Functional Assessment of Biomechanics System: Measurement Range, Accuracy, and Data Rate Specifications

The orientation sensors employed in the FAB system are capable of accurately measuring body position over a broad spectrum of human movements, and in a wide range of environments. They can capture both static body positions, as well as rapid motions without risk of data loss due to marker occlusion as is typical with camera-based motion capture systems. They operate in environments from the research laboratory to a distant mountain top. At the heart of each sensor are orthogonal triads of accelerometers, magnetometers and gyroscopes. Together with advanced multisensory fusion algorithms, the FAB system combines the data from 99 individual sensing elements into a life-like animation of the individual being tracked. Table 1 summarizes the sensor measurement range, accuracy and data rate.

TABLE 1. Orientation sensor measurement range, accuracy, and data rate specifications

Parameter	Conditions	Min	Typ	Max	Units
Measurement range:					
Acceleration	Each axis			± 6 or ±19	*g*
Angular velocity	Each axis			±750	°/s
Static accuracy (RMS error):					
Attitude	Bench testing, individual pitch/roll components	0.1	0.4	1.1	°
Heading	Bench testing	0.4	1.6	3.6	°
Relative rotational accuracy	Angular displacements 1 s apart	0.1	0.2	0.3	°
Magnetic distortion drift rate	Magnetic object placed next to sensor		1.0		°/s
Sensor element sampling rate:					
Gyroscopes			100		Hz
Accelerometers			100		Hz
Magnetometers			25		Hz
Wireless packet transmission rate			25		Hz
Latency		4	8	12	ms

MEASUREMENT RANGE

The measurement range of the FAB sensors is limited by the range of the internal gyroscopes and accelerometers. The system is capable of accurately measuring motions where the combined effect of gravity and linear acceleration is less than 1.7 *g* and the angular rotation speed is less than 600 °/s.

A system designed for faster human motions with 5 *g* accelerometers and 1200 °/s gyroscopes is also available.

ACCURACY

Each FAB sensor determines its orientation by continually estimating the direction of earth's gravity vector (vertical) and the direction of magnetic north. Based on these two estimated directions, each sensor can deduce the mapping between its internal coordinate frame and the fixed coordinate frame of Earth. This estimated Earth frame, in general, differs from the true earth frame by a small rotation about an arbitrary axis. To facilitate quantification of sensor accuracy, this rotation is broken down into pitch, roll and yaw components. The pitch error describes the angular error about the earth x-axis (east), the roll error describes the angular error about the earth y-axis (north), and the yaw error describes the angular error about the

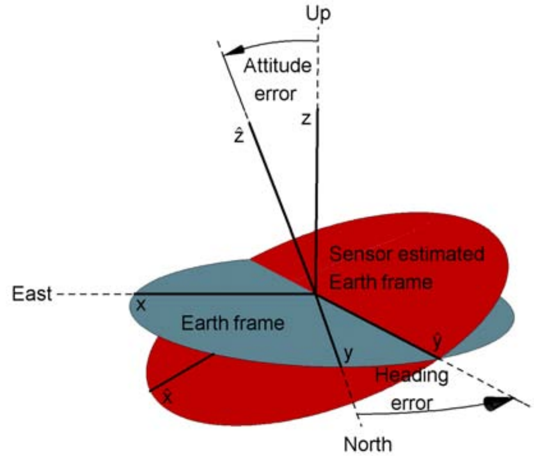

Fig. 1. Nomenclature for angular errors

earth z-axis (up). The pitch and roll errors combine to form the net attitude error, while the yaw error is equal to the heading error, as shown in Figure 1. Attitude error is caused by inaccuracy in estimating the direction of the gravity vector, and thus has properties that differ from those of heading error, which is caused by imprecision in estimating the direction of magnetic north.

When a sensor is static, or accelerating very slowly, the error in attitude is due to small imperfections in the three orthogonal accelerometer elements. These imperfections include off-axis sensitivity, non-linearity, and offset and gain drift. The cumulative effect is that the estimated direction of the gravity vector differs slightly from true vertical. The root mean square (RMS) discrepancy for the pitch-error and roll-error components of attitude were both measured to be 0.4°. The histogram in Figure 2 shows the number of sensors (N=36) that obtained different levels of pitch accuracy and shows a narrow spread about the 0.4° RMS average. The measurements of attitude accuracy were made by attaching the sensors to a disk equipped with a 0.1° resolution optical encoder, rotating the sensor through 360° in the vertical plane, and averaging the mean square error between the sensor estimate and the encoder measurement.

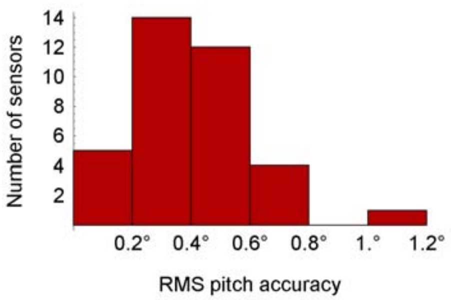

Fig. 2. Distribution of pitch accuracy over sensor sample

During capture of dynamic human motion, the accelerometers measure linear acceleration in addition to the effect of gravity. Although the fusion of gyroscope information largely filters the part of the accelerometer signal due to linear acceleration, there are fundamental limits governing how well this can be accomplished. The net result is that the attitude accuracy decreases as the intensity of motion (level of slosh) increases. The RMS attitude errors ranges from approximately 1° for slow motions to 3° - 4° for fast, repetitive motions.

The heading accuracy describes how well the sensor measures its orientation relative to magnetic north. In the presence of a homogenous magnetic field, the heading error is caused by imperfections in the magnetometer elements, the inclination angle of the local magnetic field, and warping of the field due to the sensor structure itself. In bench testing in an environment where the magnetic field is homogenous and inclined at approximately 70°, the RMS value of the heading error was 1.6°. The histogram in Figure 3 shows the number of sensors (N=30) that obtained various levels of heading accuracy and shows a spread around the 1.6° average. The heading accuracy was measured by attaching the sensors to a disk equipped with a 0.1° resolution optical encoder, rotating the sensor through 360° in the horizontal plane, and averaging the mean square error between the sensor estimate and the encoder measurement.

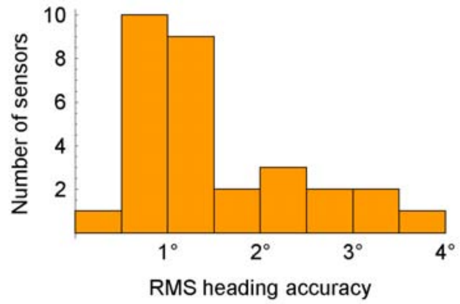

Fig. 3. Distribution of heading accuracy over sensor sample

Unlike the estimate of attitude, dynamic motion of the sensor does not deteriorate the heading accuracy. Instead, distortion of the Earth's magnetic field, such as that caused by nearby ferrous objects, becomes the dominant factor that can lead to elevated levels of heading error. An advanced Kalman filter is specially equipped to deal with these situations, rejecting the effect of this distortion for several tens of seconds. However, strong and continuous magnetic distortion will eventually cause a heading error equal to the angle between true magnetic north and the apparent magnetic north. Figure 4 shows a plot of heading error after a magnetized wrench is placed next to the sensor to confuse its estimate of magnetic north. A conservative value for the error drift rate is 1 °/s, but it depends strongly on the details of the magnetic distortion.

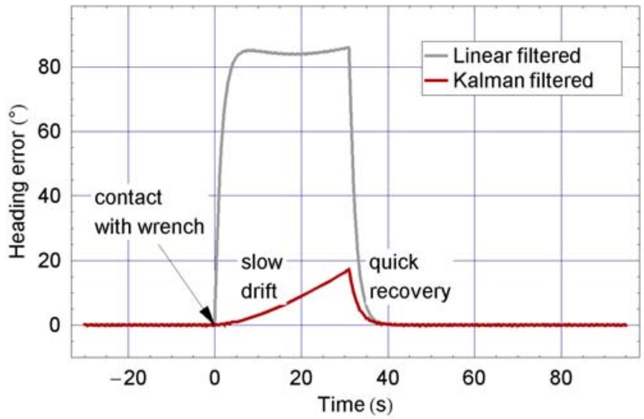

Fig. 4. Magnetic distortion rejection for 30 s contact with magnetized iron wrench

DATA RATE

The accelerometers and gyroscopes are sampled at 100Hz while the magnetometers are sampled at 25Hz. The temporal resolution is effectively limited by the gyroscope sampling frequency because the multisensory fusion algorithm extracts the high frequency orientation information from the angular velocity data. Each sensor transmits its data to the receiver at a packet rate of 25 Hz. The packets are decompressed and the angular orientation is then available as a time series with 0.04 s (25 Hz) or 0.01 s (100 Hz) temporal resolution. For real-time applications, the data has a latency between 0.04 s and 0.12 s due to internal buffering, multisensory fusion in firmware, and packet transmission.