The Next Generation Xsens Motion Trackers for Industrial Applications

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The Xsens manufactured MEMS based MTi® Motion Tracker finds its uses 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 4th generation of Xsens Motion Tracker products for industrial applications (MTi®).

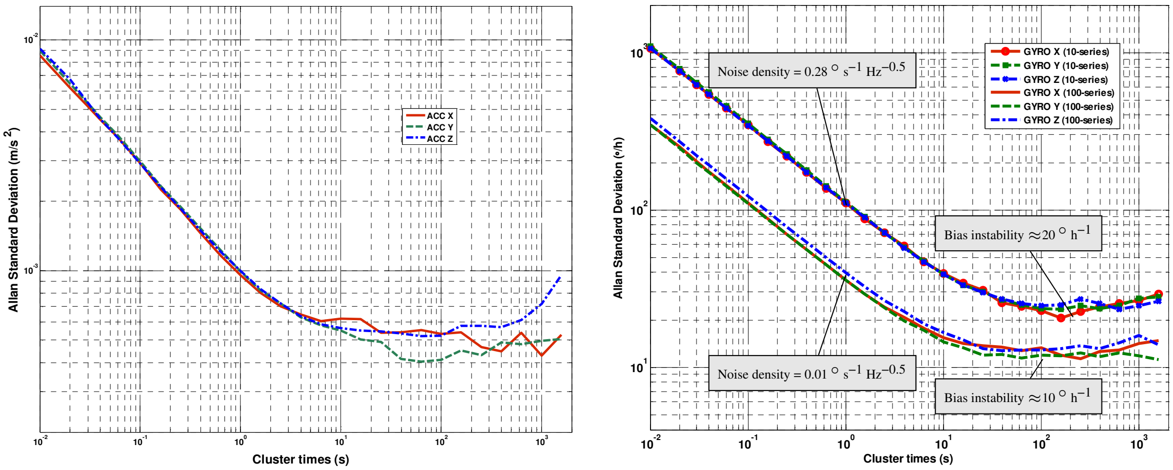
1. Introduction

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. The 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 (<\$100 per axis) and small form factor (<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 and continuous tracking estimates that are always available with reliability , 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, 4, 5, 6, 7, 8, 9, 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 light weight (11 g for OEM version) small package (<15 cm^3) with a power consumption of 650 mW. The unit is designed keeping in mind the market requirements as dictated by the user applications. The signal processing pipeline design offers immunity to vibrations beyond 400 Hz. It provides data at higher output rates (2 kHz) with low data latencies (<2 ms). The use of XEE ensures robust and reliable tracking estimates under prolonged accelerations and provides immunity against magnetic disturbances. In the following section, we present the product portfolio of the Xsens MTi® Motion Trackers. Section 3 presents the system architecture of the MTi® with details on signal processing, calibration and the Xsens *Application programming 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 were the overall performance is summarized.

Figure 1: Xsens Motion Tracker products for industrial applications (MTi®). From left to right - OEM version of MTi-10 (IMU), MTi-20 (VRU), MTi-300 (AHRS) and MTi-G-700 (GNSS/INS)



(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 2b shows Allan variance for gyroscopes used for MTi-10 series and MTi-100 series along with the noise density and the bias instability values.

2. Product portfolio

The product portfolio of Xsens MTi® Motion Tracker is classified in two ways 1) based on performance, and 2) based on functionality as shown in Table 1 and Table 2 respectively. This information available in these tables can be used by any user for selecting the appropriate MTi® for their application. Figure 2 shows the MTi® IMU component Allan Variance characterization used for determining the stochastic error measures for modelling of IMU errors [11]. The MTi-100 series uses high-performance industrial grade MEMS-based-IMU with advanced mechanical vibration and impact rejection 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$10 ° 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).

Product series	Characteristics
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.

Product codes	Functionality	Description
MTi-10/100	IMU	Calibrated inertial ($\Delta\theta$, Δv) and calibrated magnetometer data.
MTi-20/200	VRU	Accurate roll and pitch with low drift unreferenced heading.
MTi-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.

The MTi® product classification based on functionality is given in Table 2. The stand-alone IMU product groups for the MTi-10 series and MTi-100 series do not use any measurement models, as the device outputs fully calibrated sensor measurements of IMU and magnetometer without any processing 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 as well as low drift unreferenced heading. The *attitude heading & reference systems* (AHRS) unit outputs stabilized accurate heading along with accurate roll and pitch estimates. The GNSS/INS (MTi-G-700) makes use of sensory measurements from magnetometer, barometer and a high sensitivity GPS-L1

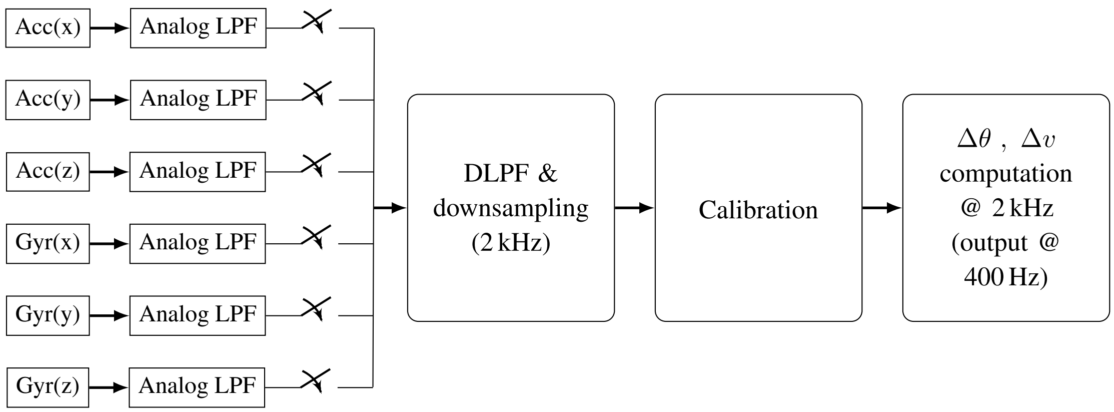


Figure 3: The analog front-end and the SDI of inertial data. The blocks give an overview of the conversion of the analog signal of the sensing elements (triad of accelerometers and gyroscopes) to the conditioned digital IMU signals i.e., integrated quantities of angular velocity and acceleration.

receiver to provide navigation estimates of position, velocity and orientation at higher data rates under high dynamics. Each product is supplied with its set of application-specific or motion-specific filter profiles, these are used to turn on/off models used within XEE. The MTi-G-700 has e.g., an automotive filter profile suited for ground vehicle applications.

3. MTi 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 with the system architecture description. This is followed by with 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 analog front-end and *strapdown integration* (SDI) block of an IMU signal processing pipeline are shown in Figure 3. A properly designed *analog low pass filter* (ALPF) ensures elimination of errors due to aliasing, high frequency noise, minimizes inter-channel delays and eliminates high frequency components like resonant frequency coupling. It also prevents saturation of the Analog-to-Digital converter. The *digital low pass filter* (DLPF) is applied to prevent aliasing of signal while down-sampling the signal in the digital domain. 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 [12]. Each MTi® is individually calibrated for and is supplied with its own unique calibration report.

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

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

The computation block performs accurate numerical computation of the integrated quantities of angular velocity ($\Delta\theta$) and acceleration (Δv) with coning and sculling error compensation. These quantities will be referred to as the SDI inertial data in the following sections [13, 14, 15]. For industrial applications, the bandwidth of motion involved is $<$200 Hz. In the Xsens MTi®, 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. The mechanical sensing elements for gyroscopes and accelerometers have a bandwidth of $\approx$400 Hz [16, 17].

System architecture

As shown in Figure 4, XEE is the multi-sensor fusion algorithm core. The XEE makes use of *Xsens Extended Kalman filter* (XKF) framework along with non-linear optimization techniques to overcome drawbacks of traditional *extended Kalman filter* (EKF) for accurate and robust tracking estimates. The in-use automatic calibration parameters as determined by XEE are applied for IMU, magnetometer and barometer signals in the calibration block. 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-700,

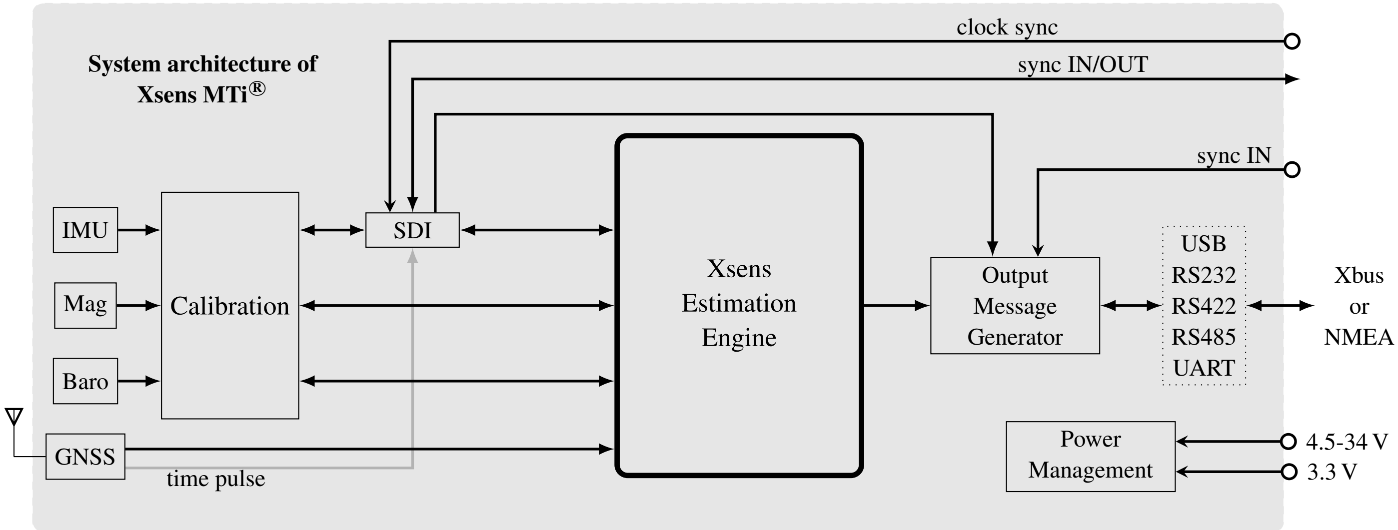


Figure 4: The basic system architecture of an MTi®. The system has at its core the estimation engine with a multi-sensor fusion algorithm XEE. The engine makes use of IMU signals for its prediction model along with measurement models for sensory information from GNSS, magnetometer and barometer to provide robust tracking estimates. The communication options along with sync and power options are also shown.

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 uses 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 all MTi®data by the means of available communication options of USB, RS232, RS422, RS485 and UART (3.3 V logic level) using different product configurations. 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. 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 strapdown 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 offers a flexible power supply option

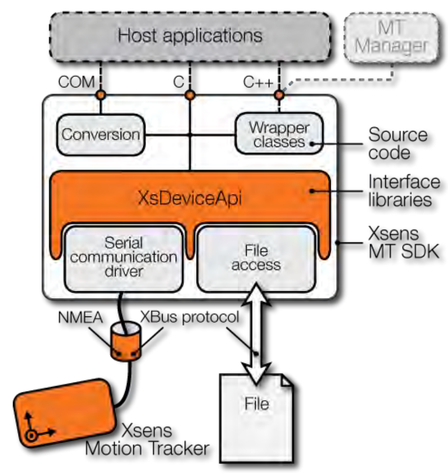


Figure 5: Application development set-up

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.

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 5, 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.

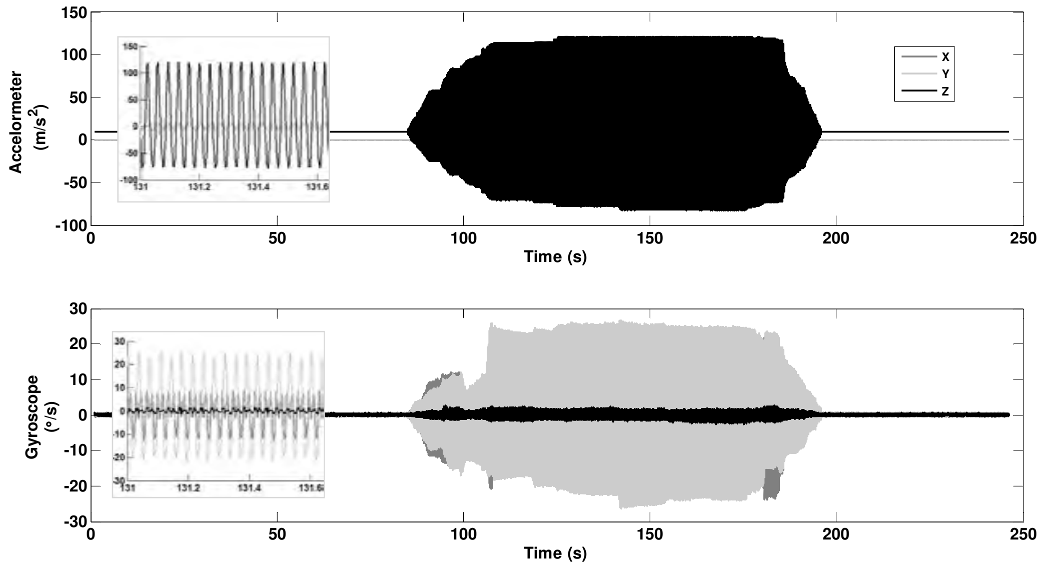


Figure 6: The accelerometer and the gyroscope signals collected for the performance test under vibrations. The Xsens MTi® was subjected to frequencies from 10 Hz-600 Hz with peak-to-peak amplitude reaching ≈16g and ≈50 ° s^{-1}. The inset figures show the zoomed in accelerometer and gyroscope signal for the time period: 131 s to 132 s.

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 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 Xsens MT 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 magfield mapper software. The magnetic field mapping software compensates for the hard-iron (offset) and soft-iron (scale factor) introduced by the platform using recorded magnetometer measurements.

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 under vibrations in marine, land and airborne platforms.

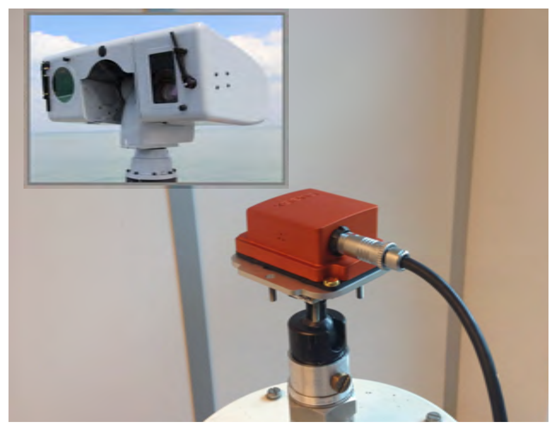


Figure 7: The MTi-100-2A8G4 Motion Tracker on the vibration platform. The inset figure on the left shows a typical marine platform that uses an MTi® in marine surveillance application.

Marine application

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 sea-worthy mechanized platform. One such

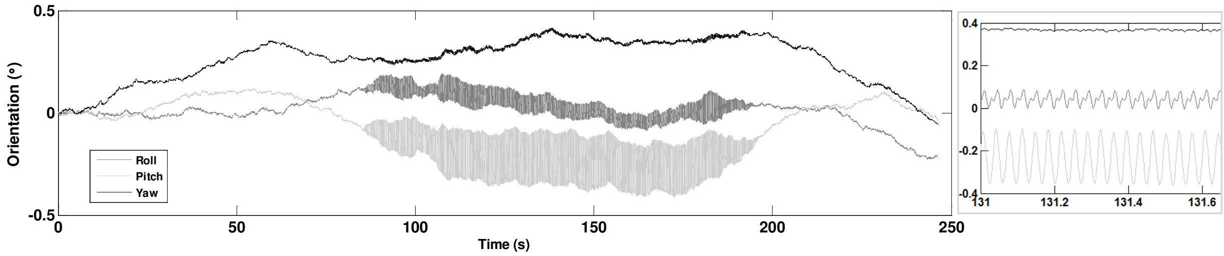


Figure 8: The orientation as obtained by dead-reckoning the gyroscope signal. The performance shows the orientation drift (only dead reckoning) to be well within 0.5° over the testing period of 4 min of which for 2 min the unit was subjected to vibrations. The orientation oscillations shown in the figure to the right (zoomed in time period: 131 s to 132 s) are representative of the actual mechanical motion performed.

(a) Highway trial with GPS outage.

(b) Urban driving trial with GPS signal deterioration.

Figure 9: The Google Earth plot as exported by the Xsens MT Manager software for MTi-G-700 data sets collected near Dordrecht (9a) and in Enschede (9b) in the Netherlands. The highlighted rectangle regions in the maps correspond to the zoomed in plots showing periods of challenging GNSS conditions. The reference trajectory is shown in blue.

application is for platform stabilization used in marine safety and surveillance applications, it is shown in Figure 7 (inset).

The MTi-100-2A8G4 equipped with accelerometers and gyroscopes with full scale range of 18g and $450\,^{\circ}\,s^{-1}$ respectively. Figure 6 shows the IMU signals collected with the unit fixed onto the vibration table (Figure 7) 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 16g rms). Figure 8 shows the orientation performance obtained by dead-reckoning of the gyroscope signals. The performance 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.

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 dual frequency receiver used in combination with a tactical grade *fibre optic gyros* (FOG) IMU. The data collected from the rover and the base station GPS receivers are processed offline using a commercially available GNSS post-processing software to get accurate GPS-*position, velocity and time* (PVT) solution. The reference trajectory is the combined forward/reverse passed (smoothed) solution obtained by fusing the post-processed GPS-PVT with the tactical grade IMU output in a customized XEE framework.

The MTi® data collected using MT Manager software can be post-processed by the user using the available filter profiles.

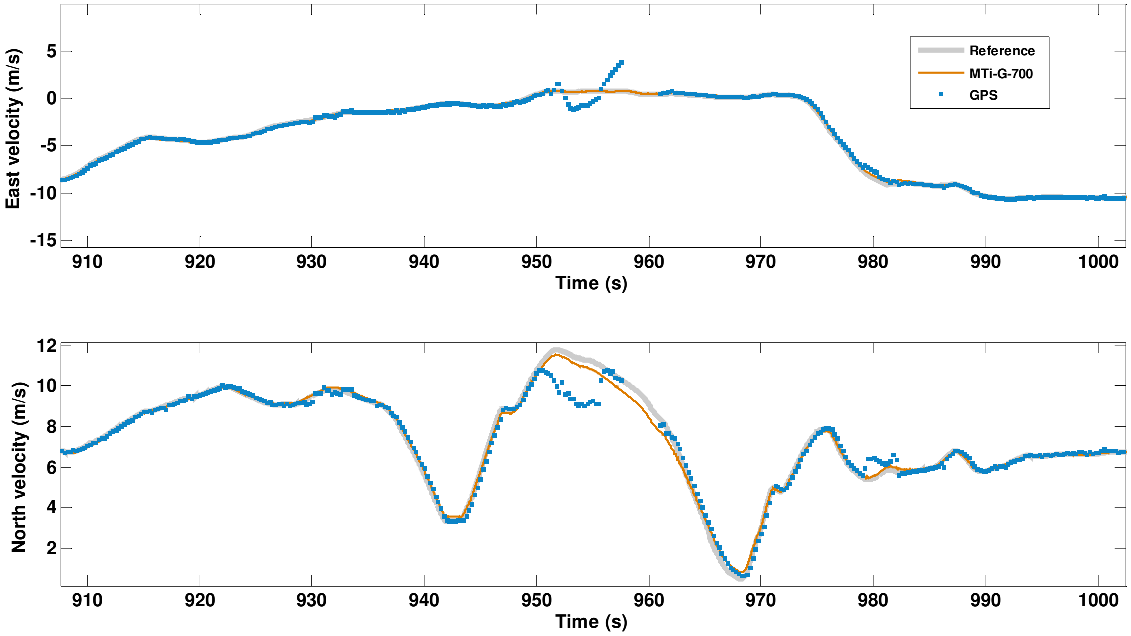


Figure 10: Velocity of the MTi-G-700 unit as compared to the reference trajectory for a enclosed region shown in Figure 9b. The GNSS data points aiding the MTi-G-700 is also shown along with the reference navigation outputs.

Figure 9 is the Google Earth export of MTi-G-700 data with *Automotive* filter profile. Figure 9a shows the trial conducted on the highway between Dordrecht and Rotterdam in the Netherlands at speeds reaching 100 km h^{-1}. The gray circle and gray cross (X) on the image indicate the start and finishing points respectively. The enclosed area highlights a trajectory part with a GNSS outage of close to 20 s. During this part, the car drives under a canal in a tunnel. The inset shows the zoomed in plot of the region, it can be clearly seen that the MTi-G-700 trajectory maps onto the reference trajectory (blue) during this period. This trial demonstrates the capability of MTi-G-700 to coast during periods of GNSS outage providing continuous navigation solution.

With an identical setup, another trial was conducted in the city of Enschede, The Netherlands (shown in Figure 9b) to analyse performance of the navigation unit. The trial involved typical city driving maneuvers with periods of intermittent GNSS deterioration. The rectangle box in Figure 9b shows the period where the car went under a railway bridge. The GNSS deterioration is reflected by the GNSS velocity outputs as seen in Figure 10. The XEE sensor fusion algorithm handles the erroneous GNSS measurement appropriately to give a reasonable navigation estimate that closely matches that of the reference as shown in Figure 10.

Airborne application

An airborne trial was conducted at the Twente airport in Enschede, The Netherlands in a Socata airplane (single-engine turboprop). The sensors used are identical to those

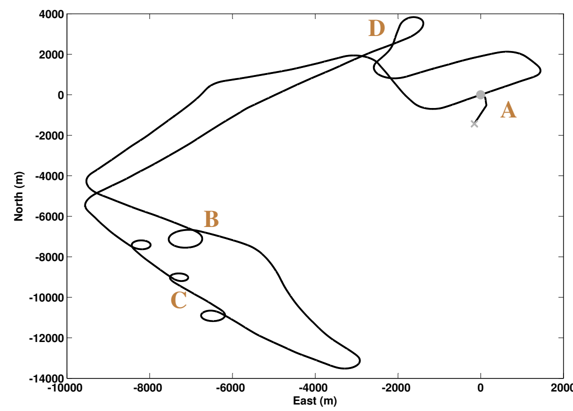


Figure 11: The course over ground of the flight test trial conducted in Twente airport in Enschede, The Netherlands. The different flight segments are labelled.

described in the previous section. Figure 11 show the *course over ground* (COG) of the flight trial. The heading comparison of the MTi-G-700 with the reference is shown in Figure 12. Figure 13 shows the elevation profile of the flight trajectory. The labels indicate the different flight segments with (A) representing the landing and take-off points, (B) indicating a constant bank turn of 30°, (C) two constant bank turns of 45° each followed by a 60° bank turn with accelerations reaching 2g's, and (D) a high bank turn (>60°) with an elevation drop of close to 80 m over 5 s followed by a climb of 80 m over 5 s which can be clearly seen close to label D in Figure 13.

Without the use of magnetometer signals for aiding, in an MTi-G-700, the heading observability primarily comes

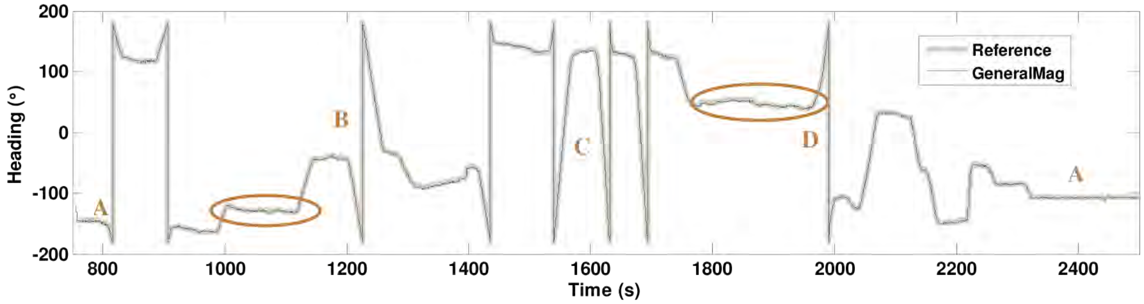


Figure 12: Heading performance of the MTi-G-700 using the *GeneralMag* filter profile. The plot shows the heading of the reference system along with those of MTi-G-700 data sets with magnetic field mapping performed using data set of the entire flight trajectory. The heading accuracy of the MTi-G-700 as compared to the reference is 1° RMS for the entire flight trajectory.

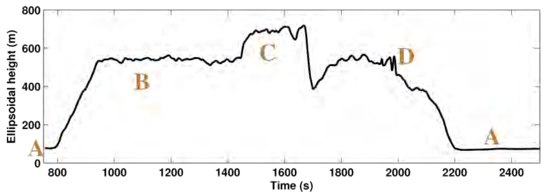


Figure 13: The elevation profile of flight test trial conducted in Twente airport in Enschede, The Netherlands. The different flight segments are labelled.

from the GNSS velocity vector. With GNSS aiding alone, the heading observability is very low or even non-existent during periods of constant velocity or stationary periods of the platform. The magnetometers during such periods provide the much needed heading observability. The use of magnetometer though is constrained by the amount of hard-iron and soft-iron introduced by the airplane. Figure 12 shows the heading performance of the MTi-G-700 motion tracker for the flight trial as compared with the reference heading output. The MTi-G-700 data is processed with the GeneralMag filter profile with magnetic field mapping parameters obtained from the maneuvers of the entire flight trajectory. The ellipses (orange) encircle periods of decreased heading performance during low-heading observability. Even with extreme banking maneuvers right before the periods of low-heading observability, the heading output overlays and closely follows the reference providing a heading accuracy of 1° RMS for the entire flight trajectory.

5. Summary

This paper presents a complete overview of Xsens MTi®: Motion Trackers designed for industrial applications. The IMU signal processing pipeline is catered for industrial application with stress on tracking performance under sustained vibrations typically experienced by a mechanized platform in land, marine, subterranean and airborne applications. The system architecture of the Xsens MTi® ensures data output with low data latency 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 to get the utmost from all the sensors, ensuring an accurate, always available, reliable and continuous motion tracking.