Kinematic Structures Description of Bionic Hand Based on VF Set

Xiancan Liu1,*, Pengying Bai1, Min Luo1, Meng Gao1, Qiang Zhan2

1 Beijing Institute of Mechanical Equipment, Yong Ding Road No.50, Hai Dian District, Beijing, China
2 Robotics Institute, BeiHang University, Beijing, China

*liuxiancan@126.com

Abstract. This paper presents a method for describing kinematic structure of bionic hand based on VF (virtual finger) set. At first, a 20 DOFs (degrees of freedom) human hand kinematic model is built, which is expressed by five fingers’ kinematic chains consisting of kinematic pairs and symbols that represent geometric relationships of kinematic pairs’ axes. Based on the concept of VF, the hand fingers are divided into two types: VF AA having adduction/abduction motion and VF FE having flexion/extension motion. The concept of VF set comprising VF AA s and VF FE s is defined, human hand and six basic grasp postures are described by VF set. Then, the structures corresponding VF AA and VF FE are given according to active and passive forms of finger joints, and VF FE Structure-Base comprising 20 conventional structures is built. Based on VF set and the structures of VF AA and VF FE, VF sets and kinematic structures of several classic bionic hands are given.

1. Introduction

Human hand is a dexterous and complex tool, which can perform different grasp tasks in our daily life, and it is very important for human being. Therefore, many bionic hands used in rehabilitation or other areas have been designed from views of bionics including anatomy skeleton and grasp characteristics of human hand. In the process of a bionic hand design, how to determine kinematic structure of bionic hand is a key part.

The classification of human hand grasp has been studied in anthropology, rehabilitation and medical science. In order to capture human hand versatility for designing prosthetic hands, Schlesinger developed a classic taxonomy of human hand grasp consisting of cylindrical grasp, precision grasp, hook prehension, tip grasp, spherical grasp, and lateral hip [1]. Napier [2] presented a prehensile classification based on function and anatomy structure of human hand, and grasp tasks are divided into power grasp and precision grasp. Based on the concept of virtual finger, Iberall [3] proposed a classification of human hand grasp including pad opposition, palm opposition and side opposition.

For human hand grasp description, there have been some researches about force or contact relation of human hand and grasped object, grasp force imposed on object, virtual fingers and opposition space etc. Arbib[4] presented the concept of VF, which is an abstract representation with a function unit for a collection of individual fingers and hand surfaces applying an opposition force. A single finger or a palm can be a VF, and several fingers grouped together to apply force or torque opposing other VFs or task torques can also be a VF. Iberall [5] proposed the term opposition to describe three basic directions where the human hand can apply forces, which includes pad opposition that occurs between
hand surfaces along a direction generally parallel to the palm, palm opposition that occurs between hand surfaces along a direction generally perpendicular to the palm, and side opposition that occurs between hand surfaces along a direction generally transverse to the palm. The opposition space can be described by both physical terms such as amount and orientation of force vectors and abstract terms such as types and numbers of oppositions, virtual-to-real finger mappings and VF lengths. Liu and Zhan [6] presented a method to describe and analyze the human hand grasp postures so as to indicate which fingers should act during grasping and the required movements of those fingers.

2. Kinematic structure of bionic hands based on VF Set

Human hand is a complex and dexterous tool with multi-DOFs, and it can perform various grasp postures in our daily life. Based on human hand skeleton (Fig.1), a kinematic model with 20 DOFs is presented, which is shown in Fig.2. We do not consider the CMC (carometacarpal) joints of four fingers because of having little effect on grasp. In the kinematic model, the thumb has 4 DOFs, 2 DOFs for adduction/abduction and flexion/extension motions in the CMC joint, two for flexion/extension in the MCP (metacarpophalangeal) joint and the IP (interphalangeal) joint, respectively. Each of four fingers has 4 DOFs, 2 DOFs for adduction/abduction and flexion/extension motions in the MCP joint, and the remaining two in the DIP (distal interphaalangeal) joint and PIP joint, respectively. All joints of the simplified human hand model are divided into two types: revolute (proximal interphalangeal) joints and universal joints. The revolute joints perform flexion/extension movement of fingers, and universal joints perform flexion/extension and adduction/abduction movements of fingers. The DIP and PIP joints of four fingers belong to revolute joints, and the MCP and IP joints of the thumb also belong to revolute joints. The MCP joints of four fingers and the CMC joint of thumb belong to universal joints. In order to conveniently analyze, it is regarded a universal joint as two revolute joints, axes of which are orthogonal and intersecting. Therefore, based on the method proposed by Yangtingli[7], the kinematic structure of human hand is expressed as follows:

\[
\begin{align*}
TC \{ R_{T, CMC \rightarrow AA} \perp R_{T, CMC \rightarrow FE} \parallel R_{T, MCP} \parallel R_{T, IP} \}, & \quad IC \{ R_{I, MCP \rightarrow AA} \perp R_{I, MCP \rightarrow FE} \parallel R_{I, PIP} \parallel R_{I, DIP} \} \\
MC \{ R_{M, MCP \rightarrow AA} \perp R_{M, MCP \rightarrow FE} \parallel R_{M, PIP} \parallel R_{M, DIP} \}, & \quad RC \{ R_{R, MCP \rightarrow AA} \perp R_{R, MCP \rightarrow FE} \parallel R_{R, PIP} \parallel R_{R, DIP} \} \\
LC \{ R_{L, MCP \rightarrow AA} \perp R_{L, MCP \rightarrow FE} \parallel R_{L, PIP} \parallel R_{L, DIP} \} 
\end{align*}
\]

(1)

Where, “\( \perp \)” represents that axis of one kinematic pair is perpendicular to axis of the other one. “\( \parallel \)” represents that one kinematic pair is parallel to the other one. The thumb chain is abbreviated to TC. IC, MC, RC, and LC are defined in the same way.
Virtual Finger (VF) is an abstract representation, a function unit that comprises at least one real physical finger. Therefore, a VF can represent thumb, index finger and all four fingers, and it applies a force or torque opposing other VFs or task torques. Anatomical joint configurations, range of motion and finger size are described as kinematic components of VFs such as lengths, widths, and orientations[5]. Human hand grasp movement is performed by combination motion of some virtual fingers. Based on revolute and universal joints of fingers, motions of each finger can be divided into two types: flexion/extension motion and adduction/abduction motion. The virtual finger having flexion/extension motion is defined as VF\textsubscript{FE}, and the virtual finger having adduction/abduction motion is defined as VF\textsubscript{AA}. If one finger has flexion/extension and adduction/abduction motions, it is considered that the finger belongs to not only VF\textsubscript{FE} but also VF\textsubscript{AA}. A set that contains different types of VFs is named VF set, which can be used to express any grasp posture of human hand bionic hands. For human hand, it can be described by VF set, as follows:

\[
S_{\text{human hand}} = \{\text{VF}_{\text{thumb-FE}}, \text{VF}_{\text{thumb-AA}}, \text{VF}_{\text{index-FE}}, \text{VF}_{\text{index-AA}}, \text{VF}_{\text{middle-FE}}, \text{VF}_{\text{middle-AA}}, \text{VF}_{\text{ring-FE}}, \text{VF}_{\text{ring-AA}}, \text{VF}_{\text{little-FE}}, \text{VF}_{\text{little-AA}}\}
\] (2)

3. Kinematic structure of bionic hands based on VF set

The two types of VFs describe what motion a finger has, but how are all joints of a designed bionic hand finger distributed? In this paper, a VF kinematic structure is expressed by revolute joints and symbols that represent the geometric relationship of active and passive finger joints.

3.1. Structures of VF\textsubscript{AA}

A VF\textsubscript{AA} has usually one DOF making the virtual finger adduction/abduction motion. The adduction/abduction DOFs locate in the CMC joint of the thumb and the MCP joints of four fingers. In this paper, the kinematic structure of VF\textsubscript{AA} is represented by a kinematic pair, and is shown in Fig.2. Therefore, while these joints are active, VF\textsubscript{AA} structures for five fingers are given as follows:

\[
\{R_{T,CMC-AA}, R_{T,MCP-AA}, R_{M,MCP-AA}, R_{R,MCP-AA}, R_{L,MCP-AA}\}
\] (3)

The VF\textsubscript{AA} structure for the thumb is the most important among five VF\textsubscript{AA} structures, because it makes the thumb to be opposite other four fingers. In addition, the CMC joint of the thumb can be passive, and the adduction/abduction of thumb is achieved by manual assistance. Therefore, VF\textsubscript{AA} structure for the thumb is expressed as \(\tilde{R}_{T,CMC-AA}\) in which “\(\tilde{\rangle}\)” represents that the CMC joint is passive.

3.2. Structures of VF\textsubscript{FE}

The flexion/extension joints of VFFE can be active or passive, so there are various VFFE kinematic structures of bionic hand finger based on different active and passive ways that can including all actuated, under-actuated and motion-coupled. When some fingers having the synchronous motion as a VFFE, in whose structure the MCP joints of fingers can be connected. We give a VFFE Structure-Base including different VFFE structures, as shown Table.1.

| Order number | DOF | Fingers | VFFE structures |
|--------------|-----|---------|----------------|
| 1            | 3   | thumb   | \(\{R_{T,CMC-FE} || R_{T,MCP} || R_{T,IP}\}\) |
| 2            | 2   | thumb   | \(\{R_{T,CMC-FE} || R_{T,MCP} || \tilde{R}_{T,IP}\}\) |
| 3            | 1   | thumb   | \(\{R_{T,CMC-FE} || \tilde{R}_{T,MCP} || R_{T,IP}\}\) |
| 4 | 3 | index finger | \{ R_{I,MCP-TE} \parallel R_{I,PIP} \parallel R_{I,DIP} \} |
|---|---|----------------|--------------------------------------------------|
| 5 | 2 | Index finger | \{ R_{I,MCP-TE} \parallel R_{I,PIP} \parallel \tilde{R}_{I,DIP} \} |
| 6 | 1 | Index finger | \{ R_{I,MCP-TE} \parallel \tilde{R}_{I,PIP} \parallel \tilde{R}_{I,DIP} \} |
| 7 | 3 | middle finger | \{ R_{M,MCP-TE} \parallel R_{M,PIP} \parallel R_{M,DIP} \} |
| 8 | 2 | middle finger | \{ R_{M,MCP-TE} \parallel R_{M,PIP} \parallel \tilde{R}_{M,DIP} \} |
| 9 | 1 | middle finger | \{ R_{M,MCP-TE} \parallel \tilde{R}_{M,PIP} \parallel \tilde{R}_{M,DIP} \} |
| 10 | 3 | ring finger | \{ R_{R,MCP-TE} \parallel R_{R,PIP} \parallel R_{R,DIP} \} |
| 11 | 2 | ring finger | \{ R_{R,MCP-TE} \parallel R_{R,PIP} \parallel \tilde{R}_{R,DIP} \} |
| 12 | 1 | ring finger | \{ R_{R,MCP-TE} \parallel \tilde{R}_{R,PIP} \parallel \tilde{R}_{R,DIP} \} |
| 13 | 3 | little finger | \{ R_{L,MCP-TE} \parallel R_{L,PIP} \parallel R_{L,DIP} \} |
| 14 | 2 | little finger | \{ R_{L,MCP-TE} \parallel R_{L,PIP} \parallel \tilde{R}_{L,DIP} \} |
| 15 | 1 | little finger | \{ R_{L,MCP-TE} \parallel \tilde{R}_{L,PIP} \parallel \tilde{R}_{L,DIP} \} |
| 16 | 1 | index finger, middle finger | \{ R_{I,MCP-TE} \parallel \tilde{R}_{I,PIP} \parallel \tilde{R}_{I,DIP} \} |
| 17 | 1 | middle finger, ring finger | \{ R_{M,MCP-TE} \parallel \tilde{R}_{M,PIP} \parallel \tilde{R}_{M,DIP} \} |
| 18 | 1 | ring finger, little finger | \{ R_{R,MCP-TE} \parallel \tilde{R}_{R,PIP} \parallel \tilde{R}_{R,DIP} \} |
| 19 | 1 | middle finger, ring finger, little finger | \{ R_{M,MCP-TE} \parallel R_{M,PIP} \parallel \tilde{R}_{M,DIP} \} |
3.3. Structures of classical bionic hands

A finger has usually adduction/abduction and flexion/extension motions, so it has not only VF\textsubscript{AA} structure but also VF\textsubscript{FE} structure, whose axes are perpendicular in the CMC and the MCP joints. Bionic hands are made up of fingers, so structures of bionic hands are consisted of VF\textsubscript{AA} and VF\textsubscript{FE} structures. By analyzing grasp functions and mechanism design, kinematic structures of several DLR Hand and i-LIMB Hand are given.

- Kinematic structure of DLR Hand is given as follows:

\[
\begin{align*}
&\text{Kinematic structure of DLR Hand is given as follows:} \\
&MC \left\{ R_{M,\text{MCP}} \downarrow R_{M,\text{MCP}} \parallel R_{M,\text{PIP}} \parallel R_{M,\text{DIP}} \right\}, \\
&RC \left\{ R_{R,\text{MCP}} \downarrow R_{R,\text{MCP}} \parallel R_{R,\text{PIP}} \parallel R_{R,\text{DIP}} \right\} \\
&\left(4\right)
\end{align*}
\]

- Kinematic structure of i-LIMB Hand is given as follows:
4. Conclusion

This paper presents a method of determining kinematic structure of bionic hand based on set mapping. The designers can directly obtain kinematic structure of bionic hand to design according to required grasp functions. The method is general for bionic hands such as prosthetic hands and dexterous robotic hands. In addition, it is easily understood and used by designers who can choose appropriate VF AA and VF FE structures according to the actual situation.

Based on the concept of virtual finger (VF), human hand fingers are divided into two types: VF AA and VF FE. It helps us understand human hand finger movement characteristic. Six grasp postures in this paper are usually used in our daily life. Of course, some grasp postures can be performed by less fingers or different fingers. For example, the best case of spherical grasp is that five fingers take part in grasp. In actual situation, even if two fingers in opposition directions can perform spherical grasp. However, it is less steady than five fingers for heavy object grasped. The VF set comprising VFs is used to describe not only six basic grasp postures but also any grasp posture. The VF set can also describe grasp postures of bionic hands and hominine hands. The description method makes people understand easily the inside structure of a bionic hand, and it shows that the relation of grasp function and the bionic hand structure.

In future works, some special VF FE structures will be added into Structure-Base of VF FE. In this paper the VF set shows which fingers take part in and what motion types the fingers in grasping. However, VF sets of some grasp postures such as tip grasp and lateral hip can have the same VF set. Therefore, the VF set will describe grasp postures in detail, and contact areas of the fingers in grasping will be expressed.

5. References

[1] Kyberd P and Pons J 2003 Proc. Int. Conf. on Robotics & Automation vol 3 pp3231-3236
[2] Napier J 1956 Bone Joint Surg 38B: 902-913
[3] Iberall T 1986 Opposition Space as A Structuring Concept for The Analysis of Skilled Hand Movements (Berlin: Springer-Verlag)
[4] Arbib M and Iberall T 1985 Coordinated Control for Movements of the Hand (Berlin: Springer-Verlag)
[5] Iberall T 1997 The International Journal of Robotics Research vol 16(3) pp285-299
[6] Liu X C and Zhan Q 2012 Medical Engineering & Physics vol 35(7) pp1020-1027
[7] Yang T L 2004 Topology Structure Design of Robot Mechanism (Beijing: China Machine Press)