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On-body inertial and magnetic sensing for assessment of hand and finger kinematics

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***Abstract*— A novel instrumentation is proposed to estimate hand and finger movements. Current dataglove systems often measure a reduced set of joint angles and lack a position and orientation measure of the hand with respect to the trunk. Our proposed system, based on inertial and magnetic sensing, is fully ambulatory, light weighted, has a low energy consumption and is therefore suitable to assess kinematics of the hand and fingers in daily life.**

Results showed an rms difference of the hand pose with an optical reference system of 16.9 ± 4.0 mm for the position and 1.5 ± 0.4 deg for the orientation. Index finger tip positions could be estimated with 5.0 ± 0.5 mm for flexion extensions movements and 12.4 ± 3.0 mm for more complex movements in which both flexion-extension and abduction-adduction movements were involved.

I. INTRODUCTION

Hand functioning is important in many daily life activities such as grasping, reaching, lifting, sensing, hand writing, sports and other fine motor control tasks. Assessment of hand kinematics is therefore necessary to gain knowledge about functioning and to evaluate various hand performance tasks in a quantitative manner. Reaching and grasping can be classified as combined motor planning tasks. It is therefore necessary to assess both the pose (position and orientation) of the hand with respect to the trunk and the pose of the articulated fingers and thumb.

Pose information of the hand can be obtained by applying a known magnetic field which can be induced using perpendicular mounted coils [1] [2] [3]. Large drawback is size and energy consumption of the magnetic source, which restricts the wearability of such a system.

Commercially available data gloves often lack to measure digit rotations in 3 degrees of freedom (DoF) [4]. Measuring the angle of Proximal Inter Phalangeal (PIP) and Distal Inter Phalengeal (DIP) joints can be modelled accurately using a single rotation axis. However, more complex joints like the Meta Carpal Phalanges (MCP) joints and the thumb's Carpo Meta Carpal (CMC) joint permit rotations around at least two axes.

We propose a new upper body sensing system that fuses information obtained from 3D inertial and 3D magnetic sensors on the hand, fingers and trunk and a permanent magnet strapped to the hand. The system is able to accurately estimate trunk orientation, the relative pose of the hand with respect to the trunk and finger kinematics.

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II. SENSOR FUSION

The first subsection describes how the pose of the hand is estimated using an 3D gyroscope and 3D accelerometer combined with a permanent magnet strapped to the subject's hand, and an array of 3D magnetometers with a single IMMS (Inertial and Magnetic Measurement System) attached to the trunk. The second subsection describes the proposed inertial and magnetic sensing system that can be worn on hand and fingers and is able to fully reconstruct joint angles and finger tip positions.

A. Estimation of hand pose with respect to the trunk

The permanent magnet strapped to the hand induces a magnetic field which is picked up by the magnetometers attached to the trunk. One can describe the measured magnetic field using:

$$\boldsymbol{y}^l = \boldsymbol{B} + J(\boldsymbol{r}^l)\boldsymbol{m} + \boldsymbol{e} \quad (1)$$

Where the superscript l indicates the particular 3D magnetometer. The total magnetic field consists of a common component $\boldsymbol{B}$ and a term induced by the magnet $\boldsymbol{m}$ described by a magnetic dipole model J [5], which is a function of the magnets' position $\boldsymbol{r}$ with respect to magnetometer l. The model assumes independent identically distributed (i.i.d) Gaussian noise $\boldsymbol{e}$. The magnets' orientation (2 DoF) is parameterised by the magnetic moment vector $\boldsymbol{m}$. After fusion with inertial measurements of both trunk and hand, a robust pose reconstruction (6 DoF) is obtained. It should be noted that the signal to noise ratio (SNR) decreases cubically with the magnet's distance. Hence, the magnetic information has a lower SNR when the hand is further away from the trunk, which eventually results in a larger dependency of inertial sensing to estimate the position.

The fusion filter is based on an Extended Kalman Filter (EKF), see Fig. 1. The state vector includes position, velocity, orientation of the target with respect to the trunk, and the orientation of the trunk with respect tot the static earth frame. Detailed information can be found in [6].

B. Estimation of finger kinematics

Estimation of joint angles within the hand as well as fingertip positions is based on fusion of a biomechanical hand model with measurements of inertial sensors which are distributed throughout the hand, fingers and thumb.

The fusion filter is also based on an EKF. The state vector includes the relative orientation of all finger segments and

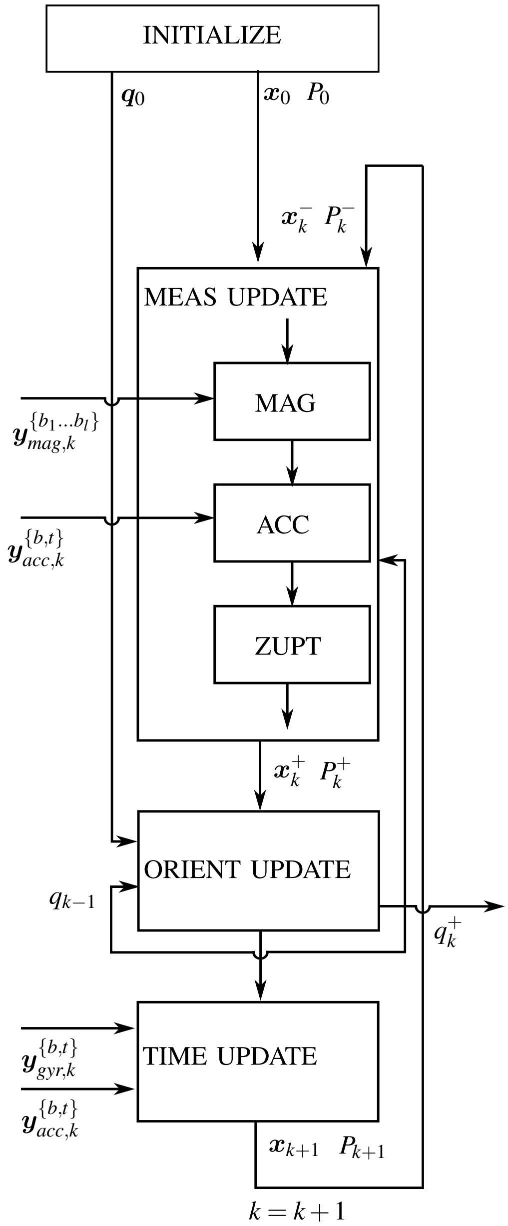

Fig. 1: Topology of the implemented EKF for estimation of the hand pose. After initialisation of both state x_0 and orientations q_0 and corresponding covariance P_0, a measurement update is performed. This step includes a magnetic update (MAG), acceleration update (ACC) and, when applicable, a zero velocity update (ZUPT). The magnetic update uses information obtained from l magnetometers. The acceleration update step uses accelerometer information of both base and target. Finally the zero velocity update applies an update when either the target velocity is zero with respect to base or when the target exceeds a pre-defined measurement volume. After the measurement and orientation update, a time update is performed which includes propagation of the state with corresponding covariance.

the positions of the finger tips with respect to the back of the hand's palm. A detailed description of the method can be found in [7].

III. Experimental Methods

For evaluation purposes various experiments were performed in a lab where the inertial/magnetic tracking system was compared with an optical reference system.

Data was sampled at 60 Hz for the inertial sensors on the trunk and 100 Hz for the inertial sensors placed on the hand. The inertial sensor system and optical system were synchronized by maximising the correlation between the estimated angular velocities of the hand obtained from both systems.

Possible gaps of the optical system were spline-interpolated with a maximum size of 30 samples.

A. Estimation of hand pose with respect to the trunk

Four magnetometers, each embodied in an IMMS (Xsens MTW), were rigidly attached to a plexi panel, which was attached to the subject's trunk, see Fig. 2. One of the IMMS was appointed as the primary sensor and designated as the origin of the trunks reference frame. In addition accelerometer and gyroscope data were obtained from this sensor.

Prior to the experiments all magnetometers were calibrated within the volume used in the experiments according a magnetic field mapping procedure [8]. In addition, the relative position and orientation between magnetometers attached to the plexi panel is required.

The target, which was placed on the hand, comprises a rigid plaster piece on which a magnet (neodymium rod, length: 2 *mm*, radius: 7 *mm*) and an IMMS were attached. The position and orientation of the magnet with respect to the local accelerometer were estimated using a ruler beforehand.

Both rigid pieces on trunk and hand were accommodated with optical markers (Optotrak, Northern Digital Inc, Waterloo, ON, Canada), such that position and orientations could be calculated and subsequently compared with our system.

The subject was asked to make repeated arm reach movements in the horizontal plane with the palm of the hand directed upwards. The movement included circular shaped trajectories such that the reaching area was maximised and being constrained by the length of the subject's arm.

B. Estimation of finger kinematics

A custom made printed circuit board (PCB) consisting of flexible and rigid structures was designed to account for the dexterity of the hand, see Fig. 3. The PCB's were placed on the dorsal side of the hand, along the phalanxes, using double sided adhesive tape. On the hand and each digit a 3D gyroscope and 3D accelerometer was deployed. In addition, a 3D magnetometer was placed on the tip digits and on the hand. Sensor data was acquired by an MCU (Atmel ATMEGA) and subsequently transferred via USB to the computer.

Optical markers were strapped to the back of the hand and the tip of the index finger, which allows a comparison in tip position estimates obtained from both systems. The

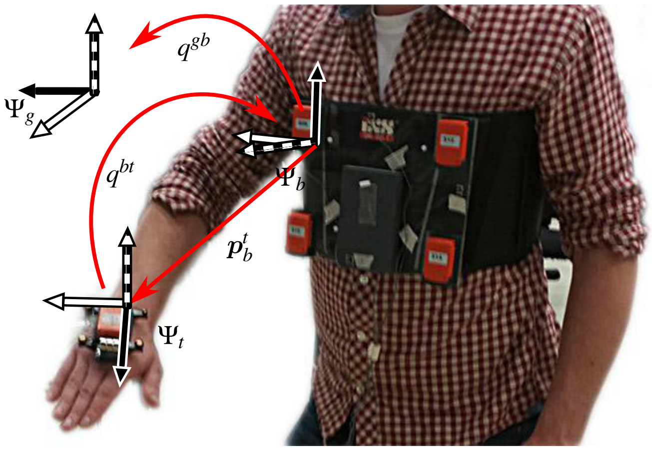

Fig. 2: Tracking instrumentation attached to trunk and right hand. Visible are four IMMS's (orange) attached to the trunk, each containing a 3D magnetometer. On the hand, a single IMMS together with a neodymium magnet (silver grey) is visible. The position of the hand ($\boldsymbol{p}_b^t$) and orientation (q^{bt}) with respect to the trunk is being estimated. For each coordinate frame the X (black), Y (white) and Z (dashed) directions are indicated.

segmental length of index finger digits as well as the position of the hand's reference frame origin with respect to the origin of the MCP joint were measured using a ruler.

First, the subject was asked to perform repeated flexion movements with MPC, PIP and DIP joints of the index finger. Secondly, the subject was asked to perform repeated, more complex, circular like movement with the index finger's tip.

IV. RESULTS

A. Estimation of hand pose with respect to the trunk

An estimation of both position and orientation of the hand with respect to the trunk is visible in Fig. 4.

The axes are defined such that X points vertically upwards (cranial), Z points in anterior direction (ventral) and Y such that a right-handed coordinate frame is formed.

Time epochs in which the SNR of the magnetic signals generated by the permanent magnet was substantially, (> 0.5 dB), are indicated (grey). The subject started with the hand far away from the magnetometers, whereas the initial estimate of the position was set to zero. Hence the estimates up to $t \approx 5(s)$ are unreliable as no information about the position was acquired yet. Good correspondence is visible between the inertial/magnetic system estimates and optical measurements, which is also confirmed by the rms difference over 5 trials between the distance measures 16.9 ± 4.0 mm (mean $\pm$ standard deviation) and error angle 1.5 ± 0.4 deg, see also Fig. 5. It should be mentioned that the first 10 seconds of each trial were not taken into account.

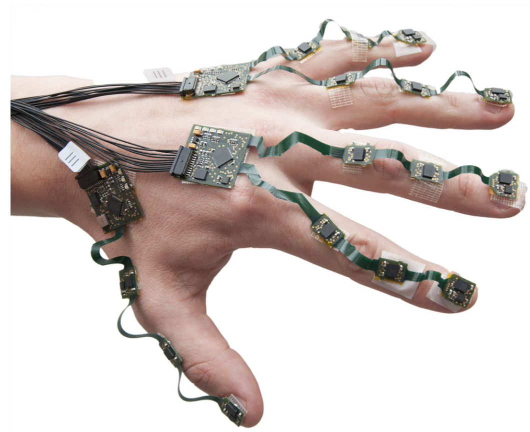

Fig. 3: Instrumentation attached to the hand for estimation of joint angles and finger tip positions. Visible are multiple 3D gyroscope and 3D magnetometer packaged in a single chip deployed on hand and fingers. 3D Additional magnetometers are placed on the hand and distal finger segments. Note that only the instrumentation on the index finger was used in this study.

B. Estimation of index finger tip position with respect to the hand

Prior to start of the index finger experiment a required calibration trial was conducted to firstly align the hand coordinate frames of optical and inertial sensors, secondly to obtain the position of the MCP joint expressed in the hand coordinate frame, and finally to obtain the position of the tip marker expressed in the distal coordinate frame.

On the left, Fig. 6 shows the position of the finger tip with respect to the back of the hand's palm, (of which the origin is defined close to the pulse with X dorsal, Y along the fingers and Z follows from the right hand rule) for a representative trial where the index finger was flexed and extended repeatedly.

The difference in position of the index' finger tip is defined as the absolute distance difference between estimated tip position by our inertial sensor system and optically measured tip position. It can be seen that the largest error contribution is caused by an error in the Z-direction during maximum flexion (up to 10 mm).

On the right of Fig. 6 a representative trial for the second movement type where circular shaped movements were performed with the index finger is shown. A large error is mainly visible in the minima of the Z-direction which corresponds with the maximum abduction angle of the MCP joint. It should be mentioned that, in contrast to section IV-A, the subject was asked to maintain the pose of the hand static where the hand palm was directed perpendicular to the local gravity vector.

The rms finger tip position correspondence was within 5.0 ± 0.5 mm for index finger during flexion movements and 12.4 ± 3.0 mm during circle shaped movements.

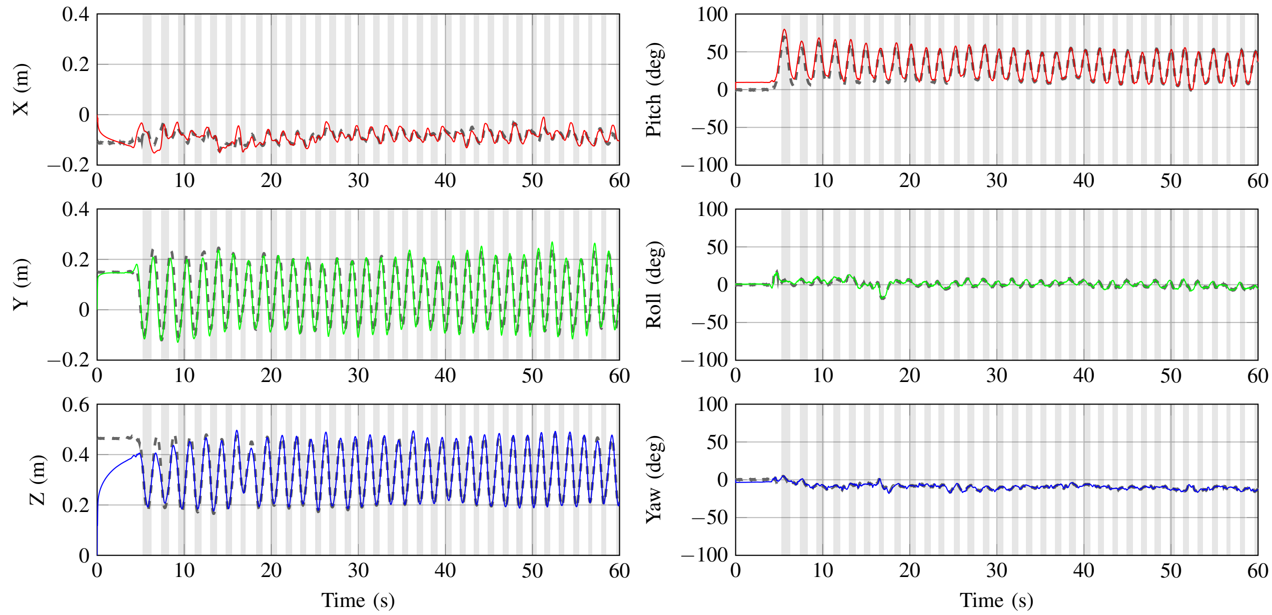

Fig. 4: Reconstruction of hand pose during a reaching task. Left: X, Y, Z position. Right: orientation expressed in Euler angles (*Pitch*, *Roll*, *Yaw*). A comparison with an optical system is made (grey,dashed). A significant large SNR induced by the permanent magnet is indicated with vertical grey bars.

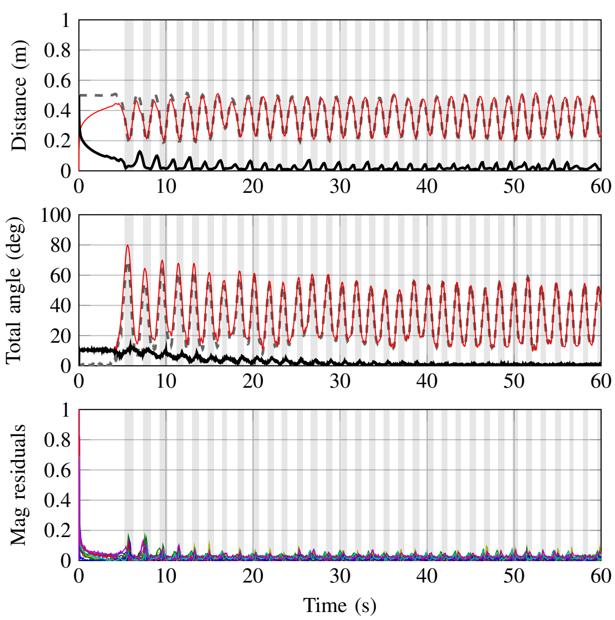

Fig. 5: Distance (top), total angle (middle) and filter residuals of magnetic measurements (bottom) during the reaching task. In the upper and middle plots the reference distance and total orientation angle is given (grey dashed) as well the corresponding differences (black). A significant large SNR (>0.5dB) induced by the permanent magnet is indicated with vertical grey bars.

V. DISCUSSION

Accurate tracking of hand and fingers is possible by fusion of inertial and magnetic sensor information.

Change in position and orientation of the hand with respect to the trunk can be estimated using inertial sensors. A permanent magnet can be used to feed the fusion filter with regular position updates that prevents position and orientation drift.

We used a constellation of four magnetometers, which were rigidly attached tot the chest via a plexi plane. However, only a minimum of two 3D magnetometers is required to distinguish between changes in magnetic field induced by the permanent magnet or due to environmental field changes. Moreover, even a single trunk magnetometer would suffice if those environmental magnetic disturbances can be avoided during the measurement.

Increasing the measurement volume is possible by adding extra magnetometers, whereas the range can be improved by a stronger magnet. However, it should be noted that the magnet's size increases significantly with respect to the size of the hand when a distance over 70 cm is to be covered. This is because the field strength decreases cubic over distance, whereas the magnet's volume scales linearly.

If the magnetometers are directly attached to the body, for instance on the sternum, soft tissue artefacts could occur resulting in estimation errors. This could be mitigated when a single trunk magnetometer is used or when the filter is modified such that calibration parameters are estimated online.

Robustness could be further improved by adding biomechanical knowledge of the consecutive links. If the orienta-

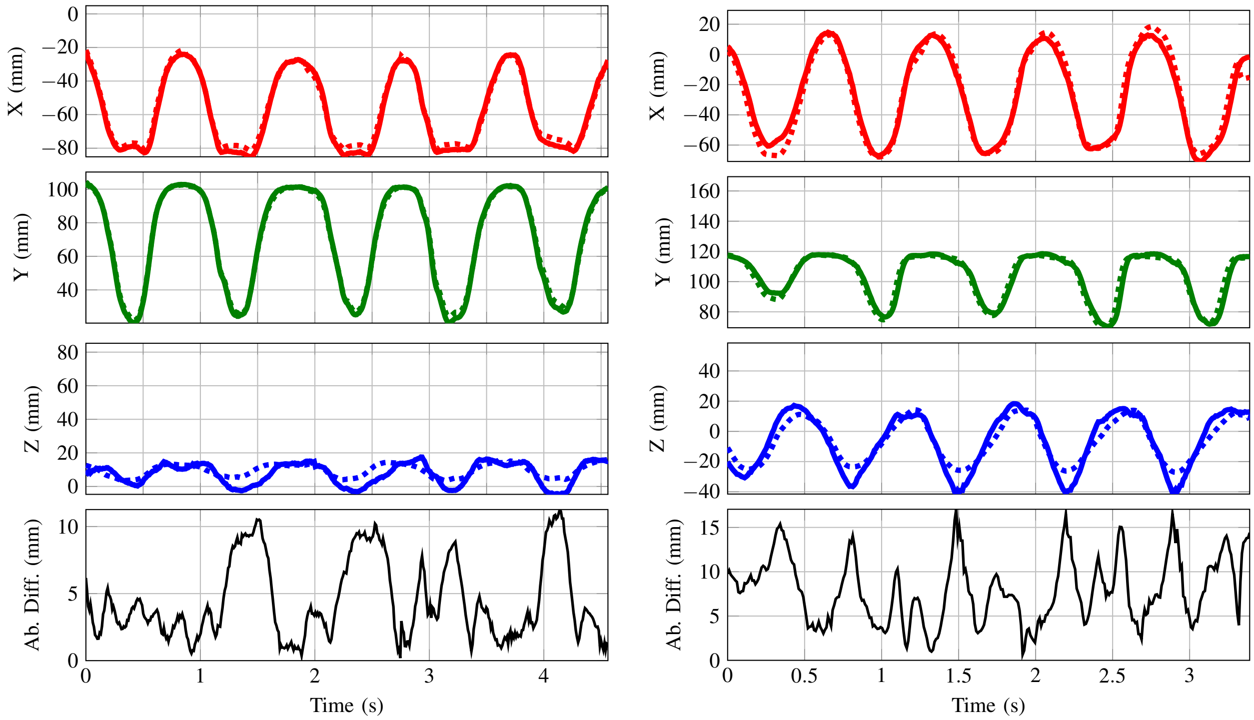

Fig. 6: Reconstruction of the index finger position (X, Y, Z) with respect to the back the hand's palm during a flexion-extension (left) and circle drawing movement (right) of the index finger measured by the optical system (solid) and estimated by the inertial sensors (dashed). The lower plots show the absolute index finger tip position difference.

tion of upper and lower arm is known, one could predict the position of the hand using forward kinematics [9].

The estimation of finger tip positions strongly relies on the biomechanical model constraints. The current filter applies soft constraints that relies on an intersecting and orthogonal joint model. However, many joints, like CMC and MCP, do not employ an ideal ball socket joint [10]. Therefore, an improved estimate is expected when more accurate joint models are used.

Besides the segment model, a calibration method that maps sensor signals to the underlying model segments is essential for proper functioning. An improved calibration procedure could be designed such that the directions of individual rotation axes, segment lengths and sensor positions are estimated online.

Calibration and estimation can be performed in parallel which will be explored in a future study. A generic probabilistic model approach will be used based on an optimization framework that eventually should result in more accurate state estimates of articulated body structure [11] [12].

In Kortier et. al. [7] additional experiments were performed which included all fingers and thumb. However, there is still need for more elaborated experiments in which the system is tested during daily life tasks.

Currently, the position of the finger tip with respect to the back of the hand is not estimated using the permanent magnet. However, this could be a large improvement in both accuracy and robustness, but requires a proper algorithm to deal with magnetic disturbances during interactions with ferromagnetic materials.

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REFERENCES

[1] F. H. Raab, E. B. Blood, T. O. Steiner, and H. R. Jones, "Magnetic Position and Orientation Tracking System," *Aerospace and Electronic Systems, IEEE Transactions on*, no. 5, pp. 709–718, 1979.

[2] D. Roetenberg, P. Slycke, and P. Veltink, "Ambulatory position and orientation tracking fusing magnetic and inertial sensing," *IEEE Transactions on Biomedical Engineering*, vol. 54, no. 5, pp. 883–890, Jan. 2007.

[3] H. Schepers, D. Roetenberg, and P. Veltink, "Ambulatory human motion tracking by fusion of inertial and magnetic sensing with adaptive actuation," *Medical and Biological Engineering and Computing*, vol. 48, no. 1, pp. 27–37, 2010.

[4] L. Dipietro, A. Sabatini, and P. Dario, "A survey of glove-based systems and their applications," *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, vol. 38, no. 4, pp. 461–482, 2008.

[5] N. Wahlstrom, J. Callmer, and F. Gustafsson, "Magnetometers for tracking metallic targets," in *Information Fusion (FUSION), 2010 13th Conference on*, 2010, pp. 1–8.

[6] H. G. Kortier, J. Antonsson, F. Gustafsson, and P. H. Veltink, "Ambulatory 6dof body segment tracking using inertial measurement units and a permanent magnet," submitted.

[7] H. G. Kortier, V. I. Sluiter, D. Roetenberg, and P. H. Veltink, "Assessment of hand kinematics using inertial and magnetic sensors." *Journal of NeuroEngineering and Rehabilitation*, vol. 11, no. 1, p. 70, Apr. 2014.

[8] M. Kok, J. Hol, T. B. Schon, F. Gustafsson, and H. Luinge, “Calibration of a magnetometer in combination with inertial sensors,” in *15th International Conference on Information Fusion, FUSION 2012*, 2012, pp. 787–793.

[9] D. Roetenberg, H. Luinge, and P. Slycke, “Xsens MVN: full 6DOF human motion tracking using miniature inertial sensors,” *Xsens Motion Technologies BV, Tech. Rep*, 2009.

[10] P. W. Brand and A. Hollister, *Clinical mechanics of the hand*. Mosby Year Book, 1993.

[11] E. Todorov, “Probabilistic Inference of Multijoint Movements, Skeletal Parameters and Marker Attachments From Diverse Motion Capture Data,” *IEEE Transactions on Biomedical Engineering*, vol. 54, no. 11, pp. 1927–1939, 2007.

[12] M. Kok, J. Hol, and T. B. Schon, “An optimization-based approach to human body motion capture using inertial sensors,” *users.isy.liu.se*.