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A Review of Robotic Hand and Its Applications

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Abstract – This study basically presents a review of robotic hands and its applications based on human hand motion. In the context of the review, different kinds of articles are analyzed. There are some hand motion-sensing methods, which are non-contact and direct contact to the hand. Wearable technology like data gloves can be shown as an example of the direct-contact method and cameras are examples of the non-contact sensing method. As indicated in the articles, both methods have advantages and disadvantages. Based on the given information in the researches, the methods used for detecting the hand motion are evaluated and compared. After comparing those methods, how the obtained data is transferred to the robotic hand and the algorithms used for this purpose are expressed. Also what the role of the machine learning at this point is underlined. Furthermore, how the accuracy and robustness level changes by using machine learning are demonstrated according to given results in those articles. Additionally, application areas of these robot hands are observed. Some examples of applications such as human-robot collaboration, robot hands for physical rehabilitation and service purposes are explained. Finally, futuristic ideas and challenges of on-going studies are discussed.

Keywords – Human hand motion, contact-based sensing, non-contact sensing, robotic hand, machine-learning

I. Introduction

Robotics is one of the most popular study fields that has been developing since the past and has experienced great developments in recent years. Robots, which are widely used in industry, medicine, health, education, military, and intelligent home applications, aim to make human life easier. With the developing technology, usage areas are increasing day by day and robots gradually become an indispensable part of human life.

One of the most important parts of the robotic applications is the robotic hand. There are different kinds of robotic hands, which are designed from past to present for grasping or performing a nice manipulation purpose. An example of a robotic hand is Gifu Hand II [1], which is designed as a standard anthropomorphic robot hand in 1998. When comes to the beginning of 2001, Gifu Hand II is developed to the Gifu Hand III [2] which is shown in Figure 1, and the developed version of the hand worked with higher performance. Another example of a robotic hand from today's technology is about a prosthetic hand produced by Touch Bionics [3]. The hand is shown in Figure 2 and it has a nice strong grip feature.

Fig. 2: Developed Gifu Hand III

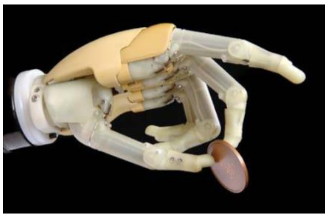

Fig. 2: A prosthetic hand

The complexity of the human hand's skeletal structure, the inadequacy of the methods used for the detection of whole hand motion, and the problems encountered in the control mechanisms have still being developed in the production of robotic hands. Human hand motion must be studied in detail to develop humanoid robotic hands. In accordance with this purpose, the skeletal structure of the hand should be analyzed first of all and the degree of freedoms and joints should be clarified for the robotic hand to be designed. In addition, the ability to grasp and manipulate objects should be examined and knowledge about the movement mechanism of the hand should be reached in deep.

The point reached after the analysis of human hand motion is related to how the motion is detected. There are different methods developed in this regard. According to the information obtained from the researches, it is possible to classify these methods under two headings. These are non-contact sensing method and contact-based sensing method. In contact-based sensing, sensors are used that directly contacted to the human hand or arm. Data gloves, EMG sensors, force-based sensors, flexibility sensors and some other kinds of sensors are the examples of contact-based sensing method. On the other hand, there is a non-contact sensing method. In this method, image-based detection is performed in general. Cameras and leap motion controller are examples of non-contact sensing method.

As stated above human hand motion is analyzed by using different detection methods, and the obtained data is used for the control and operation of the robotic hand. At this stage, the most important role falls on machine learning. Using various machine-learning algorithms, the robot is given different capabilities such as pattern recognition, gesture detection or intention recognition, with the training and testing processes of the available data. Thanks to the algorithms used for classification and recognition, accuracy and robustness levels can be increased, recognition time can

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be reduced and thus continuous work of the robot is provided.

In this paper, firstly human hand motion is analyzed, methods used for detection of human hand motion are examined, and the advantages and disadvantages of these methods are clarified and compared. Then, machine learning algorithms and models are defined and information about application areas of robotic hand is given. Finally, the difficulties encountered during the research process were discussed in the results and suggestions for future studies were given in the discussion section.

II. Materials and Method

A. Human Hand Motion Analysis

Analyzing the skeletal structure of the human hand and its ability to grasp and move the objects is one of the most complex structures of the human body. In order to implement robotic applications successfully, the skeletal structure of the human hand should be examined first. Figure 3 shows the skeletal structure of the hand and the joints [4].

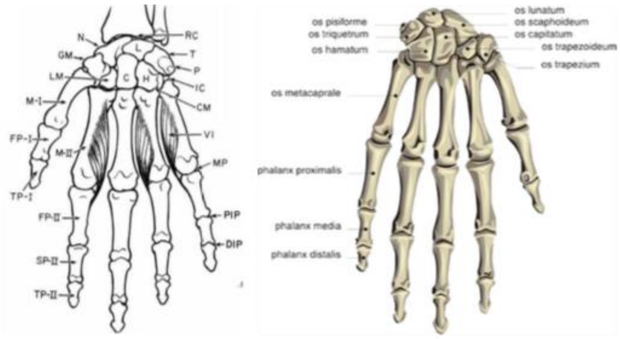

Figure 3: Skeletal structure of the human hand

Biologically, the human hand consists of 27 degrees of freedom (DoF) and joints [5]. However, robotic hands were produced in different degrees of freedom and joints in order to be easy to control and reduce the complexity of the designed robots. Different degrees of freedom and joint production of robotic hands are shown in Table 1. The result obtained from this study is increasing the degree of freedoms and joints provide to design more humanoid robotic hands while the complexity of the system is also increasing. This leads to difficulties such as being difficult to control and lowness of accuracy and robustness. By analyzing the dexterous human hand, researchers can design humanoid robotic hands or prosthetic hands. After analysis of the skeletal structure, the ability to grasp and move objects should be examined. In this regard, different studies are considered based on the type of the object. Delgado et al. [6], used Shadow robotic hand in order to analyze how human hand grasps and manipulates elastic objects. Their system is based on a new servo-tactile control strategy and also Kinect sensors for the location of the objects. Similar research [7] is conducted to analyze a robotic hand by using ultrasonic motors and an elastic element.

In another review [8], human hand movement was classified as simple and mixed movements. According to this study, simple movements are classified as holding, lifting and dropping movements that we do in daily life, while complex movements are defined as wrist movement and hand position change. Although many scientists have investigated this issue, the ability of the human hand to hold and move has not yet been fully transferred to robotic hands.

Table 1: Some examples of robotic hands

Designed Hand	Number of Fingers	Degree of Freedom (DoF)
ASIBOT Robot [9]	3	5
LISA Hand [10]	5	14
AZZURRA Hand [11]	5	16
UTAH Hand [12]	4	16
SHADOW Hand [6]	5	24
Robot Hand [7]	5	20

B. Methods for The Detection of Human Hand Motion

Once the human hand motion has been successfully analyzed, it is in the process of detecting this motion. The movement and tracking of the hand and the properties of the moving objects can be analyzed by different methods used in this stage. To perform the detection, either a sensor-based system is used, which is commonly referred to as contact-based detection, or an image-based system is used, in which any contact is not required and is referred to as the non-contact detection method. In the next section, detailed information about these methods has been given and their advantages and disadvantages have been indicated and compared.

1. Contact-based Sensing Method

As stated above, one of the methods used in the detection of human hand motion is a contact-based sensing method. As the name implies, the system that performs the detection is connected to the human hand or body and the detection process is performed. A commonly used example of this method is data gloves. Data gloves are attached to the hand where the movement is detected and the measurement is carried out by the sensors on it. Ingram et al. [13] analyzed the statistics of the right-hand movements by using a Cyber data Glove. There are 19 resistive sensors embedded in the glove and they measured the hand movements based on 19 DoF and 4 fingers hand design. Besides this study, Xiong et al. [14] used Cyber Glove II in order to design an anthropomorphic hand. Their research is based on analyzing the grasping function of the hand by measuring the joint angles with the use of the data glove. Liu [15] developed a novel-sensing algorithm by using a 6-axis force/torque sensor to detect hand motion. In this study, he also covered the glove with deformable rubber skin. As given in the examples, only data gloves are used for measuring the hand movements in these researches. On the other part, a combination of two methods can also be used for detection. An example of this kind of research is about the combination of a wearable haptic device with Kinect sensor [16]. Using the advantages of a non-contact sensing device, Kinect sensor, better performance on the detection of the hand is obtained by also using a wearable haptic in the same study. Once the motion is detected, the obtained data is transferred to the robotic hand by wired or wireless transmission. Ramaiah et al. [17] controlled their 4 fingered robotic hand by using wireless feedback. In a similar manner, Karam et al. designed wireless controlled robotic hand via a Bluetooth module. With the implementation of wireless control on robotic hands, complexity caused by connected wires can be prevented and also user-friendly robots are produced.

Another example of contact-based detection is EMG sensors. Electromyography (EMG) sensors measure the electrical signals obtained from the forearm muscles and analyze the movement. This method is commonly used in prosthesis control. References [18], [11, 19] present the use of EMG sensors in prosthetics. Johansen et al. [11] used a combination of two methods, which are the EMG sensors and Inductive Tongue Control System (ITCS) for the prosthesis application. By combining different featured methods, they obtained faster activation of some specific grasps and they proved the significant impact of the speed on the prosthesis control while others only used the EMG sensor in the application of prosthetics. On the other hand, EMG sensors are also implemented with different purposes such as analyzing hand manipulations [20], control of finger movements [21], hand gesture recognition [22] or real-time control of a robotic arm [23]. Meattini et al. [24] used 8 Differential EMG sensors on the implementation of two different robotic hands, a dexterous anthropomorphic hand and 3- fingered industrial gripper mounted on a robotic manipulator.

Various sensors are also used in this method. Five pressure sensors are located into the data glove in the design of an anthropomorphic hand [14]. In another study inertial sensor [25] is embedded in the data glove to be able to design an IMU controlled robotic hand.

2. Non-contact Sensing Method

The second method for detecting the hand motion is called as non-contact sensing. In this method, a vision-based system is implemented for the detection of movements instead of a sensory system. With this approach, any physical touch is not required to the user. Using the Leap Motion Controller or different cameras performs detection.

Leap Motion controller (LMC) is a non-contact sensing system which consists of cameras and infrared LEDs [26]. The purpose of using this kind of sensory system is hand tracking in general. Heisnam and Suthar [26] implemented Leap Motion Controller for teleoperation of robotic hand applications by tracking the movements of the hand. On the other hand, there are some researches using Leap Motion Controller for hand rehabilitation [27-29]. These researches are proven that implementation of LMC in rehabilitation prepares a way for the treatment of patients with accurate results. In a different approach of using non-contact sensing method is performed in the study of Kiselev et al. [30]. They increased the number of Leap Motion Controllers used in the system for hand gesture recognition in order to get a higher accuracy level. In a similar approach, Marin et al. [31] combined Leap Motion Controller and Kinect devices for the recognition of American Sign Language hand gestures instead of increasing the number of controllers. This proposed method is implemented in real time application and accuracy level of the system is increased from 73% (only LMC is used) to 91.28% by combining two different sensing approaches. Marin et al. used the advantage of full depth mapping of the Kinect device and good accuracy level of Leap Motion Controller in this research.

The second approach used in the context of non-contact sensing method is cameras. In order to create a vision-based system, different featured cameras such as Kinect devices [31], depth cameras [32], RGB cameras [33], are used for the detection of hand movements by capturing the motion and creating a database with images or videos.

Besides the Leap Motion Controller and different cameras, sensors are also used in the concept of non-contact detection. Kurita [34] proposed a system consists of a capacitance between the hand and the measurement electrodes. With this system, a motion detection sensor is used and the electrostatic induction current generated from the difference in the capacitance is measured. Kopinski et al. [35] used multiple time of flight (ToF) sensors which measure the distance of an object to the sensor by considering the time difference between the emitted light and its return time to the sensor when reflected by an object for the hand pose recognition.

3. Advantages-Disadvantages of These Two Methods

As a result of analyzing two different methods for the detection of human hand motion and also obtained information from several kinds of research based on the sensing type of the contact, advantages and disadvantages are given in Table 2. When the properties of the methods are examined, implementing the non-contact sensing method has more advantages over the contact based sensing method. With the advanced technology of todays, non-contact based applications are getting more attraction.

Table 2: Comparison table

	Advantages	Disadvantages
Contact-based sensing method	Ease of control	Complex connection wires
	Simple data transmission	Limited working space
		Hysteresis due to sensors
Non-contact sensing method	Faster response time	Complex data transmission
	More working space	
	Ease and comfort of usage	

C. Machine Learning in Robotic Hand Applications

Movement and different abilities of the hand, detection of motion and methods used for this purpose were examined. The most important process after this point is the analysis, classification, and application of the data on the robotic hand in a most efficient way. This is where machine learning gets involved in this topic. With the use of different machine learning algorithms in robotic applications, high-performance robotic hands can be designed after some training and testing processes. The algorithms and models used for this purpose are generally Support Vector Machine (SVM), Hidden Markov Model, Artificial Neural Networks (ANN), and others.

Support Vector Machine (SVM) classifier, which is one of the widely used machine-learning algorithms, is generally used for hand gesture recognition in robotics. The idea behind this classifier is to separate two classes with a linear line at the optimal distance. Moreover, planes in 3D representations and curves can be used where it is not possible to form a linear line between the classes. The use of SVM in the training and testing time for the recognition process, significance effect about increasing the accuracy level is observed in different studies. Shenoy et al [23] verified that 92-98% accuracy level is obtained by using SVM classifier on online EMG control of a robotic prosthesis. They also achieve stable results over a wide range of parameters and very little training time, which is less than 10 minutes. In another study, Dardas and Georganas [36] used multiclass SVM and the accuracy is 96.23% for the real-time hand gesture recognition. In addition to that, as the resolution size of sample images decreases, the recognition time also decreases and the accuracy level increases. With the reduction of image sizes, they obtained accuracy level up to 98.04% and recognition time as 0.017 seconds per frame. Rossi et al. [22] proposed a new method named as Hybrid EMG Classifier in order to deal with one of the key challenges in the control system, the accuracy. In this context, they combined SVM and Hidden Markov Model for pattern recognition and classification for prosthetics and reached 91.8% accuracy in their Hybrid model while accuracy is 84% when the only SVM is used. They have also proved that classification errors are reduced with this new model. With the analysis of different researches, usage of SVM classifier has satisfactory results on the improvement of accuracy level and recognition time about the hand gesture recognition process.

Artificial Neural Networks (ANN) is another classification method used in hand gesture recognition. ANN is a mathematical model, which is in a similar way to the human biological neural network system. This model forms from multiple neurons, connecting links and an activation function. With the use of ANN in robotics, high accuracy and robustness levels can be achieved. Ergene et al. [37] used ANN classification for imitation and learning of human hand gesture tasks for the human-robot collaboration and in the training process of their study, 19 samples were misclassified out of 192 hand gesture samples of different people. That means is the accuracy of the training is 90.1%. Kopinski et al. [35] proposed multi-layer neural network classification and they obtained execution time as less than 0.005 seconds. Besides these studies, Lu et al. [20] performed a new hybrid method with the combination of ANN and SVM classifiers and reached 97% of accuracy level. As a conclusion of these studies, neural network structure provides powerful pattern recognition about human gestures with higher accurate level.

In addition to the classifiers described above, one of the commonly used algorithms is the Hidden Markov Model (HMM). This methodology is a stochastic process that consists of hidden states and observable states. Hidden Markov Model is successfully implemented in the robotic hands with high performance and a good level of accuracy, especially higher efficiency in the real-time applications of hand gesture recognition. Gharasuie and Seyedarabi [38] implemented HMM to analyze hand motion of the numbers from 0 to 9 in real time. With this purpose, they separated hand motions in two groups, which are the link gestures and key gestures (meaningful gestures) and also they used the Baum-Welch algorithm for training HMM. As a result of this study, 93.84% recognition rate is obtained for the continuous and real-time hand gesture recognition. In another research [39], a high-performance system is obtained for the complex dynamic hand gesture recognition by using the HMM approach. This research is also implemented in real time application and K-means clustering is offered due to having higher time and recognition rates, after testing different clustering methods. Some other researches [33], [40], and [41] implemented Hidden Markov Model by using Hierarchical HMM, HMM with the incremental method, and HMM in speech recognition, respectively. As stated in these researches, implementing this approach provides high-performance systems with more accurate results. However, defining an optimal hidden state or hidden parameters are the real challenges of HMM applications.

D. Applications of Robotic Hands

Robotic hands have a wide range of application area with the implementation of cutting edge technology in this field. Some examples of robotic hand application are about Human-Computer Interference (HCI), Human-Robot Collaboration, physical rehabilitation, and prosthesis hand applications and also teleoperation of robots.

In the context of Human-Computer Interference, several applications have been performed. Haria et al. [42] implemented their robotic hand design as part of HCI. In this study, different windows on the screen of the computer are launched based on the movement of the hand, a total of seven different gestures. For instance, when the user shows the number 3 with his/her fingers to the camera, Google home page in the browser is launching or showing number 2 launches VLC media player. Figure shows one gesture example used in this study. In another research [43], an intelligent system is proposed with the purpose of HCI implementation by using hand gesture recognition. The system provides to users to have more interaction with computers without any need to mouse click and keystrokes. When this study is examined in more detail, non-contact sensing method is implemented by using cameras and colored marker. Besides the implementation of robotic hand in computer interaction, also it is implemented to control television by hand gestures. As is proven in these researches, implementation of robotic hands in HCI provides ease of use to the user.

Hand gesture is also used in the recognition of sign language applications. With the development of hand gesture recognition on the robotic hand, sign language becomes more important in the sense of the communication of deaf people. In this regard, different studies are performed in different sign languages such as American [44], Korean [45], Arabic [46] and Chinese [47] Sign Languages.

Figure 4: Implementation of SmartHand

Another application area of the robotic hands is about physical rehabilitation and prosthesis hands. Reliable motion detection thanks to EMG sensors, user-friendly robotic hand designs and also developments in hand tracking and hand gesture recognition allow the successful implementation of prosthetics. Cipriani et al. [18] designed a five-fingered wearable robotic hand, namely SmartHand, as shown in Figure 4, for the use of amputees. Likewise, there are different designs in prosthesis hand applications. For instance, Zollo et al. [48] designed an artificial anthropomorphic hand with three-fingered. In this research, they focus on the anthropomorphism and control system of the hand in order to design a humanoid robotic hand.

III. DISCUSSION

In this review study, several articles are analyzed in order to have deep information about the robotic hand and its applications. During this process, some challenges encountered by the implementation and design of robotic hands are observed and specified as follows:

- One challenge is about the detection of whole hand movements. With the implementation of different approaches, human hand motion is detected in some way. However, these methods detect only some parts of the hand, not the whole. Therefore, it is still a challenge for the researchers to create a system that can detect whole hand motion.
- Replication of human hand grasping function is also a challenge in robotic hand applications. By using different sensors and actuators, grasp function of the human hand has tried to be implemented in robotic hands up until today. However, researchers are still working on the implementation of exact grasping on designed hands.
- Another challenge is about real-time recognition of hand gestures. Training and testing process in the analyzed researches are generally performed offline. Only a few studies implemented the recognition in real-time. Because of the accuracy and response time problems, real-time recognition applications still wait to be developed.
- The last challenge observed in the articles is about the use of both hands, especially in Virtual Reality (VR) applications. In general, robotic hand design is implemented on only one hand, right or left hand. However, some applications require the usage of both hand and this issue is also considered for the design and implementation of robotic hands.

As a result of observation these challenges, some suggestions can be offered in order to overcome the problems. One suggestion about the real-time applications is to combine different featured learning algorithms and methods. As discussed in part II.C, some algorithms have a good level of accuracy while others have a fast recognition time. Real-time applications can be implemented by the combination of different methods that have higher accuracy level and faster recognition time. In the same way, whole detection of hand movements can be detected with the combination of two or more various methods. As stated previous example, taking advantage of different methods can provide more powerful system. For instance, a camera-based system, such as Kinect devices, can detect hand motions compared to others. On the other hand, some systems have a higher accuracy level although cannot fully detect hand movements, such as Leap Motion Controller. Thus, combination of these kinds of methods ensures detecting of whole hand movements.

IV. CONCLUSION

As a consequence of this study, robotic hands and its applications are described in detail. Importance of the human hand motion analysis is underlined for the robotic hand researches and different methods used for the detection of hand movements are expressed. Furthermore, the process after detecting the hand motion is explained and the role of the machine learning and its algorithms are presented. Additionally, robotic hand applications with examples used in different fields are given and some challenges and future ideas are discussed at the end.

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