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| Title | A benchmark comparison between reconfigurable, intelligent and autonomous wireless inertial measurement and photonic technologies in rehabilitation |
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| Publication date | 2011-03-17 |
| Original Citation | Walsh, M. Tyndyk, M. Barton, J. O'Flynn, B. O'Mathuna, C. 2011. A benchmark comparison between reconfigurable, intelligent and autonomous wireless inertial measurement and photonic technologies in rehabilitation. In: 3rd European Conference on Technically Assisted Rehabilitation TAR 2011, March 17 - 18, 2011, Berlin |
| Type of publication | Conference item |
| Rights | https://creativecommons.org/licenses/by/4.0/ |
| Download date | 2026-11-01 14:38:27 |
| Item downloaded from | https://hdl.handle.net/10468/390 |



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# A benchmark comparison between reconfigurable and intelligent wireless inertial measurement and photonic technologies in rehabilitation,

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## Abstract

Advanced sensory systems address a number of major obstacles towards the provision for cost effective and proactive rehabilitation. Many of these systems employ technologies such as high-speed video or motion capture to generate quantitative measurements. However these solutions are accompanied by some major limitations including extensive set-up and calibration, restriction to indoor use, high cost and time consuming data analysis. Additionally many do not quantify improvement in a rigorous manner for example gait analysis for 5 minutes as opposed to 24 hour ambulatory monitoring. This work addresses these limitations using low cost, wearable wireless inertial measurement as a mobile and minimal infrastructure alternative. In cooperation with healthcare professionals the goal is to design and implement a reconfigurable and intelligent movement capture system. A key component of this work is an extensive benchmark comparison with the 'gold standard' VICON motion capture system.

## 1 Introduction

It is now well understood that measuring and tasking real time body motion can enable corrective measures that lead to quantifiable improvements in rehabilitation results. Technology has begun to play an important role in this regard and many mature measurement and tasking solutions are now available. However there still remain a number of technological limitations preventing the widespread adoption of these systems on the healthcare frontline. This trend is prevalent in the clinical setting and also in the ambulatory home environment where it is rapidly becoming a central obstacle to the move toward affordable and proactive healthcare.

As an example gait analysis, which has been highlighted as an extremely useful tool in rehabilitation [1], can be conducted employing a number of technologies each limited by a number of factors. For instance gait has been captured using clinical stride analyzers consisting of force-sensitive insoles placed in the subject's shoes and with data forwarded to some collection device attached to the subject [2]. These insoles are limited in range such that measurements can only be taken over short distances (generally less then 15 m) and the data-collection apparatus (an ankle-worn recorder or backpack) is bulky enough to interfere with patient movement. Pressure-sensitive piezoelectric floor sensors have been suggested as an alternative to insoles [3], however a similar range constraint applies and only flat terrain is considered in the analysis. In addition many aspects of gait, for example kinematics, are not captured by such a system. Ad-hoc gait analysis systems have also been developed for instance one solution functions by means of threads attached to a pulley, which in turn are coupled to an optical length–voltage transducer [4] making the entire system large, complex and difficult to operate.

Optical systems such as high-speed video or motion capture methods are deemed, owing to their accuracy and repeatability, the 'gold standard' [1] for gait analysis. Nevertheless these solutions are accompanied by some limitations including extensive set-up (generally involving multiple cameras), precise and complicated calibration using a network of markers, restriction to clinical lab use, high cost and time consuming data analysis. Further technological advancement is therefore required to complement existing solutions and to extend their range and effectiveness outside of the clinical environment.

With this in mind this work introduces a simple, inexpensive, robust, wearable yet unobtrusive system that is intelligent and is consequently made far more user friendly. The solution can provide a clear clinical cost benefit and is not limited by infrastructure in terms of mobility and range. In addition benchmark experiments highlight how this minimal infrastructure system performs well when compared with state of the art optical systems.

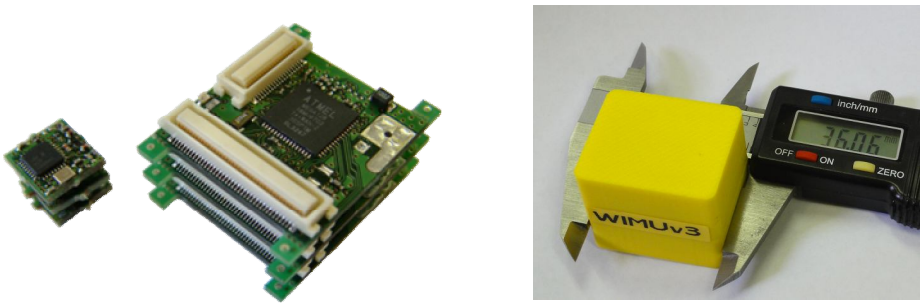
## 2 Method

A holistic and multidisciplinary approach to design is adopted comprising, hardware and embedded software development, sensor characterization and calibration outlined in [5] and front-end user configuration interface design. This is followed by a validation stage consisting of an extensive benchmark comparison between the new technology and the 'gold standard' VICON 3D motion capture system.

### 2.1 The Tyndall Wireless Inertial Measurement Unit

The Tyndall prototyping system [6, 7] has been developed to address a wide array of scenarios in the Wireless Sensor Network application space. A highly modular approach to design has been adopted negating the need to replace the mote infrastructure should a change in wireless technology, sensing capabilities or power supply be required. There are a number of benefits in adopting this modular approach to node design namely the platform is far more interoperable with a wider range of wireless technologies and should there be a need to change technology the background functionality of the network is retained and the need for sensor recalibration is removed. In addition the embedded intelligence within the system can provide the necessary filtering and processing algorithms to enable autonomous operation, adaptive sampling regimes based on sensory input and data filtering using readily available embedded C or TinyOS code libraries. The modular platform has been built in two form factors – the more mature 25mm form factor technology and an associated 10mm form factor implementation as illustrated in Figure 1(a).

The Tyndall Wireless Inertial Measurement Unit (WIMU) shown in Figure 1 (b) has been developed as part of the prototyping system. This add-on comprises a full 6 degree of freedom inertial measurement unit with 3 axis accelerometers, gyroscope and magnetometers in addition to onboard storage and power optimization circuitry. Each sensor is capable of reconfiguration to measure at various ranges depending on the application requirements.



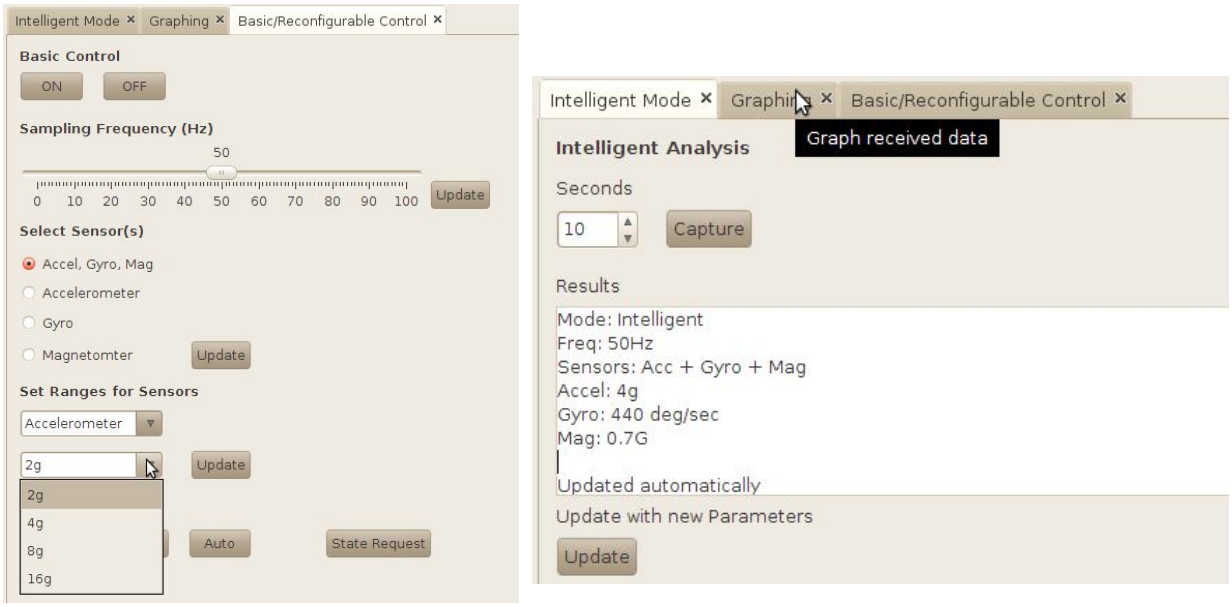

(a) (b)

Figure 1. (a) The Tyndall modular Wireless Sensor Network 10mm and 25mm Platform, (b) The Tyndall Smart Wireless Inertial Measurement Unit

### 2.2 Reconfigurable and Intelligent Wireless Inertial Measurement

Every movement regime can be deemed unique and will likely require a varying number of sensing modalities. At one end of the spectrum a 3D motion capture application will likely utilize accelerometers, gyroscopes and magnetometers to determine position accurately, whereas at the other a simple falls detection algorithm may just require accelerometry. Additionally each sensor should have adequate range to capture the inertial regime entirely and where necessary sufficient granularity to capture subtle movement. This raises the question whether a one size fits all WIMU device is capable of spanning the entire application space. Our solution makes this possible by employing state of the art reconfigurable sensor technology coupled with intelligence embedded in the system through custom recursive algorithms implemented on the device itself.

To access and configure the WIMU device a Java based GUI has been developed and has been designed to operate in two modes selected based on the expertise of the user. Firstly reconfigurable mode as illustrated in Figure 2 (a) enables the user with no prior experience with the WIMU technology but with expertise in the movement regime to configure the device based solely on familiar regime specific inputs e.g. maximum acceleration or angular velocity. Intelligent mode as illustrated in Figure 2 (b) enables the user who is expert in the technology but has no knowledge of the movement regime to ascertain the correct device configuration for a given inertial measurement application. This in turn makes the technology far more user friendly catering for the engineer and biomechanist alike and in real-time.




(a) (b)

Figure 2. The Tyndall Wireless Inertial Measurement Unit (a) Reconfigurable mode, (b) Intelligent mode

## 2.3 WIMU/VICON Benchmark Comparison

A central component of this work comprised a benchmark comparison experiment hosted at the MEDIC Centre. The trial examined the Tyndall WIMU minimal infrastructure technology as a possible complementary drop in mobile solution for the VICON 3D Motion Capture system. The test scenario was as follows: A subject was fully instrumented with both technologies simultaneously. The subject then carried out repetitive movements of the upper and lower limbs providing correlated spatio-temporal data for benchmarking. A user orientated approach to data analysis was then adopted highlighting the positives and negatives for each system from the end user's perspective. In conjunction with accessing the precision accuracy of each technology, aspects such as sampling frequency, cost, size, obtrusiveness when worn, associated infrastructure, set up time needed and calibration capabilities were also considered. The overall performance of the system was subsequently arrived at by combining the systems ability to provide precise information, from which useful clinical outcomes can be extracted, with the ease of configurability and usability of the technology.

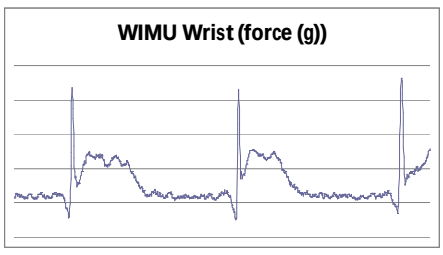
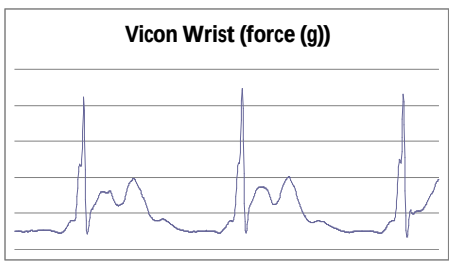
| Attribute/Technology | Tyndall WIMU System | VICON Motion Capture System |
|---|---|---|
| **Infrastructure (Size\Wearability)** | 1 Mobile Access Point and WIMUs (A node measures approx 1 $in^2$ and is attached quickly and easily) | 8 Stationary High Speed Infra Red Cameras, Retro-reflective Markers (Markers require time to affix) |
| **Cost** | <150 Euros per node | > 10,000 Euros |
| **Sampling Frequency** | 200 Hz Wirelessly | 100 - 200 Hz (Typical) |
| **Set-up time** | 4-5 mins | 25-30 mins |
| **Calibration** | Offline a priori | Real-time capable |
| **Precision Accuracy** | VICON System +/- 3.2%   | < 0.1 cm   |
| **Overall Performance** | Usability: Very Good, Precision: Good | Usability: Good, Precision: Very Good |

Table 1. Comparing Tyndall WIMU technology with the VICON 3D Motion Capture system,

## 3 Discussion

Table 1 compares Tyndall WIMU technology with the VICON 3D Motion Capture system. As would be expected the wireless solution is more miniature and mobile in comparison with the optical system however it was noted that both the retro-reflective markers and the WIMUs were equally comfortable to wear. The costs of the systems were significantly different with an entire WIMU system consisting of up to 15 WIMUs an order of magnitude less expensive. The sampling frequency of the wireless solution was shown to be capable of matching the VICON system. Configuration time differed greatly with significant time given to marker placement and system configuration for the optical technology. The WIMU technology on the other hand was simply attached to the subject and following a single regime capture employing the onboard intelligent mode the system was immediately ready to run. This was achieved within 5 minutes. The real-time calibration capabilities of the VICON system proved useful during experimentation as markers were prone to becoming dislodged following rigorous movement. The wireless devices were calibrated offline prior to testing and were subsequently subject to some drift. This drift was compensated for using some of the methodologies described in [5].

When comparing the accuracy of each system the WIMU system performed to within 3.2% of the VICON system which was considered the steady state benchmark for the experiment. The calculation was arrived at by averaging the standard deviation over 1 million samples collected during the experiment. The resultant error was as a result of a number of reasons including the systems inability to remove drift entirely. Additionally the nature of the experiment prevented exact collocation of the markers and the WIMU devices therefore some extrapolation was required and some additional error was introduced as a result. The WIMU was however shown to capture fully the entire movement regime including high and low frequency movement components.

## 4 Conclusion

This work introduced a non-complex, low-cost, miniature wearable inertial measurement system that is intelligent and as a result far more user friendly. The solution has been shown to provide a clear clinical cost benefit by adopting a user centric approach to design. In addition the technology is ambulatory requiring minimal additional infrastructure and because of its modular design approach can incorporate numerous wireless technologies with varied range depending on the application. In addition benchmark comparative experiments have been conducted to highlight the system performance and usability when compared with state of the art 3D motion capture systems. To conclude the wireless inertial solution proposed herein complements the existing ‘gold standard’ optical solution and extends its range and effectiveness outside of the clinical environment.

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