

# A Custom Base Station for Collecting and Processing Data of Research-Grade Motion Sensor Units

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**Abstract.** In studies of human biomechanics utilizing inertial sensors, motion sensor units of type Xsens are recognized as the state-of-the-art. However, the requirement to use them with a personal computer for collecting and processing data could be a limiting factor. In the present work, we demonstrate a simple solution to using up to four Xsens MTx units with a custom portable base station. The base station is capable of obtaining data from Xsens MTx units, processing the data and saving them to an SD card. Thus, it allows the use of the units outside laboratory settings without the need of a personal computer, the capability to directly use onboard custom algorithms to process the data of several units in real time, and interconnectivity with external systems for synchronized collection of multimodal data. We demonstrate these benefits by two examples: synchronized collection of data from an Xsens MTx unit and a Footscan® plantar pressure plate, and knee angle measurement using two Xsens MTx units that we validated by synchronized recording of goniometric data.

**Keywords:** MTx · Xsens · Base station · Inertial sensors · Footscan

## 1 Introduction

In recent years, microelectromechanical sensors incorporating a triaxial accelerometer, triaxial gyroscope, and triaxial magnetometer more often take place in studies of human biomechanics. In this context, motion sensor units by Xsens are recognized as the state of the art [1–4]. Such a unit, when attached to a human body segment, provides data that allow describing the motion of that segment with respect to the Earth-fixed coordinate system. When using multiple sensor units attached to different body segments, the relative motion between body parts can be estimated. When using Xsens units, however, a personal computer is needed in close vicinity which could restrict experiments that require overcoming of distances longer than those determined by the short-range connecting links.

While many studies on human biomechanics use only a single sensor modality [2–7], advancement of sensor technologies allows for deeper insights by multimodal measurements [8, 9]. In that, precise time synchronization between the different recording devices is desired [9].

In the present work, we demonstrate the implementation of a custom low-cost base station to connect Xsens modules. It allows to capture independently, process and save data of up to four Xsens MTx sensor units and also provides features for synchronization with external systems. We describe the system design and provide two application examples. The first example demonstrates synchronized data collection of inertial data from an Xsens MTx unit and plantar data from a Footscan® plantar pressure plate. The combination of the two systems could aid the study of the movement characteristics by allowing both kinetic and kinematic analysis. The second example demonstrates knee angle measurement using two Xsens MTx units. This scenario shows the accuracy of the Xsens MTx modules when performing short-time human body joint angular measurements.

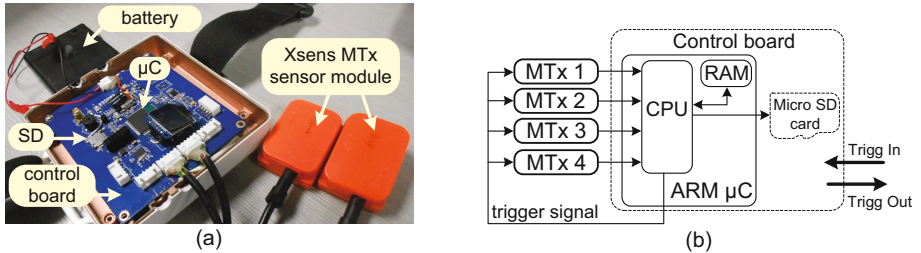
Since the communication protocol of these sensor units is open to customers, with the present work we in no way aim to replace any proprietary tools, but to confirm the flexibility of Xsens modules by demonstrating new schemes of their application.

## 2 Methods

### 2.1 Hardware Implementation of the Custom Base Station

The proposed system consists of a custom control board which supports up to four sensor modules MTx-28A53G25 (by Xsens Motion Technologies, Enschede, the Netherlands) (Fig. 1). Each sensor module contains a 3-axis accelerometer, 3-axis gyroscope, and a 3-axis magnetometer. They are connected to the host system via an RS232 interface and support baud rates of the serial interface of up to 921.6 kbps. The protocol for communication with the modules is provided by the manufacturer [10]. The sensors are capable of providing raw data and processed data. The latter include angular data and the so-called calibrated data. Calibrated data are corrected based on a physical model that reflects the response of the sensors to different external factors. For processed data, the maximum sampling frequency is 256 Hz. The range of the accelerometer is 5 g, and the range of the gyroscope is  $\pm 1200$  deg/s. Each module is provided with a synchronization input. The nominal power supply voltage of the sensor unit is 5 V with consumption of 70 mA and maximum starting current of up to 200 mA [10, 11]. The control board is based on the STM32F407 microcontroller. We chose it because it offers up to six serial ports, a reasonable amount of operational memory allowing for large communication buffers, and a hardware unit for floating point arithmetic. The system is equipped with an SD card to store acquired and calculated data. There are synchronizing output and input. Thus, the system can be synchronized with external devices for the goal of multimodal measurements. The microcontroller system requires a power supply of 3.3 V; the sensor unit rated power supply is 5 V; the voltage of four 1.5 V batteries connected in series is about 4.8–6 V and will decrease when discharging. To ensure proper power supply for each subsystem, we used voltage regulators TPS74701 and TPS61252 for the

3.3 V and 5 V power supply, respectively. A translating transceiver 74LVC4245A ensures the level shifting between the microcontroller output and MTx trigger line input, and the synchronization output. A buffer 74LVC14A ensures the level shifting between the output of external 5 V systems and the microcontroller trigger input. By jumpers, it is possible to pass the external synchronization signal directly to the synchronization input of the MTx modules or to synchronize the MTx modules by the microcontroller. The complete system is powered by a 4.8 V battery pack that ensures the operation of the system for at least one hour, depending on the particular application. The dimensions of the board are 100 mm  $\times$  120 mm.



**Fig. 1.** Illustration of the system: (a) the developed custom board (b) simplified block diagram of the base station.

## 2.2 Software Implementation of the Custom Base Station

The basic task of the firmware of the control board is to configure the operating mode of the Xsens MTx modules and receive data from them. We implemented the firmware in C language. Any recorded data on the SD card were later processed using custom software routines prepared under MATLAB environment.

- (1) *Communication with the sensor units:* The reception of data uses streaming mode and is based on interrupts. We implemented the protocol for communication with the sensors as described by the manufacturer [10]. The volume of data that comes from a single MTx inertial module is determined by its activated options [10, 11]. The total time to transfer and process data of a single sampling is limited by the sampling period. Thus, high speed of the serial interface is needed. In our case, the speed of the serial communication is 460 kbps, at a sensor sampling frequency of 200 Hz. The software ensures that there are no missing samples by checking the proper incrementing of the sample counter.
- (2) *Recording on an SD card:* Inertial data and calculated angles obtained in real time are recorded to the SD card. The recording process should not affect time performance of data collection and any signal processing tasks. To ensure this condition, we allocated two buffers A and B for each MTx module. The data from each module are temporarily stored into one of the buffers. The capacity of a buffer allows recording for at least one second. A ping-pong operation of buffers is implemented: once a buffer becomes full, next samples are collected to the other empty buffer while the content of the first one is transferred onto the card. Later, in a similar way

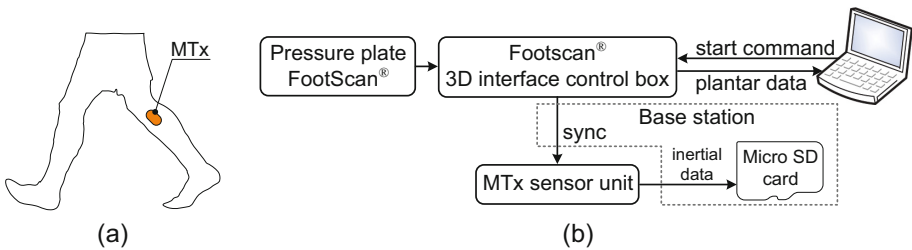
the buffers are switched again. At the selected sampling frequency, the total time to record the buffer content of all connected sensor modules on the card must be shorter than the time to fill a single buffer. Another measure to minimize the time for recording on the SD card is to store the data in the same binary format as they are received from the Xsens modules.

For the experiments demonstrating the two application examples, we enrolled a total of ten young healthy volunteers (five males and five females, weight 55–75 kg, age 23–31, foot size 23.5–27 cm) from the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences.

### 2.3 Collection of Inertial and Plantar Pressure Data

In this application example, we performed synchronous recording of plantar pressure and inertial data. Such a scenario makes sense in the context of a body sensor network-based exploration of human biomechanics [9]. Also, inertial sensor data allow for kinematic analysis, while plantar pressure data allow for kinetic analysis. Thus, the combination of the two systems provides a convenient means for exploration of human body movement.

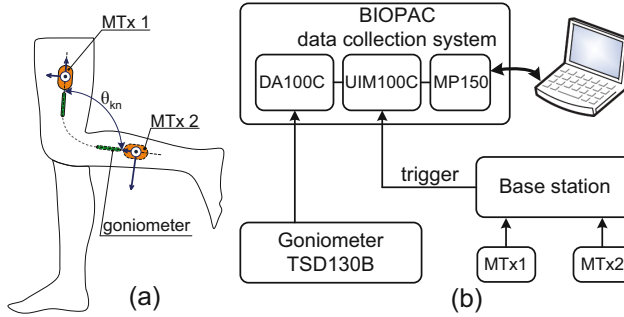
For plantar pressure data collection, we used a Footscan® system (RSscan International, Olen, Belgium, 1068 mm × 418 mm × 12 mm, 8192 sensors). It supports sampling rates of up to 500 Hz, depending on the operating mode [12]. The plate was mounted in the middle of a walkway with a total length of 8 m. Inertial data were collected from a single MTx module attached laterally under the knee on the left shank segment of the subjects. We configured the Footscan® system to act as the master, providing per-frame synchronization signal which was passed directly to the MTx module. The hardware scenario is illustrated in Fig. 2. We asked each subject to walk without shoes at his/her self-selected speed over the walkway, crossing the pressure plate. The sampling frequency of the plate was set to 200 Hz. Since the plate collects data only for a short time when the subject crosses it, we considered the data from the two modalities only for the time they were simultaneously active.



**Fig. 2.** Plantar pressure and inertial synchronous data collection (a) position of the inertial sensor on the left shank during data collection; (b) block diagram of module interconnections.

## 2.4 Knee Joint Extension Angle Evaluation

With this example, we demonstrate knee joint extension angle measurement. Such a measurement finds application when evaluating the performance of the knee joint [6]. We make use of the option for synchronized recording to prove the accuracy of knee joint angle measurement when using MTx inertial modules. The experimental setup we used is illustrated in Fig. 3a and b.



**Fig. 3.** Knee angle measurement scenario (a) attachment of the sensors (b) module connections.

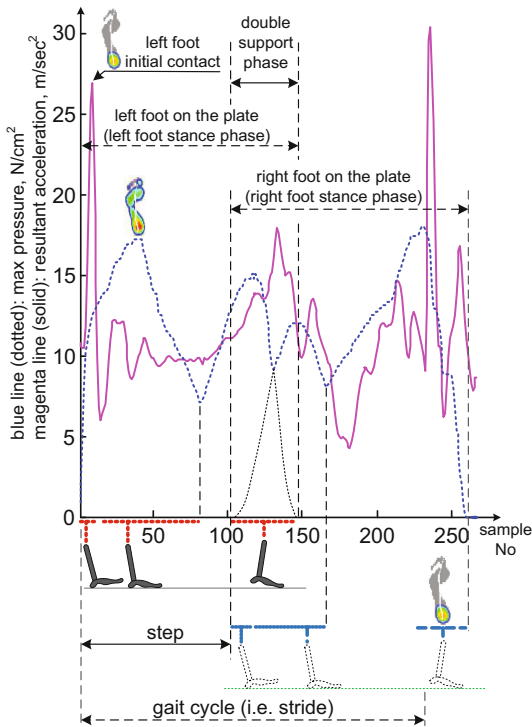
1. *MTx sensor locations and coordinate systems:* One MTx unit was attached to the left thigh laterally, and the other one was attached to the left shank laterally. In that, we adopted the MTx sensor positions, and the definitions of the femoral, tibial, and Earth-fixed coordinate systems as they were defined in [6].
2. *Validation:* For validation, we used a goniometer device (TSD130B, Biopac) connected to a Biopac data acquisition system. An effort was made to align each segment of the goniometer in parallel with the sagittal plane.
3. *Experimental procedure:* Before each data collection, a sensor-to-body calibration procedure was performed. Each data collection started simultaneously between our system and the reference system using a cable connection for the synchronization. The subject was asked to perform full flexion-extension cycles from standing position for 120 s and also walking at self-selected speed for the same duration. Each subject performed ten trials of each kind.
4. *Angle calculation:* MTx sensors provide drift-free orientation data. For the derivation of the knee joint flexion angle we used the methodology given in [6].

## 3 Results

### 3.1 Collection of Plantar Pressure and Inertial Data

The both kinds of collected data showed a repetitive pattern. An example of this pattern is shown in Fig. 4, for the case, when the left foot was the first in the gait cycle. The main phases of the gait cycle are also denoted [13–15]. In Fig. 4, the magenta curve (the solid line) represents the magnitude of acceleration vector (also referred to as “resultant

acceleration”) which is defined as  $a = \sqrt{a_x^2 + a_y^2 + a_z^2}$ , where  $a_x$ ,  $a_y$  and  $a_z$  are the components along the  $x$ ,  $y$  and  $z$  axis, respectively. As to collected plantar pressure data, in Fig. 4 the blue curve (the dotted line) represents the maximum pressure for the time interval between left foot initial contact and right foot toe-off. The curve was built based on the “Entire plate roll off” export of Footscan® pressure plate software since this export provides the pressure on the entire plate while the subject feet contact the plate [12]. The blue curve actually corresponds to the center of force path [16]. From Fig. 4 timing relations between the accelerometer signal and plantar pressure signal could be observed. For example, the time between the maximum resultant pressure at heel strike and the maximum heel pressure of the same leg can serve as an indicator for the walking performance.



**Fig. 4.** An example of synchronously collected inertial and foot plantar pressure data (Color figure online)

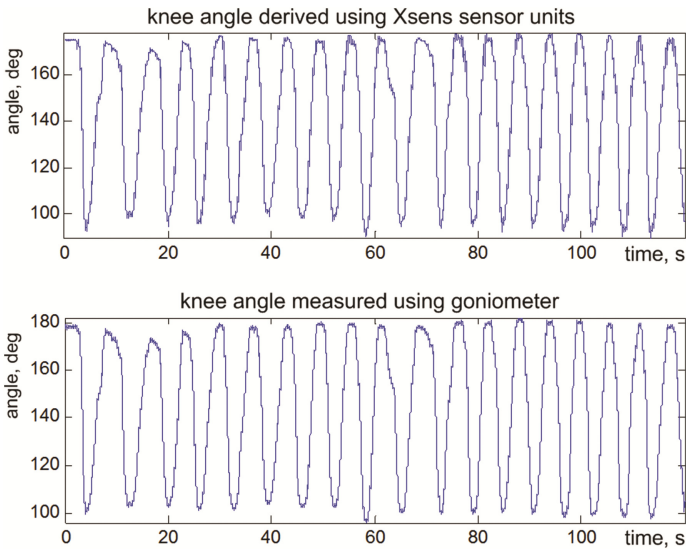
### 3.2 Knee Joint Angle Derivation

The knee joint extension angle obtained using MTx sensors showed a high correlation with the one obtained from the reference system. To estimate the accuracy of the inertial sensor measurement system, we used the root mean square error (RMSE) as an objective measure. Pearson’s correlation coefficient was also computed. Table 1 contains the

results from the validation. Figure 5 shows an example of the angular waveforms obtained from each system during left knee flexion-extension motion. The system demonstrated a high accuracy (RMSE = 3.3570) and high correlation ( $p = 0.9965$ ) with the reference.

**Table 1.** Results of knee joint angle measurement (representative values).

Test motion	Pearson's correlation coeff.	Root mean square error, deg
Left knee flexion/extension from standing position	0.9965	3.3570
Walking at normal speed	0.8964	6.1105



**Fig. 5.** Comparison between angular data of the left knee joint obtained synchronously by the proposed system and the reference during left knee flexion/extension.

## 4 Conclusions

In this work, we present a base station developed by us for collecting data from motion sensor units of type Xsens MTx. Since the communication protocol of these sensors is available, we demonstrate their flexibility for use with a custom system. In many cases, such an approach could simplify experimental scenarios. We provided two application examples with a focus on synchronized data collection from biomedical systems of different kinds. Options that can easily be utilized are to synchronize several base station boards if more than four MTx units are required or add a wireless module to achieve wireless synchronization.

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