The Next Generation Xsens Motion Trackers for Industrial Applications

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The Xsens manufactured MEMS-based Motion Tracker finds its use in industrial applications such as UAV and UGV navigation, robotics, antenna-steering and camera system stabilization platforms. These applications require control signals with very low data latency that are accurately time-referenced and are accessible with an easy-to-use API. These control signals can be IMU signals, tracking estimates of orientation, position or specific outputs like acceleration in the navigation frame. In these applications, the sensors are typically mounted on platforms that experience vibrations due to engines and actuators or interaction with the environment. The signal processing pipeline together with the sensor fusion algorithms ensure effective capturing of the dynamics of the platform under sustained vibrations, prolonged accelerations, magnetic disturbances, and provide tracking estimates that are reliable, accurate, continuously available and with high integrity. This paper presents the features and tracking performance of the 4^{th} generation of Xsens Motion Tracker products for industrial applications, namely the MTi®.

1. Introduction

A motion tracker finds itself at the core of a multitude of applications for control, platform stabilization, navigation and tracking applications in airborne, terrestrial, marine and subterranean environments. The user applications in navigation and tracking typically make use of integrated quantities of orientation, velocity or position. These integrated quantities of angular velocity and acceleration output by *inertial measurement unit* (IMU) are fundamental to the system performance. The user applications typically involve moving platforms that experience vibrations due to engines and actuators or due to interaction with the environment. Along with sustained vibrations, the moving platforms also experience prolonged accelerations and magnetic disturbances [1, 2].

Advances in *micro-machined electromechanical system* (MEMS) technology has enabled development of low-cost (ranging from <\$1 to <\$100 per axis) and small form factor (ranging from <0.02 cm^3 to <0.2 cm^3) accelerometers and gyroscope sensor components. The error characteristics inherent to these components make it fundamentally difficult to use MEMS-based IMU as a stand-alone sensory unit for user applications mentioned. To get accurate tracking estimates that are always available and reliable, it becomes crucial for these MEMS-based IMU signals to be combined with measurements from aiding sensors such as magnetometer, barometric-altimeter and *global navigation satellite system* (GNSS) in conjuction with some application specific motion models. Xsens with its years of experience in developing multi-sensor fusion algorithms has developed the *Xsens estimation engine* (XEE) sensor fusion framework. This fusion framework enables the Xsens Motion Tracker to take advantage of different aiding sensor measurements and fuse them optimally to get robust tracking estimates [3–10].

The Xsens Motion Tracker designed for industrial applications is the MTi, the product line of which is shown in Figure 1. The unit has at its core a MEMS-based IMU combined with a triad of magnetometers in a lightweight (11 g for OEM version) small package (<15 cm^3) with a power consumption of 480 mW to 650 mW for the MTi 10-series and MTi 100-series. The signal processing pipeline design (MTi 10-series/MTi 100-series) offers immunity to vibrations beyond 400 Hz. It provides data at higher output rates (2 kHz) with low data latencies (<2 ms). The MTi product series is designed keeping in mind the market requirements as dictated by the user applications. The recently introduced MTi 1-series module is much lighter at 0.66 g in a smaller package (0.373 cm^3) and with a much lesser power consumption of 45 mW [11]. In the following section, the product portfolio of the Xsens MTi Motion Trackers is presented. Section 3 presents the system architecture of the MTi with details on signal processing, calibration and the Xsens *Application pro-*

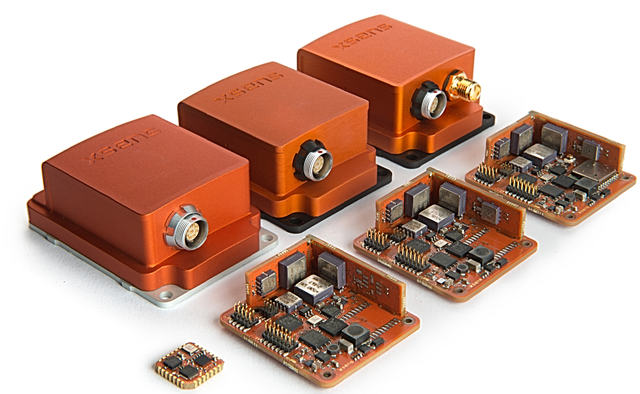

Figure 1: Xsens Motion Tracker products for industrial applications (MTi). In the bottom row, from left to right - the 1-series module, OEM version of 10-series, 100-series and MTi-G-700. In the top row, from left to right - the encased version of 10-series, 100-series and MTi-G-700.

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gramming interface (API). The performance of MTi with data sets collected on a vibration table, ground vehicle and in an airborne platform are presented in Section 4. This is followed by Section 5 where the overall performance is summarized.

2. Product portfolio

The product portfolio of Xsens MTi Motion Trackers is classified in two ways: 1) based on performance, and 2) based on functionality as shown in Table 1 and Table 2 respectively.

Product series	Characteristics
MTi 1-series	Low-cost MEMS sensors. Robust performance with low power consumption with small form factor.
MTi 10-series	Industrial grade MEMS sensors. Proven and robust estimation engine design.
MTi 100-series	Higher grade MEMS gyroscopes with advanced mechanical vibration and impact rejection. Sensor fusion engine designed for high performance under vibrations and magnetic distortions.

Table 1: The classification of MTi product based on performance.

Table 1 lists the MTi product series with the characteristics of the MEMS-based IMU sensors used. Figure 2 shows the MTi IMU component Allan Variance characterization used for determining the stochastic error measures for modelling of IMU errors [12]. The MTi 100-series uses high-performance industrial grade MEMS-based gyroscopes with very low vibration rectification errors (0.0001 °/s/g^2) and with increased immunity to influences of linear accelerations. As can be seen in Figure 2, the advanced mechanical vibration rejection gyroscope used for MTi 100-series has an in-run bias stability of $\approx$12 ° h^{-1}(typical) as compared to the industrial grade MEMS based gyroscopes used for the MTi 10-series which has gyroscopes with in-run bias stability of $\approx$20 ° h^{-1} (typical). The noise of the low-cost gyroscopes used in MTi 1-series is half of that for the MTi 100-series making it attractive for applications that require precise attitude information.

The MTi product classification based on functionality is given in Table 2. The stand-alone IMU product groups for the MTi 1-series, MTi 10-series and MTi 100-series do not use any measurement models, the device outputs fully calibrated sensor measurements of IMU with coning and sculling compensation and magnetometer without any processing done by the XEE. The *vertical reference unit* (VRU) in the MTi adds output of orientation tracking roll, pitch and heading of which the heading is not referenced to earth's magnetic field. The unit's functionality is catered for applications which require accurate roll and pitch outputs. The addition of the *active heading stabilization* (AHS) feature keeps the drift of unreferenced heading to within 1° (typical) for MTi 100-series and MTi 1-series and to within 2° (typical) after 60 min for the MTi 10-series. Details of this feature are presented with test results in Section 4. The *attitude heading & reference system* (AHRS) unit outputs stabilized magnetically referenced heading along with accurate roll and pitch estimates. The *GNSS/INS* (MTi-G-7XX) makes use of sensory measurements from magnetometer, barometer and a high sensitivity multi-GNSS receiver to provide navigation estimates of position, velocity and orientation at higher data rates. The range of supported data outputs expands with increasing sequence of product code within a series. Except for the IMU devices, the VRU and AHRS MTi devices are supplied with their own set of application-specific or motion-specific filter profiles. The filter profiles are used to turn on/off models used within XEE e.g., MTi-G-7XX has an *automotive* filter profile suited for ground vehicle applications. For

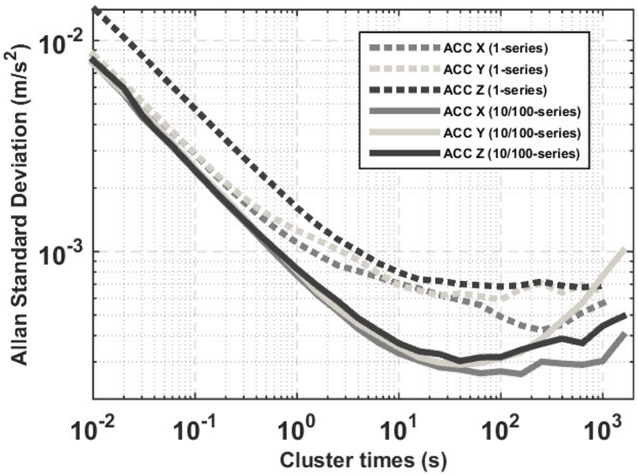
Product codes	Functionality	Description
MTi-1/10/100	IMU	Calibrated inertial ($\Delta\theta$, Δv compensated for coning & sculling) and calibrated magnetometer data.
MTi-2/20/200	VRU	Accurate roll and pitch with low drift unreferenced heading.
MTi-3/30/300	AHRS	Accurate roll, pitch and heading (magnetically referenced).
MTi-G-700	GNSS/INS	Accurate position, velocity and orientation at high data rates.

Table 2: The MTi product classification based on functionality along with product codes.

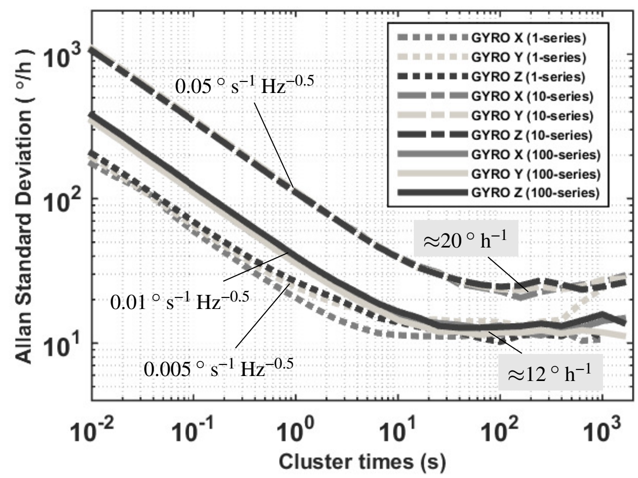
Sensor	Update rates (Hz)
SDI inertial data	400/100*
Magnetometer	100
GNSS-PVT	4
Barometer	50

* Specific to MTi 1-series.

Table 3: The maximum update rates available for each sensor unit and as used by the sensor fusion core (XEE).



(a) Allan variance curves of accelerometers



(b) Allan variance curves of gyroscopes

Figure 2: The Allan variance of the accelerometers and the gyroscopes used in the MTi product range. Figure 2a and 2b shows Allan variance for accelerometer and gyroscope sensing components used in MTi respectively. Figure 2b also points to the characteristics of the gyroscope sensing components, e.g. noise density values and the bias instability (in gray boxes).

the MTi-3/MTi-30/MTi-300, to get reliable reference heading information, the *low_mag_dep* filter profile is available for use in environments where more magnetic disturbances are expected. The information available in Table 1, Table 2 and Table 3 along with sensor data in Figure 2 can serve as reference for an user while selecting the appropriate MTi for their application.

3. Motion Tracker

This section presents the features of the Xsens MTi Motion Tracker and is organized as follows - the IMU signal processing pipeline is presented along with the system architecture description. This is followed by an overview of the Xsens *Software Development Kit* (SDK) through which all features of MTi can be easily accessed.

IMU signal processing

The IMU signal processing pipeline refers to the sequence of functional blocks involved in converting the analog signal of individual sensing elements to digital IMU signals of high integrity and accuracy. The MTi 10-series and MTi 100-series has a custom designed signal processing pipeline that ensures elimination of errors due to aliasing, high frequency noise, minimizes inter-channel delays and eliminates high frequency components. The analog front-end of an IMU signal processing pipeline is shown in Figure 3 inside the IMU sensor component block. The *digital low pass filter* (DLPF) is applied to prevent aliasing of signal while down-sampling the signal in the digital domain. In the MTi 10-series and MTi 100-series, the sampling of gyroscope and accelerometer signals in the analog front-end is done at 10 kHz for each channel, totalling to 60 ksps for the IMU sensor component. For industrial applications, the bandwidth of motion involved is <200 Hz [13, 14].

For all the products in the MTi product portfolio, the AttitudeEngine™ represented by the *strapdown integration* (SDI) block in Figure 3 performs highly accurate numerical computation of the integrated quantities of angular velocity ($\Delta\theta$) and acceleration (Δv) with coning and sculling error compensation [15]. These generated SDI quantities (orientation and velocity increments) are input to the XEE, addressed in detail in Figure 3 [16–18].

The calibration block applies the calibration parameters that correct for, amongst other things, temperature effects, scale factor, bias, misalignment and g-sensitivity errors inherent to MEMS-based gyroscope and MEMS-based accelerometer sensing elements [19]. The calibration block following the magnetometer sensing element block applies parameters of offset, scale factor and misalignment for the magnetometers as determined during the calibration process. The calibration process unique to Xsens improves the individual MEMS sensor performance by about 100 times. After calibration, residual errors across temperature for gyroscopes for g-sensitivity is <0.001 °/s/g (typical), sensitivity variation and zero-rate output is typically 0.05 % and ±0.1 °/s respectively. For accelerometers, the typical sensitivity variation and zero-g output is 0.05 % and ±2 mg respectively. Each MTi is individually calibrated across the temperature range and tested, and each unit is supplied with its own unique calibration report.

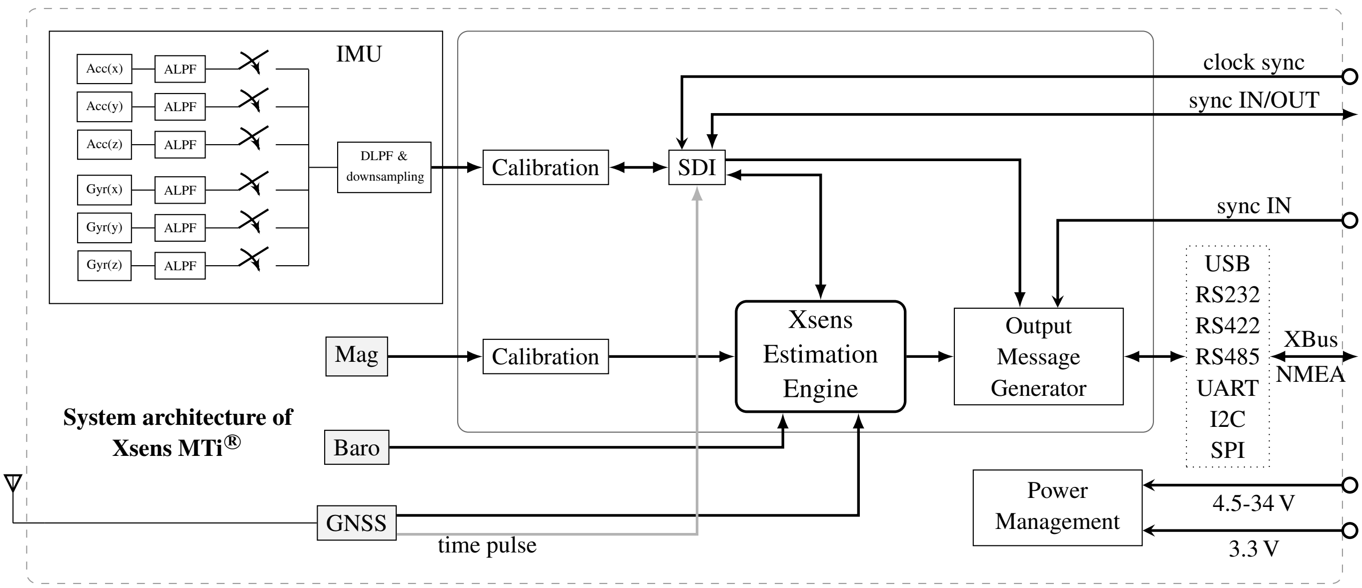


Figure 3: The system architecture of an MTi. The system has at its core the estimation engine with a multi-sensor fusion algorithm XEE. The engine makes use of IMU signals for its prediction model along with measurement models for sensory information from GNSS, magnetometer and barometer to provide robust tracking estimates. The communication options along with sync and power options are also shown.

System architecture

Xsens estimation engine block in Figure 3 is the name given to the multi-sensor fusion algorithm core. The MTi 1-series, MTi 10-series and MTi 100-series use the XKF3™ estimation module of the XEE [20]. It fuses orientation and velocity increments along with magnetometer data, to optimally estimate orientation with respect to an Earth fixed coordinate frame. The input to XKF3 is provided by the AttitudeEngine as discussed previously. The exception being MTi-G-7XX which makes use of an alternate version of the XEE where measurements from barometer and a high sensitivity multi-GNSS receiver are fused to provide navigation estimates of position, velocity and orientation.

The update rates of each sensing block are as listed in Table 3. The GNSS time pulse which is referenced to the accurate *global positioning system* (GPS) time is used by the signal processing block to correct for clock drifts of the internal MTi clock to an accuracy of 30 ns. For product types other than MTi-G-7XX, the same can be achieved by enabling the clock sync line with a sync pulse from an accurate clock. All MTi data output messages can be UTC time-referenced.

The output message generator in Figure 3 processes the tracking estimates as output by the XEE along with the SDI inertial data to provide tracking estimate samples to the desired *output data rate* (ODR) with minimal latency. *Sensor component readout* (SCR) data gives the user access to digitized voltages of sensors before they are filtered or calibrated. The user can access data by the means of available communication options of USB, RS232, RS422, RS485, UART (3.3 V logic level),

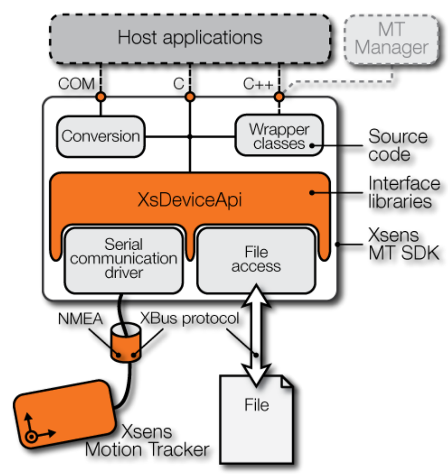


Figure 4: Application development set-up

I2C and SPI spread across the MTi product portfolio. The tracking messages can be obtained either in the open Xbus binary (Xsens proprietary) or NMEA 0183 standard (version 4.00) ASCII format.

Furthermore, the architecture facilitates various time sync-in options enabling system integrators to get tracking messages that are accurately time-referenced on request. Along with the knowledge of inter-sensory measurement timing, system integrators also require information on processing delay to effectively use MTi in their applications. For the MTi 10-series and MTi 100-series, the analog part of the IMU signal processing block discussed in Figure 3 introduces a group delay of ≈4 ms to the signal with respect to the actual physical

motion as detected by the IMU sensing elements. The use of the SDI inertial quantities along with the tracking estimates in the output message generator block keeps the processing latency for the rest of the processing blocks to within 2 ms.

The system architecture of the MTi 10-series and MTi 100-series offers a flexible power supply option 4.5 V-34 VDC along with 3.3 VDC input for applications requiring lower power consumption. The analog components used internally within the MTi have stringent power requirements. These requirements are internally handled by the power management system ensuring a stable power supply to all the internal components. For the 1-series motion tracker module, the power management system is to be handled by the host processor/system within the power supply specifications of VDD 2.16 V-3.45 VDC and VDDIO 1.8 V to VDD VDC [11].

Xsens Device API

The Xsens MTi comes with a SDK which is easy to use, understand, future proof and platform independent. As seen in Figure 4, the *Xsens Device API* (XDA) enables the host application developer to choose from COM, C or C++ interface by which to access the Xsens MTi for which the full source code is supplied. The XDA is implemented by two C-interface libraries - XsTypes and XsensDeviceAPI. The XsTypes library contains generic types and operators needed for data manipulation. The XsensDeviceAPI library contains access to functionality as implemented in product types. The XDA functions are thread-safe and support asynchronous events. The SDK facilitates access to these asynchronous events by callback functions that can be used by system integrators in their own application-specific custom functions. The SDK also comes with MT manager software application which is an easy-to-use user interface for viewing, logging and exporting

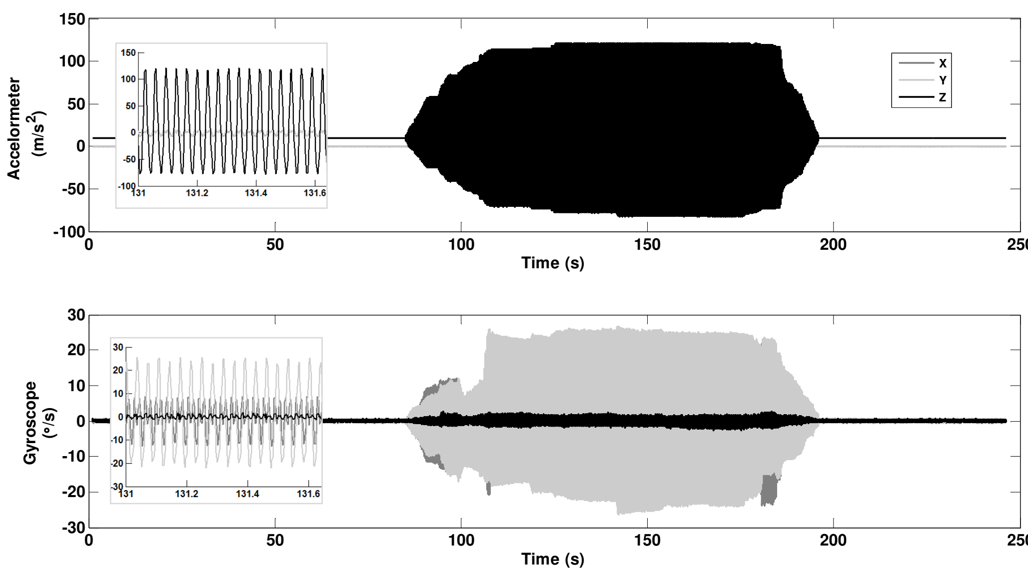


Figure 5: The accelerometer and the gyroscope signals collected for the performance test under vibrations. The Xsens MTi was subjected to frequencies from 10 Hz-600 Hz with peak-to-peak amplitude reaching ≈16g and ≈50 ° s^{-1}. The inset figures show the zoomed in accelerometer and gyroscope signal for the time period: 131 s to 132 s.

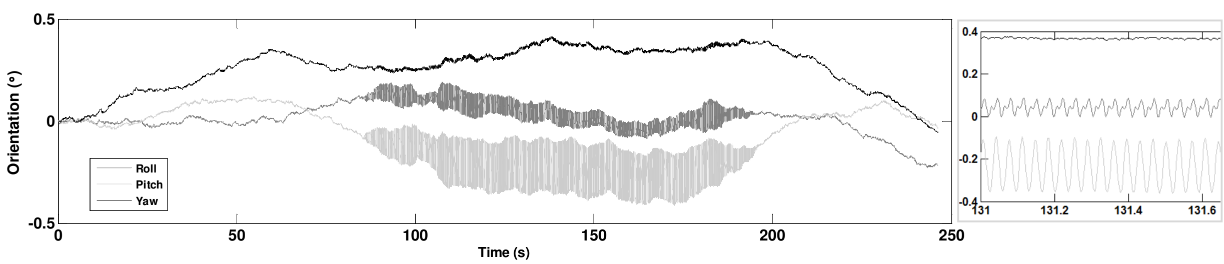


Figure 6: The orientation as obtained by dead-reckoning the gyroscope signal. The performance shows the orientation drift (only dead reckoning) to be well within 0.5° over the testing period of 4 min of which for 2 min the unit was subjected to vibrations. The orientation oscillations shown in the figure to the right (zoomed in time period: 131 s to 132 s) are representative of the actual mechanical motion performed.

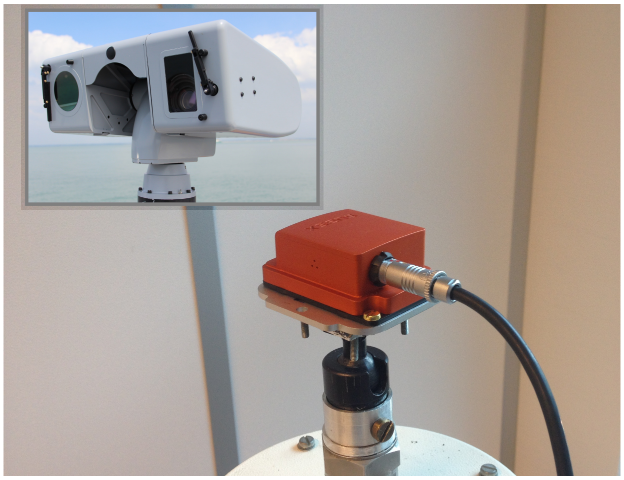


Figure 7: The MTi-100-2A8G4 Motion Tracker on the vibration platform. The inset figure on the left shows a typical marine platform that uses an MTi in marine surveillance application.

data messages from the Xsens MTi Motion Tracker amongst other things. The SDK is supplied for Windows (32-bit and 64-bit) and Linux (32-bit and 64-bit) operating systems with example code provided for MATLAB®, C, C# and C++.

The SDK also facilitates post-processing options useful for applications such as terrain-mapping and image-stabilization. To facilitate the compensation of magnetic disturbances, the Xsens MT SDK comes with a *magnetic field mapping* (MFM) software. The MFM software compensates for the hard-iron (offset) and soft-iron (scale factor) introduced by the platform using recorded magnetometer measurements.

In addition to the above, for easy integration into embedded systems, the MTi 1-series comes with an example code implementation of the XBus low level communication protocol for ARM® mbed™. The example code is in the form of a generic C99 compliant source code [21]. The development boards of MTi 1-series can be used to test for synchronization features and data visualization [22]. An MTi node is also provided for use with the *robotic operating system* (ROS), tested for indigo installation. This node can be used to access and publish data outputs of the MTi units using either standard or custom ROS built-in messages [23].

4. Applications

As discussed previously, the Xsens MTi is designed and well suited for industrial application involving land, marine, airborne and subterranean applications. This section presents the tracking performance of the Motion Tracker for use in marine, land and airborne applications.

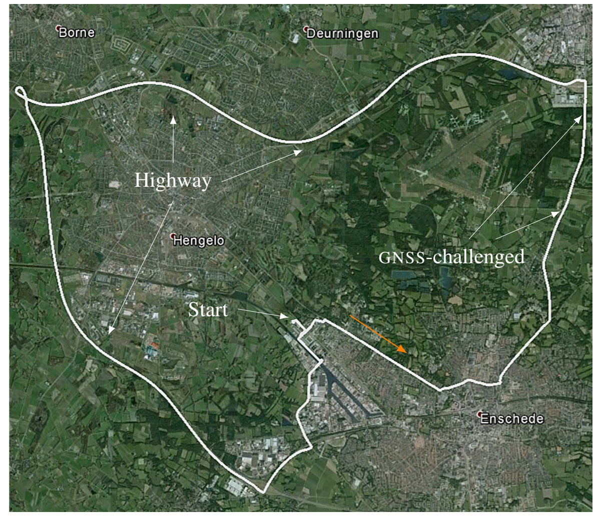
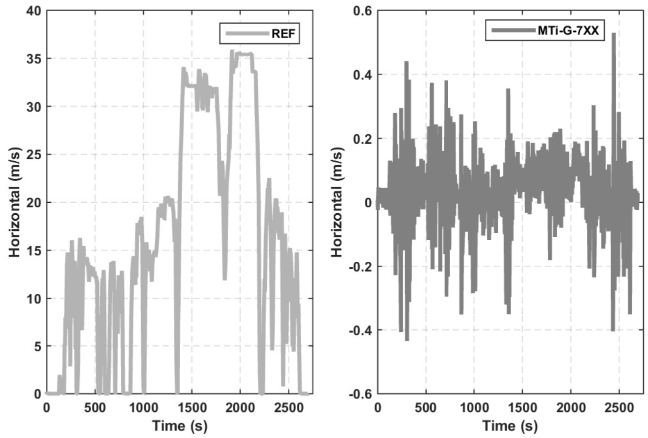


Figure 8: AUTOMOTIVE TEST: The automotive test trajectory run done near Enschede, The Netherlands. The MTi-G-7XX trajectory shown is as output by the KMZ exporter of the MT manager. The start and end points of the test run are the same as indicated in the figure. The GNSS-challenged segments point to areas with thick tree canopy.

Marine application (with vibrations)

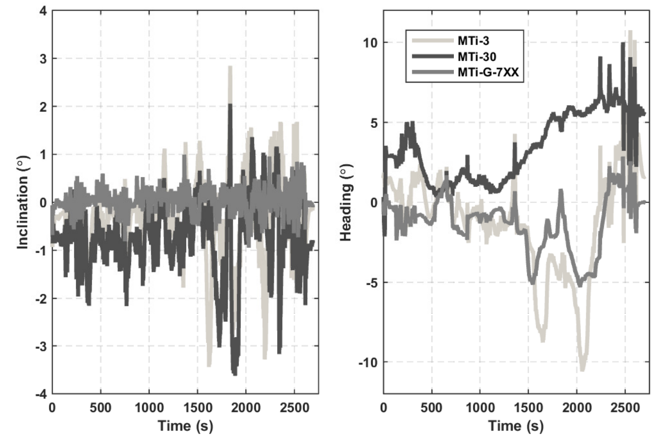
Industrial applications generally require tracking estimate of a platform with vibrations associated with the hum of engines, motors and actuators. The MTi products are designed and tested to perform under these conditions. In marine environments, the MTi is often used for platform stabilization and antenna steering purposes. Apart from real-field trials and testing performance against reference systems, the MTi units are rigorously tested in a lab using the vibration platform as shown in Figure 7. The vibration platform is able to simulate the frequency and magnitude of vibrations typical for a seaworthy mechanized platform for stabilization in marine safety and surveillance applications (Figure 7 (inset)).

Figure 5 show the IMU signals and Figure 6 show the corresponding dead-reckoned orientation of data collected with an MTi-100-2A8G4 device mounted on the vibration platform. The unit is equipped with accelerometers and gyroscopes with full scale range of 15g and 450 $^\circ$ s^{-1} respectively. Figure 7 shows the the unit fixed onto the vibration table using mounting screws. The unit was kept stationary for close to 60 s at the start and the end of the trial after which the unit was subjected to vibrations over a range of frequencies (10 Hz to 600 Hz) and peak to peak amplitudes (2g to 15g RMS). The orientation in Figure 6 shows the drift in all three axes to be well within 0.5° over a period of 4 min (dead-reckoning only). This dead-reckoning orientation performance is directly a result of the well designed IMU signal processing pipeline and the AttitudeEngine.



(a) Reference velocity profile (b) Velocity error

Figure 9: AUTOMOTIVE TEST: The reference velocity trajectory of the entire automotive test run along with the velocity error of MTi-G-7XX (*automotive*) is shown.



(a) Inclination error (b) Heading error

Figure 10: AUTOMOTIVE TEST: The inclination and heading error of an MTi-3(*general*), MTi-30 (*vru_general with* AHS) and MTi-G-7XX (*generalMag*).

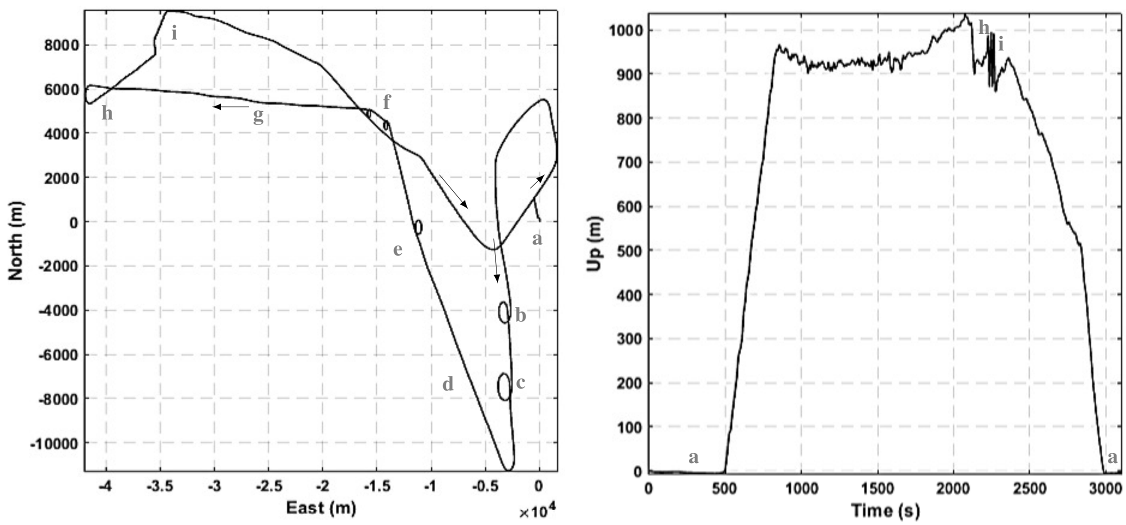
Land application

The MTi is continuously tested in real application environments and the trials conducted try to replicate at best possible the intended application. The tracking performance outputs are checked for consistency, robustness and reliability by comparing the MTi units performance against a reference system. The reference system used for outdoor trials is a GPS-L1/L2/GLONASS multi-GNSS multi-frequency receiver used in combination with a tactical grade *fibre optic gyros* (FOG) IMU. The data collected from the rover and the base station GNSS receivers are processed offline using a commercially available GNSS post-processing software to get accurate *position, velocity and time* (PVT) solution estimates. The reference trajectory is obtained by feeding in time-aligned measurement inputs of GNSS-PVT solution with the tactical grade IMU data in a batch-processing non-linear optimization module of XEE.

Apart from the possibility of getting real-time orientation, velocity, and position estimates using filter profiles from the onboard processor, the MTi data collected using MT Manager software can be post-processed by the user using the available filter profiles. Figure 8 shows the run conducted in the surroundings of Enschede, The Netherlands. MTi-G-7XX is equipped with a multi-GNSS receiver, use of multi-GNSS constellations ensures continuous availability of reliable GNSS-PVT estimates for input to XEE module even in GNSS-challenged conditions of urban canyons and tree canopies. The test run consisted of period of city driving, GNSS-challenged segments and highway driving. The horizontal velocity error of the MTi-G-7XX with the *automotive* filter profile is 0.1 m/s RMS for this test run which is a testament to the unit's robust navigation performance. Similar performance (see Figure 10) can be seen for inclination and heading obtained from MTi-G-7XX processed with *generalMag* filter profile with 0.2°RMS and 2.11°RMS respectively. The use of magnetometer measurements after an MFM procedure improves heading observability during periods of constant velocity and static conditions of the platform where there is no heading observability from GNSS-PVT measurement.

Active heading stabilization—The AHS concept featured in the VRU and AHRS versions of MTi allow for stabilization of heading in a wide variety of environments, especially useful in environments with severe magnetic disturbances. For MTi, taking into consideration the class of sensors used, dead-reckoning errors can reach a few degrees over tens of minutes. AHS feature as part of the XKF3 algorithm with informative formulation of fundamental assumptions within solid statistical framework provides low-drift unreferenced heading to typically $<1°$ and $<2°$ over a period of 60 min for the MTi 100-series/MTi 1-series and MTi 10-series respectively. Figure 10b shows the MTi-30 unreferenced heading drift limited to 5° over a challenging automotive test run showing the benefits of use of AHS functionality in similar situations. The AHS is automatically enabled with the use of *vru_general* filter profile.

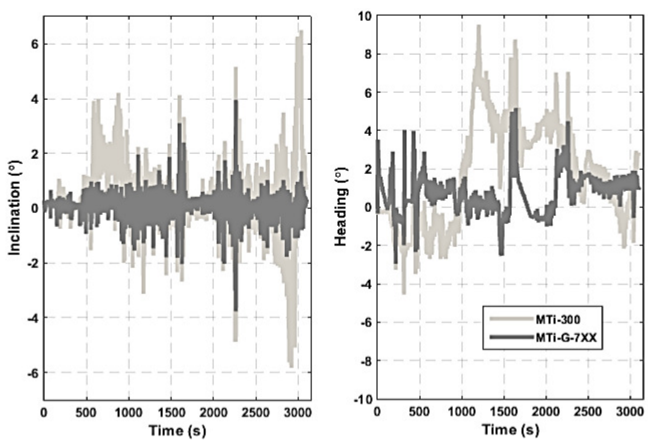
MTi 1-series—Figure 10 shows the inclination and heading performance of the MTi-3 module with the *general* filter profile. The *general* filter profile in XKF3 uses the magnetometer measurements. The inclination performance and heading error as compared to the reference is 0.82°RMS and 3.53°RMS for the test run respectively. The use of lower-noise MEMS-based gyroscopes complimented by AttitudeEngine and AHS in MTi 1-series makes it comparable in performance to that of an MTi 10-series unit using the same features.



(a) Course over ground of the flight test run.

(b) Elevation profile of the flight test run over time.

Figure 11: FLIGHT TEST: The course over ground and the elevation profile of the flight test trial conducted in Twente airport in Enschede, The Netherlands. The different flight segments marked in the figures represent the following - a) Take-off/Landing, b) 30° bank, c) higher velocity 30° bank, d) sideslip, e) 45° bank with 360° turn, f) 60° banks, g) level flight at constant velocity, h) controlled spiralling down, i) pitching up and down, generating 0 g-2.5 g.



(a) Inclination error

(b) Heading error

Figure 12: FLIGHT TEST: The inclination and heading error of an MTi-300(*vru_general with* AHS)and MTi-G-7XX (*generalMag*).

Airborne application

A flight test run was conducted at the Twente airport in Enschede, The Netherlands in a Socata airplane (single-engine turboprop). Figure 11 shows the *course over ground* (COG) and the elevation profile of the flight test run. The different flight segments are marked in the COG as well as in the elevation profile (figure 11b) which is plotted against time gives the reader an indication of the manoeuvres performed and the dynamics of the testing platform.

Figure 12 shows the inclination and heading error of MTi-G-7XX and MTi-300 for the flight test duration. The MTi-300 unit was set to *vru_general* filter profile and the onboard calculated orientation estimates were logged. The MTi-G-7XX data on the other hand, is processed with the *GeneralMag* filter profile with magnetic field mapping parameters obtained from the maneuvers of the entire flight trajectory. With extreme maneuvers right after the periods of low-heading observability (segment g), the heading error reaches 4°. The inclination and heading performance for MTi-G-7XX for the test run is 0.36°RMS and 1.26°RMS respectively.

Using the AHS feature, part of the *vru_general* filter profile, the heading drift of an MTi-300 at the end of a challenging flight test (45 min) is limited to within 2°. The inclination and heading performance for the test run for MTi-300 is 1.35°RMS and 3.25°RMS respectively.

5. SUMMARY

This paper presents an overview of Xsens MTi: Motion Trackers designed for industrial applications. The IMU signal processing pipeline with its AttitudeEngine is catered for industrial applications with stress on tracking performance under sustained vibrations typically experienced by mechanized platforms in land, marine, subterranean and airborne applications. The system architecture of the Xsens MTi ensures data output with low latency and at high update rates with different communication, power options, message outputs and time synchronizing features that are essential

for system integrators. The MTi product portfolio provides a fit for a wide range of applications giving importance to product usage and cost aspect, with product types and options spread across different functional groups and performance classes. The proven sensor fusion engine based on previous generation of products has been upgraded to the robust XEE sensor fusion engine. With AttitudeEngine for signal processing, XKF3 (MTi 1-series, MTi 10-series and MTi 100-series) and the navigation filter (MTi-G-7XX), the MTi is designed and equipped with features to get the utmost from all the sensors, ensuring an accurate, always available, reliable and continuous motion tracking.

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