Using Inertial Measurement Units for Measuring Body Segment Orientations in Indoor Environments

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Introduction

Human motion analysis is a central tool in rehabilitation, orthopaedics and many other disciplines. The standard in most of today's applications is motion capturing with optical markers and 3d camera systems. It is valued for its high accuracy, yet suffers from severe disadvantages in practice: it restricts the user to a small measurement volume, short measurement durations, wearing underwear only and is, moreover, rather sumptuous .

To overcome these limitations and to enable ambulant motion analysis, methods have been developed for motion analysis with Inertial Measurement Units (IMU). The latter measure translational acceleration, angular rate and magnetic field vector, each in 3 dimensions, by means of MEMS chips. Due to steady advances in chip manufacturing, very small and lightweight wireless IMU with battery times of several hours meet the increasing demands on accuracy and practicality.

As an additional advantage, IMU-based motion analysis can be done online. Thus, it can be employed in real time applications such as feedback-controlled neuroprostheses and active orthoses or in biofeedback systems. However, the fact that IMU measures in its own local (thus rotating) coordinate system entails some mathematical challenges. Also, IMU measure only the rate of rotation, not angles or orientations, making integration inevitable. The integrated bias sums up to a global drift that must be compensated using acceleration and magnetic field measurements. It is often ignored that indoor environments hardly ever provide the homogeneous magnetic field that is required for proper sensor fusion.

We herewith present some ideas on how to face the constraints and needs coming from medical practice. We create a lightweight algorithm that derives body segment orientations from the raw data of the IMU. We choose the example of thigh inclination and azimuth to investigate the dynamic behaviour of the algorithm. We propose a method that relies on the magnetometer data only in what it is actually needed for, i.e. for drift compensation in yaw direction. Furthermore, we seek to fill the gap of detailed experimental studies investigating the effect of magnetic disturbances on IMU-based motion analysis.

Methods

Creating an orientation estimation algorithm based on *quaternions*, i.e. complex vector representations of 3D-orientations, is the most common and optimal method regarding computational load and uniqueness. The obtained orientations can easily be transformed to the more depictive Euler angles. When sensor-to-segment orientations are known, the tracked IMU orientation directly yields the body segment orientation.

Especially due to its low algorithmic cost and its few parameters involved, the open source algorithm presented by Sebastian Madgwick in 2010 has been employed in numerous sensor systems. Inspired by his ideas, we present an algorithm motivated by the same needs, namely low computational load, easy parametrization, and robustness to magnetic disturbances.

Firstly, our approach avoids some mathematical assumptions that do not decrease the computational effort. The developed method includes the exact solution of the optimization problem inherent to inertial sensor fusion and provides easily interpretable fusion weights. In contrast, Madgwick's approach approximates this exact solution by a gradient descent step.

Another main aim of our research is to limit the impact of the magnetometer to the yaw orientation estimate. We find this important idea also in Madgwick's algorithm, yet we are able to prove that magnetic field disturbances still affect pitch and roll angle estimates by simulations with his code. With a suitably chosen projection, we avoid the latter in the new algorithm and hence make it more suitable for indoor usage, where ferromagnetic material, magnets or electrical currents may distort the earth magnetic field. This method can easily be incorporated also in Madgwick's algorithm, where it remarkably reduces yet not completely removes the effect on roll and pitch.

On the experimental side, the thigh orientation analysis of transfemoral amputees walking in an optical gait lab with IMU at both prosthesis shaft and contra-lateral thigh serves our purposes. With the highly accurate data from the optical motion capturing system as a reference, we quantify the dynamic behaviour of different algorithm configurations. The subject walks loops through the present inhomogeneous magnetic field of an indoor environment, passing through the observation volume of the optical system repeatedly. The effect of magnetic disturbances on the thigh orientation estimation is investigated. The direct comparison between human leg and prosthesis shaft is a particular advantage of the experimental setup as it also revealed the effect of soft tissue motion on orientation estimates.

Results

From the mathematical analysis of existing orientation estimation algorithms based on IMU data, we develop a computationally cheap method with a minimum of tuning parameters. The experimental comparison with the highly accurate optical reference data serves as a first justification of the straight-forward approach.

In the experiments, we observe that motion in common indoor environments may impose heavy dynamic disturbances on the magnetometers. The discussed modification of Madgwick's algorithm reduces the effect of the magnetic field on roll and pitch estimates remarkably, while in the proposed new algorithm it is totally suppressed. Still, we cannot avoid the yaw estimation to be severely affected by potential low-frequency magnetic field disturbances. The evaluation of experimental data shows that in order to eliminate such orientation estimation errors, e.g. from turning at the end of the hallway, fusion weights must be set carefully.

Conclusion

IMU-based orientation estimation is a portable solution for the analysis of human motion. It allows for many applications such as feedback-controlled neuroprostheses and active orthoses. The orientation of the IMU local coordinate system with respect to a fixed reference coordinate system is used to derive body segment orientations from the known sensor attachment coordinates. We present a computationally low-cost algorithm for the proper estimation of this time-variant orientation. It is compared to the open source Madgwick code and a slightly modified version. We improve the indoor applicability, a major challenge in this innovative field, by using magnetometers for the correction of the yaw estimation only. Experimental data motivates a careful treatment of indoor magnetometer data and underscores the advantages of the developed method.