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Strategies in vibrotactile feedback for improved upper arm posture mapping and replication using inertia sensors

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Abstract—Posture measurement and correction using inertia sensors are finding applications in rehabilitation as well as in human robot interaction systems. This paper presents two designs of arm posture mapping and replication system using inertia sensors and vibrotactile feedback device. The designs differ in the number of vibrotactile actuators and the vibration feedback pattern used. User performance in replicating arm postures when using the different systems were compared. Results show that using fewer vibrotactile actuators to provide feedback is feasible and that a more informative vibration feedback pattern could improve user response time in replicating reference arm postures.

I. INTRODUCTION

Inertia sensors are gaining traction as measuring device of motion and posture due to its small size and high accuracy. It has found applications in measuring full body motion [1], [2], [3] and in determining gait kinematics [4]. It has also been used in modeling humans in virtual applications [5], and in evaluating swimmer performance [6].

The sensor is popular in medical applications, both as a posture measuring device and as rehabilitation tool. For example, Alahakone et al. used inertia sensors to measure trunk posture [7]. In [8], Keikkers et al. detected and assessed the severity of Parkinson's disease [8]. In [9], hemiparesis was quantified using inertia sensors by measuring the hand path in pointing tasks. As a rehabilitation tool, the sensor has been employed for limb motor rehabilitation [10], [11], for detecting and preventing fall [12], and for detecting and aiding treatment of idiopathic scoliosis [13].

Key to maximizing the effectiveness of posture measurement is the use of effective feedback, especially in medical applications as it has been shown to improve chances of patient recovery [14]. Feedback takes the form of visual, audio, and tactile mode, or any of their combinations. Giansanti et al. [15] used audio feedback to help patients adjust their trunk posture. A combination of audio and visual feedback coming from a teacher, together with a robotic suit and tactile feedback, was employed in [16] to guide the movement of the upper limb. In [17] and [18], visual and tactile feedback were used to guide users in replicating the target arm posture. In [19], only vibrotactile was used to improve dynamic gait of the elderly.

In a multimodal feedback system, each modality should be designed so as not to confuse the user. The works above have demonstrated the strength of using the correct feedback in order to achieve the system's designed tasks.

(a) Inertial measurement unit (b) IMU sensors and vibrotactile feedback unit strapped on the arms.

Fig. 1. The IMU and the positioning of the sensor and the feedback unit on the arms.

In this paper, we present an upper arm posture replication system that uses inertia sensors to measure posture and vibrotactile actuators to provide feedback to the user. We compare two strategies of correcting posture with the corresponding designs of vibrotactile feedback that optimizes the number of actuators required while giving the same amount of information to the user. The main contribution of this paper is a protocol in measuring arm posture DOFs that requires only two inertia sensors and vibrotactile actuators.

The rest of the paper is organized as follows. Section II presents the posture measurement system and two strategies of using the vibrotactile feedback. In Section III, the experimental set-up for correcting the arm posture using seven subjects is presented. Section IV compares the experimental results of using the two strategies in posture correction and Section V concludes the paper and discusses future work.

II. SYSTEM DESIGN

A. Working principle of the IMU sensor

Each inertia measurement unit (IMU) outputs measurements in three dimensions. The roll (φ) of the unit is defined as the angle of the x-axis parallel to the ground. The pitch (ρ) is the angle of the y-axis parallel to ground. The yaw (θ) is the angle of the z-axis, which is in the same direction as gravity. The IMU is shown in Fig. 1(a) and its specifications are provided in Table I.

Each IMU sensor has an accelerometer, a magnetic sensor and two gyroscopes inside. The orientation of the IMU, $[\varphi_{acc}(t) \ \rho_{acc}(t) \ \theta_{acc}(t)]$, is derived from the integration of the angular velocities $[\omega_x \ \omega_y \ \omega_z]$ about the three axes of the gyroscope. They are numerically approximated, given the angular value at $(t - 1)$ and Δt , as follows:

(a) Two vibrotactile actuators (tac-tors) compared in size to a Singaporean dollar coin. (b) Design of the vibrotactile unit using feedback strategy 1. The tacto positions are encircled. (c) Design of the vibrotactile unit using feedback strategy 2. The tacto positions are encircled.

Fig. 2. The vibrotactile actuators and the two designs of the vibrotactile units.

TABLE I
IMU SPECIFICATIONS.

DOF	3 (roll, pitch, yaw)
Angular Range	360° (3 axes)
Accuracy	1° (yaw); 0.40° (pitch and roll) at 25°C
Angular Resolution	0.01° RMS
Update Rate	180Hz
Minimum Latency	2ms (RS-232)
Size	36.6 mm × 27.7 mm × 18.8mm
Power Supply	6V DC
Power Consumption	40 milliamps

$$\begin{aligned}
 \varphi_{gyro}(t) &= \omega_x(t-1) + \omega_x \Delta t \\
 \rho_{gyro}(t) &= \omega_y(t-1) + \omega_y \Delta t \\
 \theta_{gyro}(t) &= \omega_z(t-1) + \omega_z \Delta t
 \end{aligned} \quad (1)$$

After correcting for the gyroscope integration error, we finally obtain the rotation matrix:

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \quad (2)$$

where

$$\begin{aligned}
 r_{11} &= \cos(\varphi) \cos(\rho) \\
 r_{12} &= -\sin(\varphi) \cos(\theta) + \cos(\varphi) \sin(\rho) \sin(\theta) \\
 r_{13} &= \sin(\varphi) \sin(\theta) + \cos(\varphi) \sin(\rho) \cos(\theta) \\
 r_{21} &= \sin(\varphi) \cos(\rho) \\
 r_{22} &= \cos(\varphi) \cos(\theta) + \sin(\varphi) \sin(\rho) \sin(\theta) \\
 r_{23} &= -\cos(\varphi) \sin(\theta) + \sin(\varphi) \sin(\rho) \cos(\theta) \\
 r_{31} &= -\sin(\rho) \\
 r_{32} &= \cos(\rho) \sin(\theta) \\
 r_{33} &= \cos(\rho) \cos(\theta).
 \end{aligned} \quad (3)$$

The commercial IMU units used for the experiments has a built-in capability to correct for deviations due to magnetic field distortions. However, to ensure proper working the IMUs must be used away from sources of strong magnetic fluctuations.

B. Arm model

The arm is divided into two sections, the upper arm and the forearm, and each has a distinct curvature and range of motion. The arm motion, particularly of the elbow and wrist, can be modeled as a compound flexible pole (CFP). A flexible

pole is capable of bending and rotation in three dimensions with no significant deformations along its length. The CFP model is effectively massless for orientation measurements.

Each arm is attached with the inertia sensor as shown in Fig. 1(b). This arrangement enables measurement of the whole arm at two strategic points: the shoulder and the wrist, separated by two flexible poles capable of rotation, flexion-extension, and lateral bending. Thus, the arm motion can be expressed in the more intuitive form of rotation, flexion-extension and lateral bending.

The orientation of upper arm is derived from the elbow measurements $[\varphi_u(t) \ \rho_u(t) \ \theta_u(t)]$. We write the positions of the elbow (x_u, y_u, z_u) and the wrist (x_f, y_f, z_f) as:

$$\begin{bmatrix} r_{11}^u & r_{12}^u & r_{13}^u & 0 \\ r_{21}^u & r_{22}^u & r_{23}^u & 0 \\ r_{31}^u & r_{32}^u & r_{33}^u & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L_u \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} x_u \\ y_u \\ z_u \\ 1 \end{bmatrix} \text{ and } \quad (4)$$

$$\begin{bmatrix} r_{11}^f & r_{12}^f & r_{13}^f & x_u \\ r_{21}^f & r_{22}^f & r_{23}^f & y_u \\ r_{31}^f & r_{32}^f & r_{33}^f & z_u \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} L_f \\ 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} x_f \\ y_f \\ z_f \\ 1 \end{bmatrix} \quad (5)$$

where L_f is the length of the forearm and L_u is the length of the upper arm.

Moreover, given that the upper arm and the forearm forms a triangle with vertices at the wrist, elbow, and shoulder:

$$x_f^2 + y_f^2 + z_f^2 = L_u^2 + L_f^2 - 2L_u L_f \cos(\gamma_e) \quad (6)$$

The joint angle of the elbow γ_e is:

$$\begin{aligned}
 \gamma_e(t) &= \arccos(-\cos(\theta_f(t) - \theta_u(t)) \cos(\rho_f(t)) \cos(\rho_u(t)) \\
 &\quad - \sin(\rho_f(t)) \sin(\rho_u(t)))
 \end{aligned} \quad (7)$$

The joint angle of elbow γ_e is directly related to the orientation of the upper arm $[\rho_u(t) \ \theta_u(t)]$ and the forearm $[\rho_f(t) \ \theta_f(t)]$.

Fig. 3. The overview of the arm posture correction method using only vibrotactile as feedback.

C. Posture measurement unit

To measure arm posture, we use state-of-the-art inertial measurement unit (IMU) from InterSense (MA, USA) (see Fig. 1(a)), which are mounted on the arm of the subject. Each IMU is a miniature gyro-enhanced Magnetic, Angular Rate, Gravity (MARG) system. It has a total of nine degrees-of-freedom (DOF): 3 DOF linear accelerations (from the 3-axes accelerometers), 3 DOF angular velocities (from the 3-axes gyroscopes) and 3 DOF magnetic data (from the 3-axes magnetometers). Each unit provides drift-free orientation as well as calibrated accelerations, angular velocities (from 3-axis gyroscopes) and magnetic data. The IMUs compensate for drift errors by using Kalman Filter and the magnetic north and the gravity vectors as references.

D. Vibrotactile unit

The vibrotactile unit incorporates vibrotactile actuators (tactors) (see Fig. 2(a)), where each one could correspond to a DOF being measured (i.e., roll, pitch, and yaw of the forearm or the upper arm) depending on the feedback strategy. The complete units, depending on the feedback strategy, are shown in Fig. 2(b) and Fig. 2(c). The tactors are mounted on a sports band with a minimum distance between tactors maintained for optimal perception. The circuit board containing the microcontroller for the tactors is on the underside of the band. When the vibrotactile unit is strapped onto the patients, the tactors are positioned vertically with respect to the skin so that the tactors exert a normal force on the skin during vibration.

E. Vibrotactile Actuator (Tactor) Placement

The placement of the tactor affects its effectivity as a feedback mode. In order to help us decide how to position the tactors, we refer to Miles and Binseel [20], which describes a two-point discrimination threshold. This threshold specifies the minimum distance between two pressure points on the skin in order for them to be distinguishable from one another. The distance varies depending on where the tactors are placed. For the upper arm, the minimum threshold is 48 millimeters for men and 42 millimeters for women. For the forearm, the minimum threshold in both men and women is about 40 millimeters. The threshold can be increased to 50mm for optimal perception on the forearm [20].

F. Posture correction protocol

The posture replication protocol requires a master and a student. The master establishes the reference posture which

Fig. 4. The two postures used in the experiments.

the student must replicate. The postures of the master and the student are measured using the IMU sensor, while the vibrotactile feedback tells the student how to correct his posture. The overview of the system is illustrated in Fig. 3.

To be able to compare the performance of different subjects for the same postures, we recorded the master's postures instead of asking the master to repeat the postures at each experiment run. The two arm postures used are illustrated in Fig. 4.

Three DOFs of the upper are being measured, thus the posture correction protocol follows this order:

- 1) Correct the yaw (φ_u) - Move the arm left and right;
- 2) Correct the pitch (ρ_u) - Move the arm up and down; and
- 3) Correct the roll (θ_u) - Roll the arm around its axis.

At each step of the protocol, the deviation of the student's posture $\Delta\theta_u, \Delta\rho_u$, or $\Delta\varphi_u$ from the reference posture $[\varphi_{u,r} \ \rho_{u,r} \ \theta_{u,r}]$ is computed. Then using the vibrotactile feedback, the student adjusts his posture so that the deviation is within permissible range of the reference posture. As long as the deviation is not within the permissible range, the tactor would vibrate and stop once it reaches the permissible range.

Simply put, the users need to adjust the orientation of φ_u , ρ_u , and θ_u , in that sequence, in order to reach the reference posture.

G. Posture correction strategies

Providing the optimum feedback improves user performance in executing a particular task [21], [22]. In this section, we present two feedback strategies we used for the posture correction.

1) *Strategy 1 (1 tactor per DOF)*: For this strategy, we assign one tactor to every arm DOF we are measuring. The subjects have to remember which tactor corresponds to which DOF so that they would know which arm angle to correct. Fortunately since the correction protocols is sequential (see Sec. II-F), remembering the tactor assignment is easy. Feedback strategy 1 is outlined in Fig. 5. The figure shows

Fig. 5. Outline of feedback strategy 1. Take note of the use of three tactors for the three DOFs.

the order of correcting the upper arm parameter and the tactor corresponding to each one.

2) *Strategy 2 (2 tactors for 3 DOF)*: In this strategy, we use the minimum number of tactors (only two) for all the DOFs we want to measure. Subjects do not have to worry about the tactor assignment, instead, they just have to remember that the tactors will toggle to indicate that they should be correcting for the next DOF. Fig. 5 outlines feedback strategy 2 and shows that only two tactors are used for the posture correction.

To further maximize the information conveyed by the vibrotactile feedback, we varied the tactor vibration pattern to inform the subject of his progress in posture correction. Fig. 7(a) shows a complete posture correction cycle and each posture parameter θ_u , ρ_u , φ_u follows the same control scheme. Three states S_1 , S_2 , and S_3 , describes the progress of the posture correction and each one is assigned a specific vibration pattern. The vibration pattern associated with each state is illustrated in Fig. 7(b).

The states are defined as follow:

- S1 **Target direction indication:** In this phase, when the limb starts moving to the correct direction, the controller will release a linear proportional vibration pattern to inform the subject that he is moving to the right direction.
- S2 **Continue moving to target indication:** The controller will examine if the orientation deviation falls within a small range in real-time, i.e., the subject is not changing his direction radically. If deviation is within range, then the controller provides a constant vibration pattern to let the subject know that he must continue moving in the same direction at constant speed.
- S3 **Closing in on the target indication:** Once the orientation deviation is within some preset threshold value, the controller will produce a burst-like pattern to indicate that the subject is close to the reference. In this phase, once the subject's orientation is within the permissible range, the controller will stop vibrating and the controller returns to main to process the next

Fig. 6. Outline of feedback strategy 2. Take note of the use of two tactors for the three DOFs.

parameter.

With the sequential correction of the posture parameters, our system can afford to use only two tactors for feedback. The feedback toggles between the two tactors to provide the necessary information to the subjects. In fact, the number of DOFs can be extended to cover the whole arm posture.

III. EXPERIMENTAL SET-UP

A. Subjects

The subjects included seven students from the university, with age ranging from 20 to 27 years, who volunteered to participate in the experiments. All were healthy students without any medical condition that could affect their tactile sensitivity.

B. General Procedure

Another student is assigned as the master, who establishes the reference posture. The seven subjects must copy the reference posture. Students are not allowed to see the master's posture and have to rely solely on the vibrotactile feedback to correct their posture.

Prior to each experiment run, the students practice several times until they become familiar to interpreting the vibrotactile signal and moving to the indicated direction, depending on the feedback strategy. The training process requires the students to rotate the upper arm left and right around the yaw axis, up and down around the pitch axis, and around the roll axis.

For each experiment, the following procedure is followed:

- 1) The master wears two IMUs and assume the target posture.
- 2) The student wears the two IMUs and one vibrotactile unit as shown in Fig. 1(b).
- 3) The student faces in the same direction as the master and then stretches his whole arm to assume the starting position.
- 4) The student waits for the tactor to vibrate. If it does, then the student corrects for the corresponding arm posture parameter.

(a) Illustration of the finite state machine that determines the state transition for correcting the upper arm posture. φ_u is the yaw, ρ_u is the pitch, and θ_u is the roll.

(b) The vibration pattern associated with each state.

Fig. 7. The vibration pattern for feedback strategy 2.

Fig. 8. Mapping time for seven subjects of Posture 1 using the two feedback strategies.

Fig. 9. Mapping time for seven subjects of Posture 2 using the two feedback strategies.

- 5) The student must wait until the tactor ends vibrating before proceeding to the next posture parameter.
- 6) Steps 4 to 5 is then repeated for the succeeding parameters.

The same experimental set-up is applied to both feedback strategies.

IV. RESULTS AND DISCUSSION

Preliminary tests of the two feedback strategies were done with two postures and seven subjects. The postures are shown in Fig. 4. Posture 1 involves raising the arm above the head away from the body. The arm is bent at the elbow in front of the body for Posture 2.

Fig. 8 and Fig. 9 show the result for the mapping and posture correction of the seven subjects using the two feedback strategies. The average mapping time for both postures using the different strategies is summarized in Table II.

Looking at the data for Posture 1 in Table II, mapping time considerably dropped (around 30%) when feedback strategy 2 was used. For Posture 2, mapping time almost remained the same, although it still registered a drop.

The posture difficulty could help explain the discrepancy in the performance when using the different strategies. Posture 1, although it is a common posture (for example, when reaching for something above our head) is difficult to do. It takes more effort to lift the whole arm and keep it in position while fine-tuning its posture. On the other hand, Posture 2 is easier to execute and maintain since it is located in front of the body.

This implies that feedback strategy 2 could really increase mapping speed time for the subjects, especially if the posture is difficult to do. However, subjects could quickly replicate postures that are easy to do. Thus, mapping time improvement may not be considerable for such postures.

Despite the apparent improvement in mapping time, performance difference could still be observed in individual subjects. For example in Fig. 8, it took longer for Subject 1 to map Posture 1 when using Strategy 2 than when using Strategy 1. The same can be said for Subject 6 and Posture 2 (see Fig. 9). For the rest of the subjects, their performance improved when using feedback strategy 2. Overall, despite these subject specific differences, the use of feedback strategy 2 still showed improvement in posture replication (mapping)

time over feedback strategy 1.

TABLE II
AVERAGE SPEED OF MAPPING OF TWO POSTURES AMONG SEVEN USERS.

	Strategy 1 (seconds)	Strategy 2 (seconds)
Posture 1	44.02	30.93
Posture 2	31.32	31.27

V. CONCLUSION & FUTURE WORK

This paper presents an arm posture mapping and replication system using inertia sensor for measurement and vibrotactile actuators for feedback. The details of the measurement and feedback systems had been discussed in details. Moreover, we implemented two feedback strategies and assessed their effect in posture mapping time. The first strategy used a one-to-one correspondence between the arm DOF and the tactor, while the second strategy used a maximum of 2 tactors for up to 3 arm DOFs.

Experimental results showed that using feedback strategy 2 improved mapping and posture correction time of the subjects, although performance difference among individual subjects sometimes appear. More importantly, feedback strategy 2 has more pronounced effect on the posture that is more difficult to replicate.

In conclusion, feedback strategy 2 maximizes the number of DOF that can be mapped using the minimum number of tactors by improving the design of the vibration pattern. As part of future work, additional postures will be included in the experiments to further verify the effectiveness of using feedback strategy 2. Another consideration for further work is the improvement in the ergonomic design of the vibrotactile unit.

This work can find applications in the medical field, especially in the rehabilitation of stroke patients. By allowing the therapist or doctors to set the target posture, the patients can proceed with the posture mapping with or without the presence of the therapists.

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