Xsens MTw Awinda: Miniature Wireless Inertial-Magnetic Motion Tracker for Highly Accurate 3D Kinematic Applications

Monique Paulich, Martin Schepers, Nina Rudigkeit, and Giovanni Bellusci

***Abstract*—The MTw Awinda is the second generation wireless inertial-magnetic motion tracker by Xsens. The MTw enables real-time 3D kinematic applications with multiple motion trackers by providing highly accurate orientation through an unobtrusive setup. This whitepaper presents the basic working principles and architecture of the Xsens MTw Awinda system. Furthermore, the system performance is assessed and key outcomes of two real-life experiments using the Xsens MTw Awinda system are given. In the first experiment the performance during arm movements related to sports and gaming is evaluated, while the second experiment focuses on data acquired during walking and running, including exposure to magnetic distortions for extended periods of time. The results show that MTw Awinda is a flexible, easy-to-use, and reliable tool for capturing human motion in a large variety of applications, even in challenging environments.**

I. Introduction

RESEARCH on human movement has been ongoing for centuries [1], but has gained increasing interest within the last few decades due to dramatic technological and computational advances that enabled quantitative, objective, and reproducible analysis of human kinematics.

Historically, marker-based optical tracking systems have become the standard technology for motion capturing. However, optical tracking systems have some severe system-immanent disadvantages for motion capture applications. For example, markers are easily occluded during movement. Additionally, the space for the activities is limited to the area that the cameras can cover, the cameras have to be mounted in the environment, and they are sensitive to variations in lighting conditions. As a result, optical tracking systems require lab-like environments, which makes them unsuitable for a wide range of use cases.

For motion tracking applications in unconstrained environments, unobtrusive, body-worn systems that accurately track the motion are desirable. State-of-the-art MEMS motion sensors, i.e. accelerometers, gyroscopes, and magnetometers, provide ideal characteristics for such motion capture systems, since they are small, self-contained, and energy-efficient. By combining the data from all three types of sensors, highly accurate and robust orientation output for real-time applications can be obtained.

An Inertial-Magnetic Measurement Unit (IMMU) is a Motion Tracker (MT) that comprises a 3D gyroscope, 3D accelerometer and 3D magnetometer in one package, and can be combined with complex sensor fusion algorithms. IMMUs are commercially available as single trackers or as part of Body Sensor Networks (BSN), such as Xsens MVN, to capture full human body motion. In general, MTs require a power supply and a connection to the recording device (tracker-host connection), while for MTs as part of a BSN, additional connections between the MTs are required (inter-tracker connection). The easiest way to establish these connections is using cables, as done for the inter-tracker connections of the Xsens MVN Link system [2]–[4]. In the MVN Link system, cabling and battery are integrated in a suit, which is worn by the person to be captured. The main advantage of cabling is the possibility for a high tracker-host frequency without data loss.

However, cabling might not be desired for some use cases. For example, in clinical movement analysis, the use of cabled trackers might lead to slightly longer setup time for each subject, which can be perceived as cumbersome for large sample sizes. Furthermore, in ergonomics studies, cables can be a hindrance or even a safety risk for factory workers operating machinery where human-machine interaction is required.

Taking these requirements of the market into consideration, Xsens released the first generation MTw in 2011: a miniature wireless inertial-magnetic motion tracker, specifically developed for highly accurate ambulatory 3D kinematic applications. In 2016, the second generation MTw Awinda has been released [2], [3]. With these wireless motion trackers, inter-tracker and tracker-host cabling are no longer needed, therefore requiring no additional hardware to be worn on body, except for the motion trackers themselves. All motion trackers wirelessly transmit their data to the PC, via the Awinda Master (station or USB dongle) connected to a recording PC.

During development, several fundamental issues have been addressed to achieve the same performance as a traditional cabled system:

1) A wireless connection may not guarantee very high data transmission rates, particularly when multiple motion trackers are used.
2) The wireless link may introduce occasional loss of data packets.
3) Accurate, inter-tracker time synchronization is a challenge in wireless sensor networks, but essential since timing errors of just a few milliseconds might lead to unacceptable joint angle errors of several degrees, depending on MT positioning and performed motion.

Taking the above challenges into account, Xsens developed and patented a completely new signal-processing pipeline [5]–

MTw Awinda is a product by Xsens Technologies B.V., P.O. Box 559, 7500 AN Enschede, the Netherlands, T: +31 (0)889736700, F: +31 (0)889736701; www.xsens.com, patented.

[12] and incorporated this in their wireless motion tracking product: MTw Awinda.

In contrast to standard signal processing pipelines, in which lowering the output rate results in degradation of performance, Xsens developed a dedicated Strap-Down Integration (SDI) algorithm that guarantees high accuracy in dynamic conditions independent of output data rate.

Furthermore, a proprietary radio protocol called Awinda [5]–[12], based on low-cost 2.4 GHz ISM chipsets, has been designed to detect and handle occasional packet loss in real-time processing. In case data has not been transmitted successfully, it is stored in a buffer and retransmitted when possible. In addition, the Awinda protocol is capable of dynamically decreasing the output data rate, which, in combination with the SDI, prevents accuracy deterioration when data packets are lost. The sensor fusion algorithm, the Xsens Kalman Filter (XKF-hm), has been developed and optimized for human-relevant motions to maintain high performance, even with irregular measurement updates resulting from the occasional data packet loss.

The synchronization issue is also handled by the Awinda protocol, which provides accurate time synchronization of up to 20 MTw′s across the wireless network to within 10 µs, allowing to achieve 'wired like' system performance.

This paper presents the basic working principles, architectural choices and performance of the Xsens MTw Awinda system, and is organized as follows: Section II briefly introduces the MTw system and architecture. Section III presents information on the data capturing and processing of the MTw Awinda system: data sampling by the sensing elements, the SDI algorithm, description of the Awinda protocol and Xsens Kalman Filter, and the available output data parameters. In Section IV, the unique advantages of the use of the Xsens Kalman Filter in combination with human-relevant motions and magnetic disturbances are shown for a set of collected data. In Section V, the main conclusions are drawn. In the Appendix, the recommended workflow and two example applications are presented.

II. MTw System and Architecture

In this section, the main MTw system components are shortly introduced. Fig. 1 shows the overall MTw hardware. The MTw system is declared for safe use by CE and FCC certification [13]. Fig. 2 shows the interfaces between the MTw motion tracker, Awinda Master and the software interface for connecting, recording or visualization.

A. MTw

The MTw is a miniature IMMU with a package size of 47 mm × 30 mm × 13 mm and a weight of 16 g (Fig. 1a). To sense the motion, the MTw contains inertial sensor components, namely a 3D rate gyroscope and a 3D accelerometer. In addition, it comprises a 3D magnetometer, a barometer, and a thermometer. Fig. 3 provides a block diagram of the architecture.

On board of the sensor, the SDI algorithm is applied to the calibrated readings of the gyrosope and accelerometer. The output of the SDI, along with the calibrated magnetometer and barometer data, is then transmitted wirelessly using the Awinda Protocol to the Awinda Master. The data of the thermometer is used to compensate for the temperature dependency of the other sensing elements.

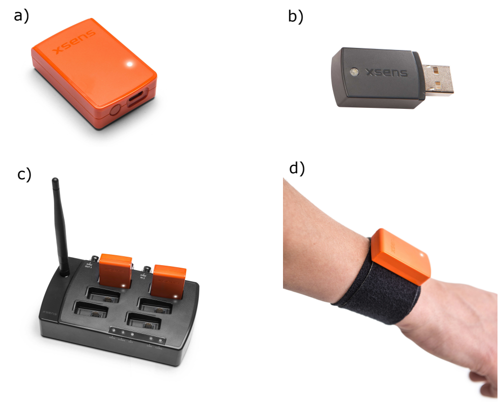

Fig. 1. The Xsens MTw Awinda hardware: a) MTw motion tracker; b) Awinda Dongle; c) Awinda Station; d) MTw body strap.

The MTw is powered using a LiPo battery, lasting for 6 h. The MTw is designed to be robust, easy and comfortable in usage, with easy placement on the body based on flexible hook and loop straps (Fig. 1d).

B. Awinda Master

The Awinda Master (Fig. 2), serves as the interface between the Awinda host (typically a PC running Xsens-based software [14]), and one or more MTw's. The Awinda Master ensures that the data from each MTw is synchronized to within 10 µs. Up to 20 MTw's can be wirelessly connected to a single Awinda Master. There are two different types of Awinda Master possible with the MTw system: the Awinda Station and the Awinda Dongle, which are both available as part of the MTw Awinda Development Kit.

1) Awinda Station: The Awinda Station (Fig. 1c) is 148 mm × 104 mm × 31.9 mm in size. It includes the external antenna and 6 MTw docking slots. These slots are used for charging the MTws and firmware updates. Additionally, the Awinda Station has 4 BNC hardware connections for TTL time-synchronization with third party devices. The range of the wireless link using the Awinda Station is typically about 50 m in line of sight, guaranteeing complete freedom of movement and recording.

2) Awinda Dongle: The Awinda Dongle is a small USB device, measuring only 45 mm × 20.4 mm × 10.6 mm with USB connector, and 33 mm × 20.4 mm × 10.6 mm without the USB connector (Fig. 1b). The dongle has the same wireless communication possibilities as the Awinda Station. However, it does not have a range extender, which reduces the range to 10 m. To maximize portability, the Awinda Dongle is not equipped with hardware interfaces for charging MTw's or BNC ports for third party synchronization.

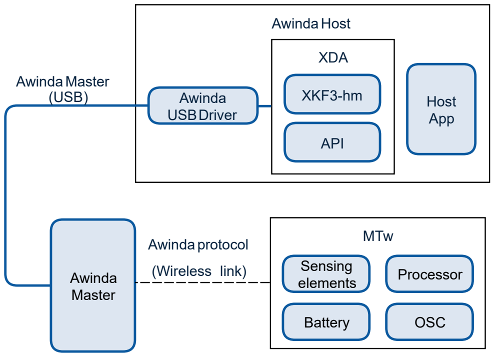

Fig. 2. Schematic and simplified overview of the chain of hardware and software components of the MTw system.

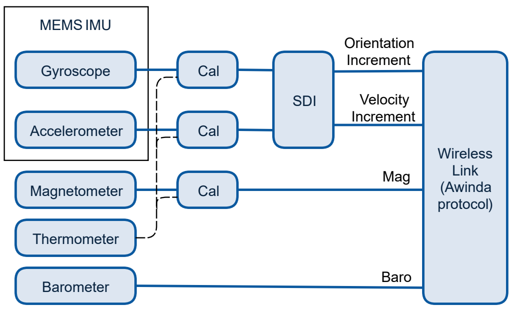

Fig. 3. MTw Awinda signal processing architecture.

C. Awinda Host

The Awinda Host (Fig. 2) receives the data from the Awinda Master through a USB connection. The host contains the Xsens Device API (XDA), of which XKF3-hm and the API are part of, as displayed by Fig. 2. XKF3-hm is a proprietary fusion filter, specifically developed to fit applications involving human movement (Section III-D). This filter provides accurate 3D orientation to the host application. The host application can be either MT Manager, the standard logging and visualization tool from Xsens, or an independently built program based on the Xsens software development kit (SDK).

III. MTw Signal Pipeline and Data Processing

In this section, the signal processing pipeline of the MTw is described. This includes details on the sensing elements, the Strap-Down Integration (SDI) algorithm, the proprietary Awinda protocol, XKF3-hm, and the data output of the Xsens MTw Awinda system.

A. Sensing Elements

1) Gyroscope: A 3D gyroscope is an inertial sensor that senses angular velocity. When integrated over time, it provides an estimate of the change in orientation. Note that errors in the sensor signal accumulate over time when integrated, leading to so-called drift.

2) Accelerometer: A 3D accelerometer is an inertial sensor that measures linear acceleration. When the sensor is not in motion, the measured acceleration equals the gravitational acceleration. The gravity vector can be used as a reference for pitch and roll, similar to the working principle of a water level.

3) Magnetometer: A 3D magnetometer is able to measure strength and direction of the surrounding magnetic field. If no magnetic disturbances are present, the magnetometer measures the Earth magnetic field. In the context of sensor fusion, the Earth magnetic field vector is often used as a reference for heading, similar to a compass needle.

4) Thermometer: A thermometer is a sensing element that measures temperature. It is often used as an aiding sensor to compensate for temperature dependencies of other sensing elements.

5) Barometer: A barometer is a sensing element that measures atmospheric pressure. For motion sensing applications, it is used as an aiding sensor to get height information.

B. Strap-Down Integration (SDI)

In traditional inertial sensing architectures, a decrease in the output frequency typically results in inaccurate orientation estimates due to low sampling rates that may cause aliasing, coning and sculling effects, etc. One of the main differences of the MTw compared to these architectures is that the pipeline of the MTw uses the SDI [7], [8], which has the advantage of high internal sampling rates, yet providing accurate data at a lower, user-selectable output rate.

Data from the accelerometer and gyroscope is captured at a sampling frequency f_S of $1000\,\text{Hz}$ and low-pass filtered at a bandwidth of $184\,\text{Hz}$. This bandwidth is wide enough for movement analysis applications and guarantees high fidelity in the recorded signals. The combination of the high sampling rate and the large bandwidth is essential, due to the non-commutative nature of 3D rotations [7], [8].

The calibrated signals are processed by the SDI algorithm at the sampling frequency f_S, which calculates and outputs orientation and velocity increments, at a variable and user-selectable output frame rate f_R. The available output data rates of the MTw Awinda system are provided in Table I. In contrast to linear down-sampling, the accuracy of the SDI output will not be affected by the specific choice of the output frame rate. Low frame rates will only result in reduced time resolution. In this way, ideal performance is guaranteed even during very high dynamics like fast movements, vibrations, or impacts.

Fig. 4 shows this property of the SDI by comparing the differences in orientation obtained by two methods. In the first method, the dead-reckoning orientation is obtained from the SDI algorithm as used for the MTw Awinda. In the second method, the dead-reckoning orientation is obtained by first applying linear down-sampling of the data as done in traditional architectures. Next, the differences are determined between these two methods and a reference obtained from a high-grade IMMU, as shown in the figure. Dead-reckoning denotes straight-forward integration of gyroscope data, i.e. no sensor fusion algorithms such as XKF3-hm are involved. The

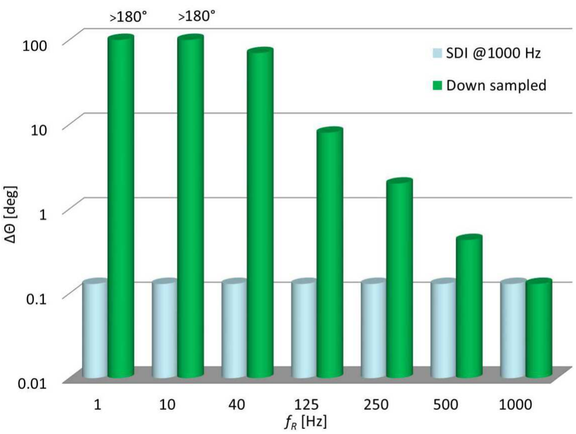

Fig. 4. Dead-reckoning orientation difference in a high dynamic situation and different output frame rates f_R, based on 1000 Hz SDI input data (blue) and linear down sampled data (green). The difference is calculated by comparing the dead-reckoning orientations to a reference orientation based on high grade IMMU data.

TABLE I
MAXIMUM OUTPUT FRAME RATE VS. MAXIMUM NUMBER OF MTW WIRELESSLY CONNECTED

Number of MTw	Maximum output frame rate f_R (Hz)
1-5	120 Hz
6-9	100 Hz
10	80 Hz
11-20	60 Hz

figure shows the orientation difference at different output data rates for the two cases. The data in this graph is based on game-like motions, consisting of angular velocities ranging up to $1000\,°\,\mathrm{s}^{-1}$ and accelerations up to $40\,\mathrm{m\,s}^{-2}$. The IMMU data has been sampled at $1000\,\mathrm{Hz}$. It can be seen that when using SDI, the orientation difference is independent of output frame rate, resulting in maintained accuracy. From the same plots, it is also evident that the performance of the traditional architecture rapidly degrades, e.g. to about $8°$ already for an output rate of $125\,\mathrm{Hz}$. Impairments become dramatic for output rates equal to $40\,\mathrm{Hz}$ and smaller.

C. Awinda wireless communication protocol

The Awinda protocol has been developed and patented [5]–[12] by Xsens to specifically address the unique peculiarities and requirements of a wireless inertial sensor network. The basic principles of this protocol are described in this section.

All MTw's belong to a single network. By an Awinda Master broadcast, the Awinda Master communicates time slots dedicated to each tracker, in which the tracker will transmit its data packet to the Master. The MTw performs this operation in intervals: the data measured during each contiguous interval are combined in a packet and transmitted during the assigned time slot. The length of the interval is dependent on the output update rate f_R. The Awinda protocol is capable of detecting and handling occasional packet loss by increasing the time intervals in real-time, and retransmitting missed data packets during recording, without affecting the achieved accuracy.

Especially in combination with the SDI, the Awinda protocol is a powerful tool to prevent accuracy deterioration when data packets are lost, as can be seen in Fig. 5. Shown in this figure is the dead-reckoning orientation obtained from the combination of the SDI and Awinda protocol (blue line), next to a simple linear interpolation scheme (red line). Both data streams are based on input data with $25\,\%$ packet-loss and the reference orientation is represented by the black line. The figure shows that increasing packets-loss leads to decreasing orientation performance for the linear interpolation method, while accuracy is maintained in data processed using the SDI in combination with Awinda.

The next four subsections provide information on essential properties of the Awinda protocol contributing to the reliability and robustness of its performance.

1) Latency: In the context of the Awinda protocol, the latency is defined as the difference between the time at which the SDI data were processed at MTw side, and the moment at which the Awinda Master offers these data to the host (e.g. the laptop running the user application). The time required for the host to read and process the data depends on its specific configuration, and it is not controlled by the Awinda system. The latency for 1 MTw is about $9.5\,\mathrm{ms}$, and for 20 MTw's it is about $19\,\mathrm{ms}$.

2) Packet retransmission: To guarantee the highest level of accuracy in offline applications, a retransmission mechanism is implemented in MTw. The Awinda Master broadcast communicates to each MTw whether the requested data has been received. In case the corresponding packet fails to be received by the Master, the MTw will store the data in a buffer for possible retransmission. The Awinda protocol has time slots allocated, which are shared between the MTw's, solely for the purpose of retransmissions. Any retransmitted data received by the Awinda Master will be removed from the buffer. This way, the data is continuously available in case of sudden connection outage. In total, the buffer can hold 1000 data packets, which corresponds to 10 seconds of missed data with MTws operating at $100\,\mathrm{Hz}$.

3) Buffer overflow: To prevent buffer overflow, the Awinda protocol combines individual increments into longer time intervals. This way, no data packets are discarded and only a decreased measurement resolution will occur.

4) Inter-tracker time synchronization: Each Awinda Master broadcast contains a timestamp indicating the broadcast time of transmission, which is then matched with the MTw internal clock. This results in an inter-tracker time synchronization well within $5\,\mu\mathrm{s}$.

D. Xsens Kalman filter for orientation

The orientation of the MTw is computed by a new Kalman filter, specifically developed by Xsens for capturing human motion, called XKF3-hm. XKF3-hm uses the data that is transmitted using the Awinda wireless communication protocol, i.e. rotation and velocity increments as provided by the SDI algorithm, and the magnetometer samples. XKF3-hm fuses

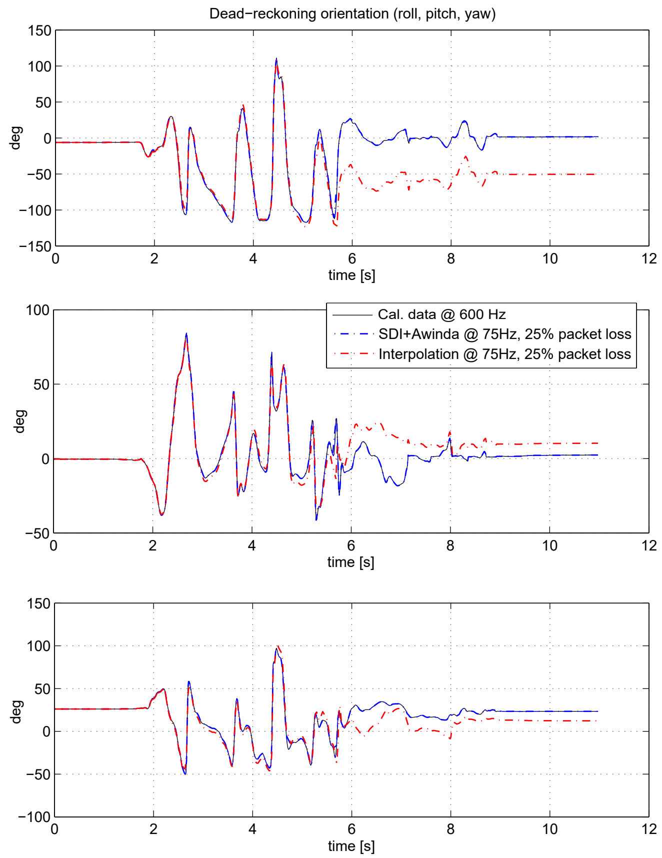

Fig. 5. Dead-reckoning orientation (roll, pitch, yaw) comparison with 25 % packet-loss probability: a) using the original calibrated data at 600 Hz (black); b) using the SDI in combination with the Awinda Protocol as implemented in MTw (blue); c) using a simple linear interpolation scheme (red).

these data into a statistical optimal and highly accurate 3D orientation estimate for both static and dynamic movements. The underlying principle of XKF3-hm is to compensate the slowly but continuously increasing orientation drift of the integrated gyroscope signal by using the gravity reference vector provided by the accelerometer, as well as the Earth magnetic North reference vector provided by the magnetometer. In this way, drift-free, absolute orientation is obtained. In case the magnetometer signal is distorted and does not measure just the Earth magnetic field anymore, estimating orientation becomes more challenging. However, XKF3-hm includes advanced models based on decades of motion tracking experience to minimize the effect of these distortions. The performance of this filter is assessed in Section IV. Additional features of XKF3-hm are presented in the next paragraphs.

1) Offline Magnetic Field Mapper: In some cases, a recalibration of the MTw's magnetometer is required (e.g. due to transport, or when rigidly attaching the MTw to a ferromagnetic object). This causes an error in the estimated orientation. The Magnetic Field Mapper (MFM) software can correct for these distortions by recalibrating the magnetometer [15]. This calibration procedure can be executed in approximately a minute and yields a new set of magnetometer calibration values of the MTw.

2) In-use Magnetic Field Mapper: The second generation MTw Awinda contains an addition to the XKF3-hm algorithm; the in-use Magnetic Field Mapper (in-use MFM). The main purpose of the in-use MFM is to estimate and correct for so called hard-iron effects, in a seamless way in the background.

3) Clipping handling: A challenge in capturing human motion lies in the fact that short occasional transients with extreme motion dynamics are relatively common, like in jumping and running, especially at the extremities. In order to capture high dynamic movements with the highest accuracy possible, the range of the inertial sensing elements, given in the top part of Table II, is carefully chosen. This decision is based on a trade-off between resolution and range. When a movement does cause the sensors to exceed their dynamic range (clipping), XKF3-hm is designed to cope with these events and reduce the effects to a minimum.

E. User output data

Different types of data are available for the user and can be obtained through the XDA and host application:

1) Calibrated Data: The available calibrated sensor data types are 3D acceleration ($\mathrm{m\,s^{-2}}$), 3D angular velocity ($^{\circ}\,\mathrm{s^{-1}}$) and 3D magnetic field (arbitrary unit A.U., normalized to 1 during factory calibration), provided in a sensor-fixed frame. 3D free acceleration (acceleration subtracted by the gravity component, $\mathrm{m\,s^{-2}}$) is available as well. This calibrated data type is outputted by XKF3-hm and provided in the earth-referenced local frame. Since the acceleration and angular velocity are derived from their respective increments, it should be noted that these measures do not directly represent the instantaneous inertial measurements, but they can be considered as a measure of the average acceleration and angular velocity of each time interval.

2) Orientation Data: 3D orientation of the sensor with respect to the earth-referenced local frame is outputted by XKF3-hm. The orientation is provided in any of the following parameterizations:

- *Euler representation*. The orientation is given by means of three successive rotations in a particular sequence (roll, pitch, and yaw). While being intuitive, Euler angles have the drawback that the data can suffer from singularities. For this reason, Euler representation should only be used for interpretation, not calculation. Instead, quaternions or rotation matrices are preferred for calculations.
- *Unit quaternions*. The orientation can be represented by a normalized quaternion q = [W X Y Z], with W the real component and X, Y, Z the imaginary parts. This format is recommended for analysis based on its mathematical advantages over the alternative representations. For visualization of 3D orientation and easy interpretation, the quaternion is typically converted into Euler angles.
- *Rotation matrix*. The orientation can be represented by a 3x3 matrix built from directional cosines describing the angles between the vector and the three coordinate axes.

TABLE II
MAIN SENSING COMPONENTS AND SIGNAL PIPELINE SPECIFICATIONS

	ACC	GYR	MAG	BAR
Sensor type	Digital	Digital	Digital	Digital
Full scale	±160 m/s^2	±2000 deg/s	± 1.9 Gauss	300-1100 hPa
Non-linearity	0.5% of FS	0.1% of FS	0.1% of FS	0.05% of FS
Bias stability	0.1 mg	10 deg/hour	-	100 Pa/year
Noise	200μg/$\sqrt{\text{Hz}}$	0.01 deg/s/$\sqrt{\text{Hz}}$	0.2mGauss/$\sqrt{\text{Hz}}$	$0.85Pa/\sqrt{\text{Hz}}$
Bandwidth	184 Hz	184 Hz	10-60 Hz (var.)	-
ADC sampling rate	1000 Hz (fix.)	1000 Hz (fix.)	20-120 Hz (var.)	20-60 Hz (var.)
SDI input rate	1000 Hz (fix.)	1000 Hz (fix.)	-	-
Output frame rate	20-120 Hz (var.)	20-120 Hz (var.)	20-120 Hz (var.)	20-60 Hz (var.)

IV. MTw PERFORMANCE EVALUATION

In this section, the performance of the XKF3-hm filter for the MTw system is presented. Two different examples for XKF3-hm are provided to show the benefits of these algorithms in human-relevant, high dynamic situations.

A. XKF3-hm Filter analysis: Experiment 1

The first experiment with XKF3-hm includes motions of the arm related to sports and gaming, like tennis, basketball and a game controller, in a magnetically undisturbed environment. The trial starts with 20 s to 30 s without motions, followed by 40 s of sports and gaming like motions. After this the arm is kept static again for 20 s to 30 s, followed by one minute of Activities of Daily Living (ADL) tasks, i.e. drinking coffee, washing dishes and writing on paper. The trial ends with 20 s to 30 s without motion.

The outcome of the XKF3-hm filter is compared to orientation obtained using a high grade reference IMMU. Both the reference IMMU and the MTw were mounted on a wooden plate, and the plate was worn on the forearm of the subject. This way, it was ensured that both the reference IMMU and the MTw had the same orientation. All movements were performed indoor in a lab, within the specified ranges of the MTw. In Fig. 6 the calibrated data of this trial is shown. The high and low dynamic parts of the trial can easily be identified and characterized in these graphs.

The orientation differences between the XKF3-hm output and the reference IMMU can be observed in Fig. 6. The orientation for roll and pitch values have an RMS of 0.29° and 0.42°, respectively. The yaw angle has a RMS value of 1.27°. Overall, the differences shown in this graph are within the specified dynamic accuracy levels of 0.75° RMS for roll and pitch, and 1.5° RMS for heading (yaw).

B. XKF3-hm Filter analysis: Experiment 2

The second XKF3-hm experiment focuses on the orientation performance of the MTw Awinda in a longer trial, including magnetically disturbed instances along the trial. This trial is performed outside on a parking lot full of cars, and consists of the first 30 s being static, followed by 11 min of walking and running. The trial ends again statically for 30 s. The MTw and the high grade reference IMMU are again mounted on a wooden plate, with the plate mounted on the torso for this experiment. All movements were performed within the specified ranges of the MTw. In Fig. 7 the calibrated data of this trial is shown. The dynamic patterns of walking and running can be observed in the acceleration and angular velocity data in the first two graphs. Magnetic disturbances of

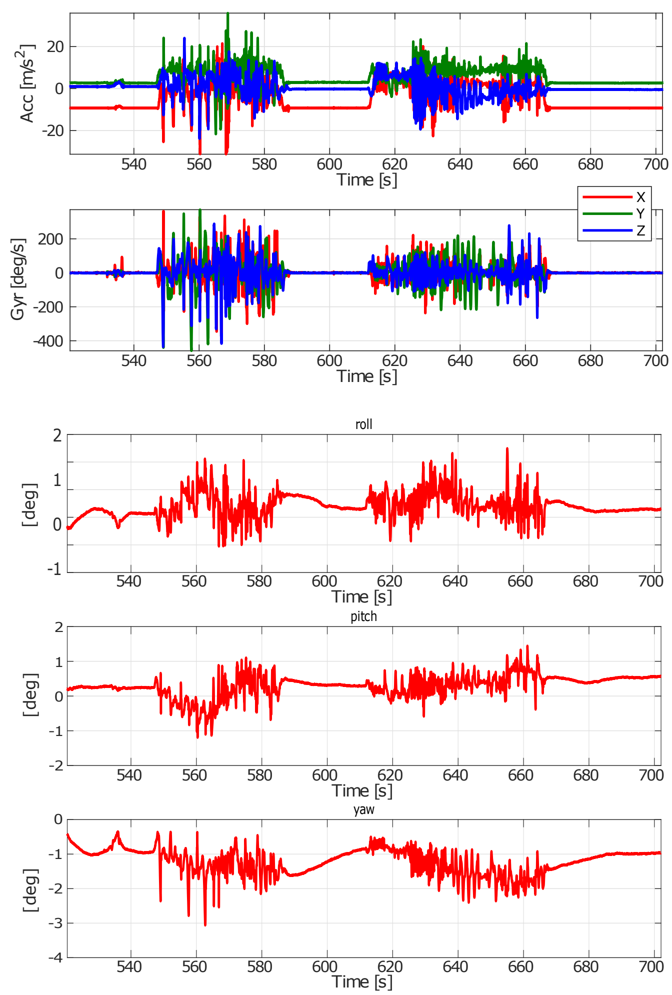

Fig. 6. The top two figures show the calibrated data (acceleration and angular velocity) of the performance test including static, game-like and sports motions (top); and the orientation differences of XKF3-hm compared to the orientation obtained using a high grade reference IMMU of the same trial.

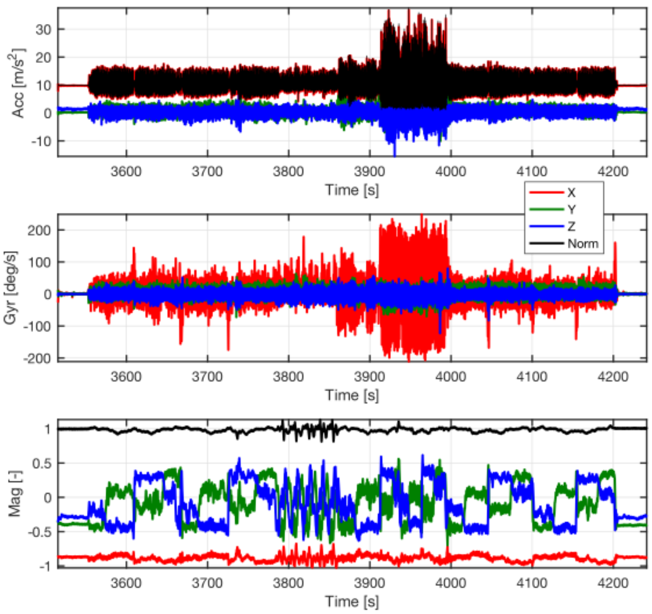

Fig. 7. Calibrated data of the performance test including static parts, walking, jogging and magnetic disturbance.

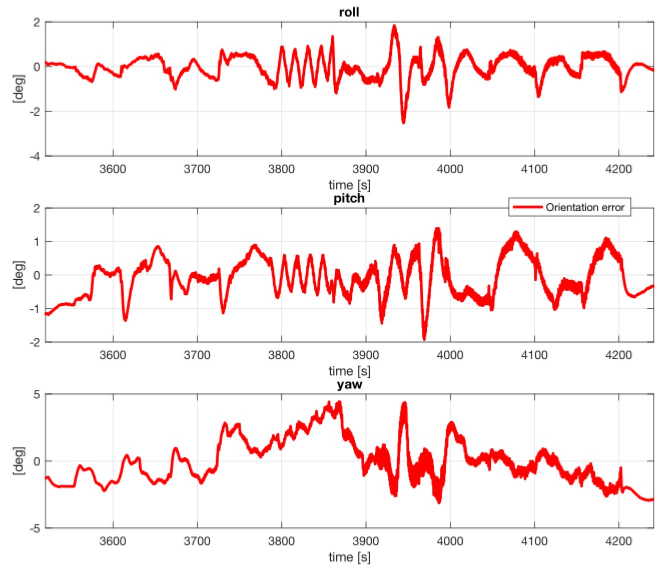

Fig. 8. Orientation difference of XKF3-hm compared to the reference orientation obtained using a high grade reference IMMU in walking and jogging, with temporary magnetic disturbances.

varying strengths occur during the whole trial, mainly between 3790 s to 3860 s of the recording (magnetic norm fluctuates from 0.8 [a.u.] to 1.15 [a.u.]).

In Fig. 8 the orientation differences between the XKF3-hm output and the reference IMMU can be observed. The difference for roll and pitch have an RMS of $0.51°$ and $0.59°$, respectively, which is well within the specified accuracy level of $0.75°$ RMS. The yaw angle has an RMS of $1.65°$, which is slightly above but close to the specified accuracy levels of $1.5°$ RMS. Since the orientation accuracy of the MTw Awinda is specified for typical circumstances, slightly increased RMS values for the yaw angle can be expected for this trial that included strong magnetic disturbances, provoked by intentionally walking in close proximity to and around cars. Note that the effects of magnetic disturbances will only be visible in the yaw angle.

The possible influence of magnetic distortions on the yaw angle is further shown by Fig. 9. This graph displays the difference in yaw angle obtained with two different methods, compared to the orientation obtained from a high-grade reference. In the first method, the yaw angle is obtained from XKF3-hm, incorporating the advantage of a robust performance, even in challenging environments. In the second method, the yaw angle was extracted solely from the output of the magnetometer of the MTw. Differences of $50°$ and higher can be observed for the orientation derived from the second method. For this trial, magnetic disturbances came from a car, but these disturbances can come from any source of ferromagnetic materials ranging from a desk or chair, to a piece of machinery or any hand-held electronic device. From the above analysis, it becomes clear that XKF3-hm is able to cope with these severe magnetic distortions.

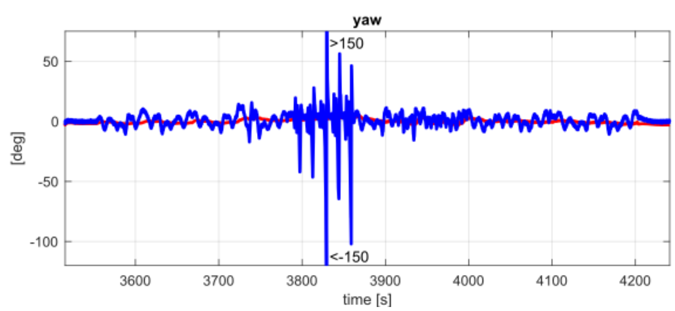

Fig. 9. Orientation differences in the yaw angle of the XKF3-hm output (method 1) and the orientation calculated by the inclination and magnetometer data (method 2), compared to the orientation data obtained by the high grade reference IMMU.

V. Conclusion

In this paper, the basic working principles and architectural choices of the Xsens MTw system have been presented and motivated. The high sampling rate of the inertial data, performed at 1000 Hz, together with the use of the SDI, allows to preserve accuracy even at lower update rates or occasional packet loss. The Awinda communication protocol between the MTw and the Master provides accurate time synchronization of up to 20 MTw's across the wireless network to within 10 µs, minimizing the overall latency and maximizing the efficiency of use of the transmission resources. The performance of XKF3-hm was assesessed and found to be accurate and robust, even in severely magnetic distorted environments.

From this level of accuracy it can be concluded that the MTw Awinda can be used as a flexible, easy and reliable tool for capturing human motion in a large variety of applications, without sacrificing performance compared to wired inertial systems or the need to avoid less-than-optimal environments for the use of IMMU technology.

APPENDIX

In the following, more practical information for the user are given, by providing some typical application examples. The first subsection will explain the recommended workflow with the MTw Awinda trackers to extract the most accurate data from them. The second subsection holds two customer application stories, based on Xsens' wireless trackers.

A. Recommended workflow

In order to produce the most accurate data from inertial motion trackers, there are a few important notes to keep in mind. As mentioned in section III-D, the orientation estimation for the MTw Awinda is based on a Kalman filter, which typically processes data sequentially, and over time builds up over time. Therefore, a short period of time just after startup ($10\,\mathrm{s}$ to $15\,\mathrm{s}$) is needed with no or low dynamic movements and preferably without magnetic distortions. This process is called 'filter warm-up'. After filter warm-up, the data acquisition can start. Data acquisition is possible using MT Manager or MT SDK, accessible through example code provided in several programming languages. During recording, it is recommended to prevent clipping, and to minimize periods with wireless disconnections, in order to prevent buffer overflow. Stored data packets are transmitted during and at the end of the recording, through the process explained in Section III-C2. This process will be most efficient with the MTw's well within the wireless range of the Awinda Master.

After data acquisition an .mtb file will be produced. This format can be loaded into MT Manager or the MT SDK for analysis or export into text format.

B. Application examples

Xsens' customers have applied MTw in a wide range of applications, by exploiting the advantages of this easy-to-use, wireless and accurate inertial motion tracker. In this white paper two application examples are described. More examples can be found on the Xsens website as *customer cases* [16].

1) Rehabilitation research: This example shows how the MTw is applied in assessing shoulder function in scapula dyskinesis by one of Xsens' customers. They explain the added benefit of the MTw Awinda in their application: "Currently used measures are not reliable or objective, clinically not suitable, static or invasive (e.g. visual based scapular dyskinesis tests, optoelectronic markers, scapula locators or bonepins)" [17]. 20 healthy subjects were measured with the MTws mounted on the scapula, thorax, upper arm and fore arm (see Fig. 10). 3D kinematics of the scapula with respect to the thorax were calculated based on the orientation data of the MTw, for 3D scapular motion at $0°$, $30°$, $60°$, $90°$ and $120°$ arm elevation. The intra- and inter-observer reliabilities were found to be high, concluding that this experimental setup could be used for the objective assessment of 3D shoulder kinematics during dynamic tasks.

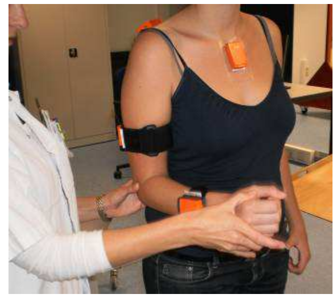

Fig. 10. Wireless measurement of scapular dyskinesis with the MTw.

2) Sports: While the trials of the above example are performed indoors, in a clinical setting, other applications use the MTw in their most flexible setup. The MTw Awinda can be used out of the lab since the data only needs to be logged on a simple laptop, located within a wireless range of $50\,\mathrm{m}$. A study has been performed with runners, which revealed "non-uniform and significant changes in running mechanics" [18]. In line with this research, a project was started to track the running biomechanics during a full marathon and investigate the effects of fatigue on the individual running technique [19]. The athlete was equipped with the MTw Awinda sensors attached to the trunk, pelvis, upper legs, lower legs and feet. The sensors wirelessly sent their data to a laptop mounted on a bicycle that accompanied the runner, which allowed data collection and real-time data analysis by using a remote connection during the entire $42.2\,\mathrm{km}$ (26.2 miles) marathon. "We have been able to collect data in a lab setting before, but there is a significant difference between simulating a marathon and actually running one," said one of the researchers of the project.

Fig. 11. Wireless measurement of runners in a natural, outdoor environment.

REFERENCES

[1] D. Roetenberg, *Inertial and Magnetic Sensing of Human Motion*. PhD Thesis, University of Twente, 2006.
[2] Xsens Technologies, "Xsens MVN." https://www.xsens.com/products/xsens-mvn-analyze/.
[3] Xsens Technologies, "Xsens MVN." https://www.xsens.com/products/xsens-mvn-animate/.
[4] M. Schepers, M. Giuberti, and G. Bellusci, "Xsens MVN Whitepaper: Consistent Tracking of Human Motion Using Inertial Sensing," 2018. Document MV0424P.A.
[5] G. Bellusci, R. Zandbergen, and P. J. Slycke, "Reduced Processor Load for Wireless Communication Between Master Unit and Sensor Unit," 2015. EU Patent: EP2958337 B1.

[6] G. Bellusci, R. Zandbergen, and P. J. Slycke, “Reduced Processor Load for Wireless Communication Between Master Unit and Sensor Unit,” 2014. US Patent: US9526028 B2.
[7] H. J. Luinge, F. Dijkstra, and G. Bellusci, “Reduction of Link Requirements of an Inertial Measurement Unit (IMU/AP) for a Strapdown Inertial System (SDI),” 2013. EU Patent Application: EP2645061 A3.
[8] F. Dijkstra, H. J. Luinge, G. Bellusci, and P. J. Slycke, “Reduction of IMU/AP Link Requirements for SDI,” 2012. US Patent: US8952785 B2.
[9] H. J. Luinge, F. Dijkstra, and G. Bellusci, “Compression of IMU data for Transmission of AP,” 2013. EU Patent Application: EP2645110 A1.
[10] H. J. Luinge, G. Bellusci, and F. Dijkstra, “Compression of IMU data for Transmission of AP,” 2012. US Patent: US8981904 B2.
[11] F. Dijkstra and P. J. Slycke, “A Method and a System for Enabling a Wireless Communication Between a Master Unit and a Sensor Unit,” 2009. EU Patent: EP2320288 B1.
[12] F. Dijkstra and P. J. Slycke, “Method and System for Enabling a Wireless Communication Between a Master Unit and a Sensor Unit,” 2010. US Patent: US8947206 B2.
[13] Xsens Technologies, “Mtw Awinda User Manual,” 2016. Document MW0502P.
[14] Xsens Technologies. http://wwwxsens.com.
[15] Xsens Technologies, “Magnetic Field Mapper Documentation,” 2017. Document MT0202P.
[16] Xsens Technologies, “Xsens Customer Cases.” https://www.xsens.com/customer-cases/.
[17] Xsens 3D motion tracking, “Wireless Measurement of Scapular Dyskinesis with IMMS.” https://www.xsens.com/customer-cases/wirelessmeasurement-scapular-dyskinesis-imms/.
[18] J. Reenalda, E. Maartens, L. Homan, and J. Buurke, “Continuous Three Dimensional Analysis of Running Mechanics During a Marathon by Means of Inertial Magnetic Measurement Units to Objectify Changes in Running Mechanics,” *Journal of Biomechanics*, vol. 49, pp. 3362–3367, 2016.
[19] Xsens Technologies, “3D Analysis of a Full Marathon.” https://www.xsens.com/customer-cases/3d-analysis-of-a-full-marathon/.