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Sensor Evaluation for Tracking Upper Extremity Prosthesis Movements in a Virtual Environment

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Abstract— **The use of virtual reality technology in the field of amputee rehabilitation is in its earliest stages of development. A virtual environment (VE) will facilitate the early rehabilitation of a patient before they are clinically ready to be fitted with an actual prosthesis. Success will be defined by delivering accurate position and orientation data of the arm to the virtual environment. We have applied an inertial measurement unit (IMU) and a linear displacement sensor to a prosthetic arm to track its movement in a virtual environment. Preliminary results show that even with advances in MEMS (microelectromechanical systems) sensor technology integration error is likely too significant to make an IMU an acceptable choice for position measurement.**

I. Introduction

THE loss of an arm or hand is one of the most devastating events that can happen to a person. Rehabilitation after an amputation is a slow process which requires patience and cooperation between the patient, his or her family, and health practitioners. There are nine phases of amputee rehabilitation: preoperative, amputation surgery, acute postsurgical, pre-prosthetic, prosthetic prescription and fabrication, prosthetic training, community integration, vocational rehabilitation, and follow-up [1]. With today's rehabilitation practices, patients must wait until after the prosthetic prescription and fabrication phase before they can learn to use a prosthesis. If the patient is given the opportunity to learn to use a prosthetic device in the pre-prosthetic or prosthetic prescription and fabrication phase, the rehabilitation time required to go through all nine phases can be significantly reduced.

A virtual reality environment (VE) would allow a patient to begin learning how to use a prosthetic device before being able to wear an actual prosthesis due to wound healing issues etc. The rehabilitation therapist would also benefit from this virtual environment because the environment may be programmed to provide feedback on the patient's movements and give simple instructions to the patient without requiring the therapist to intervene. A number of virtual environments have been designed for other rehabilitation practices with most of them targeting stroke rehabilitation [2]-[4].

A VE would also facilitate the delivery of amputee rehabilitation over the internet thereby providing therapy to patients in remote locations such as northern communities or war conflict areas who would otherwise be underserved. Since the environment would probably be used in the absence of technical assistance, the user must be able to set up the system with minimal configuration requirements. A MEMS inertial tracking device is small enough to be comfortably worn and easily shipped to remote or dangerous locations. Since the device consists of MEMS and solid state components, it is physically robust enough to be shipped long distances and would survive most usage scenarios. Furthermore, calibration of the device can be done with software that requires only that the user wear the device and run the program. This paper will discuss the tracking device and the preliminary results obtained from a prototype.

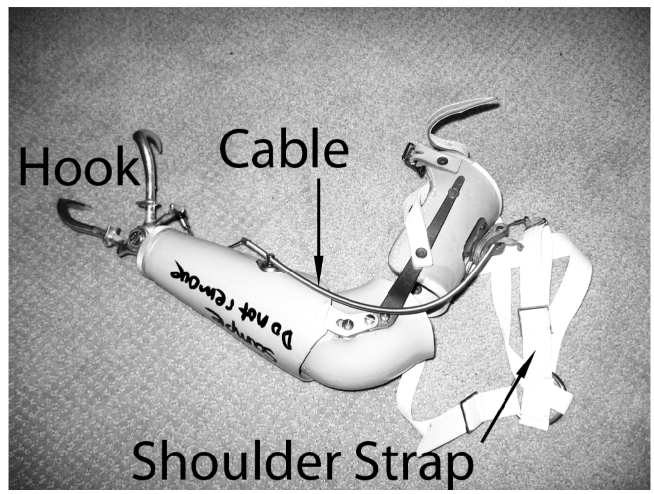

Fig. 1. Common configuration of a prosthetic arm currently in use today.

II. The System

The tracking device system consists of an inertial tracking device which maps the movement of the patient's arm in 3D space, and a linear displacement sensor which measures the width of the open hook. Together, these sensors provide all of the usage data necessary to simulate the movements of a prosthetic arm in a virtual environment. Fig. 1 shows a prosthetic arm which is most commonly used by people with upper extremity amputations. The patient wears the device on their residual limb and the shoulder strap wraps around the opposite shoulder. The shoulder strap is connected to a cable which is routed down the arm to the hook or other terminal device. The patient forward flexes his or her shoulders to pull the cable, which in turn pulls the hook apart. Since this type of mechanical prosthesis is the most commonly used, it will be the type of prosthesis emulated in the VE. Fig. 2 shows the prototype system used to emulate the prosthesis. There is no actual prosthetic device worn by the patient, and no part of the system comes in contact with the wound. This allows the patient to learn to do all of the motions that are required when controlling a real prosthesis, but without having to have any devices in contact with the wound. The IMU is positioned just below the elbow above the wound and the linear displacement sensor is worn on the back of the upper arm against the triceps (where the shoulder strap would normally be connected to the cable on a real prosthesis). The whole system consists of a shoulder strap, the IMU device, a linear displacement sensor, and a PC.

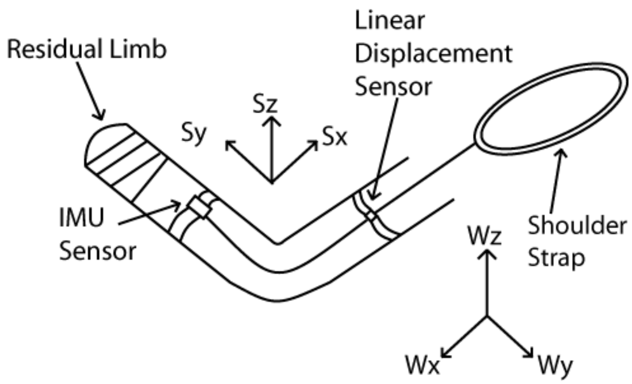

Fig. 2. System used to emulate a mechanical prosthesis in a VE.

A. Inertial tracking device

An inertial measurement unit (IMU) consists of three orthogonal gyroscopes and three accelerometers which are coaxial with the gyroscopes. This provides linear acceleration data and angular velocity data which are sufficient to track movement in space. This type of movement is referred to as six degree of freedom (6DOF) movement because the object is free to translate along any of three axes, and also free to rotate about three axes.

An accelerometer or gyroscope provides measurement data referenced to its sensitive axis. An IMU has three axes and provides linear acceleration data along these axes and rotational velocity data around these axes. A local sensor-referenced coordinate system is defined with axes coaxial to the sensor's sensitive axes. The origin of this sensor-referenced system is defined where the three axes meet, and moves freely with the sensor. When tracking an object, it is convenient to relate all measurements to a fixed reference point in space. That point can be arbitrary, but once defined, must not be moved. In this case, a world fixed coordinate system is defined with the origin at the starting point of the IMU before any movement, and this origin is the fixed reference point. All position data is referenced to this point. The sensor coordinate system (with axes Sx, Sy, and Sz) and the world coordinate system (Wx, Wy, and Wz) are shown in Fig. 2

Since the data output by the IMU is always given in the sensor-referenced coordinate system, a vector rotation is required so that all measurements are used in a world coordinate system. Each measurement must be rotated from the sensor-referenced coordinate system to a world coordinate system, so that movement can be tracked relative to a fixed point in space rather than relative to the sensor. This requires that a rotation based on the previously calculated orientation is applied to each sample before it is used to calculate the new position and orientation. Using the method for coordinate system transformations given in [5], a rotation matrix was derived. This rotation matrix is given in (1) where θ_z is the angle between the Wx axis and the resultant vector when the Sx axis is projected on the Wx-Wy plane. Likewise, θ_y is the angle made between the Wz axis and the resultant vector when the Sz axis is projected onto the Wz-Wx plane, whereas θ_x is the angle generated between the Wy axis and the projection of the Sy axis onto the Wy-Wz plane. Xb is the orientation vector in the sensor-referenced system, and X is the resultant vector in the world-referenced system.

$$X = \begin{bmatrix} \cos\theta_z \cos\theta_y & -\sin\theta_z \cos\theta_x + \cos\theta_z \sin\theta_y \sin\theta_x & \sin\theta_z \sin\theta_x + \cos\theta_z \sin\theta_y \cos\theta_x \\ \sin\theta_z \cos\theta_y & \cos\theta_z \cos\theta_x + \sin\theta_z \sin\theta_y \sin\theta_x & -\cos\theta_z \sin\theta_x + \sin\theta_z \sin\theta_y \cos\theta_x \\ -\sin\theta_y & \cos\theta_y \sin\theta_x & \cos\theta_y \cos\theta_x \end{bmatrix} X^b \tag{1}$$

At system startup, the world coordinate system and the sensor coordinate system share the same origin. The Wz axis points in the direction opposite to gravity. The orientation of the system is always defined by the angles θ_x, θ_y, and θ_z as discussed previously, and as used in (1).

For an initial calibration, the orientation of the sensor with respect to gravity is found using the accelerometer data while the device is stationary. The acceleration vector measured by the sensor while stationary is the gravity vector. Using this gravity vector, θ_x, θ_y, and θ_z can be found. These angles are the initial orientation of the sensor with respect to the world coordinate system.

After the initial orientation is found using the accelerometers, the gyroscope data is used to track the orientation over time. The gyroscope provides rotational velocity in degrees per second. Since the rotational velocity is a vector, the rotation matrix (1) can be applied to the gyroscope data before the data is integrated to find the angle the gyroscope rotated through. This is required at every sample. For each sample, the gyroscope data is referenced to the world-referenced system using the orientation found prior to the current sample. The world-referenced rotational velocity sample is then multiplied by the sample period, giving the angle the gyroscope rotated through in degrees with respect to the world-referenced system. The angle through which the device rotated during that sample is then added to the previous orientation angle, giving the new orientation.

The accelerometer measurements are rotated in the same manner as the rotational velocity, using (1) and the orientation angles previously found. The outputs given by the accelerometers are in m/s^2 which must be double integrated to get linear position. Since the accelerometer data has been rotated to the world-referenced coordinate system, the double integrated data gives position referenced to the starting point in the world fixed coordinate system.

B. Linear Displacement Sensor

The linear displacement sensor is a device which produces an output based on the position of a magnet along a plastic shaft. In the prosthetic tracking device, it provides the data required to calculate how wide the user is opening the terminal device (in this case a hook) by measuring how far the cable attached to the shoulder strap has been pulled. The sensor's output voltage is directly proportional to the distance being measured. The linear displacement sensor will be integrated with the IMU once it is clear that the IMU is suitable for position tracking.

III. Preliminary Results

The IMU chosen for inertial measurement is Analog Devices' ADIS16350 [6]. The accelerometers have measurement range of ±10 g (±98.1 m/s^2) and the gyroscopes provide a range of ±300 ^{o}/s. The accelerometers and gyroscopes both have 14 bit resolution. The accelerometers have a sensitivity of 2.522 mg (0.02474 m/s^2) per LSB and the gyroscopes have a sensitivity of 0.07326 ^{o}/s per LSB. This device was chosen for this study because it provides digital outputs and the published specifications for it are as good as or better than other similar devices on the market.

It was decided that a system designed from the ground up would be more suitable for this application than a commercially available motion tracker because designing a system allows development using the most cutting edge sensors available and also allows the most optimized solution, thereby reducing the PC system requirements. This way, the system can be designed specifically for the VE.

A. The Gyroscopes

The device was rotated ninety degrees about the Wz axis and then back to the starting point. Fig. 3 shows the angular velocity which the gyroscope produced around each of the three axes. The angular velocity data was then rotated using (1) and the gyroscope's bias was removed by calculating the mean gyroscope output while stationary and removing that value from each measurement. Fig. 4 shows the orientation angles calculated for each axis. The angles calculated show the general direction of movement, but the magnitude of the movement is incorrect, implying that a scaling factor may be required.

As can be seen, the gyroscope produces reliable data which can be used to keep track of the orientation of the device. It is required for the device to be accurate for a long enough time to do one rehabilitation exercise motion. One motion is approximately thirty seconds, depending on the exercise the patient is required to perform. The drift of the gyroscope (the tendency for the bias of the gyroscope to change over time) has very little effect on the accuracy of the orientation data over this time period.

B. The Accelerometers

Fig. 5 shows the raw data the accelerometers produce when the device is moved on a table a distance of 15 cm along the Wy axis and then back to the starting position along that same axis. It can be seen that gravity is present in the acceleration data, with the largest gravity component showing up in the negative z direction. This gravity component must be removed before the linear movement of the device can be calculated. In order to remove the gravity component, the accelerometer data must be rotated from the sensor-referenced system to the world-referenced system. Fig. 6 shows the accelerometer data once it was rotated to the world-referenced system using (1). The gravity component has also been removed from the data in Fig. 6.

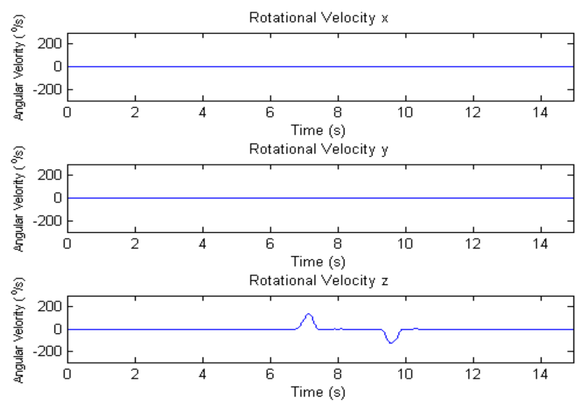

Fig. 3. Angular velocity data as produced by the gyroscope.

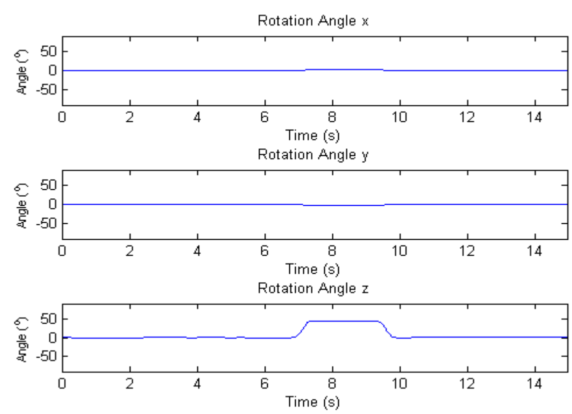

Fig. 4. Orientation angle of the device

Before the sensor was moved, the sensor coordinate system and the world coordinate system were nearly coaxial. No rotation was performed and as such, any movement in the y direction of the sensor should be movements in the y direction both of the world coordinate systems. This implies that even if (1) is applied to the sensor data, the resultant world referenced data should be the same. Fig. 6 shows that this appears to be the case, and using (1), any of the gravity component which is present in the x and y direction (appearing as bias in the sensor referenced data) was referenced all to the z direction and easily removed.

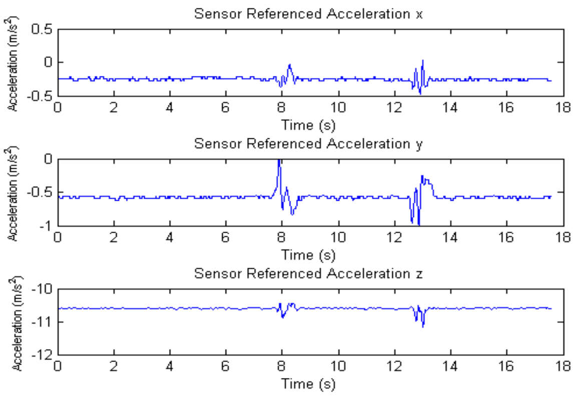

Fig. 5. Raw accelerometer data as measured by the sensor.

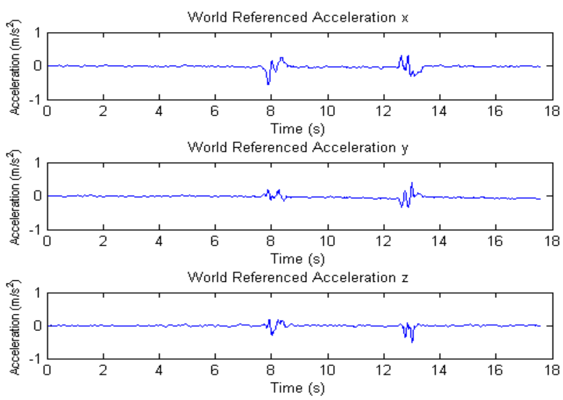

Fig. 6. Acceleration data referenced to the world coordinate system with the gravity component removed.

Even though there was only movement in the y direction, there are x and z components of acceleration, likely due to vibration as the sensor was moved along the table. When the accelerometer data was integrated once to get velocity, the result did not show the movement in the y direction clearly. This may be due to the accelerometer data bias not being perfectly removed, vibrations caused by sliding along the table being more significant than expected, and the accelerometer noise being of the same order as the movement data. More testing and investigation are required.

IV. Discussion and Conclusion

Additional work is required to determine the source of the data errors. It is suspected that a band pass filter would be able to remove the excess vibrations caused by movement along the table and more effectively remove the accelerometer's bias. It may also be necessary to model the accelerometer noise using probabilistic methods and then filter the data using a real time filter which doesn't require post-processing (such as a Kalman Filter). As well, more advanced gravity removal and coordinate rotation algorithms are likely required.

Another option would be to use an accelerometer with a higher sensitivity. In our experience, the accelerations are on the order of 1 m/s^2 while this sensor is capable of measuring 98.1m/s^2. A sensor such as Analog Devices' ADIS16364 [7] has higher sensitivity and the same resolution as the ADIS16350 used here. The ADIS16350 has a typical output noise of 0.343335 m/s^2 rms, which is on the same order as the movement. The ADIS16364 has a typical output noise of 0.04905 m/s^2; an order smaller than the movement. This is likely the most limiting factor of the accelerometer measurement.

Other projects have made use of an IMU for tracking orientation of body segments such as work done in [8], which uses three IMUs to estimate the orientation of each segment of an upper limb (shoulder, upper arm and forearm). The authors did not track absolute position, only limb segment orientation, but found the IMUs to be satisfactory for tracking orientation.

Based on preliminary results, the MEMS IMUs available now appear to be capable of tracking orientation, but are too inaccurate to track position with the required degree of accuracy.

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