Embedded Sensors System Applied to Wearable Motion Analysis in Sports

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Abstract: This paper presents two different wearable motion capture systems for motion analysis in sports, based on inertial measurement units (IMU). One system, called centralized processing, is based on FPGA + microcontroller architecture while the other, called distributed processing, is based on multiple microcontrollers + wireless communication architecture. These architectures are designed to target multi-sports capabilities, beginning with tri-athlete equipment and thus have to be non-invasive and integrated in sportswear, be waterproofed and autonomous in energy. To characterize them, the systems are compared to lab quality references.

1 INTRODUCTION

Electronics in sports monitoring has been a growing field of studies for the last decade. From the heart rate monitors to the power meters, sportsmen are using them every day to monitor their trainings (Bouillod et al., 2014).). However those data are not enough to help the sportsmen to improve their performances, they only measure overall output parameters that are the consequence of the effort, and thus, lack on the important mechanical elements: including the pose and gesture, which are crucial basic parameters (Oggiano et al., 2008).

In the meantime, motion capture systems have been developed, based on vision (Vicon, Dartfish,…) or inertial measurement units (IMU) (Xsens, Inertia,…) (Brigante et al., 2011) (Marin-Perianu et al., January 2013) and massively used in robotics, movies and games industries. However, these systems require a heavy calibration process and need controlled environment (ambient light, restricted zone, no obstacles…) and/or massive equipment, and thus are unusable for on-field measurements. Our approach is to integrate common IMU, which are nowadays large scale produced micro-electro-mechanical systems integrated in everyday electronics (smartphones, game controllers...), in an autonomous embedded system to monitor the sportive activity, even in field conditions.

Our IMU based monitoring system allows embedded data logging for post-processing motion analysis, which is not possible with commercially available solutions, where the wireless connection can be lost due to the limited range (allowing only short loop training monitoring) or attenuation (due to the water in swimming conditions).

On-the-field high level sportsmen monitoring implies the system to be wearable and non-invasive to limit the loss of performances. It has moreover to be waterproof due to sweat during the effort, and, of course, for swimmers monitoring.

Our wearable system allows embedding relatively low complexity algorithm in order to add postural and specific motion patterns real-time feedback to already existing indicators (hear-rate, powermeter...).

In this paper, we will expose the currently available systems in sports and motion capture. Then we will discuss about our approach on the embedded motion analysis development. In a third part, we will present the selected applications field, the experiments we have been working on, and the results we have obtained. Finally, we will develop some of our project perspectives.

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2 AVAILABLE SYSTEMS

Sports equipment manufacturers offer a large panel of dedicated sensing devices to monitor parameters (Heart rate, oxygen consumption, mechanical power, etc) during an activity. Some of them are easy to use outdoor, we will call them embeddable equipment; some others are more dedicated to lab tests.

2.1 Embeddable Sports Equipment

Referring to the majority of large scale distribution sports equipment, such as HRM, speed and distance measurement (on bikes, or via GPS for runners), stepping cadence measurement, brain activity (Comani et al., 2013)…

The main characteristics of these devices are:

- They provide low frequency information (0.5 to 3Hz),
- Data are pre-processed to be easily understood by the user, even with low specific skills (a bike computer displays the distance and speed although it measures the wheel rotation count and frequency),
- They don't need external power supply, they work on batteries.

One of the data that is currently not monitored in embeddable equipment is the sportsman posture.

2.2 Lab Sports Equipment

Lab equipment in sports is generally more complex equipment which is used to precisely monitor and optimize sportsmen or hardware (bike, helmet, saddle position…) at one point. In this category, we include ergometers like BikeFitting (Shimano) or Cyclus 2 (RBM elektronik-automation), and wind turbines for aerodynamic tests.

The main differences with embeddable equipment are (one or more):

- They are larger/heavier,
- They use much more energy to run,
- They provide high frequency data and/or raw measurement data.

Some of these instruments are focused on the user posture, in order to improve his global efficiency and performance.

However, this is just a single-shot operation, which could be improved by "on-field" real-time feedback.

2.3 Motion Capture Equipment

This third sort of equipment is currently rarely used for sports applications, except for some researches in biomechanics. It consists of objects motion measurement in a calibrated area; the main application of this technology is for animation. The two main kinds of system we can find to measure a human skeleton posture are:

- Computer vision base systems use reflective tags, positioned over the subject body, and a network of infrared cameras. The tags positions in a calibrated volume are calculated by a central processing unit, and post-processing is needed to retrieve the body segment orientations,
- IMU-base systems use attitude sensors attached to the user's body, on each monitored segments. The global posture of the body is then computed by fixing the segments dimensions and joints on the skeleton. We can find wired and wireless versions of this system.

However it always needs a computer to process the data in a close range around the experiment.

Regarding these information, none of these system are embeddable for real-time sportsman feedback in real-life conditions.

3 OUR APPROACH

The growing interest in sports performances and the lack of embedded posture analysis and feed-back, coupled with our knowledge in embedded systems led us to develop wearable motion analysis systems. We based our development on IMUbased motion capture systems, using commercially available digital 9-axis (3-axis accelerometer, 3-axis gyroscope and 3- axis magnetometer) IMU sensors chips (like the ones used in smart-phones or game controllers to determine the device orientation), which we coupled with our reconfigurable multi-sensors embedded architecture.

As the IMU-based motion analysis of a skeleton needs to measure the orientation of each bones, or segment, we needed to collect and process the data from multiple IMU sensors dispatched over the sportsman body. To do so, we explored two kinds of processing architectures, which we are going to describe.

3.1 Centralized Processing

Our first approach was to position micro sensors tags over the body, all wired to a central processing unit (called "Reconfigurable Multi-sensors Embedded Architecture", AREM in French) composed of a Field Programmable Gate Array (FPGA), which is essentially a programmable logic circuit, to handle the sensors interconnections, and a microcontroller, to handle the data-processing (Figure 1).

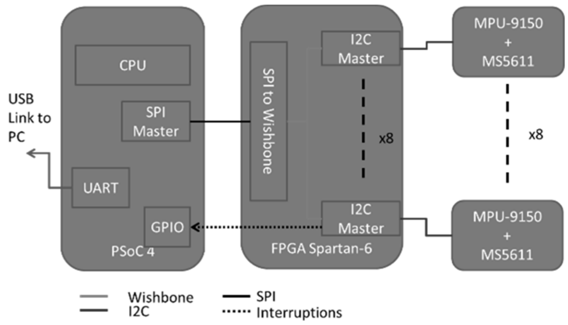


Figure 1: Centralized embedded motion system synopsys.

3.1.1 First Design

On the first version of AREM architecture, we used common IMU sensors using Inter-Integrated Circuit (I2C) communication standard, MPU9150 from Invensense as sensor tags. Each one of these sensors was connected to the FPGA via wires (Figure 2 middle). The FPGA was programmed to handle one I2C bus master per tag, which allows to synchronously, and simultaneously poll each sensor. Finally, a microcontroller was connected to the FPGA as a master to control the process, get the sensors data, process them, and send the results back to a computer via USB cable.

This architecture was not properly an embedded system as it wasn't working on batteries, nor communicating wirelessly.

However, it was a first prototyping step to integrate multiple motion measurement sensors in one system.

3.1.2 Integrating the Design

In order to fulfil the wearable constraints, the design had to be improved in several ways:

- The sensors had to be smaller and integrated into a textile,
- The central processing unit had to be smaller, to communicate wirelessly with an external device (eg. computer, smartphone…) and to work on batteries.

The first step was to reduce the size of the sensors tags. In order to improve the measurement and reduce the chip size, we change the sensor tag to the MPU-9250, which package is smaller, handles faster acquisition and is able to communicate via Serial Peripheral Interface (SPI) bus. We designed smaller support Printed Circuit Boards (PCB), and replaced the standard cable wiring with ultra-thin wires (Figure 2right, Figure 3a).

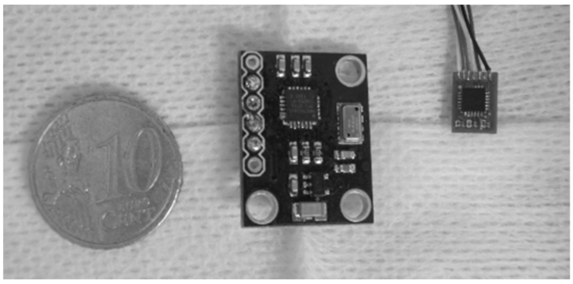


Figure 2: AREM v0 sensor tag (middle), AREM v1 sensor tag (right).

Then, we have tried different methods to integrate the sensors into textiles. The first one was to sew wire guides to the t-shirt, then maintaining the tags with a piece of Velcro (Figure 3b). In a second time, we integrated the whole sensor + wire into the t-shirt using silicon coated heat transfer film (Figure 3c).

About the processing unit, we have switched from a microcontroller + FPGA solution to an all-embedded solution based on the Xilinx Zynq programmable system on-chip (PSoC) which offers a better communication between the two parts, processing power (with an ARM Cortex A9 dual-core processor) and an improved energy efficiency.

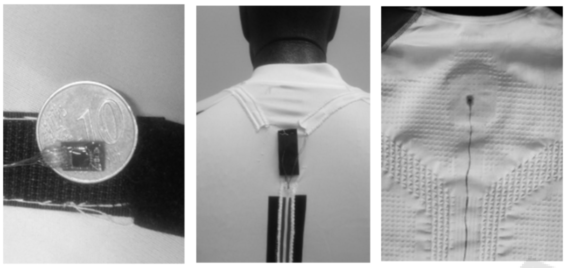
3.2 Distributed Processing

Our second though was to work on a distributed sensors network: each sensor is equipped with a battery, a microcontroller and a wireless communication module. This design targets a lower local computational power as each tag only has to process its data and send the results to the network. Consequently, the processor frequency could be lower, and each tags power consumption, which enables to use smaller batteries. With this architecture, we place one unit per sensed bone, and an access point to collect all the data.

We built our system around another IMU, the ST iNemo-M1, which is composed of a 6-axis IMU (Accelerometer + Magnetometer), a 3-axis gyroscope and an ARM STM32 microcontroller which is used to handle all the computation and to handle the whole tag (with communication and battery management).

To transmit the processed data wirelessly, we chose to use ESP8266 WiFi modules, working in station mode, and connecting to a standard WiFi Access-Point. The system is equipped with a USB connector to charge the battery and communicate with a computer (during debug, or to transfer data), a Serial-ATA connector connected to a SPI bus, to enable extension capabilities, and a programming connector for the STM32 microcontroller.

The designed PCB (Figure 4) is 31 x 44mm, and the circuit is 13mm high, including the battery and connectors, for a 15g weight with a 300mAh battery. In normal operation mode, the battery lasts 2h30.



(a) (b) (c)

Figure 3: (a) New MPU9250 tags with thin wires, (b)(c) Sensors tags integrated into a t-shirt.

3.3 Architectures Comparison

These two architectures have advantages and drawback which make them more or less suitable depending on the application. In Table 1, we compared the most noticeable parameters.

To summarize, for small skeleton cases (1-5 bones), the distributed computing is more interesting in consumption and cost. For bigger systems, the centralized processing is more efficient, though more complex to develop.

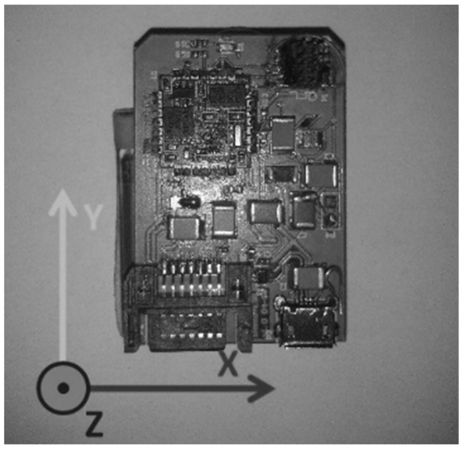


Figure 4: AREM Gateway tag.

The main limitation for distributed processing in large systems (more than 15 bones) could be the wireless data throughput.

4 APPLICATIONS

We wanted this architecture to be versatile and adapted to as many sports as possible. To begin, we chose to design it to work on a triathlete, so to be able to capture data for swimming, cycling and running. The first two parts mostly consist on monitoring the trunk and legs position during the activity, and to work in standard conditions. The last one was more challenging because it has to be waterproof and to monitor the trunk and arms of the athlete, without being intrusive or modifying the movement.

Table 1: AREM Architectures comparison.

Parameters	Centralized processing	Distributed processing
Batteries	Only 1 battery to handle	Multiple batteries in a standard application
Power consumption	One large power consumption for the central processing unit and low power consumption for the tags, low dependence over tags count	Each tag has a bigger consumption tough lower than the central processing unit. System consumption is lower from 1 to 3 tags
Sensors interconnection	Wires have to be integrated into the textile, the positioning is hard to modify	Communication is wireless, the sensors can be put anywhere
Sensors integration into the textile	Tags are very small and easy to integrate without notice for the sportsman	Tags are heavier and larger, which makes the positioning more uncomfortable
Hardware complexity	The tags are simple, only chips, but the central processing unit is a complex mixed hardware/software design	The complexity is dispatched over the whole system, making the design easier
Cost	Low cost sensors and high cost central processing unit. The system growth cost is less important	High cost tags, and no central processing unit, the system cost is linear with the monitored segments count
Robustness	Low sensitivity over radiofrequency conditions	Sensitive to WiFi radiofrequency occupation

5 TESTS AND RESULTS

In order to test and validate our systems, we have been working in collaboration with elite athletes in lab conditions.

5.1 Centralized Processing

5.1.1 Cycling Study

The first test of our architecture was with the centralized processing version (AREM v0). The test was realized on a cyclist riding on a treadmill during a standing position study about efficiency (A. Bouillod et al., 2014). We have positioned 6 sensors on a cyclist (1 at the middle of the spine, 1 at the top of the spine, 1 on each hip, 1 on each clavicle) and 1 sensor under the saddle.

This version of the architecture was a proof of concept and didn't process any data and sent the sensors data back to the PC at a 7Hz rate, and allowed to monitor parameters like the bicycle lateral sways, which increase the mechanical cost.

5.1.2 Hand Movement Analysis

We also have been working with J-D. Lemos on the iGlove project to use our AREM centralized architecture, with MPU9250 tiny tags, to analyse a hand movement for surgery students training (J.D. Lemos et al, 2014).

5.2 Distributed Processing

The first step for the distributed system validation, as it embedded more complex algorithm, able to compute the tag orientation in space, was to characterize its response by comparing with a known laboratory vision based system. Then we tested it on multiple sports activities.

5.2.1 Comparison with Vicon

To validate the AREM Gateway (distributed architecture), we have been comparing a tag orientation with a Vicon capture (12 MX3+ cameras). To do so, we fixed the tag on a cardboard frame basis equipped with 3 Vicon reflective tags (Figure 5a) and rotated it along X, Y and Z axis consecutively. The data processed by the tag (25Hz) and captured by the Vicon (200Hz) were logged to be compared in post-processing. The frame orientation was calculated from the markers positions, and compared to the output data send by the tag (Figure 5b). We see that the general aspect is good: the mean error is 2.5 degrees and the standard deviation is of 6 degrees.

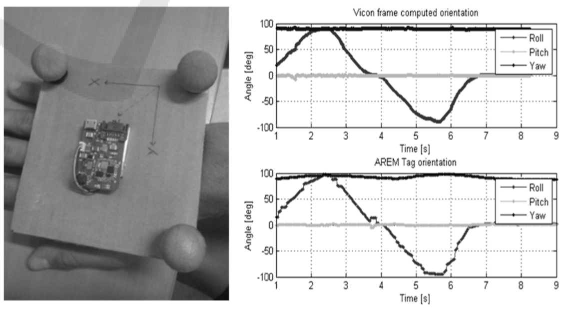
In a second time, we tested the system behaviour on a common crawl swimming movement to ensure the functionality on complex actions.

5.2.2 Tests on Sportsmen

After this first specification, we have tried our system on cyclists, runners and swimmers (using waterproof bandages to protect the circuit). We have noticed that, while suitable for bike and running, the WiFi communication is not usable in water (since any air path between the tag and the access-point is obstructed by about 2cm of water, so the tag is submerged, the sent packets are lost and the communication is no more usable). This leads us to reconsider the wireless communication strategy for the distributed system.

6 PERSPECTIVES

The next step of our project will be to add an embedded memory to log raw and processed data for further analysis (and to allow outdoor tests, or underwater tests, without using access-points or computers) and to re-engineer the wireless communication on the distributed tag to work in water. In a second time, we will be working on the real-time pattern recognition and feedback to the user to enable on-field performances optimization feedback.



(a) (b)

Figure 5: (a) AREM Gateway on a Vicon frame, (b) Roll orientation comparison with Vicon.

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