Communications

Estimating Body Segment Orientation by Applying Inertial and Magnetic Sensing Near Ferromagnetic Materials

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***Abstract*—Inertial and magnetic sensors are very suitable for ambulatory monitoring of human posture and movements. However, ferromagnetic materials near the sensor disturb the local magnetic field and, therefore, the orientation estimation. A Kalman-based fusion algorithm was used to obtain dynamic orientations and to minimize the effect of magnetic disturbances. This paper compares the orientation output of the sensor fusion using three-dimensional inertial and magnetic sensors against a laboratory bound opto-kinetic system (Vicon) in a simulated work environment. With the tested methods, the difference between the optical reference system and the output of the algorithm was 2.6° root mean square (rms) when no metal was near the sensor module. Near a large metal object instant errors up to 50° were measured when no compensation was applied. Using a magnetic disturbance model, the error reduced significantly to 3.6° rms.**

***Index Terms*—Disturbances, motion tracking, validation.**

I. INTRODUCTION

In rehabilitation, ergonomics and sports physiology, posture and movement analysis is one of the central assessment tools [1]. Current state-of-the-art technology allows accurate motion analysis in fixed laboratory setups. Under field conditions, for example at the actual work place during actual work, possibilities are limited. Miniature inertial and magnetic sensors have been proposed and successfully applied for ambulatory motion analysis [2]. Gyroscopes are often combined with accelerometers, used as an inclinometer, and magnetometers, used as a compass, for stable orientation measurements [3], [4]. Ferromagnetic materials, like iron, and other magnetic materials near the sensor will disturb the direction and density of local earth magnetic field and will therefore distort these orientation estimates [5]. Magnetic interference impedes many applications with ferromagnetic materials in an unknown surrounding. These materials are encountered in many work places, for example in back or neck load estimation for ergonomic purposes at assembly lines [6]. In these studies, posture angles of the shoulder and arm are important parameters that could be measured by inertial sensors.

Previously, we presented an algorithm for orientation estimation of human motion featuring magnetic disturbance compensation [7]. The orientation filter was tested under well-controlled conditions but no functional movements were evaluated. In this study, the orientation output obtained with this Kalman-based filter using the three-dimensional inertial and magnetic sensors is validated against a laboratory bound opto-kinetic system in a simulated assembly line work environment.

II. METHODS

A complementary Kalman-based filter was used to estimate the orientation by combining 3-D gyroscope, accelerometer and magnetometer signals using a model of the system and relevant signals. The gyroscopes measure angular velocity and are integrated in time to obtain the orientation of the sensor module. An absolute reference for orientation is provided by the accelerometers and magnetometers to prevent drift. Inclination is derived from the accelerometers using a model in which the gravitational acceleration $\mathbf{g}$ and the acceleration of the sensor $\mathbf{a}$ are separated [8]. When no ferromagnetic materials are present near the sensor module, the local earth magnetic field presents a good reference of the heading direction. The total magnetic flux and the dip angle of the magnetic field are constant in this homogeneous field and are used as a measure of disturbance. In case of a detection of a magnetic disturbance, less weight is assigned to the magnetometers and the estimation relies more on the gyroscopes and accelerometers.

A. Measurement Setup

The algorithm was tested in experiments by comparing the orientation as calculated by the filter to the orientation that was obtained by a laboratory bound 3-D optical tracking system Vicon 370 (Oxford Metrics) consisting of six cameras operating at 50 Hz. The calibrated volume size was $4000 \times 2000 \times 2000\ \mathrm{mm}$. The error was defined as the smallest angle about which the estimated orientation by the Kalman-based filter had to be rotated in order to coincide with the orientation obtained by the reference system. Three optical markers with a diameter of 25 mm were attached in an orthogonal arrangement to the sensor module on 10-cm carbon fiber sticks in order to measure the sensor orientation. For the experiments, a MT9-A (Xsens Technologies) inertial and magnetic sensor module was used. The signals of the sensors were sampled at 100 Hz with 16-bit resolution.

B. Experiments

The comparison of the Kalman-based filter with the reference system was performed with five subjects. A sensor module with optical markers was placed on the wrist of the subject. For each subject eight trials were recorded, varying from 30 s to 5 min. Each trial began with three seconds without movement in order to obtain the initial sensor offsets. In the first two trials, the subject performed abduction/adduction and flexion/extension of the arm without ferromagnetic materials in the measurement volume. In the second set of two trials, the same arm movements were now performed in the vicinity of a steel case with dimension $70 \times 35 \times 90\ \mathrm{cm}\ (\mathrm{W} \times \mathrm{D} \times \mathrm{H})$. The third set of five trials consisted of simulated assembly line work. The subject packed and unpacked small objects from a carton box that was positioned on the metal case. These experiments were processed with the described Kalman-based filter with and without the magnetic disturbance model.

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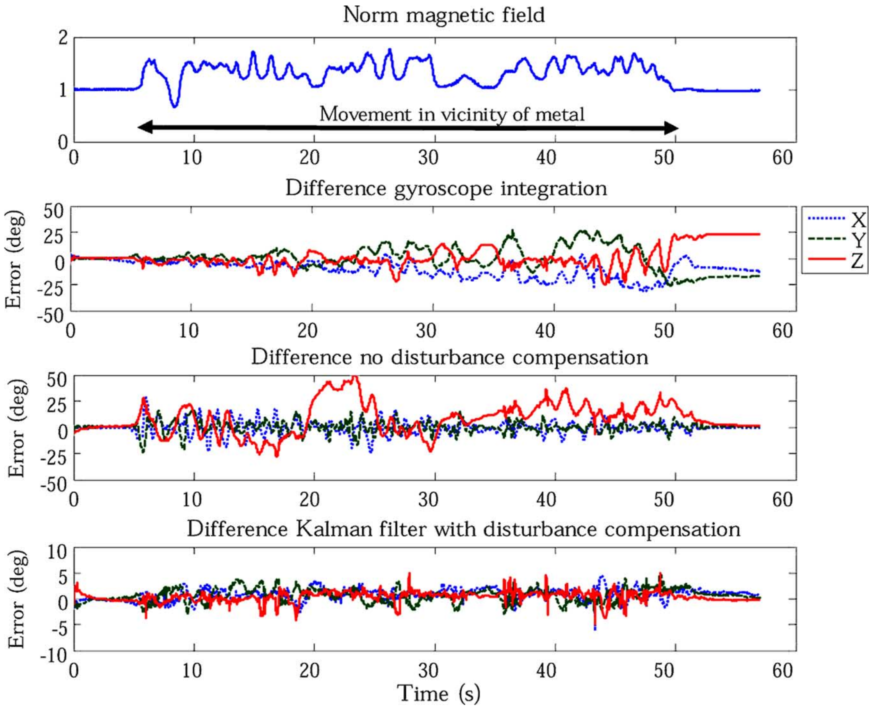

Fig. 1. Orientation estimation from the inertial and magnetic sensor measurements compared to the optical reference system in a simulated work task. First: normalized magnetic flux density. During the movements of the arm, the magnetic norm is quite variable which is caused by the disturbed magnetic field. Second: orientation angle difference in three axes when only gyroscopes are used. Third: Kalman-based filter orientation estimation with equal weight to accelerometer and magnetometer without disturbance model. Fourth: Kalman-based filter with magnetic disturbance model.

III. RESULTS

Disturbances of the heading estimates due to the magnetic disturbance by the metal case for a typical trial of the simulated assembly line experiment are shown in the upper graph of Fig. 1. In the first 5 s, the sensor module is in a nondisturbed area and the magnetic norm equals one. During the movements near the metal case, it can be seen that the norm is quite variable. After 50 s, the arm is retreated from the disturbed area and the norm equals one again.

The subsequent graphs show the differences of the orientations obtained with the inertial and magnetic sensor module with respect to the optical reference system. In the second graph, it can be seen that the drift error becomes significant after only a few seconds when only gyroscopes are used. The third graph presents the output of the Kalman-based filter with an equal weight factor of the accelerometers and magnetometers without magnetic disturbance compensation. When the arm enters the disturbed area, the orientation error around the Z-axis becomes quite large. After moving the arm away from the metal case, the error converges back to zero. The disturbance is also noticeable in the other axes, since the magnetic field also influences the inclination component (dip angle). The lower graph illustrates that the orientation estimates using the full Kalman-based filter with magnetic disturbance model is not disturbed and drift free. The difference in orientation between the filter and the optical reference system of the complete trial is 3.4° root mean square (rms). In total, 10 trials with arm abduction/adduction and flexion/extension were recorded without magnetic disturbance, two for each of the five subjects. From the same set of movements, nine trials were successfully captured in the vicinity of the metal case. The rms error when no metal was near the sensors was 2.6° with a standard deviation (SD) of 0.5. With the metal case and no compensation applied, the rms error was 13.1° (SD 3.0). In the simulated assembly line experiments, the error was 19.8° (SD 3.6) with no compensation. Using the magnetic disturbance model and the described filter, this rms error reduced significantly (paired t test, $p < 0.01$) to 3.6° (SD 0.6).

A. Accuracy of the Reference System

In the experiments, small variations in the marker distances were observed. Errors of a few millimeters will results in errors of a few degrees when converting the marker positions into a reference orientation frame. Fig. 2 shows the relation between the markers distance and the difference in orientation estimates between the reference system and the Kalman-based filter. The rms error of the reference system was approximately 1.0° (SD 0.3).

IV. DISCUSSION

In this study, the accuracy and stability of orientation estimation fusing inertial and magnetic sensors with a Kalman-based filter was compared with a laboratory bound 3-D optical tracking system. The results show that the rms difference between the two systems is 2.6° when no metal is in the measurement volume. When a sensor module attached to a body segment moved near a large ferromagnetic object, instant errors up to 50° were measured when no compensation for disturbances was applied. Using the magnetic disturbance model, the accuracy of the orientation estimate near metal increased significantly to 3.6° rms with no drift. The errors are dependent on the distance to the metal case and the complexity of the movements. Disturbances encountered in this setup could be representative for assembly line work. However, performances may decrease in workplaces with moving parts since the properties of these disturbances are not modeled in the filter. Some of the differences could explicitly be characterized as errors in the camera based system due to variations in the distances between markers. These variations could be caused by camera noise, limited sight of markers, or vibrations of the marker frame [9]. The major part

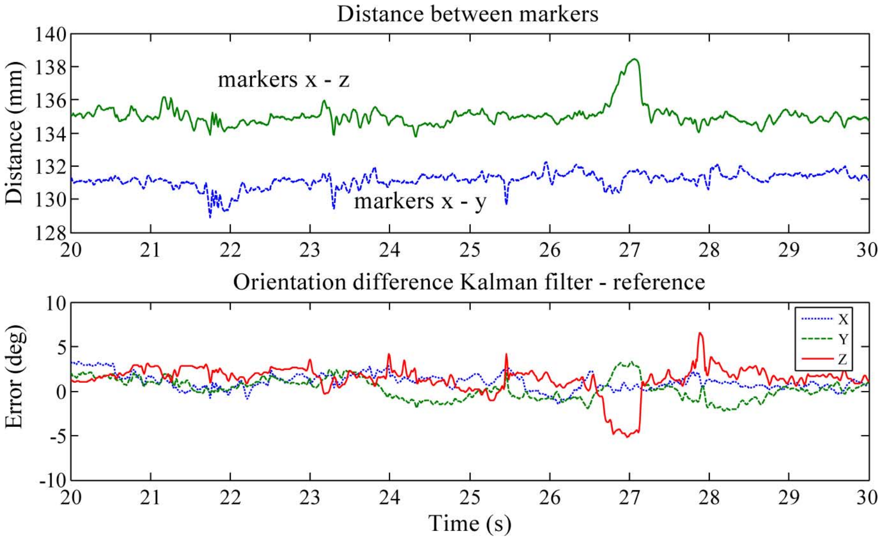

Fig. 2. Upper graph: distances in millimeters between x and y markers and x and z markers. Lower graph: detail of orientation angle difference between Vicon system and the Kalman algorithm. Note the correlation between the error in the reference system and the difference between Vicon and Kalman filter.

of the differences between the two systems is caused by modeling errors in the Kalman-based filter. Sources of errors are the estimates of the acceleration of the segment and magnetic disturbance vector. This latter vector is calculated based on the magnetic field vector estimates of the gyroscopes and magnetometers. When the magnetometers detect a disturbance from a changing dip angle and/or a changing magnitude, the orientation estimation will rely more on the gyroscopes and accelerometers. Because during the change, the information from the magnetometer is not taken into account, drift around the vertical axis can occur. However, with a constant magnetic disturbance, for example no movement near a metal case, no additional errors will be introduced. Finally, noise, nonlinearity, and limited resolution of the sensors are a source of errors.

The proposed method can be used for analyzing multiple body segments by putting a sensor module on each segment. The orientation and magnetic disturbance will be estimated by the filter for each segment. Anatomical constraints can be used to link the different segments and enhance the orientation estimation [10]. It should be investigated whether magnetic disturbance information from one sensor module can be used to predict the disturbance near a sensor module on a different segment. When markers or inertial sensor modules are attached to a body segment, they should be calibrated to this body segment in order to obtain the orientation of this body segment. It should be noted that the problem of relating sensor to body segment has not been addressed in this study. Despite the choice of bony landmarks for placement, the skin under the sensor modules or markers will move with respect to the bones and will cause errors. Several compensation algorithms and solutions like cluster markers have been proposed to estimate the actual joint position and orientation from the marker positions on the skin [11]. These methods should be optimized for inertial sensor modules since the net effect of the movement artifacts of a cluster of optical markers on the skin will be different than of one sensor module.

In conclusion, the accuracy of orientation measurements fusing inertial and magnetic sensors substantially improves considerably with the use of a magnetic disturbance model and enables ambulatory measurements at places were ferromagnetic materials are present.

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