A LOW COST WEARABLE WIRELESS SENSING SYSTEM FOR CAPTURING HUMAN ARM POSTURES IN POST-STROKE REHABILITATION

Chee Kian Lim, I-Ming Chen, Zhiquiang Luo, Song Huat Yeo
School of Mechanical and Aerospace Engineering, Nanyang Technological University
50 Nanyang Avenue, Singapore 639798
Singapore
limck@pmail.ntu.edu.sg

ABSTRACT
Being able to track human body kinematics allows clinicians to classify and analyze a stroke patient’s progress which aid in the rehabilitation program. Monitoring and capturing real time body motion further permits corrective measures to be implemented for more effective rehabilitation results. Existing motion capture (mocap) system available in the market is either too costly, or complicated and bulky to be efficiently employed for personal use. In this current work, an innovative and unobtrusive wearable sensing system is being proposed. This compact and cost effective mocap approach effectively captures human joint angles and does that hinder limb motion as commonly encountered in other existing systems. The paper details the design and implementation of the proposed sensor and sensing methodology. The tested wireless sensor is able to detect the posture and movement of the human arm with particular attention to its application in post stroke rehabilitation for the healthcare service. Real time experimental data are collected from a subject using a hand exerciser and compared with a commercial motion capture system. The results demonstrate the feasibility and viability of the proposed sensing system in tracking human arm postures and movement.

KEY WORDS
Low cost wearable system, motion capture, rehabilitation

1. Introduction
Stroke involves the sudden loss of brain functions due to certain disturbances in the blood supply to the brain. It also results in inability of limb movement, loss of speech or vision functions due to the death of associated brain cells [1]. Recent evidence has demonstrated that intensive and repetitive practice is effective in the recovery of functional motor skills [2]. However, such effect requires extensive medical exercise and patient’s own sustainable motivation. Thus, how to effectively regain the motion function of stroke patient becomes an important research topic [3].

Rehabilitative therapy is essential to the treatment process to help stroke survivors regain their limb functions. The most common objective of stroke rehabilitation is to achieve a level of physical and psychological functioning that allows patients to return home and perform everyday activities. Rehabilitation exercises are thus specifically designed to match the goals of each individual. Study in [4] shows that the trajectories of upper extremity of stroke patients are characterized by increased movement variability, increased motion segmentation, and by spatial and temporal coordination in comparison with healthy people. In addition, recovery from the stroke has strong correlation with the smoothness of upper extremity motion [5]. Upper limb motor recovery during post-stroke rehabilitation can be also improved by iterative training of simple, isolated and single joint movement [6]-[9]. During stroke rehabilitation, doctors would like to assess human body gestures in order to perceive joint motion during activities of daily living in patients with movement disorder. Examination on the performance of their upper extremity motion when patients do simple tasks is crucial in effectively designing and appraising rehabilitation therapy and treatments for upper limb movement disorders. For example, Constraint Induced Movement Therapy (CIMT) requires stroke patients to undergo functionally relevant repetitive task practice with the paretic limb that includes shaping procedures for up to 6 hours each week day [10].

Commercial mocap systems are widely available in the market. For example the inertial-based mocap system like IGS-190 from Animazoo and MVN from Xsens, optical-based system like Vicon and OptiTrack, fiber-optical system like ShapelWrap from Measurand and Data Glove from 5DT. Each system has their pros and cons with a common shortfall in providing ease of use due to the interfacing suit requiring elaborate preparation and calibration. Furthermore with the intended interface suit, it impedes free movement of the limbs that translates to already restricted motion of the user. Apart from the complexity in the implementation of the above mentioned systems, cost inhibits the prospect of employing such systems for personal use. Henceforth, this work embarks on the design of a compact sensing module that is able to detect the angular joint angles of the human limbs. The wearability of the proposed mocap system is further enhanced with the innovative use of plasters that adheres and conforms to the human skin. Application of the
sensor module is simply by pasting the adhesive plaster on the intended location of the human limb. This novel and localized approach resolves the inherent issue of using an interface suit that hinders motion highlighted previously.

In the subsequent sections, the design of the sensor module and its sensing principle is expounded. The packaging of the sensor along with the new plaster-based design will be illustrated. Following that, sensor network communication and software architecture employed in the proposed system is discussed. Last but not least, the results from real-time capture of the intended shoulder and elbow joint angles using the proposed sensing system will be presented with conclusions drawn from the comparison to an existing mocap system.

2. Sensor Module

The wearable sensor module consists of an Optical Linear Encoder (OLE), an accelerometer, a Digital Signal Controller (DSC), and a CAN controller. The OLE module is able to measure joint angles. The accelerometer gives the orientations of the limb segment on which the sensing module is mounted. The electrical block diagram and the actual component circuit of the sensing module are depicted in Fig. 1 (a) and (b) respectively.

2.1 Optical Linear Encoder (OLE)

A miniature optical linear encoder is mounted below the sensor board as shown in Fig. 1(b). The novelty behind this setup is such that the sensor head is fixed with the linear encoder strip as the moving element. This has significantly improved the robustness and performance of the OLE sensor and also provided unlimited sensing range. The base structure guides the encoder strip to traverse and maintain a constant gap between the encoder strip and the sensing head. The OLE consists of an infra-red emitter and a receiver built in a single package [12], [13]. The infra-red light from the emitter is reflected off the reflective encoder strip and the receiver converts the reflective light information into the number of pulse counted indicating the distance travelled. Each pulse from the linear encoder represents a distance of 0.1mm between the lines. Therefore coupling the encoder strip together with the emitter and the receiver, displacement information can be acquired.

In order to obtain the angle of a human joint (e.g. elbow), the sensing module is attached on one’s limb segment (e.g. the upper arm) via a plaster. The schematic of this innovative design is presented in Fig. 2. The key advantage of this approach is that it does intervene and restrict the limb movement during operation. Being compact and light further enhances the user experience.
and comfort even during extended use.

The linear encoder strip slides freely along its longitudinal axis on the human arm. As the elbow bends, the plaster design engages the linear encoder strip pulling it along. This displacement, Δx, is captured via the sensor head as illustrated in Fig. 3. Since,

$$\Delta x = D$$

and circular arc’s length is expressed by,

$$\Delta x = \frac{\alpha}{360^\circ} \cdot 2\pi R$$

The joint angles can be estimated with the linear displacement information using equation (3) as follows,

$$\alpha = \frac{D}{R} \cdot \frac{360^\circ}{2\pi}$$

(3)

The radius of the elbow joint, R, is assumed to be constant as the encoder strip envelops round the intended joint. Since biometric data, such as bone length and structure and skin characteristics, varies from person to person, calibration of the motion capture process is required. A scale factor (SF) is inserted into the equation (3) to compensate for these biometric parameters,

$$SF(D_c) = \frac{D_c}{R} \cdot \frac{360^\circ}{2\pi}$$

(4)

$$SF(D_c) = \frac{D_c}{D_c} \cdot \frac{360^\circ}{2\pi}$$

(5)

The scale factor is determined by a calibration process,

- Joint poses predefined gestures (αc = 0°, 30°, 60°, 90°, etc).
- Dc, the distance travelled by the encoder, is recorded from the OLE readings.
- SF(Dc) is computed by equation (5), with known αc and Dc.
- A look-up table is formed by the pairs of SF and Dc. Thus when using (4) to calculate the actual joint angle, SF(Dc) with respect to each value of Dc = D is interpolated from the table using Catmull-Rom spline [14].

2.2 Accelerometer

In static condition of accelerometers, the gravity vector is composed by the three orthogonal accelerations [15]. Hence, pitch and roll angles in the global coordinate can be expressed as,

$$\theta = \sin^{-1} \left( \frac{a_x}{g} \right), \phi = \sin^{-1} \left( \frac{a_y}{g \cdot \cos \theta} \right)$$

(6)

Where \([a_x, a_y, a_z]^T\) is the gravity vector measured in its local coordinate.

3. Kinematics Model of Arm

In this work we assume human arm activities as articulated motions of a rigid link-joint mechanism. A 7-DOF model is utilized to kinematically describe the transformation of human arm movements. Fig. 4 illustrates the coordinate frames established by using the Denavit-Hartenberg (D-H) parameters. With reference to Fig. 4, frame 0, frame 1 and frame 2, having a common origin represent the 3 DOFs of the shoulder joint. Frame 3 denotes the center of the elbow joint. Similarly, frame 4, frame 5 and frame 6 describe the wrist joint. The transformation matrix from frame \((i-1)\) to \(i\) is formulated, based on the coordinate arrangement depicted in Fig. 4 as,

$$T_{i-1}^{-1} = \begin{bmatrix} c_{\theta_i} & -c_{\alpha_i} s_{\theta_i} & s\alpha_i s_{\theta_i} & a_i c_{\theta_i} \\ s_{\theta_i} & c\alpha_i c_{\theta_i} & -c\alpha_i s_{\theta_i} & a_i s_{\theta_i} \\ 0 & s\alpha_i & c\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(7)

where \(\theta_i\) is the joint angle from the \(x_{i-1}\) axis to the \(x_i\) axis measured about \(z_{i-1}\) axis; \(d_i\) is the distance between frames \(i-1\) and \(i\); \(\alpha_i\) is the distance from the intersection of \(z_{i-1}\) axis and \(x_i\) axis to the \(i^{th}\) frame; and \(a_i\) is the offset angle from \(z_{i-1}\) axis to \(z_i\) axis measured about \(x_i\) axis. Specific values of these D-H parameters are listed in Table I. This kinematic model allows us to compute the translation of any frame with respect to any other frame, as long as the parameters \(\theta_i, d_i, \alpha_i, \) and \(a_i\) are known, by the kinematic equation as follows,

$$T_n = T_{n-1}^{-1} T_{n-2}^{-1} \cdots T_1^{-1}$$

(8)

3.1 Graphical User Interface

A rigid link-joint arm is modeled in the simulation environment providing user with a visualization of the arm posture and movement as presented in Fig. 5. The joint angles can be displayed real-time via the Information Window. In addition to showing the current joint angle, the program also records all joint angle information into a text file for further analysis.
4. Sensor Network Communication

To capture the motion of human arm, three sensing modules and a Data Concentrator are connected to form a sensor network. Two versions of body sensor network were developed: one uses by CAN bus for data transmission; and the other communicates by a wireless protocol. The CAN bus version is used in the applications where fast data transmission is required (raw data sampling is performed at constraint in the transmission speed, the wireless version limits the sampling rate at 25Hz, and is relevant to the applications where motion analysis is performed in an off-line manner.

4.1 Communication via Wireless Network

The wireless sensing nodes are necessary because of their potential use in standalone applications. The sensor is controlled by a 16bits microcontroller dsPIC33F32MC204 of Microchip. This controller has rich peripherals to interface with various sensors. The OLE is connected to the Quadrature Encoder Interface (QEI). The accelerometer is connected to the SPI. The microcontroller samples every sensor by interrupt. The OLE is sampled by QEI interrupt, while a timer interrupt samples the accelerometer signals. In this way, each sensor is sampled by a specific interrupt routine. After each sample, the latest sensor readings are stored in the microcontroller memory. When sensor node sends out the sensing data, it looks up the memory and acquires data from there. By using a 2.4GHz radio transceiver CC2420, the sensor is able to communicate with base station wirelessly through IEEE 802.15.4 MAC protocol. The microcontroller talks to CC2420 through SPI.

The base station consists of the RF station and one USB virtual serial adapter. The RF station is controlled by a MSP430F1612 ultra-low power microcontroller from Texas Instrument that operates with TinyOS. CC2420 is used for wireless communication. The USB adapter converts the USB port into a virtual serial port, so that the application device, such as PC and PDA, could talks to base station through normal COM port setup. The wireless communication between sensor nodes and the base station (at application device) is through 2.4GHz radio using IEEE 802.15.4 Media Access Control layer. Every sensor node talks to the base station through a star topology as shown in Fig. 6.

5. Software Architecture

The software in PC comprises four layers, data collection, data organization, simulation engine, and interface as depicted in Fig. 7. In general, the data collection performs the task to acquire sensor data through the wireless (RF) communication. The data organization performs two tasks: (a) mapping the sensor data into the constructed arm model and (b) forming the data structure for the simulation. The simulation engine includes both the rendering engine and the physics engine. The rendering engine, employing the OpenGL technique as the core function library, is responsible for rendering all objects in the simulation; while the physics engine, employing the ODE (Open Dynamic Engine) library to perform the collision detection and control the arm dynamics, is responsible for controlling the object’s dynamics movement. These two engines receive the data from the data organization layer and work with each other to create a simulation environment. The interface is to show the simulation window, information window and other GUI elements, which is useful for the user to interact with the simulation.
6. Experimental Investigation

In order to validate the feasibility and viability of the proposed sensing system for capturing human arm postures for rehabilitation, we embarked on a simulation that replicates stroke patient using the arm exerciser as shown in Fig. 8. The motorized exerciser is able to guide the arm along a predetermined trajectory at various angular velocities.

The objective is to acquire both the shoulder and elbow joint angles for tracking and computation of any instantaneous arm posture. As illustrated in Fig. 9 showing the side profile of the skeletal view of a right arm, with both the joint information, arm posture can be mapped out accordingly. As expounded in the preceding sections, the accelerometer is able to detect the pitch and roll angles with the OLE inferring to the joint angle that it is capturing. Hence by employing a single unit of the proposed sensing module, we are able to acquire both the desired joint angles in this experiment and we coined this scheme as the “Armsuit”.

Tests were conducted for 30 cycles each at four angular velocity, 30rpm, 40rpm, 50rpm and 60rpm. Subject starts the cycle at an initial position and recording of both angles are stored in the PC. Fig. 8 and 9 presents the shoulder and elbow joint angles correspondingly. From the data log, we are able to determine the frequency of each plot and verified with the input angular velocity. The graphs in Fig. 10 and 11 also validated the consistency and repeatability of the sensor in capturing the planned joint angles.

The capability and performance of the Armsuit is benchmarked against a commercial inertial-based mocap system, IGS-190 by Animazoo as shown in Fig. 8(b). The same subject undergoes the exact sequence as the Armsuit experiment and the matching angles are compiled and compared. The results for the 40rpm run are depicted in Fig. 12 and 13. The elbow joint angle measurement matches well by both systems in terms of the range of its magnitude. The accuracy displayed by both systems can be credited to the single-degree-of-freedom elbow joint allowing accurate and direct measurement. One may observe that for the shoulder joint measurement, there is discrepancy in terms of the lower extremity of the captured results. This can be attributed by the inherent characteristics of the IGS-190 inertial-based system where the 19 inertial gyros are located on predetermined positions on the bodysuit. Readouts of the sensors are mapped to the Biovision Hierarchy (BVH) architecture.
where the joint angles are being computed. These joint angles are based on the respective skeleton joints location approximated by the user during the calibration phase. Since these joint locations are estimated, there will be intrinsic errors during the calculation of the joint angles. Further to that, as the shoulder joint essentially possesses three-degrees-of-freedom and when the arm is moving along the designated trajectory of the exerciser, the gyros on the suit along the arm actually transverse out of plane. This too contributes to the consistent difference between the shoulder joint angles by the two systems.

The distinction between the proposed sensing system, Armsuit, as compared to the IGS-190 will be that joint angles are measured directly whereas for IGS-190, joint angles are inferred from the approximated skeleton hierarchy information. The feasibility of employing the proposed sensing system for human arm postures detection is validated via the experimental results. The system demonstrates good performance in terms of the accuracy of the angle measurements and repeatability under various dynamic conditions. Due to its novel and direct acquisition of the desired joint angles, a low cost sensing system for capturing arm postures is realized.

7. Conclusion

A wearable wireless sensing system for capturing human arm postures in post-stroke rehabilitation was proposed, designed and assessed in this paper. The described system includes an accelerometer and an OLE sensor that is innovatively packaged in a plaster-based design translating to the following advantages:

1. System is compact, lightweight and does not restrict motion and plaster conforms and adheres to human skin even during stretch.
2. System is easily attached onto arm with minimal external assistance.
3. Modular design allows sensors to be attached and remove from plaster after use promoting better hygiene for patients.
4. Affordable, low cost and effective system for personal/home use.

The performance of the proposed system was established against a commercial mocap system showing good accuracy and repeatability. With this low cost proposition, stroke patients can utilize this system at the comfort of their home with doctors and clinicians monitoring their progress or rehabilitation session remotely.
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