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

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***Abstract*—To support real-time 3D kinematic applications, Xsens introduces the MTw, a highly accurate miniature *wireless* inertial motion tracker. This new product eliminates the requirement for inter-tracker cabling, uniquely enhancing the freedom of movement and flexibility of use of traditional inertial based movement analysis systems. At the same time, the fundamental advantages of inertial technology compared to e.g. optical-based systems are preserved, namely: cost effectiveness, highly accurate drift-free orientation, and robustness to occlusion. This paper describes the basic working principles and architectural choices of the Xsens MTw system.**

I. INTRODUCTION

ANALYSIS of human movement has been ongoing for centuries [1] . Technological and computational advances allowed more quantitative and objective analysis to be carried out. This involved placing markers on the body, often bony landmarks, and measuring motion based on light (reflected or emitted). Arrangement of cameras ensure that it is also possible to measure this movement in 3D. However, the space for the activities is limited to the area that the cameras can cover, and the markers are easily occluded during movement.

Micromachining technology ensured that inertial sensors such as accelerometers and gyroscopes could be so small that they could be assembled into small casing (inertial measurements units (IMUs) or motion trackers (MTs)) and worn on the body [2]. Combining data from gyroscopes and accelerometers (and later magnetometers), it is possible to record movement of the MT anywhere in space, without the need for cameras [1]-[2]. Inertial sensing technology has opened new doors for measuring movement outside the lab and incorporating vast, or infinite recording volumes. Replacing the cameras external of the body with sensing elements on the body has great advantages in that the MTs can measure movement of the segment they are in contact with [2]-[12], allowing for immunity to occlusion and marker swapping. Furthermore, because there is no longer a need for a dedicated lab or infrastructure of any kind, costs are significantly decreased.

However, unlike camera-based systems, MTs require a power supply and a connection to the recording device; therefore they often involve cables. The main advantage of inter-tracker and tracker-host cabling is the guarantee that all recorded data is transmitted to the recording device without any data loss.

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Until recently at Xsens, cables were still required between the MTs and between the MTs and the host. Xsens solved the problem of the need to physically connect the subject to the recording device by incorporating the Xbus Master. This device collects data from all connected motion trackers, synchronizes these data and transmits them wirelessly, using Bluetooth technology, to the measuring PC. While inter-tracker cabling may not pose a problem for some applications (e.g., full body human motion capture offered by Xsens MVN [13]-[14], where the cables are integrated in the suit worn by the actor), it may pose at least a perceived problem in other applications. In sports studies, athletes may feel inhibited by the presence of cables. Consider a baseball pitch, with a cable traversing the length of the arm, it is possible to measure baseball pitching with the Xbus Kit, but athletes often perceive the motion as inhibited prior to the measurements. In clinical movement analysis, the presence of cables limits the practical use of the system due to the subject feeling constricted in their movement and due to the time needed by the clinician to set the subject up in the measuring system. In ergonomics studies, cables can often be a hindrance for factory workers operating machinery where man-machine interaction is required.

Taking the requirements of the market into consideration, Xsens introduces the MTw [15], a miniature *wireless* inertial motion tracker, specifically developed for highly accurate ambulatory 3D kinematic applications. With this system, all inter-tracker and tracker-host cabling are no longer needed. All wireless motion trackers send data wirelessly to the PC, via the Awinda Station, placed on the desk next to the recording PC or to a wireless USB dongle. This means that only the motion trackers are needed on the body for measurements.

When developing a completely wireless inertial measurement system, several fundamental issues must be addressed to achieve the same performance as a traditional cabled system:

1) A wireless connection can 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. The importance of this can be explained by thinking of classical movements performed while, for example, playing tennis. In this case the arm may reach angular velocities of up to 1000 deg/s. Timing errors of just a few milliseconds between the motion tracker placed on the lower arm and that

placed on the upper arm would give unacceptable elbow angle errors of several degrees.

The first two issues described above have motivated Xsens to design a completely new signal-processing pipeline.

In MTw the inertial data from gyroscopes and accelerometers are internally sampled at a high frequency (1800 Hz) to guarantee accuracy under very dynamic conditions such as fast movements, vibrations, and impacts. The data are then digitally filtered and down-sampled to 600 Hz. Based on these data and using a strap-down integration (SDI) algorithm [16]-[17], the MTw further calculates rotation and velocity *increments*, which are then transmitted through the wireless link. The major advantage of using the SDI algorithm is that the full 3D tracking accuracy can be maintained even if the output update rate from the MTw is very low (e.g. few tens of Hz). In fact, lower update rates will only result in a decreased measurement time resolution but *the same accuracy* as using much higher output rates is preserved. A specific Xsens Kalman filter has been developed to deal with the nature of wireless transmissions. This solution, in combination with the SDI algorithm, allows to guarantee performance even when irregular measurement updates occur due to occasional packet loss in real-time processing. To address the third issue, a patented radio protocol called Awinda ®, based on the IEEE 802.15.4 PHY standard and using low-cost 2.4 GHz ISM chipsets, has been developed. The Awinda protocol provides accurate time synchronization of up to 32 MTw's across the wireless network to within 10 microseconds, allowing to achieve 'wired like' system performance.

This paper describes the basic working principles and architectural choices of the Xsens MTw system, and it is organized as follows. In Section II, the MTw hardware is shortly introduced. Section III presents the MTw working principles: the signal pipeline and the details of the Awinda protocol are described. In Section IV, the unique advantages deriving from the use of the SDI in combination with the Awinda protocol when facing lower update rates or occasional packet loss, are shown from a set of collected data. Finally, in Section V the main conclusions are drawn.

II. MTW SYSTEM

In this section, the main MTw system components are shortly introduced. Fig. 1 shows the overall MTw hardware.

A. Interfaces

Fig. 2 shows the possible interfaces between the MTws, the different possibilities of Awinda Master and the recording or visualising software, contained within the Awinda host.

B. MTw

The MTw (size 34.5 mm x 57.8 mm x 14.5 mm, weight 27 g) is the miniature inertial measurement unit. The MTw contains 3D linear accelerometers, 3D rate gyroscopes, 3D magnetometers and a barometer.The MTw also contains a transceiver, which shares the clock (OSC) with the MCU. The OSC, has an oscillator of 20ppm. Using the sensing

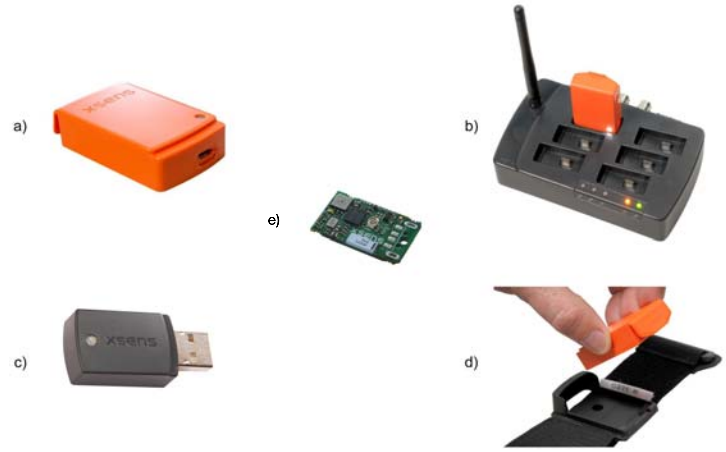

Fig. 1. The Xsens MTw hardware: a) MTw Sensor; b) Awinda Station; c) Awinda Dongle; d) MTw body strap; e) Awinda Master OEM.

elemements, the MTw measures its own motion. Since data is sampled at a very high rate (see Section III.*D*), the data must be processed on board, using strap down integration (SDI). The MTw performs the SDI of the inertial data and transmits this wirelessly, according to the Awinda protocol, to the Awinda Master. The MTw is powered using an LiPo battery. The battery can be in operation for 3.5 hours, and it is fully recharged after one hour docked in the Awinda Station. The MTw housing has been designed with a click mechanism, to ease positioning onto the body using the click-in body straps provided; shown in Fig. 1.

C. Awinda Master

The Awinda Master serves as the interface between the MTw system host (typically a PC running Xsens-based software [15]), and the MTw's. The Awinda Master has a very accurate clock, with an oscillator of 1 ppm, it is in control of the timing of data generation and transmission, ensuring that the data from each MTw is synchronised to within 10 microseconds. The Awinda Master receives MTw data, keeps global synchronization between wirelessly connected MTw's and manages packet retransmission for off-line processing, if data packets are missed (see Section III.*F*). The physical wireless connectivity between the MTw and the Awinda Master is based on the IEEE 802.15.4 PHY standard using the ISM band centered around 2.4 GHz. Up to 20 MTw's can be wirelessly connected to a single Awinda Master. Fig. 2 shows the different types of Awinda Master possible with the MTw system. The standard shipment includes both the Awinda Station and the Awinda Dongle. An alternative is a solution designed to be embedded in third party hardware, this is the Awinda OEM Master. The Awinda Station is 148 mm x 104 mm x 61.9 mm (L x W x H) in size. As Fig. 2 shows, the Awinda Station has the most options readily available, including the external antenna, ability to dock six MTw's at a time for battery charging and for firmware updates. Additionally, the Awinda Station has four hardware connections for digital I/O time-synchronization with compatible auxiliary external systems. The range of the

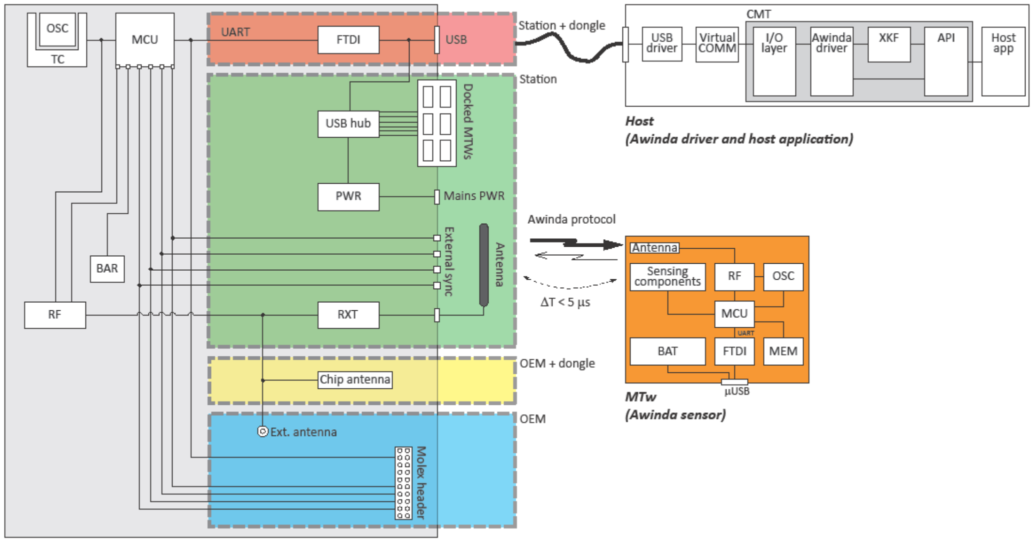

Fig. 2. Schematic overview of the interfaces between the hardware and software of the MTw system.

wireless link using the Awinda Station is typically about 50 m in line of sight, guaranteeing a complete freedom of movement and recording. The Awinda Dongle is a small USB device, measuring only 45 x 20.4 x 10.6mm, with the USB connector (33 x 20.4 x 10.6mm without). The dongle has the same wireless communication possibilities as the Awinda Station. However it does not have a range extender, therefore the wireless range is 10m, rather than 50m. Hardwired interfacing like docking and synchronisation with third party devices, are not possible with the dongle, ensuring that it is kept very small to maximise portability. Finally, the Awinda OEM Master is a PCB board (that which is used for the dongle). The PCB measures just 27 x 16 mm. While the OEM solution does not have the docking capabilities of the Station, the sync interface is still present and can be activated using an added Molex header. The UART can also be interfaced to this header. For more details about OEM integration possibilities, contact info@xsens.com.

D. Awinda Host

Fig. 2 shows the interfaces between the components, and the communication modalities of the wireless system. The Awinda Master receives data from each MTw. Fig. 2 shows that the Awinda host consists of the USB drivers, which create the virtual COMM. This can be accessed by the low-level I/O layer of CMT, which delivers data to the Awinda driver. The Awinda Driver has multiple functions, including controlling and configuring the Awinda Master, and reordering, when necessary of any recorded data. A filter, XKF, provides accurate orientation to the API and host application. The host application can be either MT Manager, the standard logging and visualisation tool from Xsens or a self-built programme based on Xsens software development kit (SDK).

III. MTW WORKING PRINCIPLES AND SYSTEM ARCHITECTURE

In this section, the main architectural design choices of the MTw system are described and motivated.

A. MTw signal processing pipeline motivations

One of the main limitations of the signal processing architecture of the traditional Xsens motion trackers is that the entire pipeline runs at a single frequency, the output frequency. The user can select this frequency. However, choosing low frequencies would result in inaccurate filter outputs (e.g. caused by aliasing, coning and sculling effects, etc.), since the output frequency is the same as that internally used to sample the analog signals from the inertial sensing elements. This would be a fundamental problem for the MTw sensors, due to the requirement of preserving the highest level of accuracy even with relatively low measurement update rates (typically down to few tens of Hz), introduced by the presence of the wireless transmission link.

The solution developed by Xsens to address this problem is to work with rotation and velocity *increments* instead of gyroscope and accelerometer samples as directly measured at the ADC sensing element outputs[1]. When correctly calculated, these increments accurately describe the motion of the motion tracker and a lower output update rate will only result in larger increments and more coarse measurement *resolution*, since the increments are simply calculated in wider time windows. However, and this is the fundamental point, the performance will be independent of the output frequency, and the same accuracy as using higher output rates is preserved[2].

[1]Note that the use of incremental quantities has originally been developed for tactical high grade inertial measurement units, and it is now an industry standard for that segment. The application to MEMS grade inertial sensors is relatively novel.

[2]Similarly, occasional packet loss due to unreliable wireless transmission link only results in larger update time intervals, but again, the performance remains unchanged. This issue will be further addressed in the next sections.

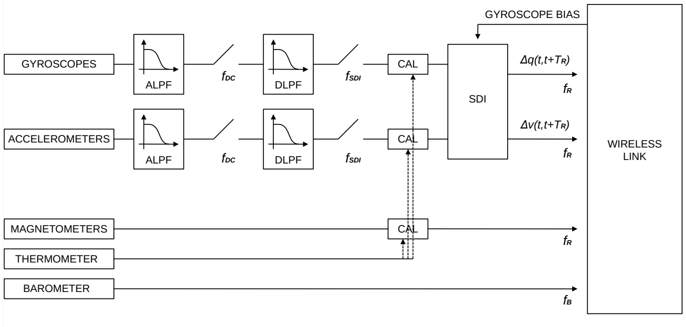

Fig. 3. Block diagram of the MTw signal processing architecture.

B. MTw signal pipeline architecture

The new signal processing pipeline developed for MTw serves to the purpose of calculating rotation and velocity increments from the 'raw' signals measured from the gyroscope and accelerometer sensing components. Fig. 3 provides a block diagram of the architecture. As shown in this figure, as well as the inertial sensor components, the MTw contains another 3 sensing elements: 3D magnetometers used (as a compass) for heading stabilization, a barometer used to measure the altitude, and a thermometer used to compensate for the gain and bias temperature dependency of the other sensing elements. The signal processing of the data from these sensor components is straightforward, as is clear from Fig. 3; for this reason, it will not be addressed further. Therefore, the following section will only focus on the processing of the inertial data.

The analog signals, as recorded from the gyroscopes and accelerometers sensing components, are low-pass filtered with a third order Bessel architecture; the filter frequency response is shown in Fig. 4. The -3 dB analog filter bandwidth B is equal to about 140 Hz and 120 Hz for the gyroscopes and accelerometers channels, respectively, and the filter group delay is of about 2 ms, in both cases. The chosen bandwidths are wide enough for movement analysis applications and allow to guarantee a very high fidelity in the recorded signals. The analog to digital conversion sampling rate f_{AD} is equal to 1800 Hz. This choice, together with the filter design specifications, limits possible aliasing effects. In fact, the filter attenuation in the bandwidth $2B$ around f_{AD}, which represents the first portion of the frequency spectrum folded back around the zero frequency after digital conversion, is of about 60 dB both for the accelerometers and for the gyroscopes channels. In this way, ideal performance is guaranteed even during very high dynamics like fast movements, vibrations, or impacts.

The full scale of the inertial sensing elements, given in the top part of Table I, covers most of the possible user scenarios in movement analysis and sports applications.

To relax the computational requirements of the successive steps in the signal pipeline, the digital samples at 1800 Hz are low-pass filtered and down-sampled at $f_{SDI} = 600$ Hz for further processing. A finite impulse response (FIR) 21 coefficients equi-ripple low-pass digital filter is used to the purpose. This step is required to eliminate high-frequency components prior to the down-sampling. As it can be seen from its frequency response, shown in Fig. 5, the filter introduces negligible distortions in the signal bandwidth B (the maximum ripple in B is smaller than 0.01 dB). At the same time, aliasing after down-sampling at 600 Hz can be neglected, for the bandwidths of interest, since the filter attenuation for frequencies between $f_{SDI} - B$ and $f_{SDI} + B$ is in excess of 55 dB.

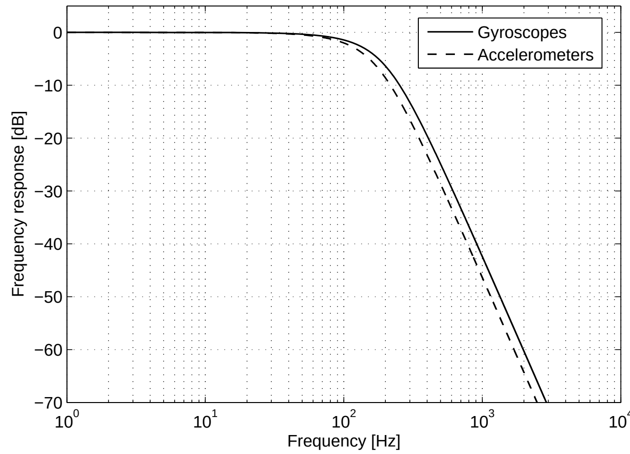

Fig. 4. Frequency response of the used 3rd order analog low-pass Bessel filter (ALPF), both for the gyroscopes and for the accelerometers channels.

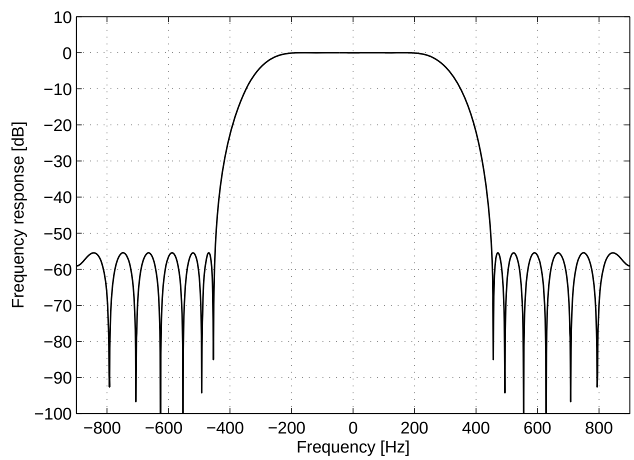

Fig. 5. Frequency response of the used FIR equi-ripple digital low-pass filter (DLPF).

The 'raw' digital data are then converted to calibrated data (expressed in m/s^2 and rad/s, for accelerometers and gyroscopes, respectively) using calibration parameters estimated at factory by Xsens during an individual sensor calibration procedure. This is a highly sophisticated process, which compensates for deterministic (but variable from sensor to sensor) component errors. The calibration models include compensation for bias, gain, axes misalignment, g-sensitivity and temperature effects.

The calibrated digital samples at frequency f_{SDI} are processed by the SDI block. The SDI algorithm computes the rotation and velocity increments, at a *variable* and *user selectable* output frame rate f_R. It is important to underline that the SDI input frequency $f_{SDI} = 600$ Hz is large enough

TABLE I
MAIN SENSING COMPONENTS AND SIGNAL PIPELINE SPECIFICATIONS

	ACC	GYR	MAG	BAR
Sensor type	Analog	Analog	Digital	Digital
Full scale	$\pm$160 m/s^2	$\pm$1200 deg/s	$\pm$ 1.5 Gauss	300-1100 hPa
Linearity	0.2%	0.1%	0.2%	0.05%
Bias stability	-	20 deg/hour	-	100 Pa/year
Noise	0.003 m/s$^2/\sqrt{\text{Hz}}$	0.05 deg/s$/\sqrt{\text{Hz}}$	0.15 mGauss$/\sqrt{\text{Hz}}$	0.85 Pa$/\sqrt{\text{Hz}}$
Analog bandwidth	120 Hz	140 Hz	10-60 Hz (var.)	10-30 Hz (var.)
ADC sampling rate	1800 Hz (fix.)	1800 Hz (fix.)	20-120 Hz (var.)	20-60 Hz (var.)
SDI input rate	600 Hz (fix.)	600 Hz (fix.)	-	-
Output frame rate	20-120 Hz (var.)	20-120 Hz (var.)	20-120 Hz (var.)	20-60 Hz (var.)

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

Number of MTw	Maximum output frame rate $f_R = 1/T_R$
2	120 Hz
6	75 Hz
12	50 Hz
32	20 Hz

for human movement applications, even during very high dynamics. This means that the fundamental hypothesis of piecewise constant angular velocity and acceleration profiles within the elementary sampling time interval $\delta T = 1/f_{SDI}$, to calculate exactly the rotation and velocity increments, is satisfied. Therefore, and this is important to note, the accuracy of the SDI output will not be affected by the specific choice of the output frame rate f_R (in the absence of non-idealitites; this issue will shortly be addressed at the end of this section).On the contrary, low frame rates will only result in a more coarse time resolution, but the same accuracy as using higher frame rates, is preserved. This point will be clearly shown in the next Section III.E.

The possible output frame rate f_R is variable in the range 20-120 Hz, and can be selected by the user. The maximum selectable output rate is dependent on the actual number of MTw's connected, due to the limited wireless transmission resources available. Table II shows the maximum selectable output frame rate, vs. the maximum number of MTw wirelessly connected. It should be noted that the values described are the maximum, therefore not taking into account the need for retransmissions. When retransmissions are required, these values will decrease, depending on the amount of retransmissions needed.

To conclude this section, in the bottom part of Table I the main architectural choices of the MTw signal pipeline, previously discussed, are summarized for convenience.

C. *Awinda wireless communication protocol*

In this section, the main requirements and basic principles of operation of the Awinda communication protocol, are summarized. This patented protocol has been developed by Xsens to specifically address the unique peculiarities and requirements of a wireless inertial sensor network.

1) Awinda protocol requirements: When developing the communication protocol between the MTw's and the Awinda Station, the following fundamental requirements have been set:

- It should be possible to implement the protocol using standard low-cost radio technology, which typically have limited transmission rates available (e.g. around 250 kbps). The protocol should also take into account that the motion tracker is battery powered and that power consumption needs to be kept to the minimum.
- The protocol should efficiently support both real time visualization with minimum latency, and data recording preserving the highest level of accuracy, for further analysis.
- The protocol should be able to cope with dynamic situations including varying packet-loss probabilities and occasional periods of out-of-range, without sacrificing performance.
- Accurate time-synchronization between all connected MTw's with a maximum time difference of $\pm$5 microseconds should be guaranteed.
- The number of MTw's connected vs. the update rate should be maximized.
- Should be very robust under challenging wireless conditions.

2) Awinda protocol basic principles: The Awinda protocol implements a star-topology wireless sensor network in which the MTw's transmit their data to the Awinda Master,and the Master returns a broadcast message used for detection, synchronization and control. All MTw's belong to a single network and connect to a unique Master using the same physical channel. Time division multiple access (TDMA) is used to share the transmission resources. Using the timeslot assigned for transmission, each MTw sends its data to the Station. The MTw performs this operation in intervals: the data measured during each contiguous interval are combined in a packet and transmitted during the assigned timeslot. At the same time, the measuring of data for the next interval is performed. Therefore, the size of this interval defines the output update rate f_R. The increments, however, are not transmitted as directly calculated at frame rate f_R, but they correspond to an increasing interval starting at a given time instant T_0; i.e. at the i-th interval the MTw sends the increments $\Delta \boldsymbol{q}(T_0, t)$, $\Delta \boldsymbol{v}(T_0, t)$, with $t = T_0 + iT_R$. T_0 represents the last time interval in which the inertial data were correctly received by the Awinda Master and it is communicated to the motion trackers in each Awinda Master broadcast. In this way, occasional packet loss will only result in larger time intervals, but similarly as decreasing the output update rate, it will not affect the achieved accuracy, even in real-time applications.

3) Latency: Since the Awinda system can operate at relatively low update rates (down to 20 Hz) the latency becomes an important issue to address for real-time visualization or control. In the context of the Awinda protocol, the latency is defined as the difference between the time at which the SDI data were generated at MTw side, and the moment at which the Awinda Station 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 under the control of the Awinda system. The l;atency for 1 MTw is about 12ms, and for 2 MTw is about 14ms.

4) Packet retransmission: To guarantee the highest level of accuracy in off-line applications, a retransmission mechanism is implemented in MTw. Conventional wireless protocols address potential packet loss at the transmitter side by awaiting a confirmation from the receiver. In case the transmitter does not receive this confirmation, it retries sending the data after the failed transmission. This conventional method, however, has a significant drawback, since time needs to be allocated in the timeslot of each MTw for the receiver to send the acknowledgment and to retransmit the data when the MTw did not receive the acknowledgment. In this way, transmission efficiency is limited. This also means that in order not to affect the capacity too much, the number of retries is limited in most cases; for high loss probabilities this approach would deteriorate performance.

The Awinda protocol addresses the problem differently. The retransmission timeslots are allocated and shared between the sensors. The control of the retransmission for the different MTw's connected is performed at the Awinda Station, and the MTw is not depending on the reception of the Station broadcast as done in conventional wireless protocols. This has two advantages: (1) using the link to the host application, the Station can determine whether the missing data is essential and needs to be retransmitted, and (2) the Station can efficiently schedule retransmissions among different MTw's allowing to achieve an overall higher update rate.

The MTw stores the inertial data in a buffer, for possible retransmission in case the corresponding packet fails to be received by the Station. When the MTw receives a request from the Awinda Station to retransmit the data of a certain interval, it concludes that any older data in the buffer is obsolete and deletes all these data from the buffer.

5) Buffer overflow: Depending on the period of duration in which the MTw is out of the range of the Station, buffer overflow might occur. The Awinda protocol handles this situation to minimize performance impairments. In fact, when the buffer is filled, the MTw starts to merge contiguous rotation and velocity increments, to make room to store new incoming inertial data. In this way, only a decreased measurement resolution will occur, but no performance impairment is experienced, as it would happen e.g. by simply discarding incoming packets when the buffer is filled.

6) Inter-tracker time synchronization: Each Awinda Station broadcast contains a timestamp indicating the broadcast time of transmission. The receiving MTw uses this timestamp for resetting its clock. The clock accuracy of the MTw is 20 ppm. herefore, the maximum drift that the clock of the MTw can experience at the minimum update frequency of 20 Hz (see Table II), is 1 microsecond. An MTw is able to determine the time of arrival of the Station broadcast with a maximum jitter of approximately 3 microseconds. This results in overall synchronization errors between any MTw's well within the ± 5 microseconds target. If the MTw is temporarily out of radio range of the Station and does not receive the broadcast, its clock will be skewed with respect to the Station reference timing. To address this issue, the skew factor is estimated at the MTw, and used to correct the timing during occasional periods of out of radio range of the Station. This mechanism is sufficient to guarantee robustness against occasional packet loss, since the clock skew depends mainly on temperature, which can be assumed constant during the short time intervals in which the MTw does not receive the Station broadcasts.

D. Xsens orientation Kalman filter for MTw

The orientation of the MTw is computed by a new Kalman filter for 3 degrees-of-freedom orientation, specifically developed by Xsens for the MTw, and called XKF-3w. XKF-3w uses the rotation and velocity increments as provided by the SDI block, together with the magnetometer samples, to compute a statistical optimal 3D orientation estimate of high accuracy and with no drift for both static and dynamic movements. XKF-3w can be described as a sensor fusion algorithm where the measurement of gravity (provided by the 3D accelerometers) and the Earth magnetic north (provided by the 3D magnetometers) compensate for the otherwise slowly but continuously increasing orientation drift deriving from the angular velocity integration. To account for the variable measurements update rate, caused by the unreliable wireless transmission link and the potential loss of MTw data packets, the measurement noise and the process model parameters are modeled as dependent on the actual update rate. The details of the actual filter implementation go beyond the scope of this paper, and for this reason they are omitted.

E. User output data

Different types of data are available for the user:

1) Awinda Data: they contain the gyroscopes and accelerometers data expressed in rotation and velocity increments in a variable time interval T_I, respectively:

$$\Delta \boldsymbol{q}(t, t+T_I) \quad , \quad \Delta \boldsymbol{v}(t, t+T_I) \tag{1}$$

T_I is the interval of time in which the rotation increments are calculated and it is related to the MTw output period T_R as: $T_I = (K_P + 1)T_R$, where K_P is the number of consecutive packets lost with respect to the last successful packet reception. The Awinda data provide the highest level of accuracy in the representation of the inertial quantities, being directly related to the actual output data. Therefore, Xsens recommends the use of these quantities when further calculations are required.

2) Calibrated Data: The rotation and velocity increments in a generic time interval T_I can be easily expressed in the conventional measures of angular velocity ω_I and acceleration a_I (in deg/s and m/s^2, respectively). For this reason, for user convenience this output data format is provided as well by Xsens. ω_I and a_I are calculated by simply inverting the relations[3]:

$$\Delta \boldsymbol{q}(t, t+T_I) = \exp\left(\frac{1}{2}T_I \boldsymbol{\omega}_I\right) \tag{2}$$

$$\Delta \boldsymbol{v}(t, t+T_I) = T_I \exp\left(\frac{1}{2}T_I \boldsymbol{\omega}_I\right) \boldsymbol{a}_I \exp\left(\frac{1}{2}T_I \boldsymbol{\omega}_I\right)^c \tag{3}$$

for angular velocity and acceleration, respectively. However, it should be noted that $\boldsymbol{\omega}_I$ and $\boldsymbol{a}_I$ do not directly represent the actual inertial measurements, but they can be considered as a measure of the *average* angular velocity and acceleration in the time interval $[t, t+T_I]$, respectively. Clearly, depending on the specific update rate and application, these quantities are good approximations of the actual inertial sensors measurements.

3) XKF-3w Data: The XKF-3w provides as output the orientation of the sensor-fixed coordinate system with respect to a Cartesian Earth-fixed coordinate system. The output orientation is given in any of the following parameterizations:

- Unit quaternions (also known as Euler parameters).
- Euler angles (roll, pitch, and yaw, also known as Cardan or aerospace sequence).
- Rotation matrix (directional cosine matrix).

IV. MTw PERFORMANCE EVALUATION

In this section, the performance of the MTw system is presented. Two different examples are provided to show the benefits of the SDI algorithm in combination with the Awinda protocol. In the first example, the SDI orientation error is evaluated when decreasing the output frame rate. It will be shown that low frame rates (down to 20 Hz) will only result in coarser time resolution, but the same dead-reckoning orientation accuracy as using higher frame rates is preserved. In the second example, the dead-reckoning performance provided by the SDI algorithm in combination with the Awinda protocol when occasional packet-loss occurs is compared with a simpler scheme in which the missed data are estimated at host side with a linear interpolation operation.

[3]Note that in actual implementation, eq. (2) is replaced by a second order Taylor approximation, while eq. (3) simply by: $\Delta \boldsymbol{v}(t, t+T_I) = T_I \boldsymbol{a}_I$.

A. SDI orientation error vs. output frame rate

In this subsection, the SDI orientation error $\boldsymbol{\epsilon}_{SDI}$ is evaluated for different output frame rates. $\boldsymbol{\epsilon}_{SDI}$ is defined as:

$$\boldsymbol{\epsilon}_{SDI} \triangleq \boldsymbol{e}_{SDI}{}^{(o)} - \boldsymbol{e}_{SDI}{}^{(i)} \tag{4}$$

where $\boldsymbol{e}_{SDI}{}^{(i)}$ and $\boldsymbol{e}_{SDI}{}^{(o)}$ are the MTw orientation (in Euler angles) calculated from dead-reckoning at the SDI block input and output, respectively. Eq. (4) represents the additional orientation error introduced by the SDI algorithm, with respect to the case of directly using the calibrated accelerometers and gyroscopes samples at $f_{SDI} = 600$ Hz. Therefore, it can be considered a measure of the impairments introduced in the representation of the sensor dynamics by the use of rotation and velocity increments calculated at a *lower* output frame rate f_R.

Fig. 6 shows on the top part the accelerometers and gyroscopes signals recorded at $f_{SDI} = 600$ Hz at the SDI input for the trial analyzed in this subsection. The recording contains very high dynamics, including fast movements and impacts, resulting in acceleration values reaching about 15 g and angular velocities in excess of 1000 deg/s. On the bottom part, the same figure shows the SDI dead-reckoning orientation error $\boldsymbol{\epsilon}_{SDI}$, for different values of the output frame rate, and for the roll, pitch, and yaw angles in the three subplots, respectively. It can be seen that in all cases $\boldsymbol{\epsilon}_{SDI}$ can be neglected, being in the order of 10^{-10} deg. As previously motivated, lower output update rates only result in a more coarse time resolution, but the same accuracy as using the calibrated data at 600 Hz is achieved, even under very dynamic conditions. Similar results can be found from the integration of the accelerometers signals. This is in line with what expected from the analytical derivations as in the previous subsections.

B. SDI in combination with Awinda protocol performance vs. packet loss probability

In this subsection, the dead-reckoning performance provided by the SDI algorithm in combination with the Awinda protocol when occasional packet-loss occurs, is provided. Fig. 7 shows in black the orientation (roll, pitch, and yaw) as estimated from dead-reckoning on the original calibrated data at 600 Hz. For comparison, the orientation obtained from dead-reckoning at 75Hz and for different packet-loss rates, both using the SDI data in combination with the Awinda protocol as implemented in MTw (in blue), and from a simple linear interpolation of the missed data samples performed at the host side (in red), are shown. It can be seen that the solution developed in MTw is immune to packet loss. In fact, similarly as for the case of lower update rates, occasional loss of packets will only result in coarser time intervals (as it can be seen from the zoomed portion of the top plot, shown in Fig. 8), but the same accuracy as using the original data at 600 Hz is preserved. On the contrary, the use of a simple data interpolation is not able to correctly describe the motion of the MTw during periods of missed packets. This results in orientation errors of several degrees after only a few seconds, already for packet loss probability of 5%, and of a few tens of degrees when increasing the packet loss up to 25%.

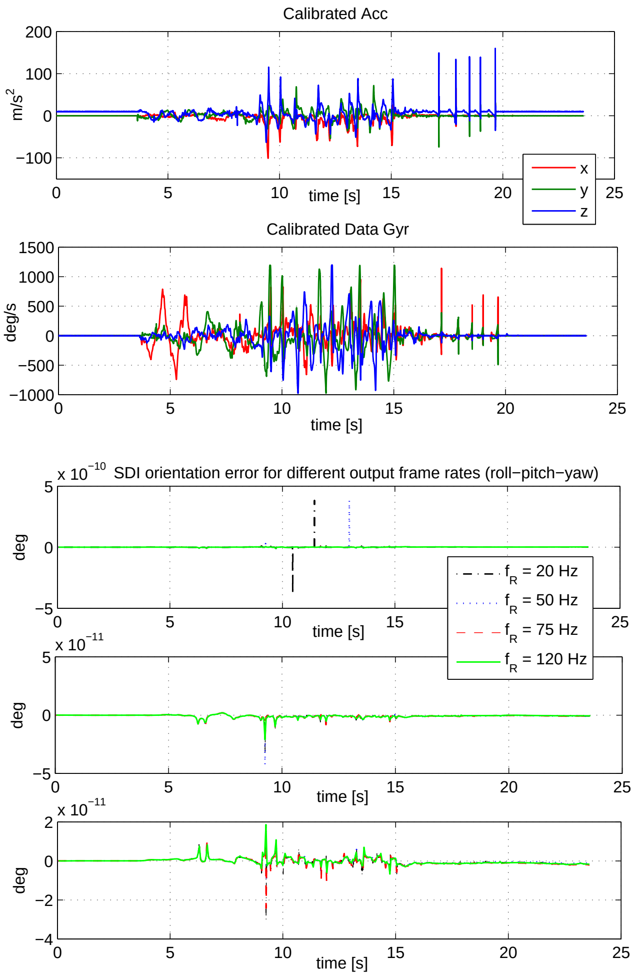

Fig. 6. Calibrated accelerometers and gyroscopes signals at SDI input (top); SDI orientation error (roll, pitch, yaw), defined as in eq. (4) for different output frame rates (bottom).

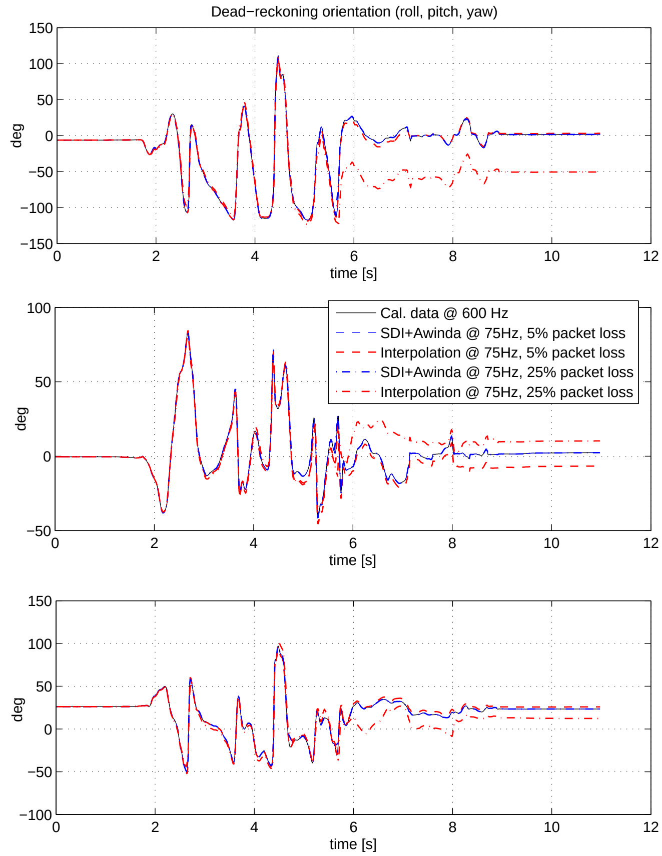

Fig. 7. Dead-reckoning orientation (roll, pitch, yaw) comparison: a) using the original calibrated data at 600 Hz (black); b) using the SDI in combination with the Awinda Protocol as implemented in MTw, for different packet-loss probabilities (blue); c) using a simple linear interpolation scheme for different packet-loss probabilities (red).

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 1800 Hz, together with the use of a strap-down integration algorithm, allows to preserve accuracy even when lower update rates, down to 20 Hz, are used, or occasional packet loss occur due to the presence of the wireless transmission link. The Awinda communication protocol between the MTw and the Station provides accurate time synchronization of up to 32 MTw's across the wireless network to within 10 microseconds, minimizing the overall latency and maximizing the efficiency of use of the transmission resources. In this way, the unique flexibility and easiness of use of wireless technology are exploited without sacrificing performance compared to a traditional wired inertial based movement analysis system.

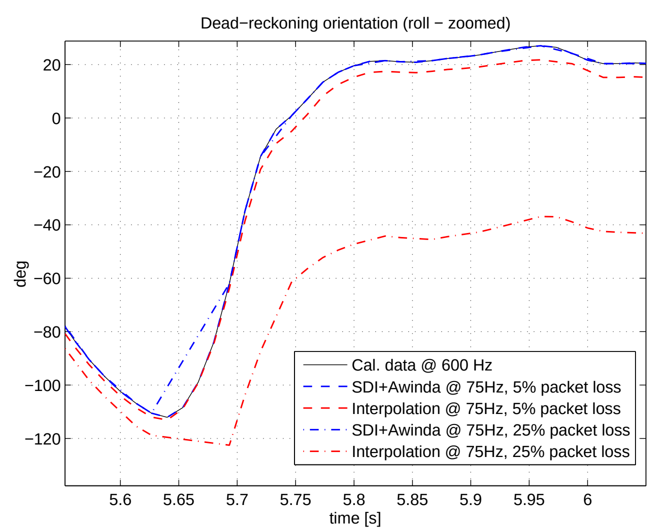

Fig. 8. Zoomed portion of the roll-angle from Fig.7.

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