Title: Quality assessment of an UWB positioning system for indoor wheelchair court sports

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Authors: Bertrand Perrat[1], Martin J Smith[1], Barry S Mason[2], James M Rhodes[2], Vicky L Goosey-Tolfrey[2]

[1] The University of Nottingham (UK)
[2] Loughborough University (UK)

Contact Details : Bertrand Perrat

Email: isxbp1@nottingham.ac.uk

Address: Nottingham Geospatial Institute, Nottingham Geospatial Building, The University of Nottingham, Jubilee Campus, Triumph Road, Nottingham, NG7 2TU

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Abstract

Ultra-Wide Band radio positioning systems are maturing very quickly and now represent a good candidate for indoor positioning. The aim of this study was to undertake a quality assessment on the use of a commercial Ultra-Wide Band positioning system for the tracking of athletes during indoor wheelchair court sports. Several aspects have been investigated including system setup, calibration, sensor positioning, determination of sport performance indicators and quality assessment of the output. With a simple setup procedure, it has been demonstrated that athletes tracking can be achieved with an average horizontal positioning error of 0.37 m (σ = ± 0.24 m). Distance covered can be computed after data processing with an error below 0.5% of the course length. It has also been demonstrated that the tag update rate and the number of wheelchairs on the court does not affect significantly the positioning quality; however, for highly dynamic movement tracking, higher rates are recommended for a finer dynamic recording.

Keywords: Player tracking, Ultra Wide Band, Training, Coaching, Error analysis

1. Introduction

There is an interest in the use of technology to enhance the performance of athletes in wheelchair sports whether this is for improving equipment within sports or monitoring athlete's performance. However, monitoring athletes during competition can be problematic. There are many challenges both in the collection and analysis of the data collected to fully understand where athletes can improve their performance. To add to the complexity of measuring athletes movements, team sports involve many players competing at one time on a pitch indoors or outdoors.

There are an increasing number of methods for tracking moving objects. Outdoors, Global Navigation Satellite System (GNSS) technology, normally the Global Positioning System (GPS), is often the simplest method to adopt [1] but indoors the situation becomes more complex as visibility of satellites for a GPS solution is not feasible or practical. There are however a number of systems available for indoor tracking [2]. These systems usually rely on different radio technologies such as WiFi [3–5], RFID [4,5] or Ultra-Wide Band [5–7]. There are also a number of image based systems relying on infra-red [8] or traditional images [9]. This study focuses on the use of an Ultra-Wide Band (UWB) radio positioning system [10] which has been developed for the manufacturing, warehouse, and other industrial purposes. UWB systems are based on the use of fixed sensors around the region of movement where these sensors track the positions of tags which are fixed to the target object.

For every tracking application there is a requirement for a certain level of accuracy to ensure the location data collected is fit for purpose. As UWB radio positioning has not been designed for monitoring athletes, there is an even greater need to assess the capability of this technology to ensure the data collected and the derived information is valid.

2. Aims and objectives

The general aim of the current research was to determine the quality of position that can be achieved by the UWB system during a range of movements specific to the wheelchair court sports. The following objectives were investigated:

1. System setup
    a) Setup and configuration quality
    b) Sensors spatial configuration
2. Positioning quality analysis
    a) Stationnary positioning
    b) Dynamic positioning
    c) Impact of wheelchair environment
    d) Filtered positioning quality analysis for distance measurement
    e) Tag mounting location

3. Indoor Tracking System

3.1. Background

UWB is a short-range, large bandwidth radio technology. Its signal properties offer a strong multipath resistance and good penetrability in materials, which makes it particularly suitable for indoor environments. Additionally, the use of UWB pulses enables a very good time-domain resolution which allows such radio systems to be used for precise location and tracking [10–14].

Impulse-radio-based UWB systems are composed of sensors and tags. Sensors are receivers distributed around the area of interest while tags are fixed on objects to be located and emit UWB pulses. The UWB pulse is received by a set of sensors which is used to compute a location based on Time Of Arrival (TOA), Time Difference Of Arrival (TDOA) or Angle Of Arrival (AOA) techniques [15,16].

The TOA technique uses the time of flight of the UWB pulse to determine the distance between the tag and the sensor. For each sensor, this leads to a sphere of possible solutions. The position is then estimated by intersecting spheres of several sensors, a technique commonly known as multi-lateration [17]. However, TOA requires a perfect time synchronisation of all sensors and tags alongside a time stamped UWB pulse so the time of flight can be determined. These requirements are critical and generally not practical for commercial systems.

The TDOA technique is based on the TOA principle but instead of computing the time of flight of an UWB pulse directly, it computes the difference in time of arrival between several sensors receiving the same UWB pulse. As this technique is time based, all sensors must be time synchronised. However, a benefit over TOA is that tags do not need to be synchronised.

If the orientation of the sensor is known, it is also possible to use the AOA technique to estimate the tag position. This is achieved for each sensor by determining the direction of arrival of the UWB pulse. Position can then be estimated by intersecting AOA of several sensors, a technique commonly known as multi-angulation [17].

All of these techniques are frequently combined together using non-linear regression or Kalman filtering to optimise the positioning quality [18].

3.2. Ubisense real-time location system

This study focuses on the use of a commercial impulse-radio-based UWB system from Ubisense [6] (UWB system). This system is one implementation of UWB tracking among others. It is composed of sensors (Figure 1a) and tags (Figure 1b). Sensors are stationary and suitably distributed around the playing area to locate the positions of the tags "worn" by the athletes. Typically, 4 or 6 sensors would be used to surround an indoor wheelchair rugby court (28 m x 15 m).

**************** INSERT Figure 1: Ubisense Real-Time Location System

All sensors are linked by an Ethernet cable to a master sensor for time synchronisation. The tag location information is computed and displayed on a computer connected to the system. According to Ubisense Real-time location system (RTLS) specifications, an accuracy of 15-30 cm with an update rate over 10Hz can be expected.

The system is transportable so it can be easily deployed during competition or training at multiple venues. For this study, the system was installed and calibrated following Ubisense's recommended procedure. The first stage of the calibration is to determine sensor positions by measuring the distance between each sensor and two reference points. This is easily performed with a laser distance measurer. Each distance measured is given as an input to the Ubisense software which determines sensors' position. The next step is to perform the cable offset correction to take into account the different length of wires used to allow for time synchronisation. The last step is to determine the orientation of each sensor. Several methods are proposed by Ubisense. The method used in this study is a "dual calibration" which identifies both cable offset correction and sensors orientation at the same time using a surveyed point, approximately in the middle of the area of interest, so its coordinates are known. A tag is left stationary at this point whilst the system calibrates each sensor as the tag position is known [19]. Once this has been done, the system is set up and ready to use. A complete installation and calibration takes approximately 1 hour.

The UWB system only outputs tag positions so other information such as speed and distance travelled are derived from these coordinates. The different analysis and processing techniques presented in this study were integrated in software specifically developed at the University of Nottingham for indoor wheelchair court sports to assist sport scientists and coaches. Some examples of applications can be found in [20,21].

4. Methodology

4.1. Trials and location facility

All trials discussed in this paper are using the Ubisense RTLS system. Trials were undertaken in a large sports hall with a viewing gallery for setting up the surveying equipment (Section 4.2) providing a good view of the playing area (Figure 2).

**************** INSERT Figure 2: Viewing gallery showing the Leica TS-30 surveying equipment and one UWB sensor on an elevated stand

4.2. Surveying equipment

The Leica TS-30 is a robotic total station that allows classic surveying tasks (angle and distance measurement) and also tracking of a moving prism shown in Figure 4.

According to the Leica specifications [22] the tracking mode gives a positioning accuracy of 3 mm + 4 parts per million (ppm). With a 40 m maximum range for the trials presented, the ppm part can be neglected. Timing specifications give a maximum measurement rate of 5 Hz for the tracking mode.

When computing distance travelled from measured positions, the measurement frequency is a limitation. If the length of a trajectory is computed directly from the sum of distances between successive Leica TS-30 positions, it will be under-estimated as straight lines will join the points. In order to correct this under-estimation and knowing that Leica TS-30 measurements are precise in position, an interpolation is applied to more closely follow the track (Figure 3). The interpolation used is a cubic interpolation so the interpolated trajectory effectively goes through all Leica TS-30 measured points as they are known to be precise in position.

***************** INSERT Figure 3: Interpolation benefits to more closely follow the track

As a conclusion, we can say that the Leica TS-30 can also be used as a gold-standard for the distance assessment. However, this is true as long as the Leica TS-30 gives enough measurements for the interpolation to fill gaps. All Leica TS-30 traces used in this paper have been checked to ensure no unacceptable gaps (> 0.5 s) were present.

4.3. Data collection

As the aim was to assess the UWB positioning quality using the Leica TS-30 as a gold-standard, it was necessary to mount tags and prism as close as possible. Another critical requirement with the Leica TS-30 is to maintain a line-of-sight between the total station and the prism for the tracking. So mounted on a wheelchair was a pole with the prism on top and a plate attached to accommodate the tags, see Figure 4. With this setup, the actual horizontal position of the prism and tags is almost the same; the small offset being negligible compared with the expected system accuracy (15-30 cm). This setup was very convenient as the wheelchair can be pushed normally keeping the line-of-sight between the Leica TS-30 and the prism. Another advantage of this setup is that it was possible to reproduce wheelchair sports movements in an ecologically valid environment.

***************** INSERT Figure 4: Tags and prism mounted on a wheelchair

4.4. Data processing and smoothing

The processing workflow can be seen on Figure 5 and time synchronisation is required after positions are determined as both systems are using their own internal clock for time stamping. The time synchronisation is achieved based on Fast-Fourier Transform (FFT). Once the time synchronisation is complete, the common time window is determined to make sure both systems are running during the analysis period. From here, several movement parameters and quality indicators are computed.

The first quality measure is obtained by computing the horizontal position error of each UWB measurement compared to the interpolated Leica trace considered as the gold standard. The second quality indicator is based on the distance covered as it is one of the key metrics used to monitor sports performance. This was computed by summing up the distance between consecutive points for both Ubisense tags and the Leica TS-30 interpolated data. However, as the UWB positions are subject to random noise, a filter was applied to mitigate this effect. The filtering used was a 3-pass sliding-average with a window size proportional to the acquisition frequency.

***************** INSERT Figure 5: Workflow of the processing used in this study

5. Trials, Results and Analysis

5.1. System setup

5.1.1. Setup and configuration quality

The first objective was an assessment of the setup procedure recommended by Ubisense, which is a quick, low-cost and practical approach to the system installation. As mentioned in Section 3.2, the main step during this installation is to input sensor locations into the Ubisense software. Sensor locations were obtained by laser distance measurements relatively to two reference points, one at either end of the playing area.

In order to assess the precision of the laser measurement technique; sensors and reference points have been surveyed with the Leica TS-30. Comparing laser distances with Leica TS-30 equivalent distances gives a root mean square error of 4 cm which is a typical result according to the measurement technology used.

The distance measurements were provided to the Ubisense Location Engine Configuration (LEC) tool [23] which computed estimates for sensors' locations. The comparison between these estimates and the ground truth provided by the Leica TS-30 has been made for one particular setup of 5 sensors (Table 1). This shows an expected result from the Ubisense setup procedure. There is some evidence of small systematic bias (for example all negative X differences) and random measurement errors (for example the variation in the negative X values) which are of a typical magnitude for the system.

***************** INSERT Table 1: Sensors position differences using Ubisense LEC tool

5.1.2. *Sensors spatial configuration*

One advantage of a flexible UWB system is that the sensors' distribution can be adjusted to optimise the coverage of the area being tracked. Trials were undertaken in order to find the optimum sensors' spatial distribution to cover an indoor wheelchair rugby court.

In order to assess the impact of sensor locations on the output of the system, the wheelchair has been used with both tags and prism mounted. The trajectory pattern used to maximise coverage of the playing area is shown in Figure 6. Positioning quality has been evaluated with a statistical analysis on the horizontal positioning error of the UWB system obtained as described in Section 4.4.

***************** INSERT Figure 6: Trajectory pattern used for sensors spatial configuration analysis

Different configurations have been tried to get an optimal coverage of the court using respectively four, five and six sensors. Using four sensors, one in each corner of the court, resulted in a mean error of 0.40 m ($\sigma = \pm$ 0.28 m). Similar results were obtained when adding one sensor on one of the middle side with a mean error of 0.39 m ($\sigma = \pm$ 0.29 m). Finally, slightly better results (Ubisense track closer to the TS-30 track) were obtained using six sensors, one in each corner at 4m height and two on the middle sides at 2 m providing a mean error of 0.35 m ($\sigma = \pm$ 0.23 m). This is the optimum setup tried and is the one used for all the trials presented next. A spatial analysis has been performed to identify possible areas with bad coverage. However, it appeared that the noise and random errors of the system did not allow for the identification of consistently weak areas.

5.2. *Positioning quality analysis*

5.2.1. *Stationary Positioning*

In order to assess the stationary positioning quality, tags were left stationary for 5 minutes in known court locations. As an example, Figure 7 shows the output of one tag left stationary on a corner of the playing area and is a typical pattern of measurements from various positions around the court. The plot shows that positions out of the UWB system are separated into two distinct clusters. This clustering can be explained by the noise due to sensors sets switching as described in Banerjee [24] which also propose a particle filter to mitigate this effects.

***************** INSERT Figure 7: Stationary tag positioning

5.2.2. *Dynamic Positioning*

The first assessment evaluated the horizontal positioning error of each position output by the UWB system. In order to collect data relevant to indoor wheelchair court sports, trials were conducted during a simulated wheelchair rugby match with 1 participant playing 4 quarters of 8 minutes. The participant was asked to simulate a match play including turns, pivots, back and forth movements with rapid changes of speed. An example of a trajectory during a quarter is visible on Figure 8.

***************** INSERT Figure 8: Example trajectory during a quarter of a simulated match

Two matches of this format have been conducted. Table 2 presents the statistical analysis of the error for both two matches.

***************** INSERT Table 2: Mean (m) ± standard deviation (m) of the UWB positioning error during 2 simulated matches with 9 tags operating at 3 different update rates

Results illustrated the accuracy of the system with a horizontal positioning mean error of 0.37m and a standard deviation of ±0.24m. Detailed results are presented to highlight the consistency of the system. Note that numbers obtained are similar to those obtained in the sensor spatial configuration trial (Section 5.1.2) where a mean error of 0.35 m and a standard deviation of ±0.23 m were found. Additionally, the tag update rate does not seem to affect the positioning quality according to the values grouped by update rate.

Finally, the cumulative distribution function (CDF) of the positioning error has been computed and a typical example is shown on Figure 9. The CDF has been represented for the 3 different tag update rates used (4Hz, 8Hz, 16Hz) using the horizontal error on one simulated match (4 quarters of 8 min). The closeness of curves in Figure 9 show that tag update rate doesn't have a significant impact on the error distribution which confirms that the tag update rate does not affect the positioning quality as already seen on Table 2. The 90th-percentile positioning error is 0.63m regardless of tag rate. Similar results were obtained with an equivalent setup procedure in Muthukrishnan [18] where it is also compared to more complex system setups. The nominal update rates (4Hz, 8Hz, 16Hz) were checked against the time stamped measurement records and agreed within less than 1Hz.

***************** INSERT Figure 9: Cumulative Distribution Function of the positioning error

5.2.3. Impact of wheelchair environment

Results presented in previous sections were obtained with only one wheelchair moving on the court which is not representative of a wheelchair rugby environment. In order to address this, a match (4 quarters of 8 minutes) has been simulated with another wheelchair interacting on the court. To simulate a game this involved close engagement between the wheelchairs and more distant separation between them. The positioning quality was assessed using the statistical analysis on the horizontal positioning error described in Section 4.4. These trials were done using the setup with 5 sensors described in Section 5.1.2 which reported a mean horizontal positioning error of 0.39 m (σ = ± 0.29 m).

During the first two quarters, one wheelchair was tracked by both the UWB system and the Leica TS-30, whilst the second wheelchair remained untracked. The first and second quarters reported a mean error of 0.38 m (± 0.30 m) and 0.39 m (± 0.35 m) respectively. Such results demonstrate that perturbations caused by a second wheelchair on court do not influence the positioning quality. To determine whether the tags were working entirely independent, the second wheelchair was also tracked by the UWB system during the third and fourth quarters. Subsequently, error values remained similar, with a mean error of 0.38 m (± 0.26 m) and 0.36 m (± 0.27 m). As a result, tracking several independent objects in close and distant relationships did not affect the positioning quality.

Finally, some real match data has been investigated to evaluate the impact of having eight athletes and one referee on the court. Due to the need of a constant line of sight between the surveying equipment and the object tracked, no reference data was available. However, the data has been investigated regarding its availability (presence of data gaps) and visual correctness of the track.

As the real match data was obtained using a tag mounted on the foot strap, the presence of data gaps was compared to the results obtained in Section 5.2.5 using a similar tag mounting location. A gap is defined as being a data outage for more than 0.5s. The results from Section 5.2.5 are representative of a situation where only one wheelchair is on the court. Over the 488.1 seconds of the trial, 32 gaps were detected, giving an average occurrence of 1 gap every 15.25 seconds of an average duration of 1.20 seconds. The gaps distribution is visible on Figure 10.

***************** INSERT Figure 10: Distribution of the data gaps with one wheelchair on the court

Moving to the real match data, the whole match was considered with the 4 quarters of 8 minutes including any stop in the game (ball out of play, fouls, …) representing a total dataset of approximately 70 minutes. Over the 4196.8 seconds of the dataset, 299 gaps were detected, giving an average occurrence of 1 gap every 14.0 seconds of an average duration of 1.28 seconds. Similarly, the gaps distribution is visible on Figure 11.

***************** INSERT Figure 11: Distribution of the data gaps during a real match with 8 athletes + 1 referee on the court

The second aspect of the data that has been investigated is the visual correctness of the track. This visual investigation also included a real-time replay of the track to detect any unnatural or irregular movement of the athlete. After investigation, no major anomalies or irregularities could be detected. An example of the track produced for a quarter during a real match is visible on Figure 12.

***************** INSERT Figure 12: Example of an athlete's trajectory during one quarter of a real match

5.2.4. Filtered positioning quality analysis for distance measurement

Before being able to compute the distance covered, UWB measurements were processed using the smoothing described in Section 4.4. Then distances are computed for both UWB smoothed measurements and 'interpolated' Leica tracks and compared.

Detailed results are presented in Table 3 which summarises the errors obtained for 9 tags, operating at 3 different update rates, during the 2 simulated matches.

***************** INSERT Table 3: Distance error of 9 tags operating at 3 different update rates during 2 simulated matches

The mean error on the distance travelled for all tags of the UWB system is 0.45% of course length. Each quarter trajectory was approximately 1000m in length therefore a 0.45% error is equivalent to 4.5m. Additionally, results showed that the higher the update rate, the better the distance estimate. This can be explained as the trajectory will be composed of more points which give a better recording of the dynamics with the same positioning quality (Section 5.2.2).

5.2.5. Tag mounting location

Section 5.2.4 presented the results for distance estimation considering different update rates with tags attached as shown in Figure 4. In order to find mounting locations more appropriate to wheelchair court sports, a specific trial was conducted with tags located in different places on the wheelchair or worn by the athlete. Below are the detailed tag mounting locations considered:

- Vest: Tag positioned between the scapula using a GPS vest worn by the participant
- Frame: Tag attached to the wheelchair frame located at the front of the chair.
- Foot strap: Tag positioned onto the foot strap of the wheelchair
- Camber bar: Tag secured to the camber bar of the chair located beneath the seat.

Additionally, one tag was left attached to the prism pole to allow for a direct comparison with the results presented in Section 5.2.4. A quarter of 8 minutes has been simulated and distance estimates have been computed for each tag. The Leica TS-30 has measured a distance of 752.81 m for this quarter. Results are summarised in Table 4 which also includes the number of data gaps (no measurement for more than 0.5s) for each tag.

***************** INSERT Table 4: Distance estimates and data gaps for different mounting locations

6. Discussion

The setup procedure that has been used and assessed in the current study was recommended by Ubisense which was chosen for its simplicity, convenience and speed of set up. Results of Section 5.1.1 showed that the root mean square error using a laser distance measurer is around 4 cm when measuring the distance between each sensor and reference points. This was an acceptable result for the technology used. More expensive, time-consuming and complex setup procedure are possible [18,19] but wouldn't be as easy and quick to deploy for a mobile system used in a sports environment.

Several sensor configurations were investigated to optimise coverage of the court. The best configuration was obtained using 6 sensors, with one in each corner of the court 4m high and 2 on the middle-sides of the court 2m high. With such a configuration the mean horizontal positioning error was found to be 0.35 m ($\sigma = \pm 0.23$ m). The stationary positioning analysis in the study showed that the distribution of computed positions is typical of an UWB radio-positioning systems with evidence of sensors set switching noise [24].

An important aspect of this study was the dynamic positioning quality assessment using a robotic total station with tracking capabilities. Previous studies were limited on dynamic assessment by performing only basic linear drills [25], differential comparison (tags comparison instead of a gold-standard comparison) [7] or by asking participants to follow a predefined path marked on the ground [25]. These have shortcomings for the validation of an UWB system in a sports performance context where athletes perform multi-directional movements at varying intensities. A more recent study [26] addressed most of these shortcomings by using a trundle wheel to obtain a distance reference. While this allows more freedom for the players, it still has some limitations in the dynamics that can be tracked and the measure may not reflect exactly the actual distance covered by the athlete. Finally, as mentioned by the authors [26], the trundle wheel provides a way to assess distance estimation but does not provide any information about the positioning quality. The protocol using a robotic total station addresses these shortcomings. Results during 2 simulated matches showed a mean horizontal positioning error of 0.37 m ($\sigma = \pm 0.24$ m) which correlates with the sensors spatial configuration analysis results ($\mu = 0.35$ m, $\sigma = \pm 0.23$ m). This validated the capacity of an UWB system to track highly dynamic movements. Additionally, having a second wheelchair moving and tracked on the court did not affect the positioning quality. While it was not possible to use the surveying equipment during a real match due to the need for a constant line of sight, some real match data has been investigated. Two aspects were considered, the availability and regularity or smoothness of the track. The availability study was based on a direct comparison to the results obtained in Section 5.2.5. With only one athlete on the court, on average, a data gap occurred every 15.2 seconds for an average outage of 1.20 seconds. During a real match, with eight athletes and one referee on the court, the occurrence rate slightly increased to one gap every 14.0 seconds for an average outage of 1.28 seconds. The comparison of the respective gaps distribution (Figure 10 and Figure 11) shows that larger gaps (> 2.5 seconds) are more likely to appear during a real match situation. However, this difference is not significant since 94% of the gaps are below 2.5 seconds in the real match dataset compared to 97% in the single wheelchair situation. Additionally, the visual correctness of the track has been checked using a real-time replay and did not show any evidence of major anomalies or irregularities. As a conclusion, going from a single athlete on the court to a real match situation with eight athletes and one referee only slightly degrades the performance of the tracking system. However, according to the results of our analysis, the degradation is not significant and does not affect the suitability of the system to be used for indoor wheelchair court sports.

The next focus of this study was on the distance covered, an important metric in analysing athlete's performance. A previous study [26] assessed that the same UWB system can provide a distance estimate with an error of 3.45 ± 1.99 % of the course length in a basketball context. These results were obtained using a combination of Kalman filter and low-pass filter. The approach adopted in this study uses a 3-pass sliding average (Section 4.4). Using this filtering technique the distance can be known with a mean error below 0.5% of course length. This difference in results may also be partly explained by the protocol used in [26] as the trundle wheel does not follow exactly the same path as the tag. Also, the tags update rate in [26] (4Hz) may contribute to a reduced quality of distance measurement. The present work found that higher tag update rates (≥ 8 Hz) are more suitable for distance estimation as outlier effects can be more easily mitigated by the processing and are also giving the finest recording of the dynamics.

The tag attached to the prism pole provided the best distance estimate with results in agreement with those found in Section 5.2.4. Regarding mounting locations relevant to wheelchair sports, the vest appeared to show the smallest error. It also appeared that lower mounting places are more subject to data gaps which could affect the distance estimate. Nevertheless, the magnitude of error was still minimal regardless of location, and lower places may offer the most practically relevant tag locations.

7. Conclusion

This study has assessed the quality of an UWB system for tracking wheelchair athletes indoors. With a quick and easy deployment procedure, dynamic tracking can be achieved with a mean horizontal positioning error of 0.37m ($\sigma = \pm 0.24$ m). Additionally, distance covered can be determined with an error below 0.5% of course length with adequate data processing. Tag update rates did not have a significant impact on the positioning quality; however, higher rates (≥8 Hz) provided a greater number of points to more closely record the high dynamic movements. It was also found that having many wheelchairs on the court did not have a significant effect on the positioning. Finally, several tag mounting places have been tried with the smallest error obtained for the tag worn by the athlete in a GPS vest. Although the results presented are sport specific the method has wider potential application to other indoor and possibly outdoor sports.

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Tables :

Table 1: Sensors position differences using Ubisense LEC tool

	X [along court] difference (m)	Y [cross court] difference (m)	Z difference (m)	Total difference
Sensor 1	-0.224	-0.031	0.094	0.245
Sensor 2	-0.128	-0.058	0.001	0.141
Sensor 3	-0.069	-0.134	0.017	0.152
Sensor 4	-0.102	+0.050	0.037	0.119
Sensor 5	-0.165	-0.252	0.002	0.301

Table 2: Mean (m) ± standard deviation (m) of the UWB positioning error during 2 simulated matches with 9 tags operating at 3 different update rates

	Match 1				Match 2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Tag 1 (16Hz)	0.33 ± 0.21	0.31 ± 0.21	0.36 ± 0.26	0.34 ± 0.22	0.39 ± 0.24	0.34 ± 0.22	0.41 ± 0.25	0.39 ± 0.27
Tag 2 (16Hz)	0.36 ± 0.23	0.31 ± 0.22	0.36 ± 0.25	0.35 ± 0.23	0.40 ± 0.22	0.34 ± 0.23	0.40 ± 0.24	0.39 ± 0.26
Tag 3 (16Hz)	0.36 ± 0.22	0.34 ± 0.21	0.39 ± 0.24	0.37 ± 0.22	0.40 ± 0.26	0.37 ± 0.21	0.41 ± 0.25	0.41 ± 0.25
Tag 4 (8Hz)	0.34 ± 0.21	0.33 ± 0.21	0.36 ± 0.25	0.36 ± 0.22	0.39 ± 0.23	0.33 ± 0.23	0.40 ± 0.24	0.39 ± 0.27
Tag 5 (8Hz)	0.36 ± 0.22	0.34 ± 0.21	0.38 ± 0.26	0.37 ± 0.22	0.41 ± 0.24	0.37 ± 0.24	0.41 ± 0.24	0.42 ± 0.25
Tag 6 (8Hz)	0.35 ± 0.21	0.34 ± 0.26	0.37 ± 0.25	0.36 ± 0.23	0.40 ± 0.24	0.37 ± 0.22	0.41 ± 0.25	0.41 ± 0.28
Tag 7 (4Hz)	0.35 ± 0.27	0.32 ± 0.22	0.38 ± 0.25	0.36 ± 0.24	0.39 ± 0.26	0.33 ± 0.23	0.40 ± 0.25	0.40 ± 0.26
Tag 8 (4Hz)	0.35 ± 0.23	0.32 ± 0.21	0.39 ± 0.25	0.36 ± 0.24	0.39 ± 0.26	0.34 ± 0.22	0.41 ± 0.26	0.40 ± 0.26
Tag 9 (4Hz)	0.36 ± 0.23	0.34 ± 0.22	0.41 ± 0.28	0.36 ± 0.24	0.38 ± 0.30	0.38 ± 0.25	0.42 ± 0.26	0.42 ± 0.26
Mean	(16 Hz) 0.37 ± 0.23 m		(8 Hz) 0.37 ± 0.24 m		(4 Hz) 0.37 ± 0.25 m		(Total) 0.37 ± 0.24 m	

Table 3: Distance error of 9 tags operating at 3 different update rates during 2 simulated matches

	Match 1				Match 2			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Tag 1 (16Hz)	-0.05%	-0.40%	0.00%	0.04%	-0.55%	0.22%	-0.07%	-0.36%
Tag 2 (16Hz)	-0.62%	-1.05%	-0.25%	-0.56%	-0.90%	-0.35%	-0.14%	-0.36%
Tag 3 (16Hz)	-0.44%	-0.76%	-0.06%	-0.43%	-0.72%	0.13%	-0.08%	-0.02%
Tag 4 (8Hz)	-0.63%	-1.09%	-0.38%	-0.50%	-0.80%	-0.56%	-0.46%	-1.04%
Tag 5 (8Hz)	-0.40%	-0.97%	0.01%	-0.35%	-0.72%	0.00%	-0.04%	-0.17%
Tag 6 (8Hz)	0.27%	0.20%	0.49%	0.33%	-0.12%	0.78%	0.42%	0.63%
Tag 7 (4Hz)	-0.92%	-1.68%	-0.80%	-0.82%	-1.22%	-1.07%	-0.46%	-1.19%
Tag 8 (4Hz)	-0.05%	-0.56%	0.07%	0.31%	-0.54%	0.00%	0.22%	-0.12%
Tag 9 (4Hz)	-0.21%	-0.72%	-0.09%	-0.27%	-0.51%	0.49%	-0.01%	-0.11%
Mean	(16 Hz) 0.36 %		(8 Hz) 0.47 %		(4 Hz) 0.52 %		(Total) 0.45 %	

Table 4: Distance estimates and data gaps for different mounting locations

	Distance estimate	Error (%)	Data gaps
Prism pole	751.8 m	-0.13 %	1
Vest	755.4 m	0.35 %	6
Frame	750.1 m	-0.36 %	31
Foot strap	745.9 m	-0.91 %	32
Camber bar	736.9 m	-1.85 %	34

Figures :

a) Sensor (20cm x 14cm x 9.5cm) b) Tag (40mm x 40mm x 10mm)

Figure 1: Ubisense Real-Time Location System [6]

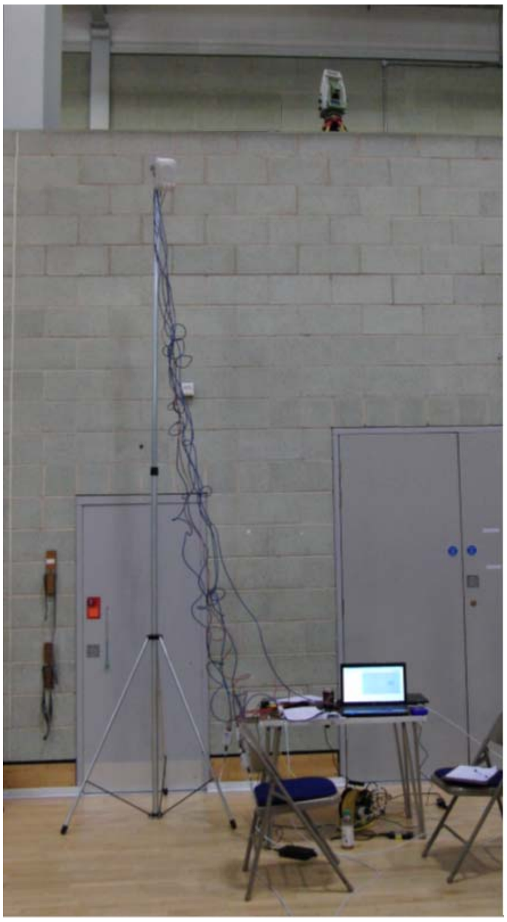

Figure 2: Viewing gallery showing the Leica TS-30 surveying equipment and one UWB sensor on an elevated stand

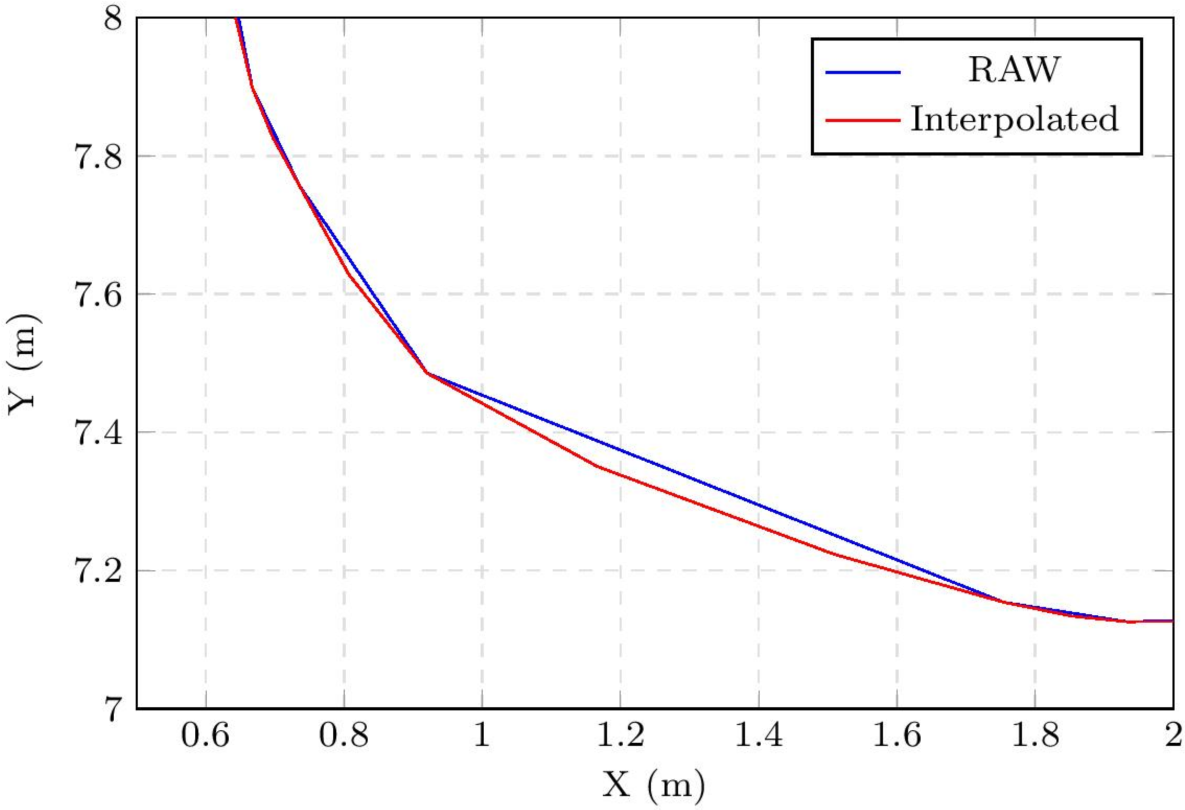

Figure 3: Interpolation benefits to more closely follow the track

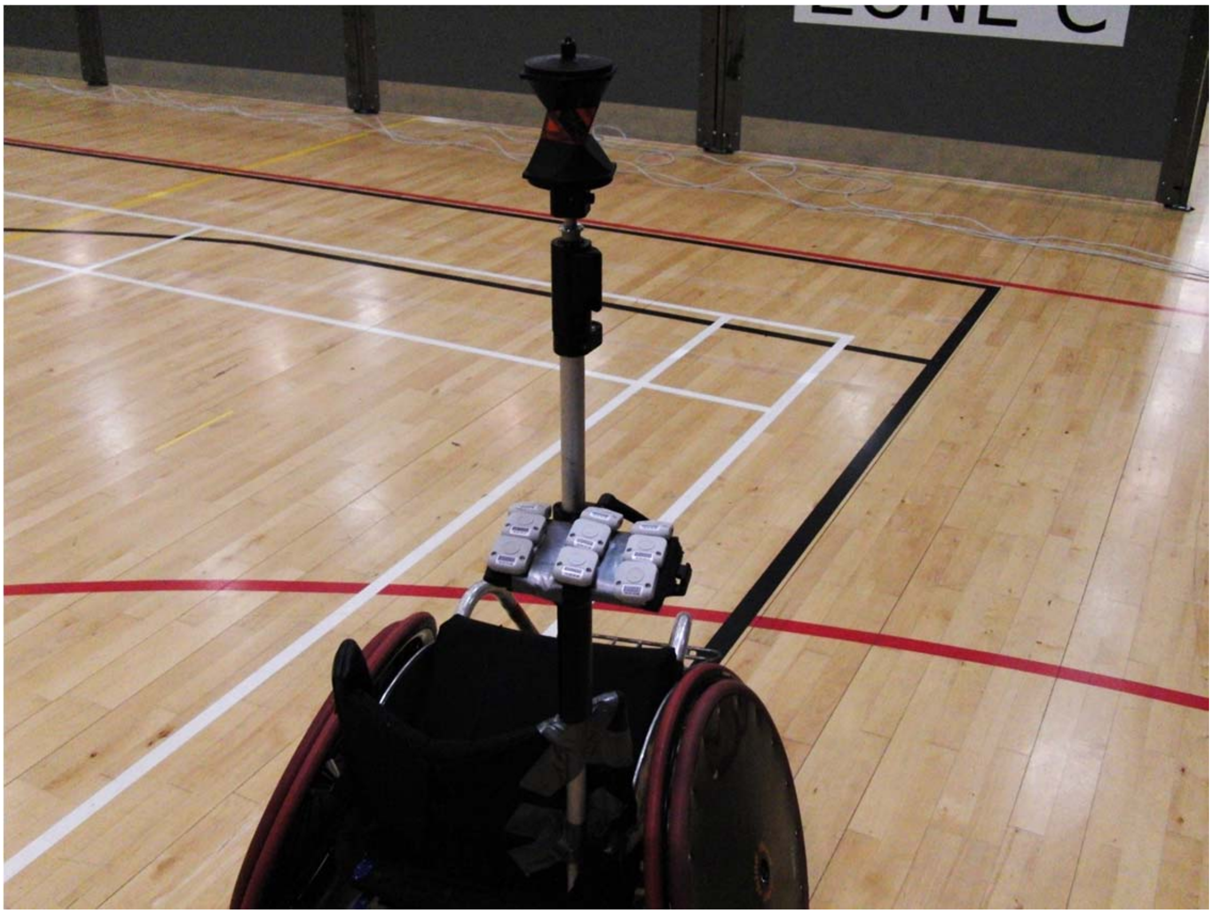

Figure 4: Tags and prism mounted on a wheelchair

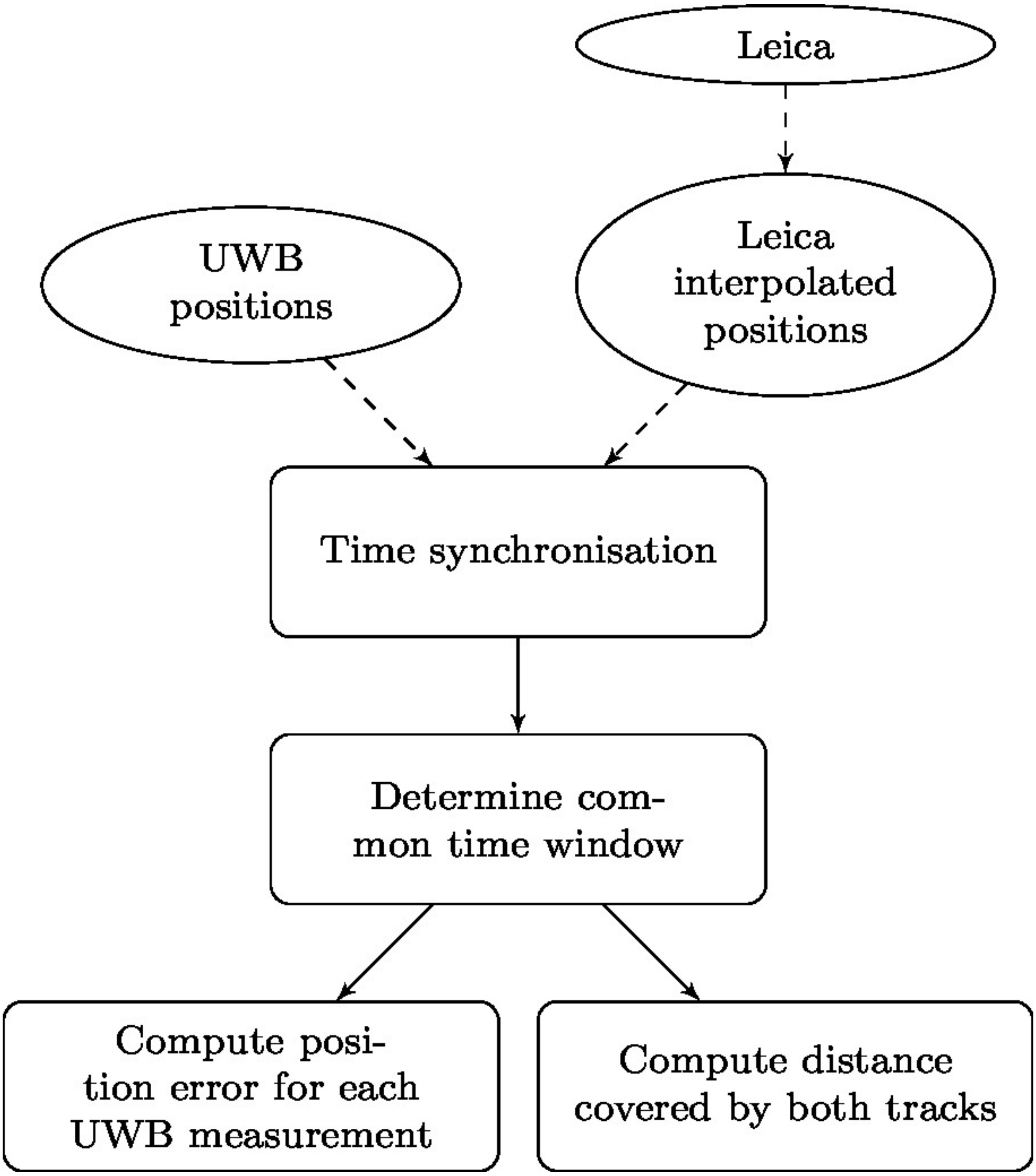

Figure 5: Workflow of the processing used in this study

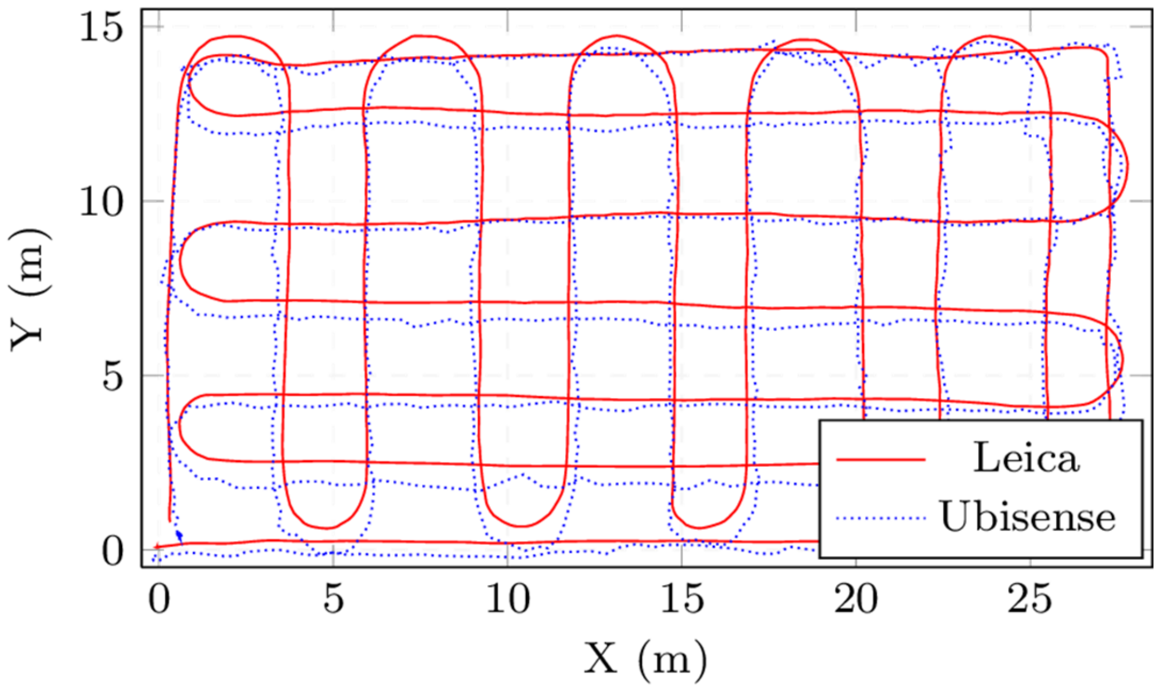

Figure 6: Trajectory pattern used for sensors spatial configuration analysis

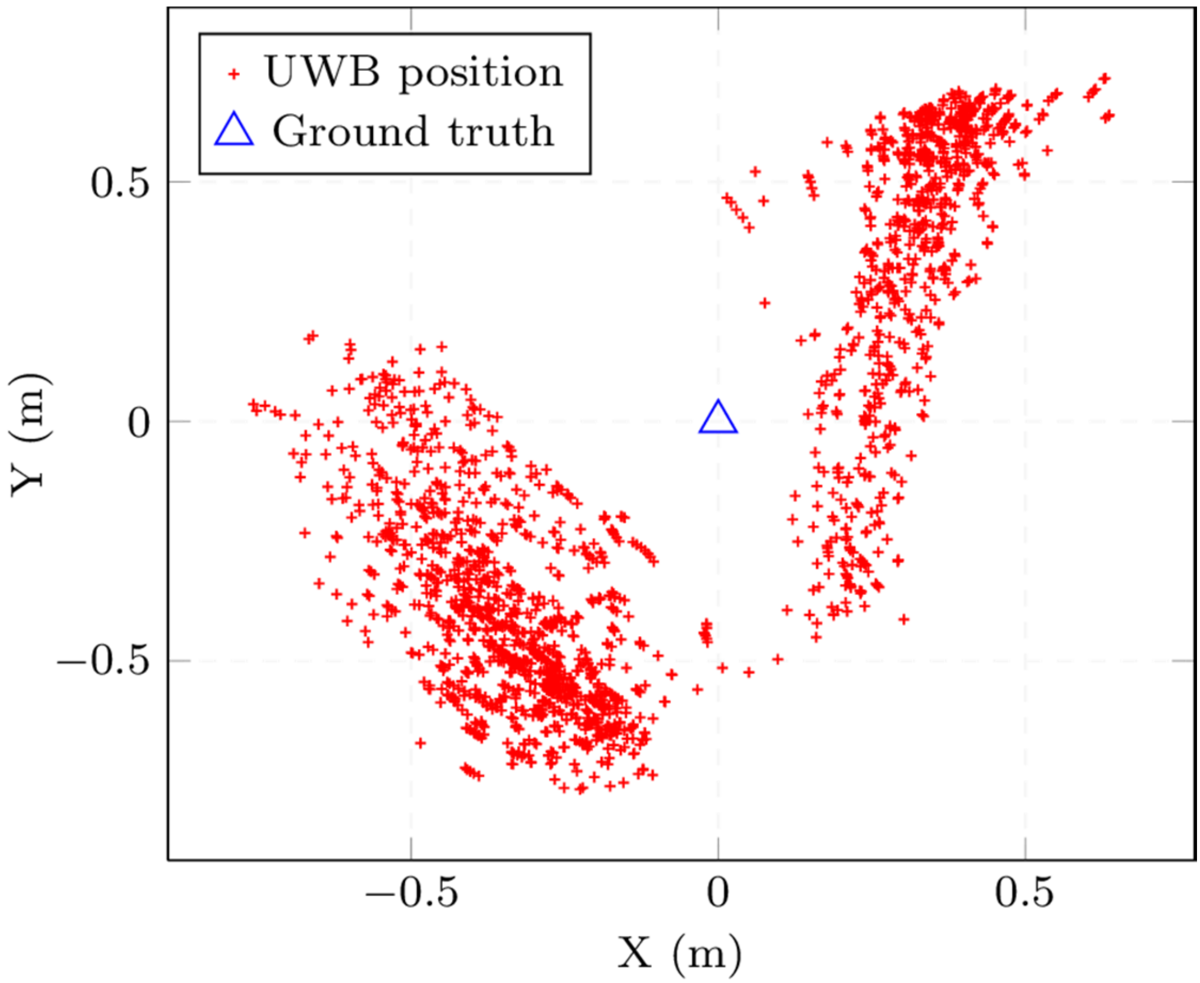

Figure 7: Stationary tag positioning

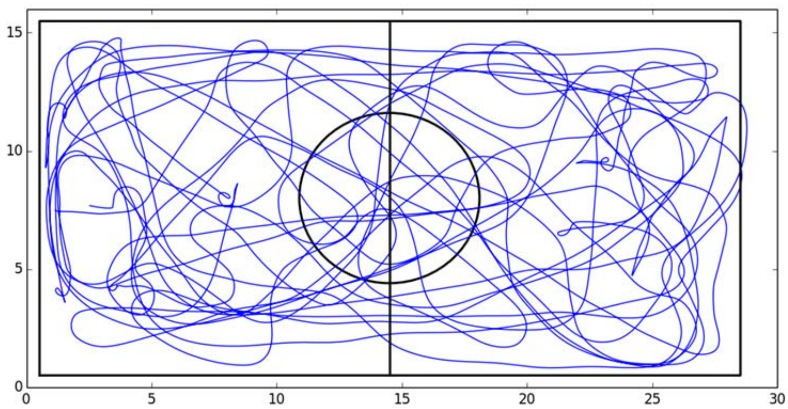

Figure 8: Example trajectory during a quarter of a simulated match

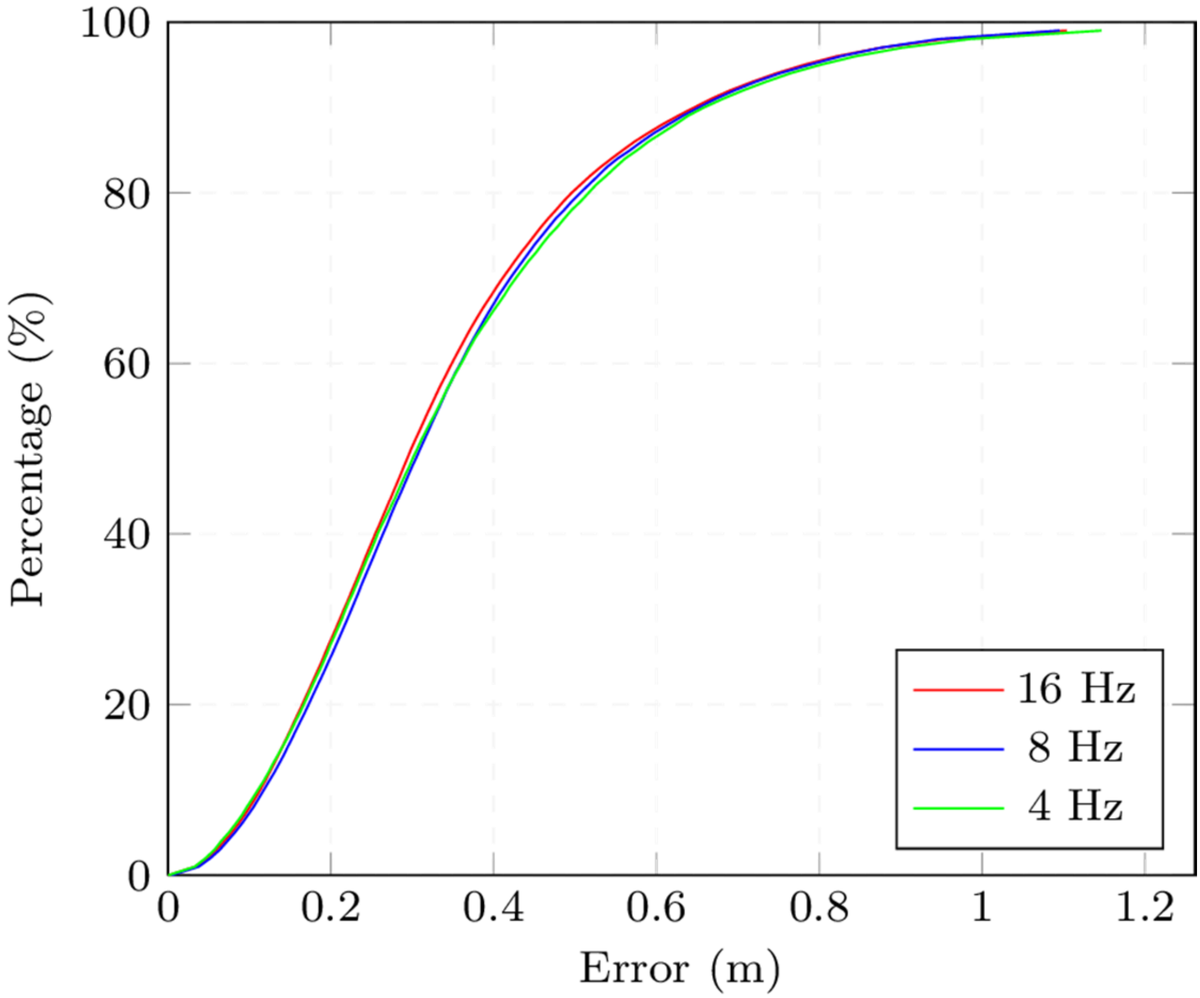

Figure 9: Cumulative Distribution Function of the positioning error

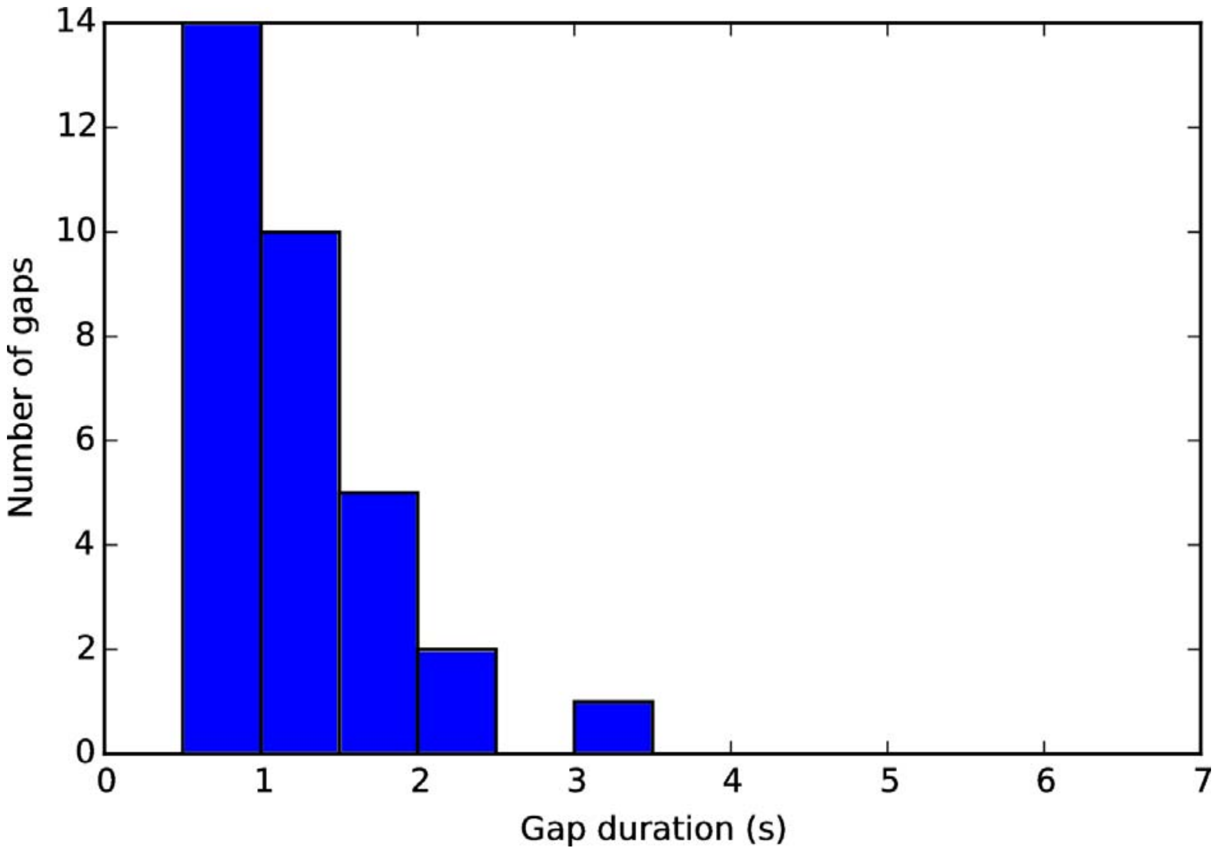

Figure 10: Distribution of the data gaps with one wheelchair on the court

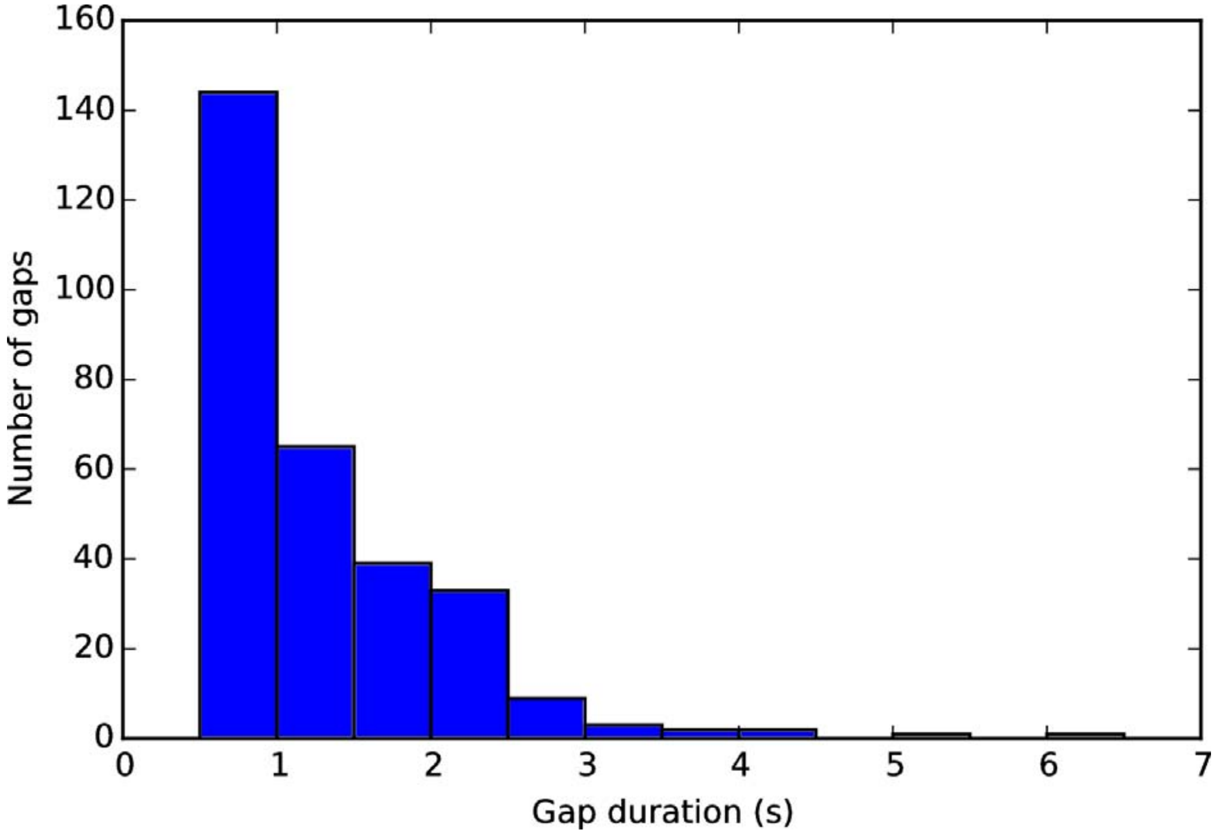

Figure 11: Distribution of the data gaps during a real match with 8 athletes + 1 referee on the court

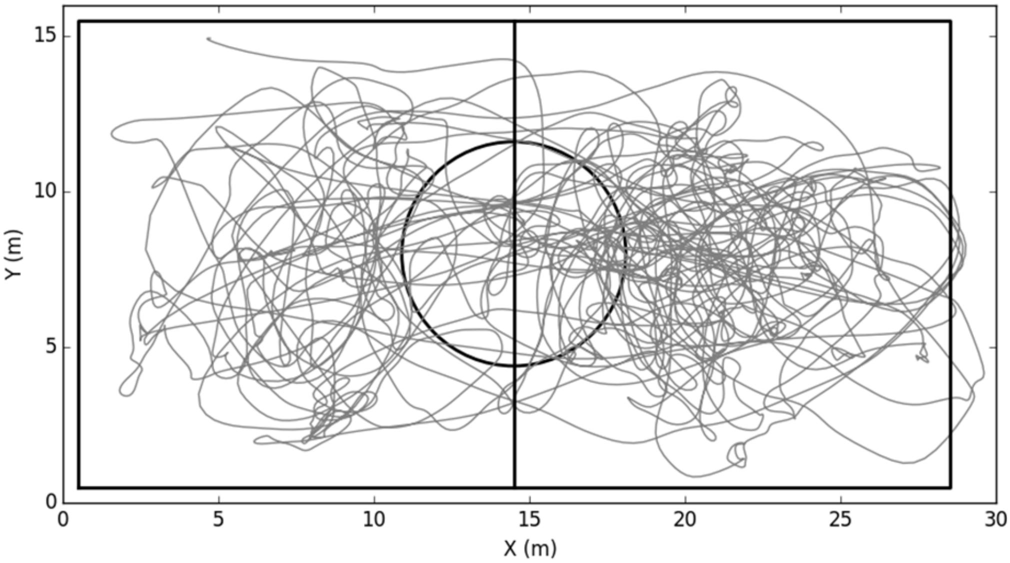

Figure 12: Example of an athlete's trajectory during one quarter of a real match