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A Multiprotocol Wireless Sensor Network for High Performance Sport Applications

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Abstract: The use of a network of wearable sensors placed on the athlete or installed into sport equipment is able to offer, in a real sport environment rather than in the unspecific spaces of a laboratory, a valuable real-time feedback to the coach during practice. This is made possible today by the coordinate use of a wide range of kinematic, dynamic, and physiological sensors. Using sensors makes training more effective, improves performance assessment, and can help in preventing injuries. In this paper, a new wireless sensor network (WSN) system for elite sport applications is presented. The network is made up of a master node and up to eight peripheral nodes (slave nodes), each one containing one or more sensors. The number of nodes can be increased with second level slave nodes; the nature of sensors varies depending on the application. Communication between nodes is made via a high performance 2.4 GHz transceiver; the network has a real-life range in excess of 100 m. The system can therefore be used in applications where the distance between nodes is long, for instance, in such sports as kayaking, sailing, and rowing. Communication with user and data download are made via a Wi-Fi link. The user communication interface is a webpage and is therefore completely platform (computer, tablet, smartphone) and operating system (Windows, iOS, Android, etc.) independent. A subset of acquired data can be visualized in real time on multiple terminals, for instance, by athlete and coach. Data from kayaking, karting, and swimming applications are presented.

Keywords: inertial sensors; array sensor systems; wireless systems; sport performance assessment

1. Introduction

High performance sport, i.e., sport at the highest level of competition, requires advanced technology, as each competitor tries to gain the winning edge through incremental improvement. Data acquisition plays a fundamental role in this competitive environment, as it supplies athletes and coaches with quantitative insights into every aspect of performance [1–3].

Sensors used in sport data acquisition range from kinematic (GPS units, accelerometers, gyroscopes, velocity meters, etc.) to dynamic (load cells, strain gages, brakes, etc.) and physiological (heart rate monitors, thermometers, etc.) [4–10]. Several types of sensors are often bundled together: A typical example is the cycling computer that acquires data coming from the global positioning system (GPS), heart rate monitor, power meter, gears, and more [11].

Systems used in sports normally feature a central unit (master node), where the microcontroller (MCU—microcontroller unit) is located, and a series of sensors (slave nodes) [12]. The communication between master and slave nodes can occur via cables (wired sensor network) or be wireless (wireless sensor network, WSN). WSNs are particularly suitable in sport applications, as cables can hinder the motion of the athlete(s) during training and competitions [13].

Nowadays, several wireless protocols are available on the market; Table 1 illustrates the main features of each of them. These vary in topology, application throughput, complexity of the software interface, ease of configuration, addition of extra sensor nodes, transmission range, and power consumption [14–22]. Concerning the maximum data rate and transmission range, these values must be understood as maximum theoretical values that can be obtained only in an outdoor space free of obstacles and radio interference.

Table 1. Comparison of different wireless communication protocol.

Standard		Max TX Range[1]	Max Data Rate	Application Throughput	Band	Application	Topology
ZigBee	IEEE 802.15.4	100 m	500 kbps	35.0 kbps	2.4 GHz	Wireless Sensors	Star, Mesh
Z-Wave	Proprietary	100 m	100 kbps	6 kbps	900 MHz 2.4 GHz	Wireless Sensors	Mesh
ANT+	Proprietary	30 m	60 kbps	260kbps	2.4 GHz	Wireless Sensors	Star, Tree, P2P, Mesh
Bluetooth	IEEE 802.15.1	10 m	1–3 Mbps	2.1Mbps	2.4 GHz	Wireless Sensors	P2P, Star
Bluetooth 4.0 LE	IEEE 802.15.1	100 m	2 Mbps	305 kbps	2.4 GHz	Wireless Sensors	P2P, Mesh, Star, Broadcast
Bluetooth 5.0 LE	IEEE 802.15.1	400 m	2 Mbps	1360 kbps	2.4 GHz	Wireless Sensors	P2P, Mesh, Star, Broadcast
Wi-Fi	IEEE 802.11a WLAN	5 km	54 Mbps	20 Mbps	5 GHz	PC based data acquisition	Star, Tree, P2P
Wi-Fi 4	IEEE 802.11n	250 m	600 Mbps	72 Mbps	2.4 GHz	PC based data acquisition	Star, Tree, P2P
WiMAX	IEEE 802.16 WWAN	15 km	75 Mbps	4–8 Mbps	2.3-5.8 GHz	MobileInternet	Star, Tree, P2P

[1] (open-air outdoor).

For a long time, in the sport device industry, proprietary and incompatible WSN standards only have been used. Indeed, only in early 2000 was a wireless common communication standard suited for sport and health applications defined and agreed among different main vendors (advanced and adaptive network technology—ANT+ [22,23]). The main features were a very low energy consumption, a high number of connectable nodes, and high robustness to interference. Nowadays, the growing popularity of consumer portable devices, such as tablets and smartphones featuring embedded Bluetooth [23], and more recently, Bluetooth low energy (BLE) [24], has led to a large diffusion of "apps" suited for connection with sport systems. For example, when Apple Inc. supplied BLE in its devices, several fitness products were developed with a MAC iOS software to be compatible with these terminals [25]. Thus, today, the development of a new WSN cannot ignore the use of such personal mobile terminals and should leverage the transmission protocols available on them (typically Wi-Fi and Bluetooth). The use of ANT+ on a mobile phone, for example, would require the use of additional hardware.

Moreover, today, with 75%, the Android operating system (OS) holds the biggest market share for tablets and smartphones, while Windows and MAC iOS are still dominant in laptop and desktop computers [26]. This requires the development of different software tools depending on the nature of the terminal and the relevant OS.

Therefore, from a communication protocol point of view, the constraints in building up an effective WSN suited for sport applications can be identified in the use of personal portable terminals, wide transmission range among the nodes, low power consumption, and easy addition of extra sensor nodes. The transmission range is a particularly severe constraint, as most existing systems for sports are designed for personal area networks (PANs) [27,28] or body sensor networks (BSNs) [29], which cover a very short distance.

In this paper, we present a WSN for sport applications based on a multiprotocol architecture: The communication with the user is based on a Wi-Fi link, while data transmission between the nodes is made via high performance 2.4 GHz modules. Furthermore, the user interface will be implemented on a simple webpage, readable by a web browser on any kind of OS and terminal. The architecture is composed of a main node where, for example, the sensors that have to measure parameters related to the overall performance (i.e., the speed or the acceleration of a boat) are mounted: Inertial measurement unit (IMU), GPS, etc. The slave nodes can be adapted to host different kinds of sensors, for instance, a thermometer, a potentiometer or an encoder. Both the master and slave nodes can be configured to host different kinds of sensors. This means that the whole system can be customized with minimal hardware and software modifications, greatly reducing the development time and cost.

2. Materials and Methods

Some WSNs for particular sporting applications require, for example, a large number of sensors placed in a specific position and often located at a great distance from each other. In these cases, the design of a WSN must consider the attenuation of the transmitted signal; this is caused not just by the distance between the nodes themselves but also by the presence of obstacles between them as, among others, the bodies of athletes and the sport equipment. In fact, even the structure and the materials used for their manufacture can represent a shield for radio transmission (for example, both the hull and the shaft of a kayak paddle are made of carbon fiber). Ditto, the presence in the nearby area of other radio devices that work in the same frequency band of smartphones, Wi-Fi or Bluetooth networks, etc. They introduce electromagnetic noise and, consequently, a significant reduction in the real range of transmission of the nodes.

For example, a WSN suitable for yacht racing could be composed of nodes mounted in very distant places [30]. Furthermore, the transmission system of the WSN could interfere with other on-board radio systems. Therefore, the only solution could be to install more nodes at a smaller distance between them: Some of them could, in fact, not collect data from sensors at all and work as simple repeaters of the signal coming from other nodes.

The architecture of the proposed WSN is depicted in Figure 1. The Master Node can be connected with the User Terminal (i.e., tablet, smarphone, PC, etc.) by a Wi-Fi link over a dedicated WLAN and a webpage for realtime feedback of training or download of the whole session data. The master node can communicate with up to eight first level peripheral nodes via 2.4 GHz transceiver ISM band modules (based on the Nordic Semiconductor chip nRF24L01+) which guarantee a real life range in excess of 100 m and an acceptable power consumption. Furthermore, each of the eight first level peripheral nodes can connect to up to eight second level nodes if an increase of sensor nodes or a wider range is required.

The system was originally designed for application in elite flatwater kayaking [31]. For this reason, it will be called e-kayak in the following. The main technical specifications of this project are as follows:

- Measurement of boat displacement and velocity by means of high frequency GPS (sampling frequency $\geq$ 10 Hz);
- Measurement of triaxial acceleration and triaxial angular velocity (sampling frequency $\geq$ 50 Hz);
- Measurement of force on the paddle and footrest of each athlete (sampling frequency $\geq$ 50 Hz);
- Real-time visualization of speed and stroke frequency on athlete and coach terminals;
- Wireless data download and system diagnostics from any platform and OS (Windows, MAC iOS, Android);
- Battery time for all the master and slave nodes $\geq$2 h to acquire a whole training session without the need to recharge.

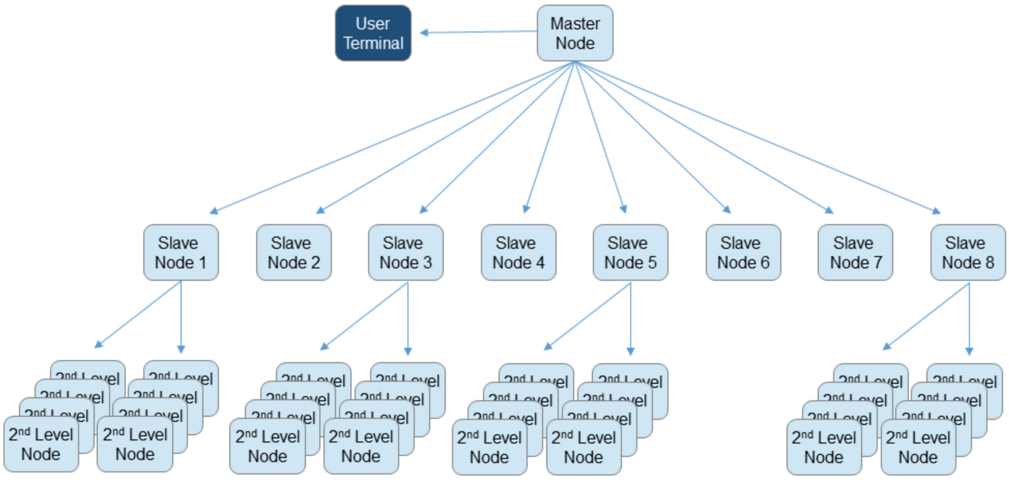


Figure 1. Wireless sensor network (WSN) architecture.

2.1. Choice of Radio Transmission Device

For a proper assessment of the performance of a flatwater kayak team, information on both dynamic and kinematic quantities is required. The former ones represent the measure of the forces applied by the athletes while the latter are the result of the action of such forces on the motion of the boat. Each paddle and footrest, which represent the slave nodes for the WSN, has therefore been equipped with strain gauges to measure the intensity and the coordination among these forces. By contrast, the velocity and the triaxial accelerations are measured, respectively, by a high frequency GPS and an IMU placed on the master node. As a result, each boat will be equipped with a master node and two slave nodes for each paddler.

The range constraints in this application are particularly demanding: A racing kayak can have up to four paddlers (K4), each having a paddle and a footrest. Each paddle and footrest, equipped with a force sensor, is a slave node.

Unlike in rowing, the paddle is not attached to the boat, so a wireless connection is required to avoid hindering the motion of the athlete. A typical K4 boat is about 11 m long, so even placing the master node in the middle of the hull, the distance between it and the farthest slave node can be up to 4–5 m, in a very noisy environment with bulky obstacles, namely the bodies of the athletes (Figure 2).

Figure 2. A K4 racing kayak.

This is outside the typical range of both Bluetooth and ANT+, the most widely used protocols for sport applications (see Table 1). A comparative test of the range of some commercially available wireless modules has shown that the one with longer range is the nRF24L01P+PA+LNA, (by Chengdu Ebyte Electronic Technology Co., Ltd., Chengdu, China) (Figure 3).

The module is a low power single chip transceiver for the global, license-free 2.4 GHz ISM band with high-speed communications (up to 2 Mbit/s). It consists of a fully integrated frequency synthesizer (Gaussian frequency shift keying—GFSK modulation), a power amplifier, andd a modulator–demodulator block, and it is based on the Enhanced ShockBurst protocol engine [32]. This makes it ideal for building wireless networks in a wide range of applications. Equipped with an external antenna, this module can cover a distance, measured in an open field, in excess of 100 m, with data loss <1% on a data rate of 1 kBps (declared range of the module is in fact 2500 m). Its power consumption of 100 mW, while higher than other modules, is still compatible with the two hours of battery time required by the project specifications.

Figure 3. The nRF24L01P+PA+LNA module.

All system parameters (e.g., output power, frequency channels, protocol setup, and air data rate) are programmable through the serial peripheral interface (SPI) serial link. The data rate of 250 kbps, 1 Mbps, or 2 Mbps is configurable on air. The same modules can be mounted on master and slave nodes; the network can be composed up to eight peripheral nodes. At power on, all slave nodes transmit and receive over a "handshake" frequency, while the master node scans continuously for new slave nodes on that frequency; once the slave has been detected, its frequency is switched to the "running" frequency by the master node. Using multiple "running" frequencies, it is possible to operate different systems without interference.

2.2. Choice of User Communication Protocol

The project specifications require communication between user and system and data download to be carried out from any kind of platform (smartphone, tablet, laptop PC) with any kind of OS (Windows, MAC, Android). While nRF24L01+ is arguably the best choice for data transmission between master and slave nodes, it is not featured in smartphones or laptop computers, so adopting it for user interaction would mean having to design a plug-in module and a different app for every OS. Wi-Fi modules, on the other hand, are installed by default on virtually every mobile device. Furthermore, a Wi-Fi interface can be designed as a webpage. This means it is readable with any device and OS, as long as a web browser is present. No other app needs to be installed. Finally, data download via Wi-Fi prevents all problems related to connection via cable (USB or similar) in the wet, windy, or snowy environments which are typical of outdoor sports.

The firmware installed on the master node microcontroller and Wi-Fi module generates a purpose-made WLAN. Several users can connect to the WLAN and load the communication webpage (Figure 4). This includes, on the left side of the page, commands for acquisition start–stop, data download, system status (battery level, memory status, number of connected nodes) and, on the right side of the page, a subset of parameters, for instance, speed and stroke frequency, which are refreshed at 5 Hz and shown on a graph.

Figure 4. The webpage acts a communication interface.

Thus, in a typical situation, the athlete can have immediate feedback on his training on his smartphone placed in the cockpit of the canoe, while the coach, who usually follows the kayak on a motor boat during training sessions, can manage the acquisition and download data on a PC. Several e-kayak systems can operate at the same time without interference. Each one creates its own WLAN, identified by a serial number and, if necessary, password protected. A single coach can therefore supervise multiple boats. Data download speed is about 300 kBps (i.e., data from a typical 90 min training session for a K1 boat can be downloaded in less than a minute). Moreover, data download is also possible, if it is required, using a USB cable (up to 6 Mbit/s).

2.3. Design of the Master Node

The master node is composed of an MCU, a GPS module, a 9-axis inertial measurement unit (IMU), an nRF24L01P+PA+LNA module, and a Wi-Fi module (Figure 5a).

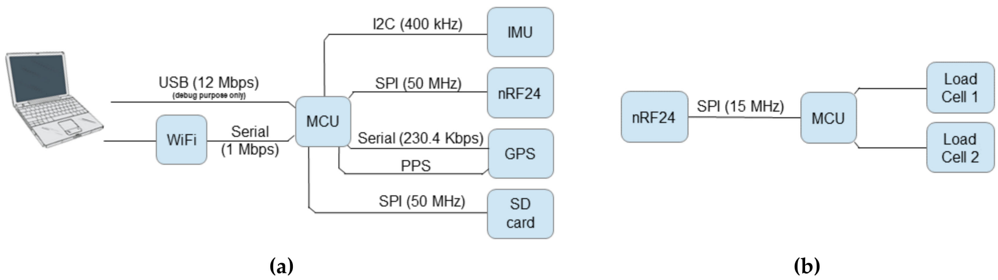


Figure 5. Block scheme of the master node (**a**) and slave node (**b**). IMU = Inertial measurement unit, MCU = Microcontroller unit, GPS = Global positioning system, SPI = Serial peripheral interface, PPS = Pulse per second.

The GPS module has a sampling rate of 20 Hz. Since the maximum stroke rate of an athlete during a sprint is about 180 strokes per minute (i.e., 3 Hz), the module can measure speed fluctuations at each stroke (intracyclic speed). The module communicates with the MCU via a serial port at a speed of 230.4 Kbps. The IMU has a sampling frequency of 50 Hz and is connected to the MCU by an I2C (inter-integrated circuit) serial bus link (up to 400 kHz).

The management of the e-kayak WSN is computationally rather demanding. The MCU is tasked with acquiring data from GPS and IMU, communicating with the slave nodes via nRF24L01+ modules and with the user via Wi-Fi, calculating real-time parameters and storing the data in a micro SD memory card. For this reason, the chosen MCU is Pjrc's Teensy 3.6. It is arguably the most powerful Arduino clone available on the market, featuring a 32-bit 180 MHz ARM Cortex-M4 processor with a floating point unit. It also features an on-board micro secure digital (SD) slot and several serial ports for communication with peripherals. Since GPS data, IMU data, and sensors data have different sampling frequencies and time scales, they are synchronized using the GPS receiver PPS (pulse per second) signal.

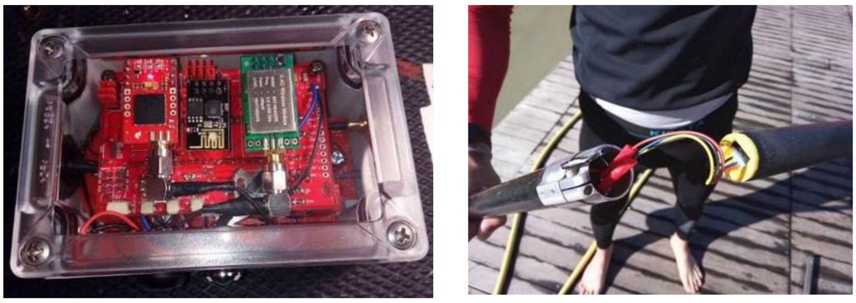
A custom-made board has been designed (Figure 6a) to accommodate all the main components, as well as a charge circuit and all the necessary interfaces with the commands (switch, button, leads, etc.). The node is placed in a waterproof case for on-board use.

The master node is powered by a 3.7 V, 1200 mAh LiPo battery. It can also be connected to a PC via USB cable for system diagnostics.

2.4. Design of the Slave Nodes

The main components of a slave node (Figure 5b) are the MCU, the nRF24L01P+PA+LNA module, and the signal conditioning circuits for the force sensors (two channels are available): A load cell or a strain gage bridge placed on the paddle shaft or on the footrest (two sensors in the latter case). Since the computational burden of the master node is much lighter, a smaller MCU, namely an Arduino Nano (based on the 16 MHz ATmega328 processor), has been adopted. The slave node is powered by a 3.7 V, 500 mAh LiPo battery and it is equipped with a battery charge circuit.

In particular, for the e-kayak system, two custom-made boards have been designed, for the paddle nodes and for the footrest nodes, respectively. They only differ in their form factors, the one for the paddle being long and thin enough to be placed inside the shaft (Figure 6b).



(a) **(b)**

Figure 6. (**a**) Master node in a waterproof case; (**b**) slave node placed in the paddle shaft.

3. Results

The proposed WSN system presents two main features that make it more widely exploitable in several sport applications with respect to other commercially available systems:

- High flexibility in number and type of employable sensors;
- Possibility to cover a wide sensor area by using second level Slave nodes;
- OS independent user interface represented by a simple web browser.

The acquired data can be visualized and analyzed on purpose-made apps that are specific to each sport application. In this section, we present applications of the proposed system in different configurations showing acquired data and a brief description of the specific app for the data analysis.

Figure 7 depicts the app developed for the e-kayak system equipped with a master node that hosts GPS and IMU and two slave nodes with force sensors on footrest and paddle, respectively. The screen shows all data acquired during a K1 training session: At the top left graph, the data of roll speed (red), yaw speed (yellow), and pitch speed (green, hidden) are shown. The bottom left graph shows the forces on paddle (red) and foot rest (green), while the graphs on the right side of the page depict (from top to bottom) the acceleration on the three axis, the boat's speed, and the traveled distance. All these measurements were taken in synchronous mode, so an increase in the stroke rate and force (e.g., at about 220 s) corresponds to an increase of the roll speed as well as the boat's acceleration and speed.

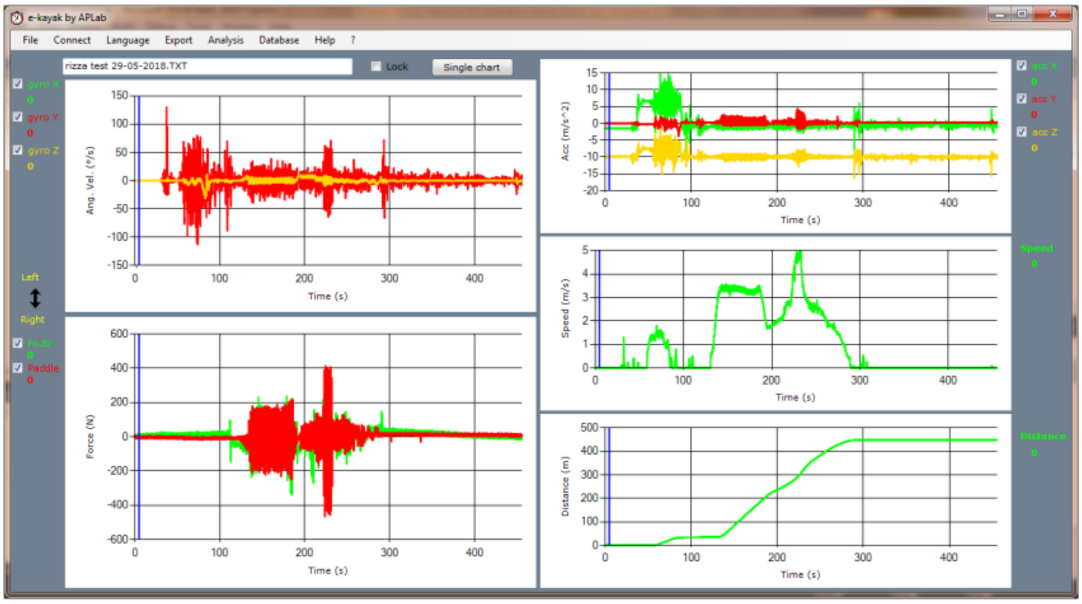


Figure 7. Example of screenshot of the application for e-kayak session analysis.

Figure 8 shows data from a measure of a session of K2 training for which the system was equipped with four slave nodes: Two for the paddles and two for the footrests. In particular, it depicts a detail of an acquisition of the forces applied by the two athletes on their paddles. One can note a rather good synchronization between the athletes and a good symmetry, for both of them, of the force applied on the left paddle (positive side of the waveform) with respect to the right one (negative side of the waveform). On the other hand, there is a remarkable difference in the force applied by the two kayakers.

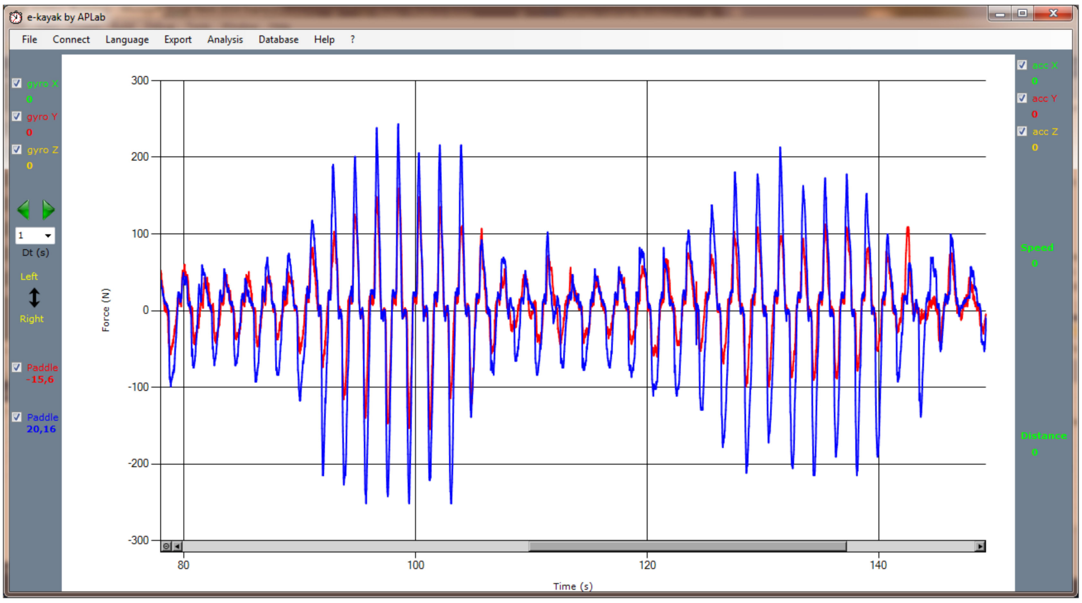
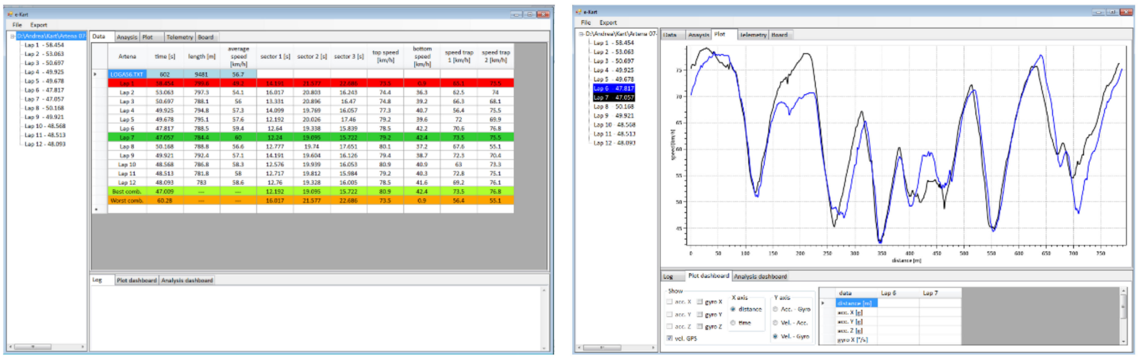


Figure 8. Force on the paddles measured on K2.

Figures 9 and 10 show some screenshots of preliminary measurements of a session of karting race. In this case, the system was equipped only with the master node to acquire data from GPS and triaxial accelerometer and gyroscope. In particular, Figure 9a shows the screenshot of the analysis app where the measures of the time lap, speed in the selected sectors, lap distance, and the average, top, and bottom speed are reported for each lap. Figure 9b shows the curves of the kart's speed, for each lap in a different color, with respect to the position on the track. Finally, Figure 10 shows a screenshot from the same app where the user can, graphically on the map, select the positions of the markers to identify the different sectors on the track. Moreover, the user can analyze the different trajectories together with the speed (the curve at the bottom of the screen) for each lap.



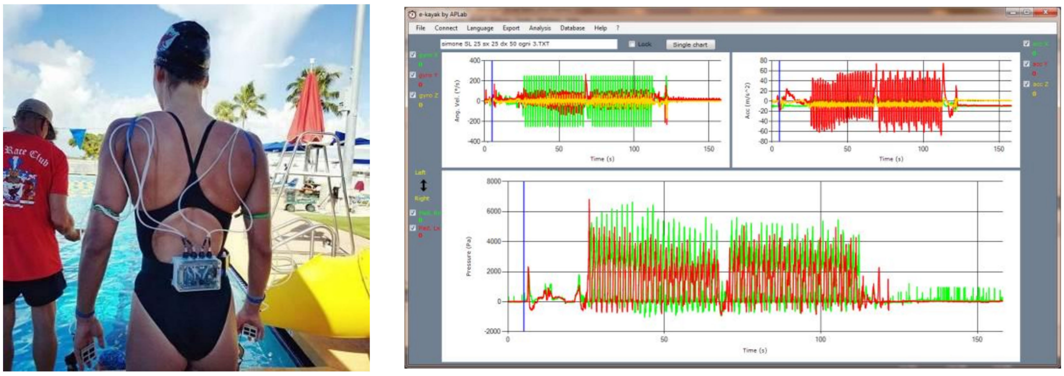
(a) **(b)**

Figure 9. Examples of screenshot of the application for karting session analysis. (**a**) Analysis app; (**b**) kart's speed.

Figure 10. Screenshot of the application for karting session analysis.

Figure 11 shows an application of the system for measures of swimming training. In this case, the system was equipped with a master node only. This has been equipped with two differential pressure measurement devices (measuring the difference in pressure between hands' palm and back) for the evaluation of the forces applied by the swimmer with her arms.

The system is placed on the back of the swimmer, as shown in Figure 11a. Thanks to the triaxial accelerometer–gyroscope unit, it is possible to assess the effectiveness of each stroke (see Figure 11b) [33].



(a) **(b)**

Figure 11. (**a**) System equipped for swimming; (**b**) screenshot of the app analysis.

4. Conclusions

A modular architecture for a WSN designed for sport applications has been introduced, which has better characteristics in terms of range, number of nodes, and interoperability with respect to existing systems. While originally designed for racing kayaks, the system can easily be adapted to rowing, sailing, swimming, and kart racing.

The use of different protocols for communication between nodes and user interaction optimizes the performance of the system without complicating user experience. On the contrary, the user can manage acquisition and data download from any kind of portable device with a web browser. Future improvements of the system will see the integration of heart rate monitors and differential high frequency (50 Hz) GPS with real-time Kinematic and post processing corrections.

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