Proceedings of the ASME 2014 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference
IDETC/CIE 2014
August 17-20, 2014, Buffalo, New York, USA

DETC2014-34675

MODELING HUMAN HAND AND SENSING HAND MOTIONS WITH THE FIVE-FINGERED HAPTIC GLOVE MECHANISM

Zhou MA
Robotics and Mechatronics Lab
George Washington University
Washington, DC, USA

Pinhas Ben-Tzvi
Robotics and Mechatronics Lab
George Washington University
Washington, DC, USA

Jerome Danoff
Department of Exercise Science
George Washington University
Washington, DC, USA

ABSTRACT

This paper presents the design and application of a newly developed five-fingered haptic glove mechanism. This haptic device is a lightweight and portable actuator system that fits on a hand. The new five-fingered glove is adaptable to a wide variety of finger sizes, without constraining the range of motion which makes it possible to accurately and comfortably track the complex motion of the finger joints and add a sense of touch to each finger of the user. Based on this glove, a novel method was developed to build an accurate human hand model which includes finger length and joints location. The parameters of the hand are determined by a circle fitting procedure from a collection of points. The method of least squares fitting of circles is used to analyze the kinematic model. The center and the radius of the fitting circle are the joint location and the finger length respectively. The experimental results demonstrate that the newly developed five-fingered glove is capable of reliably modeling hand kinematics and measuring fingers' motion. These capabilities are often needed for monitoring and assisting rehabilitation activities of the hand as well as applications involving virtual reality and teleoperation.

1 INTRODUCTION

Due to its highly complex structure, the human hand is capable of conforming to the shape of objects to be grasped [1]. Hand motion and modeling its kinematics have been challenging problems for researchers [2,3]. The precise teleoperation [4], Virtual Reality [5-7], and rehabilitation [8-10] tasks of haptic gloves require an accurate human hand model (i.e., finger length and joints location) in order to achieve an accurate control and reduce the motion sensing errors.

With the technological developments in recent years, the most common instruments and methods for measuring hand kinematics are glove-based electro-mechanical sensing devices [11-13] and vision-base hand motion tracking with [14-16] or without the use of markers [17-20].

Glove-based input devices are worn on the hand, thus most of these devices have several drawbacks in terms of friendly operation: they hinder the ease and naturalness of hand motion, and require long, complex setup/calibration procedures to get precise measurements. Besides, some of them are very expensive. However, they can deliver the most complete measurements which can be easily processed to extract the motion of the hand in real-time with minimum processing effort. In addition, some haptic gloves are also capable of providing force feedback to the finger which is ideal in many applications.

Markerless visual tracking systems have the potential to provide natural, non-contact methods to measure hand motions. However, since the hand contains 27 degrees of freedom [21] such high-dimensional state-space usually demands intensive computation and leads to low update rate. Marker-based capture systems usually consist of surface markers and capture devices such as the Vicon motion capture system. They offer higher precision and faster measurements compared with the markerless vision-based hand sensing system. However, they are inconvenient to use since the markers have to adhere to the hand's surface during all the measurement procedures and time-consuming calibration is required.

Quantitative measurement of hand position and orientation is fundamental for hand motion analysis. During assessment of hand function, both finger joint locations and finger lengths are essential factors. However, most of the cited studies have focused on the analysis of finger joint angles during a specific movement to evaluate active range of motion, while finger length, which highly affects the fingertip position, has not been analyzed. Since finger rotation axes are difficult to locate, the length of the finger is prone to artifact errors. Thus, greater detail is required for improving finger length measurement accuracy. The authors therefore propose using a novel haptic-glove (the CAD model is shown in Fig. 1) method based on an articulated hand model to measure finger length from multiple movements. This device is a newly developed lightweight and portable five-fingered haptic glove that fits on a bare hand. It is adaptable to a wide variety of finger sizes, without constraining the range of motion, which makes it possible to accurately and comfortably track the complex motion of the finger joints and add a sense of touch to the users' fingers. Based on this glove, a novel method was developed to build an accurate human hand model, which includes finger length and joints location. The parameters of the hand are determined by a circle fitting procedure from a collection of points. The method of least squares fitting of circles is used to analyze the kinematic model. The center and the radius of the fitting circle are the joint location and the finger length respectively. The results of the experiments demonstrate that obtained hand kinematic model is reliable and accurate.

This paper is organized as follows: Section 2 briefly summarizes the mechanical and electrical design of the glove system. Section 3 discusses a method for measuring finger length to model the hand using least squares circle fitting procedure from a collection of points and uses the proposed glove to realize the method. Section 4 describes a hand motion experiment to evaluate both the glove design and the hand model. Finally, Section 5 provides the conclusions and discusses future work.

2 FIVE-FINGERED HAPTIC GLOVE DESIGN

2.1 Mechanical Design

The five-fingered haptic glove is a follow-up to the 2-finger glove previously developed [22]. It is a lightweight, portable, sensing/actuating system that fits on a bare hand and is attached to finger tips as shown in Fig. 2. The total weight of the five-fingered prototype is 275 g, including one 9 V rechargeable battery (20 g), one control unit (25 g), six actuator assemblies (30 g each) and mechanical skeleton (50 g).

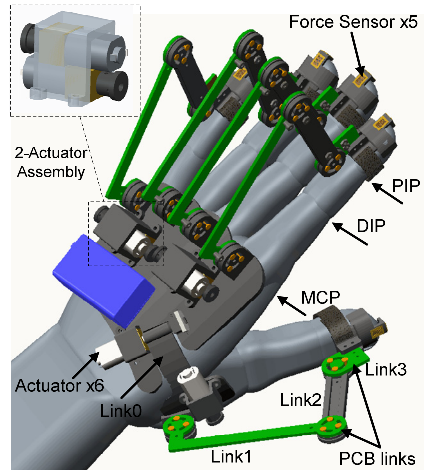

Figure 1. MECHANICAL CAD MODEL OF THE GLOVE.

Because all necessary components are light and contained inside the glove, the user can move each finger freely without being tethered or feeling fatigued.

In order to lighten and simplify the whole glove, the movements of the Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints of each finger are coupled together with one actuator module. The actuator unit consists of a brushed DC-motor. The maximum speed of the actuator module is 150 rpm when powered with a 9 V battery. At this speed, the time of the hand's motion, from a fully opened to a closed configuration, and vice versa, is about 1 second. Two dyneema cables are attached to the pulley and routed along the exoskeleton to the fingertip. Cable transmission is chosen because it can provide adequate power through narrow pathways and allow the actuator to be located away from the dexterous fingers. In addition, cables are compact, light-weight, and cost-effective and simplify the transmission. Bidirectional force control is enabled by antagonistically actuating the two cables, transferring this force along the exoskeleton to the finger tip.

The links of the five-fingered glove form a series of three linkages over each individual finger [22]. According to [23] the axes of the human fingers are not orthonormal to the sagittal plane, the inclination of a joint is defined as the angle of deviation of the axes from the normal position within the frontal plane. Human finger does not bend in a single plane since the relative orientation of the finger joints axes is not perfectly parallel to each other. A simple planar linkage was not acceptable because of its discomfort and tendency to shift at the attachment joints. As a result, the mechanism limits the range of motion of the finger and the measurement accuracy.

The two features of the glove, which eliminate this problem, are the passive pivot and flexible link of the PCB (printed circuit board). The passive pivot joint allows the finger to bend in the direction of abduction/adduction freely, while maintaining the accuracy of the sensor measurement. This allows the long PCB link to accommodate to finger joint inclination, while keeping the pad block firmly attached on the fingertip.

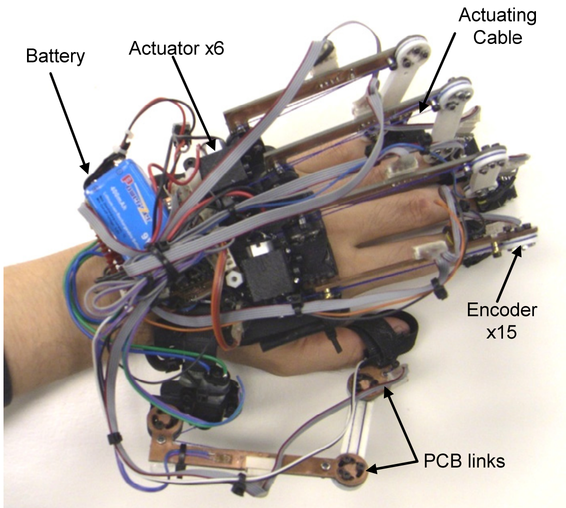

Figure 2. HAND AND THE FIVE-FINGERED GLOVE SYSTEM.

The mechanical links for each finger are the same except for the thumb. Due to the unusual geometry of the thumb joint and its large workspace volume, the three linkage design would not comfortably and adequately secure an exoskeleton mechanism to the thumb's proximal link. Thus, one more link was added to the thumb base to decouple its off-axis rotations as shown in Fig.1 (denoted by "Link 0").

The size and shape of human fingers may vary significantly among individuals and among different fingers (e.g., the lengths of middle finger and the little finger are quite different). To avoid custom glove dimensioning for different users, a single adaptable design is desirable. Because each articulated linkage mechanism remains extendable when each finger is fully stretched, the same finger mechanism can easily adapt to different finger lengths. After performing several wear tests, this glove mechanism was able to adapt to 11 different users' hands whose finger lengths ranged from 60 mm to 89 mm.

2.2 Electrical Design

The block diagram of the electrical system design for this device is shown in Fig. 3. The system is composed of a host unit and a portable haptic glove. The host unit is made up of a wireless RF transmitter (XBee, 1 mW transmission power at 2.4GHz providing a 30 m working range indoors) and a PC which collects, records and displays the joint angle and force measurement, while simultaneously sending the control data back to the glove system. The haptic system includes a glove skeleton and an electrical control interface.

The focus of the electronics is on the development of a circuit interface board in a compact size which will incorporate a 15-channel A/D converter, 5 differential input channels, 6 DC motor drivers, a wireless module and microcontroller.

To reduce the complexity and bulk of the mechanical and electrical construction between the fingers and maximize the

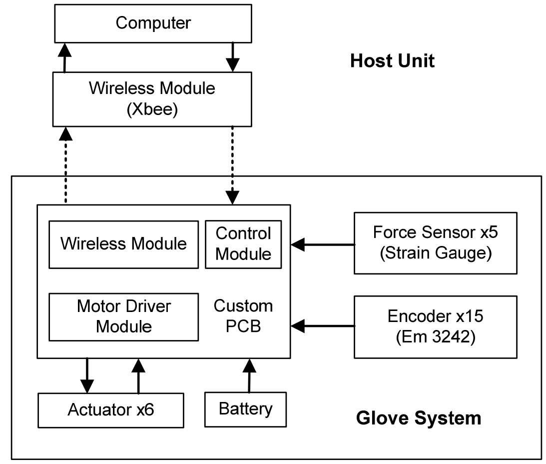

Figure 3. ELECTRICAL DESIGN DIAGRAM OF THE GLOVE SYSTEM.

finger workspace, two customized PCBs with mounted three angular position encoders (Hall element sensor EM-3242) are used as the two links of the finger mechanism (Link1 and Link3 as shown Fig. 1). The three angular encoders (two on Link 1 and one on Link 3) provide accurate joint angle measurements for calculating each finger's configuration and position. After calibration, the joint rotation resolution of the Hall-effect rotation sensor was experimentally determined to be 0.37 degrees [24]. The joint angle error was less than 0.8% of the total range of motion (120 degrees) and the error was well below the Just Noticeable Difference (JND) of approximately 2.5 degrees for the PIP and MCP joints [25]. Thus, no extra angular encoder sensors are needed to be attached to the joint. These encoders are soldered directly onto the PCB board, which is used as both a mechanical link and a carrier of electrical components and signals. This dual function makes the glove mechanism lighter without sacrificing strength. Strain Gauge sensors were used to measure contact forces, which are mounted on the fingertip pad as shown in Fig. 2. Motor current is also measured through a shunt circuit on the custom PCB. Thus, both joint angle and torque/force measurements are collected for feedback control and for data analysis.

The control module is a MK20DX128 microcontroller (32 bit ARM Cortex-M4 by Freescale) which manages the sensor measurement and performs several functions: reading and conditioning the sensor data, controlling the force magnitude applied at the user's fingertips through controlling the motor rotation, and communicating with the host unit. In this case, the microcontroller speed is set to 96 MHz. Additionally, software running on the control module conditions the rotation and force signals with low pass filters. Since humans are sensitive to high-frequency information, the loop of the control program runs at 1.3 kHz. This high cycle frequency not only provides a realistic touch feeling to the haptic glove user, but also helps maintain the stability of the whole system and provide precise output force.

The battery is a Powerizer LI-9V400 (9 V, 400 mAh, dimensions 48×26×16 mm, with 20 g of weight) which can last as long as 70 minutes for continuous operation. Communication between the haptic glove and host computer is via wireless RF modules. The wireless transmission speed is 115.2 Kbits/second. The transmitted data from the haptic glove include finger joint angles and measured fingertip contact forces. The data that the haptic glove receives consist of motor speed and forces to be applied to the operator's fingers. The adoption of the RF module and the compact mechanical and electrical design has resulted in a glove that is wireless, portable and self-contained.

Three different modes were used for the implementation of this haptic glove system:

1. Variable parameters configuration mode: Variable parameters could be changed through wireless communication, such as object stiffness, position parameters, PWM frequency, device address (for multiple gloves), serial baud rates, and timeout value.

2. Human Computer Interface (HCI) modes: Forces are calculated on the host computer and transmitted wirelessly to the glove to be communicated to the user. This feature is particularly useful when dexterous manipulation in Virtual Reality Simulation is involved.

3. Human Robot Interface (HRI) modes: The glove can be used to control mobile robots [26-28]; torque or object distance feedback is produced locally by the glove in the form of a variable force.

3 MODELING THE HUMAN HAND

3.1 Finger Length Measurement

The glove design allows an individual to place the glove on their hand and get actual finger angles regardless of the hand size. Thus, the key elements of modeling the hand are: 1) to measure the length of the user's fingers, which directly takes input from the individual user, and 2) to map the mechanism joint positions directly into human finger angles through forward and inverse kinematics based on the finger length and the fixed glove mechanism geometries.

The finger length measurement is one of the main difficulties in building a hand model. External measurement with a caliper or MRI and CT scans are used frequently to measure finger lengths, but these methods fail to provide accurate finger length information due to the lack of accurate distinguishable skin or bony landmarks [29-31]. As shown in Fig. 4 and Fig. 5, bone link lengths are not equal to the effective finger phalangeal length. The movement of each joint can be considered as the female bone rotation about the center of curvature of the male bone surface. Thus the joint center can be anatomically estimated as the center of bone head curvature. It is supposed that the center of rotation is fixed since the geometric curvature of the bone head is constructed with circular arc segments. Similarly, the finger skin creases are not in the same position as the underlying joint. Thus, the center of rotation and the real finger length are difficult to determine from direct measurement methods.

Surface marker measurement method is another assessment technique to measure the finger length [32-35]. Yet a main drawback to this approach is the occlusion of markers of the optical assessment method. This issue worsens when the number of markers is increased, especially when the user is performing an object manipulation task. In addition, the surface marker method is normally unavailable to users in some specific applications, such as teleoperation in the field. Thus, a method for easily and accurately identifying the hand kinematic parameters is required.

The proposed solution determines the finger length parameters using a circle fitting procedure from a collection of points with the five-fingered glove mechanism. In this paper, only planar movements are considered and the axis of rotation is supposed to be perpendicular to the plane of motion.

After wearing the glove, the user is asked to rotate the MCP joint of the finger in flexion/extension direction while keeping the PIP and DIP joints to zero degree as much as possible. Meanwhile, the glove records the fingertip curve-like trajectory. The method of least squares fitting of circles [36] is used to analyze the kinematic model.

In general, suppose that the fingertip trajectory has a collection of $n \geq 3$ points in x-y coordinates (as shown in Fig.

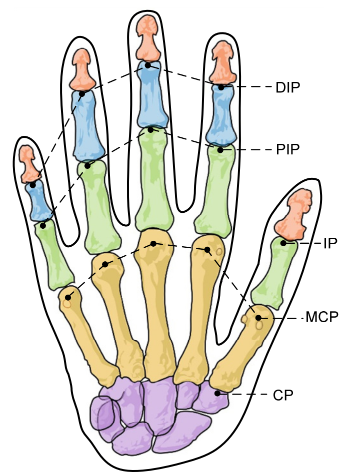

Figure 4. BONES OF THE HUMAN HAND.
(Adopted from http://en.wikipedia.org/wiki/hand)

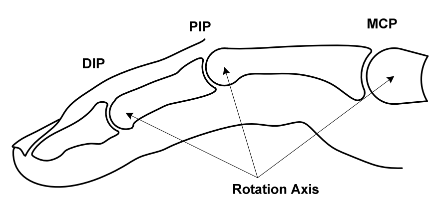

Figure 5. LATERAL VIEW OF A DIGIT SHOWING THE THREE PALMAR PLATES OF THE DIP, PIP AND MCP JOINTS IN RELATION TO THE NORMAL ANATOMY.

6), and let (x_i, y_i) represents the ith measured data point. Suppose the rotation axis of glove mechanism link1 is the original point of x-y coordinates. The purpose is to find a circle that best represents the data that are described by $(x-a)^2+(y-b)^2=r^2$, where the center (a,b) and the radius r are the values to be determined. The center and the radius of the fitting circle are the joint location and the finger length respectively.

The least squares error criterion for circle fitting is given by:

$$S(a,b,r)=\sum_{i=1}^{n}\left(r-\sqrt{(x_i-a)^2+(y_i-b)^2}\right)^2 \qquad (1)$$

The sum S is a function of a,b and r, without constraints. Hence, an obvious approach is to choose a,b and r to minimize S. Differentiation of S yields

$$\frac{\partial S}{\partial r}=-2\sum_{i=1}^{n}(\sqrt{(x_i-a)^2+(y_i-b)^2})+2nr \qquad (2)$$

$$\frac{\partial S}{\partial a}=2r\sum_{i=1}^{n}(\frac{x_i-a}{\sqrt{(x_i-a)^2+(y_i-b)^2}})+2na-2\sum_{i=1}^{n}x_i \qquad (3)$$

$$\frac{\partial S}{\partial b}=2r\sum_{i=1}^{n}(\frac{y_i-b}{\sqrt{(x_i-a)^2+(y_i-b)^2}})+2nb-2\sum_{i=1}^{n}y_i \qquad (4)$$

The extremum can be obtained by simultaneously equating these partial derivatives to zero,

$$\frac{\partial S}{\partial a}=\frac{\partial S}{\partial b}=\frac{\partial S}{\partial r}=0 \qquad (5)$$

After solving these equations with MATLAB, the rotation center (a,b) and the finger length r can be found.

According to [29], lengths of three phalangeal segments of each finger are approximated determined by a “Fibonacci” sequence, i.e. 2, 3, 5, 8, from distal to proximal. Thus, the length of each phalanx is the sum of lengths of the other two distal segments. Following this relationship, the length of each phalangeal segment can be calculated. The finger length results may be stored to allow the same user to use the device again without recalibration.

3.2 Kinematic Analysis

All joints in the glove design were realized through revolute pin connections. For each finger, the haptic mechanism and the finger itself can be modeled as a combined six-bar mechanism, as shown in Fig. 7, where the palm is taken as the

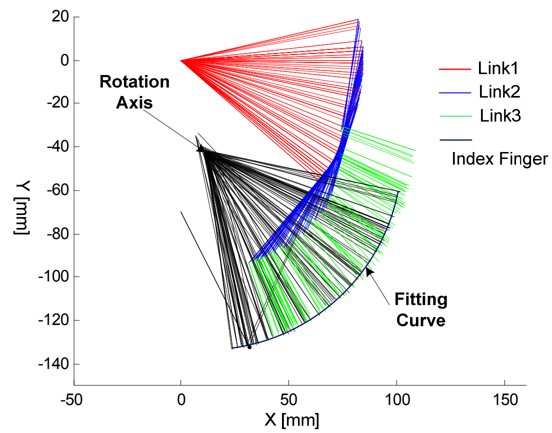

Figure 6. FINGER LENTH MEASUREMENT.

ground link. Each finger consists of three links and the haptic mechanism for each finger has three links as well.

It should be noted that both the end link of the mechanism and the fingertip are fixed together, so they are considered as one link. Therefore, there are 6 links in total (i.e., 1 ground link, 3 finger links, and 2 haptic mechanism links) and 6 revolute pin connections (ignoring the Adduction/Abduction).

Based on Fig. 7, the following equations can be derived based on forward kinematics

$$\alpha_1=\theta_1+\theta_2+\theta_3-\alpha_2-\alpha_3 \qquad (6)$$

$$\begin{aligned} &x_{B_0}+\overline{B_0B_1}\cos\alpha_1+\overline{B_1B_2}\cos(\alpha_1+\alpha_2)+\overline{B_2B_3}\cos(\alpha_1+\alpha_2+\alpha_3) \\ &=\overline{A_0A_1}\cos\theta_1+\overline{A_1A_2}\cos(\theta_1+\theta_2)+\overline{A_2A_3}\cos(\theta_1+\theta_2+\theta_3) \end{aligned} \qquad (7)$$

$$\begin{aligned} &y_{B_0}+\overline{B_0B_1}\sin\alpha_1+\overline{B_1B_2}\sin(\alpha_1+\alpha_2)+\overline{B_2B_3}\sin(\alpha_1+\alpha_2+\alpha_3) \\ &=\overline{A_0A_1}\sin\theta_1+\overline{A_1A_2}\sin(\theta_1+\theta_2)+\overline{A_2A_3}\sin(\theta_1+\theta_2+\theta_3) \end{aligned} \qquad (8)$$

where:

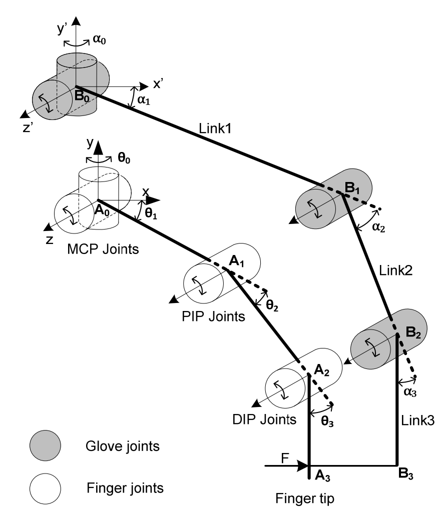

Figure 7. KINEMATIC ANALYSIS OF THE FINGER AND GLOVE.

$\overline{B_{i-1}B_i}$: The length of i^{th} mechanism link

$\overline{A_{i-1}A_i}$: The length of i^{th} finger link

α_i : The joint angle of the i^{th} mechanism link

θ_i : The joint angle of the i^{th} finger link

After solving equations (6)–(8), θ_1 , θ_2 and θ_3 can be obtained as follows:

$$\theta_1 = \arctan\frac{N}{M} + \arccos\frac{p_1^{\ 2} + p_2^{\ 2} + N^2 - M^2}{2p_1\sqrt{M^2+N^2}} \tag{9}$$

$$\theta_2 = \arccos\frac{M^2 + N^2 - p_1^{\ 2} - p_2^{\ 2}}{2p_1p_2} \tag{10}$$

$$\theta_3 = \alpha_1 + \alpha_2 + \alpha_3 - \theta_1 - \theta_2 \tag{11}$$

where:

$M = x_{B_0} + \overline{B_0B_1}\cos\alpha_1 + \overline{B_1B_2}\cos(\alpha_1+\alpha_2) +$
$\overline{B_2B_3}\cos(\alpha_1+\alpha_2+\alpha_3) - \overline{A_2A_3}\cos(\theta_1+\theta_2+\theta_3)$

$N = y_{B_0} + \overline{B_0B_1}\sin\alpha_1 + \overline{B_1B_2}\sin(\alpha_1+\alpha_2) +$
$\overline{B_2B_3}\sin(\alpha_1+\alpha_2+\alpha_3) - \overline{A_2A_3}\sin(\theta_1+\theta_2+\theta_3)$

$p_1 = \overline{A_0A_1}$, $p_2 = \overline{A_1A_2}$

Equation (9)-(11) illustrate that if the joint angles for the three links of the mechanism ($\alpha_1, \alpha_2, \alpha_3$) are known, the microcontroller can calculate the exact finger position. Finally, when the finger length and joint angles are both collected, the hand model will be displayed in 3D graphics on the host unit.

4 EXPERIMENTS: SENSING THE HAND MOTION

On the host unit, a 3D GUI was programmed with MATLAB to show the hand kinematics in real time. The GUI can simulate the posture of fingers and display the positions of the fingertip, with three DOF (MCP, PIP, and DIP joints) for each finger as shown in Fig. 8. The palm is considered as a flat surface since palm curve variations are not significant. Experiments to measure hand motions are performed to evaluate the effectiveness of the proposed method.

The hand opening and closing task was chosen as it represents the most basic finger movement. In this experiment, one user was asked to wear the five-fingered glove prototype and to move all fingers in close/open maneuvers. The glove was controlled to follow the finger movements by minimizing the force between the fingers and the glove throughout the motion. And the actuators were controlled to actuate the finger mechanism and compensate for the static friction of the device.

The user was asked to repeat two close/open hand maneuvers five times in approximately 3 seconds. The 15 joint angle sensors of the glove measured the joints angles at a sampling frequency of 300 Hz. Before recording the data, the user spent several minutes to get used to the system. The graphical results for two close/open maneuvers acquired by the user's index finger during the test are reported in this paper as a representative example of the total test results. As a representative example of the test results, Fig. 9 displays three

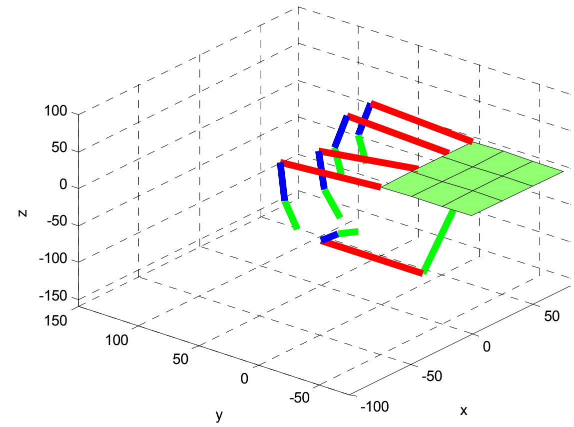

Figure 8. 3D GUI OF HAND KINEMATICS.

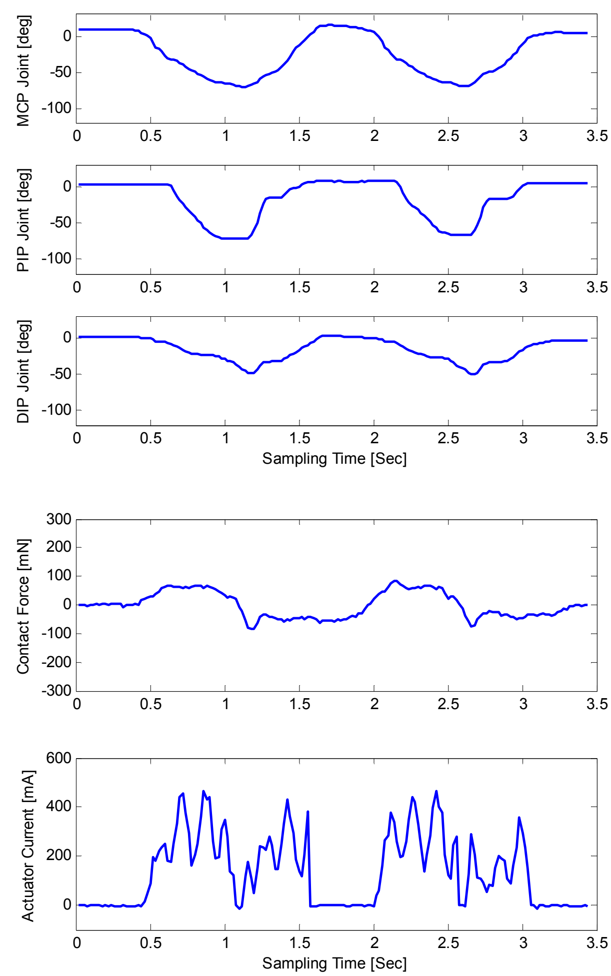

Figure 9. MOTION DATA OF INDEX FINGER

measured joint angle trajectories of the index finger, the corresponding force data and the motor current values. In the test, the user took about 1 second for one full close/open maneuver. At such high speed, the maximum force between the finger and the glove mechanism is less than 100 mN, which implies that the actuator compensated for the mechanism's internal friction successfully. The small contact force observed is due to the inertia and friction of the glove, but the movement of the glove is controlled smoothly. These results demonstrate that the newly designed five-fingered glove is capable of reliably modeling the hand kinematic model and measuring finger motion.

After repeatability test, the difference between each test is on the order of a few millimeters. The accuracy of the calculated finger position is limited by the following error sources:

1) The Hall effect sensors are calibrated using a 12-bit absolute encoder and have a maximum error of $\pm 1°$.
2) The length of each phalangeal segment undergoes slight change because of the soft nature of the fleshy attachment locations.
3) The base and fingertip location of the glove link (B_0 and B_3 as shown in Fig. 7) are not perfectly fixed to the hand during the test.
4) Lengths of each phalangeal segments of each finger are approximated according to [29].

5 CONCLUSIONS

This paper proposes a new method to determine finger length information and model hand kinematics in real time through a newly developed five-fingered haptic glove mechanism. The glove system architecture is also presented. This lightweight self-contained glove is adaptable to a wide variety of finger sizes without constraining the range of finger motion. With this glove system, finger length information can be acquired easily and intuitively so that the joint angle for different subjects can be calculated through forward and inverse kinematics. The finger length information is extracted from a circle fitting procedure from a collection of measured data points. The method of least squares fitting of circles is used to analyze the kinematic model. Finally, a motion sensing experiment of a human hand is presented. Compared with vision-based hand motion sensing systems, this method requires much less computational capability and leads to high update rate. It is also low cost and easy to set up and calibrate.

Future work will include improving the main control board (the custom PCB, as shown in Fig. 3) to also work as a main bracket, which supports all the motors and mechanical links. This improvement will greatly reduce the total weight and size of the device. Future work will also include adding an IMU unit to the glove system to facilitate the measurement of whole hand position and orientation such that the system can be used for rehabilitation applications or integrated with virtual reality environments.

REFERENCES

[1] Tubiana, R., Thomine, J., and Mackin. E., 1984. *Examination of the hand & upper limb*. WB Saunders.

[2] Wilson, F., 1988. *The hand: How its use shapes the brain, language, and human culture.* Vintage.

[3] Murgia, A, 2005. "A gait analysis approach to the study of upper limb kinematics using activities of daily living," PhD Thesis, University of Reading, U.K.

[4] Kobayashi, F., Ikai, G., Fukui, W., and Kojima F., 2011. "Two-Fingered Haptic Device for Robot Hand Teleoperation". *Journal of Robotics*, vol. 2011.

[5] CyberGrasp Manual, version 2.0, Immersion Corporation, San Jose, CA, 2007.

[6] Bouzit, M., Burdea, G., Popescu, G., and Boian, R., 2002. "The Rutgers master II— New design force-feedback glove". *IEEE/ASME Trans. Mechatronics*, vol. 7, no. 2, pp. 256-263.

[7] Blake, J., and Gurocak, H., 2009. "Haptic glove with MR brakes for virtual reality". *IEEE/ASME Trans. Mechatronics*, vol. 14, no. 5, pp. 606-615.

[8] Connelly, L., Jia, Y., Toro, M., Stoykov, M., Kenyon R., and Kamper, D., 2010. "A Pneumatic Glove and Immersive Virtual Reality Environment for Hand Rehabilitative Training after Stroke". *IEEE Trans. on Neural Systems and Rehabilitation Engineering*, vol. 18(5), pp. 551-559.

[9] Worsnopp, T., Peshkin, M., Colgate, J., and Kamper, D., 2007. "An Actuated Finger Exoskeleton for Hand Rehabilitation Following Stroke". International Conference on Rehabilitation Robotics, pp. 896-901.

[10] Wang, J., Li, J., Zhang, Y., and Wang, S., 2009. "Design of an Exoskeleton for Index Finger Rehabilitation". Proc. Conf. of the IEEE Engineering in Medicine and Biology Society, pp. 5957-5960.

[11] Dipietro, L., Sabatini, A., and Dario, P., 2008. "A survey of glove-based systems and their applications". *IEEE Trans. Syst., Man, Cybern.*, Part C, vol. 38, no. 4, pp. 461-482.

[12] Bianchi, M., Salaris, P., Turco, A., Carbonaro, N., and Bicchi, A., 2012. "On the use of postural synergies to improve human hand pose reconstruction". In Haptics Symposium (HAPTICS), pp. 91-98.

[13] Borghetti, M., Sardini, E.,and Serpelloni, M., 2013. "Sensorized Glove for Measuring Hand Finger Flexion for Rehabilitation Purposes". *Instrumentation and Measurement, IEEE Transactions on*, vol. 62, iss. 12, pp, 3308-3314.

[14] Liu, H., 2011. "Exploring Human Hand Capabilities Into Embedded Multifingered Object Manipulation". *Industrial Informatics, IEEE Transactions on*, Vol. 7, iss. 3, pp. 389-398.

[15] Metcalf, C., Notley, S., Chappell, P., Burridge, J., and Yule, V., 2008. "Validation and application of a computational model for wrist movements using surface markers". *IEEE Trans. Biomed. Eng.*, vol. 55, no. 3, pp. 1199-1210.

[16] Carpinella, I., Jonsdottir, J., and Ferrarin, M., 2011. "Multi-finger coordination in healthy subjects and stroke patients:

a mathematical modelling approach". *Journal of neuroengineering and rehabilitation*, 8(1), 19.

[17] Erol, A., Bebis, G., Nicolescu, M., Boyle, R., and Twombly, X., 2007. "Vision-based hand pose estimation: a review". *Computer Vision and Image Understanding* (CVIU), 108 (1–2), pp. 52-73.

[18] Gorce, M., Fleet, D., and Paragios, N., 2011. "Model-based 3d hand pose estimation from monocular video". *IEEE Trans. on PAMI*, pp. 1-15.

[19] Erol, A., Bebis, G., Nicolescu, M., Boyle, R. D., and Twombly, X., 2005, June. "A review on vision-based full dof hand motion estimation. In Computer Vision and Pattern Recognition-Workshops". CVPR Workshops, IEEE Computer Society Conference on, pp. 75-75.

[20] Pamplona, V. F., Fernandes, L. A., Prauchner, J. L., Nedel, L. P., and Oliveira, M., 2008. "The image-based data glove". In Proc. of the 10th Symposium on Virtual and Augmented Reality, SVR.

[21] Agur. A., A., and Lee, M., 1999. Grant's Atlas of Anatomy, 10th ed. Lippincott Williams and Wilkins.

[22] Ma, Z., and Ben-Tzvi, P., "RML Glove - An Exoskeleton Glove Mechanism with Haptics Feedback". *IEEE/ASME Transactions on Mechatronic*, In-Press, 2014. doi: 10.1109/TMECH.2014.2305842

[23] Kapandji, I., 2007. The Physiology of the Joints, Volume I: Upper Limb. Churchill Livingstone.

[24] Ma, Z., and Ben-Tzvi, P., "Design and Optimization of a Five-Finger Haptic Glove Mechanism". under review, Journal of Mechanisms and Robotics.

[25] RLE Progress Report No. 135, 1992, Massachusetts Institute of Technology [Online]. Available: http://www.dtic.mil/dtic/tr/fulltext/u2/a266730.pdf pp. 305.

[26] Ben-Tzvi, P., Goldenberg, A., Zu, J.W., 2010. "Articulated Hybrid Mobile Robot Mechanism with Compounded Mobility and Manipulation and On-Board Wireless Sensor/Actuator Control Interfaces", *Mechatronics Journal*, vol. 20, no. 6, pp. 627-639.

[27] Ben-Tzvi, P., 2010. "Experimental Validation and Field Performance Metrics of a Hybrid Mobile Robot Mechanism", *Journal of Field Robotics*, vol. 27, no. 3, pp. 250-267.

[28] Ben-Tzvi, P., Goldenberg, A.A., Zu, J.W., 2008. "Design and Analysis of a Hybrid Mobile Robot Mechanism with Compounded Locomotion and Manipulation Capability", *Transactions of the ASME, Journal of Mechanical Design*, vol. 130, no. 7, pp. 1-13.

[29] Buryanov, A., and Kotiuk, V., 2010. "Proportions of Hand Segments". *International Journal of Morphology*, 28(3), pp. 755–758.

[30] Bugbee, D., and Botte, J., 1993. "Surface anatomy of the hand: The relationships between palmar skin creases and osseous anatomy". *Clinical orthopaedics and related research*, 296, pp. 122-126.

[31] Chauhan, P., Kalra, S., Jain, SK.,Munjal, S., and Anurag, A., 2011. "Relationship between palmar skin creases and osseous anatomy". *J. Morphol. Sci.* vol.28, no.3, pp.184-188.

[32] Zhang, X., Lee, S. W., and Braido, P., 2003. "Determining finger segmental centers of rotation in flexion–extension based on surface marker measurement". *Journal of biomechanics*, 36(8), 1097-1102.

[33] Cameron, J., and Lasenby, J., 2008. "Estimating human skeleton parameters and configuration in real-time from markered optical motion capture". Articulated Motion and Deformable Objects, *Lecture Notes in Computer Science*, vol. 5098, pp. 92-101.

[34] Funatomi, T., Yamane, T., Ouchida, H., Iiyama, M., and Minoh, M., 2013. "Deriving Motion Constraints in Finger Joints of Individualized Hand Model for Manipulation by Data Glove". In 3DTV-Conference, 2013 International Conference on, pp.95-102.

[35] Veber, M., and Bajd, T., 2006. "Assessment of human hand kinematics". Proc. IEEE Int. Conf. Robot, pp.2966-2971.

[36] Kasa, I., 1976. "A circle fitting procedure and its error analysis". *IEEE Trans. Instrum. Meas.*, vol. IM-25, pp. 8-14.

