Towards Finger Motion Tracking and Analyses for Cardiac Surgery

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Abstract. Robot Assisted Surgery is attracting increasing amount of attention as it offers numerous benefits to patients as well as surgeons. Heart surgery requires a high level of precision and dexterity, in contrast to other surgical specialties. Robot assisted heart surgery is not as widely performed due to numerous reasons including a lack of appropriate and intuitive surgical interfaces to control minimally invasive surgical tools. In this paper, finger motion of the surgeon is analyzed during cardiac surgery tasks on an ex-vivo animal model with the purpose of designing a more intuitive master console. First, a custom finger tracking system is developed using IMU sensors, which is lightweight and comfortable enough to allow free movement of the surgeons fingers/hands while using instruments. The proposed system tracks finger joint angles and fingertip positions for three involved fingers (thumb, index, middle). Accuracy of the IMU sensors has been evaluated using an optical tracking system (Polaris, NDI). Finger motion of the cardiac surgeon while using a Castroviejo instrument is studied in suturing and knotting scenarios. The results show that PIP and MCP joints have larger Range Of Motion (ROM), and faster rate of change compared to other finger/thumb joints, while thumb has the largest Fingertip WorkSpace (FWS) of all three digits.

Keywords: Robot Assisted Surgery, Finger Tracking, Cardiac surgery

1 Introduction

Minimally invasive surgery brought a remarkable improvement over open surgery in terms of hospitalization time and patients scarring [1]. On the other hand, this method has complicated surgery performance due to a range of problems such as fulcrum effect, inaccurate scaling, and lack of precision, dexterity and intuitive handling [2] . Robot Assisted Surgery (RAS) has addressed some of these problems. Among many available robotic systems, Da Vinci is currently the only widely used in hospitals [3]. In the field of cardiac surgery, however, RAS has not been widely adopted [3] and its application is mainly limited to mitral valve repair [2–4] and in smaller extent, coronary artery revascularization [2, 3], closure of simple septal defects, tricuspid valve repair, and cardiac tumor removal [4] . In the literature, cost and steep learning curve of currently available systems are counted as reasons for this [1, 3, 5, 6]. Despite Da Vinci system with 7 DOF master station and a wide range of tools the control of fine movements required in heart surgeries is still an issue [6–8]. In addition, the lack of haptic feedback [1, 5, 7, 8] , and the system bulkiness [1, 7] motivate research on more intuitive control of the robotic surgical tools for this surgical area [8]. The most important step towards designing a teleoperation system that deals with the restricted space of heart surgeries and a finer set of motions required is to gain a thorough understanding of the characteristics of finger/ hand motions of cardiac surgeons. The characteristics of finger motion required for complex surgical tasks are necessary for developing better, more customized master-slave robotic tools for cardiac surgery. Therefore, the aim of our work is to track and analyze finger/hand motion during cardiac surgery with the purpose of extracting ROM for each finger and thumb joint as well as FWS during different maneuvers of cardiac surgery.

2 Related Works

Finger motion tracking can be implemented for many purposes such as tele–operating a robotic hand [9], or patient motion analysis in order to study diseases [10, 11]. Different methods to implement finger tracking include using: 1) Inertial Measurement Unit (IMU) based sensors [12, 13] 2) optical tracking systems [9, 11, 14–17] 3) exoskeleton based systems including anthropomorphic exoskeletons attached to fingers, or highly redundant exoskeleton attached on top of the hand and wrist [18], 4) magnetic sensing [19], 5)flex sensor based [20], and 6) fusing several methods together [21]. When it comes to surgeon fingers tracking, optical tracking methods are highly vulnerable to occlusion [22]. Exoskeleton based finger-tracking methods, on the other hand, are usually bulky for surgery, and in some models suffer from inaccuracy due to misalignments of the exoskeleton and the finger joints [18]. IMU sensors, are relatively small, lightweight and occlusion free method of acquiring three rotation angles for each link of the hand/finger. Nevertheless, their values might drift after a while, and experience some magnetic interferences.

Hand motion analysis is a useful tool in different applications. Researchers in [21] analyzed three different methods of data glove, force sensors and EMG sensors in order to study human hand motion. The hand motion analysis is typically used to study physical impairments [10, 11], electrical stimulation of hand [15], analyze joint loads [16], gestures [23], or to find comfort zone of fingers when interacting with smartphones [17] .

Surgical tool tracking has already been studied in the literature using either 2D or 3D image processing [24], or mounting optical tracking markers [25]. Therefore, it is apparent that developing a reliable platform for analyzing finger motions is necessary.

Our Contributions: We propose a tracking system customized for hand tracking of surgeon which is occlusion-free, precise and lightweight to collect data during specific cardiac surgery tasks. We have identified ROM and FWS of the three digits (Middle, Index and thumb) in different stages of the surgery.

3 Hand kinematic Model

In order to study hand/finger motions, a good understanding of biomechanics of hand is essential. A full hand consists of 27 bones including fingers, thumb, palm, and wrist [22]. Each finger is comprised of three parts of bones called phalanges. Fingers are attached to Metacarpals through Metacarpophalangeal (MCP) joint, which is followed by Proximal interphalangeal joint (PIP) and Distal interphalangeal joint (DIP). Thumb, however, which plays a crucial role in human manipulation capability, consists of two phalanges followed by a Metacarpal bone attached to Carpus [18]. Various approaches have been put forward to model hand/finger kinematics [26, 27]. In this study, we are mainly interested to model middle finger, index finger and thumb, therefore we utilize simple model proposed in [27] , which can be seen in Fig.1.

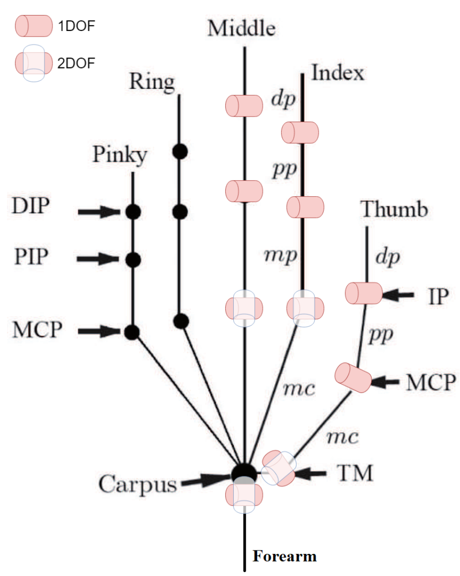


Fig. 1. Finger joint models used in our method

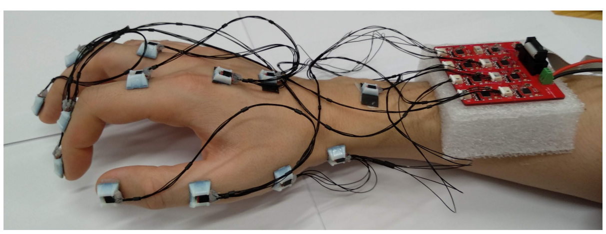
As it can be seen in fig.1, DIP and PIP joints in index and middle fingers as well as IP and MCP joints in thumb all have one revolute joint, whereas MCP and CMC joints have two DOF revolute joints. We measure absolute orientation of each phalange by a single IMU. Therefore, the joint angles can be calculated by simply subtracting the orientation of two consecutive IMU sensors. Sensors are aligned with the finger/thumb lengthwise (Y axis) while the sensors Z axis is perpendicular to the the fingers/thumb. Let us assume ϕ,θ, ψ for rotation around Z, Y and$X$ axis, respectively. Therefore, for instance, ϕ_{MCP} and θ_{MCP} which show ϕ and θ angles for MCP joints, can be calculated as follows:

$$\phi_{MCP} = \phi_{MC} - \phi_{MP}, \theta_{MCP} = \theta_{MC} - \theta_{MP} \tag{1}$$

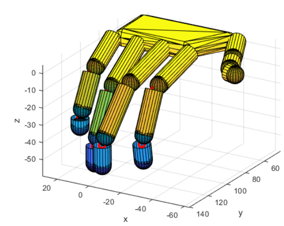
Having all the required joint angles allow calculation of fingertip positions for the two fingers and the thumb using forward kinematics [26]. DenavitHartenberg (DH) parameters of the fingers and the thumb and forward kinematics calculations are used according to SynGrasp toolbox [28].

4 Experimental setup

The tracking system consists of 10 BNO055 IMU sensors (4 on the thumb and 3 on index and middle fingers). IMU sensors are connected to an acquisition board comprised of multiple Microprocessor Units (MCU) running Arduino firmware. Each MCU connects to two IMU sensors on a single I2C bus. Orientations from each sensor are sent to the computer with frequency of 50Hz through a serial port. Fig.2 shows the experimental implementation of the data acquisition system.



(a) Our custom Hand Tracking system.



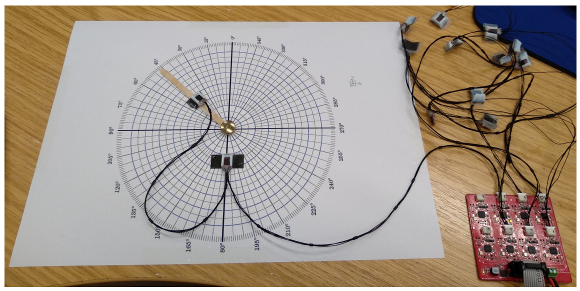
(b) Reconstructed model of the hand in computer.

Fig. 2. Experimental setup for hand/finger tracking.

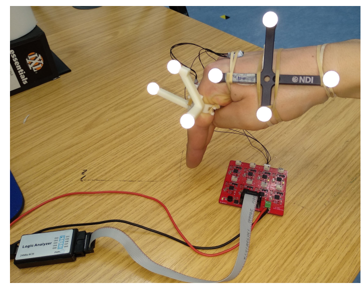
In addition to the sensors internal calibration process, we remove the offset by measuring the angle values at the beginning of the test.

4.1 Accuracy assessment of IMU finger tracking system

In order to validate accuracy of the hand tracking system,, digit orientations and joint angles estimated by the IMUs were compared to a ground truth. As it can be seen in Fig.3a, an angled circle is used as a ground truth to test the accuracy of IMU sensors for each orientation. Results show that average error is 4.1° with a standard deviation of 2°. Researchers in [12] assessed accuracy of the same sensors in a planar pose and reported average error of $3° \sim 6°$ with standard deviation of 1.7° for different angles. The researchers in [13] reported in Static angle errors of $\leq 2°$ for their developed IMU-based hand tracking system.



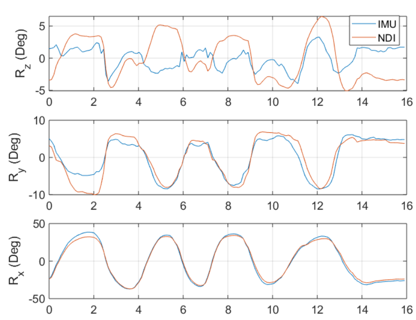
(a) Accuracy assessment setup in planar mode.



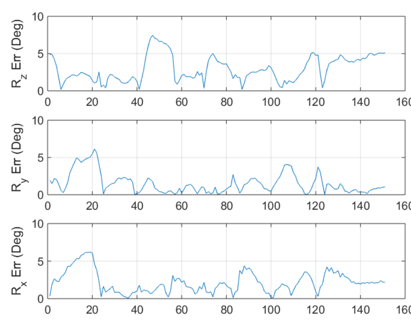
(b) Accuracy assessment in 3D space.

Fig. 3. Accuracy assessment setup.

In addition, a dynamic angle verification was carried out using Polaris Spectra system (NDI) to verify the accuracy of the tracking system. A custom tool with markers (Fig.3b), which also houses IMU sensors, is designed and attached to the Index finger, and orientations were measured relative to the marker and the sensor fixed on the palm. Fig.4 shows simple flexion extension movements of the index finger and their corresponding error values. According to experimental tests, the measurement error is less than 8° for rotating around Z, Y and X axis of the sensor.



(a) Finger joint angles extracted from IMU sensors and NDI Polaris system.

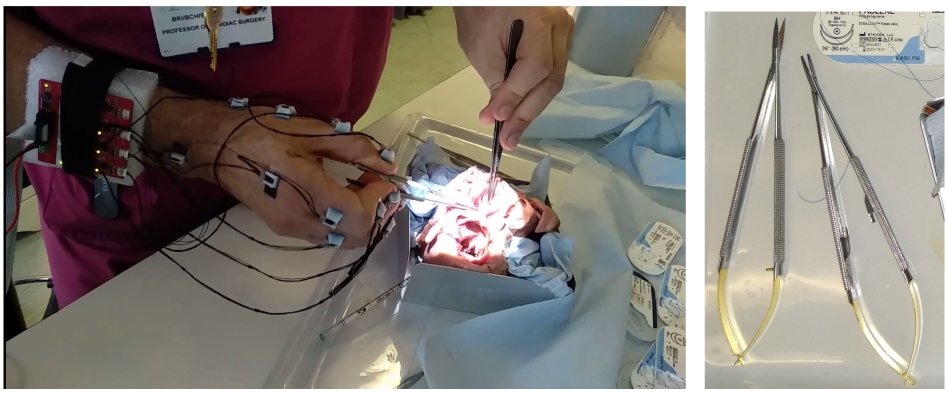


(b) Joint angle error with respect to NDI Polaris system.

Fig. 4. Finger motions: Flexion, Extension. IMU sensors compared with NDI Polaris motion capture system.

4.2 Cardiac Surgery data collection

An experienced cardiac surgeon performed typical mitral valve surgery and aorta suturing tasks on an ex-vivo pigs heart specimen with the tracking system fitted to his hands, as as shown in Fig. 5. The tasks were performed using 7” Castroviejo Needle Holder Plier Straight and 7” Castroviejo Micro Scissor.



(a) Finger/Hand data collection using our developed system during the Mitral Valve surgery.

(b) A set of Castroviejo instruments used in the experiment.

Fig. 5. Cardiac surgery data collection setup and instruments.

4.3 Results and discussion

ROM and FWS are two important features of finger motion. They were extracted in [11] and [15] in order to study human functional abilities and to explore hand grasp patterns, respectively. In our study, ROM for each joint of the surgeons fingers has been extracted and is shown in Table.1. Fig. 6,7,8,9 demonstrate joint angles for a sample suturing operation.

Table 1. Range of motion (ROM) for surgeons fingers. (Degrees)

Action Type	Index DIP	Index PIP	Index MCP		Middle DIP	Middle PIP	Middle MCP		Thumb DIP	Thumb MCP	Thumb CMC		Wrist	
IMU angle	ϕ	ϕ	ϕ	θ	ϕ	ϕ	ϕ	θ	ϕ	ϕ	ϕ	θ	ϕ	θ
Knotting	23	40	30	10	50	85	60	21	35	38	25	15	25	41
Suturing	15	25	19	12	39	60	55	30	22	15	15	20	45	45

* ϕ stands for flexion–extension movement of fingers, whereas θ stands for abduction movements.

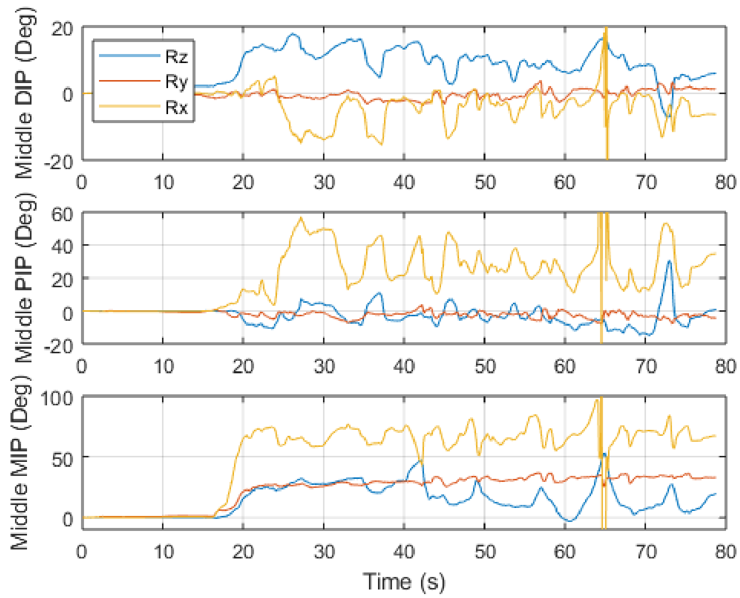


Fig. 6. Middle finger joint angles

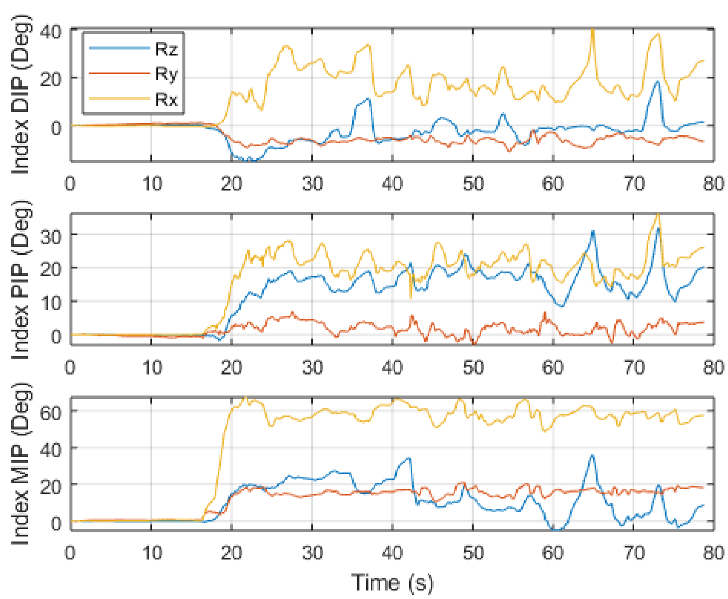


Fig. 7. Index finger joint angles

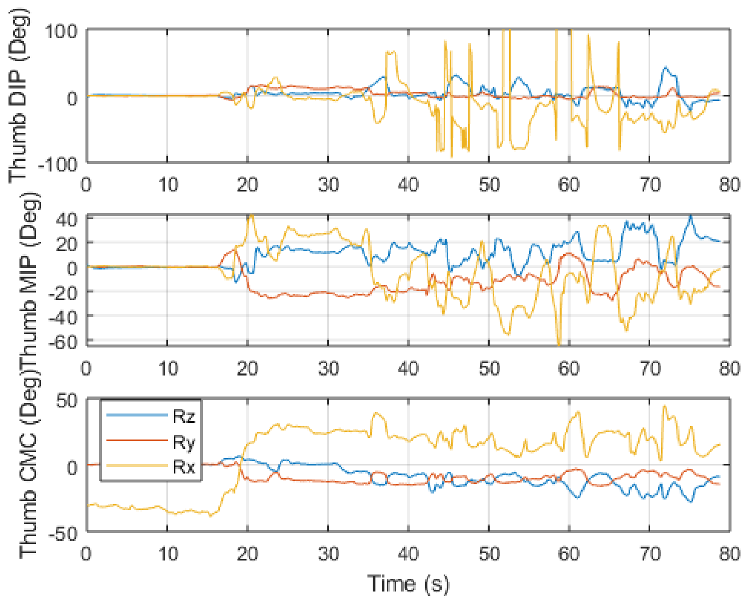


Fig. 8. Thumb joint angles

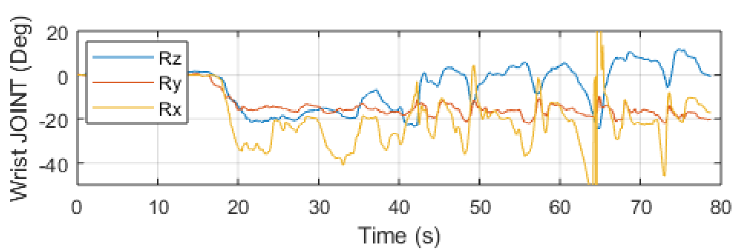


Fig. 9. Wrist joint angles

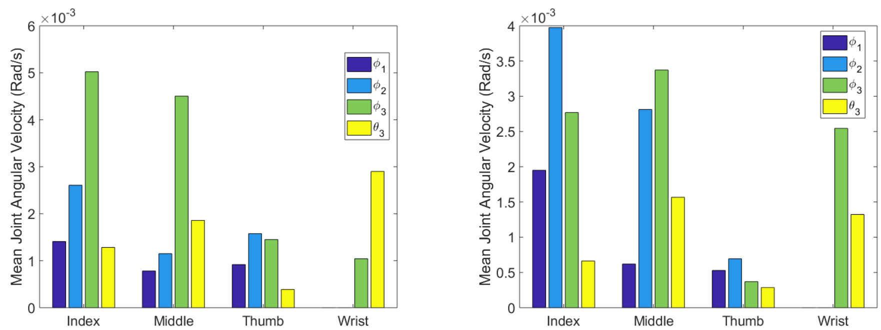
Rate of change is another valuable characteristic of finger joint motion which demonstrates how fast each joint is moving. Assuming $\phi_{[n]}$ as a discrete–time series of joint angles, the angular velocity (ω) is calculated as follows.

$$\omega_{[n]} = (\phi_{[n]} - \phi_{[n-1]})/Fs \tag{2}$$

Where Fs =50 is the sampling frequency. Now, the average angular velocity (ω_{avg}) of a series with N samples is calculated as follows:

$$\omega_{avg} = 1/N \sum_{n=1}^{N} \omega_{[n]} \tag{3}$$

Fig. 10 shows rate of change for two different surgical scenarios. In addition, FWS during the surgery is shown in Fig.11 .



(a) Knotting. (b) suturing.

Fig. 10. Mean rate of change for each joint (joints are numbered from 1 for DIP joint).

A close look into the ROM results show that MCP and PIP joints in middle finger have a relatively higher range of motion compared to others. Furthermore, according to Fig.10, PIP and MCP joint are the ones that are changing fastest. Finally, Fig.11 shows that FWS for the thumb has larger space compared to the middle and index fingers.

5 Conclusion

In this paper, motion of the fingers and the thumb during typical cardiac surgery tasks was studied. A custom IMU–based finger tracking system has been developed which is lightweight, comfortable, and precise enough to track the surgeons finger motions. The captured data during the heart surgery shows that PIP and MCP joints are moving faster and more than the other tracked joints. In addition, the thumb has larger FWS in this study. The outcome of this research will

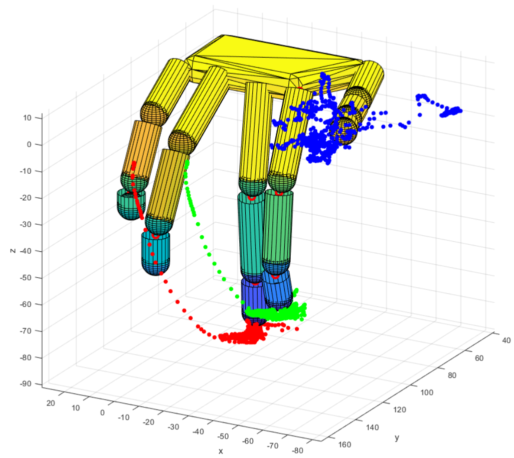


Fig. 11. Fingertip position during the suturing process with Castroviejo tool

be further utilized in designing a new intuitive way of controlling tele–operated surgical robot tools for heart surgeries. In future steps, surgical tools will also be monitored and their motion analyzed together with finger/thumb motions.

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