, but VGT cannot produce a tripod grip. However, we argue that the tripod grip can be substituted by the tip grip. The result for lateral, power, tip, extension, and spherical grip are illustrated in figures 10 to 14, respectively. In addition to that, we compete in the CYBATHLON challenge in May 2022 as Karla Bionics. In this competition, our pilot with the VGT-based arm prosthesis needs to transfer 8 small objects from one desk to another desk. Objects are marble, lego block, credit card, key ring, keys, poker chip, pen, and USB-C. He accomplished the task in under 3 minutes.

Fig. 10. Lateral grip

Fig. 11. Power grip

Fig. 12. Tip grip

Fig. 13. Extension grip

Fig. 14. Spherical grip

5 Disscusion and Conclusion

The VGT is developed from a basic whippletree mechanism through abstraction, method of negation, and systemic variation process. In abstraction, we find the main characteristics of the whippletree mechanism. In the method of negation, we explore the alternate solution and design space. In the systemic variation, we manifest all possible solutions and select the most suitable one. This process is similar to the analysis-synthesis bridge model [10] and TRIZ abstraction process [11]. In addition, the combination of a possible solution in the general classification is similar to the morphological method [12]. We argue that the process of abstraction, negation, and systemic variation can be a powerful methodology to generate a novel solution from an existing solution. We believe that this process can be used elsewhere.

The developed VGT is capable to produce lateral, power, tip, extension, and spherical grip without changing the setting or mode of operation. It also includes the thumb movement and uses only one simple-shaped moving part. Thus, VGT is effective and efficient to achieve hand functionality, especially in gripping. However further study is needed, especially in measuring the technical performance of VGT with a standardized test and evaluation for further medical trial or case report.

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