Towards Radio Localisation of Running Athletes

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***Abstract*—The use of ubiquitous computing for sport performance monitoring was demonstrated in recent work. In this paper, a custom-designed radio-based localisation system and its applicability for tracking a running athlete were presented. The system uses 2.4GHz radio with a Time-of-Arrival (ToA)-based localisation protocol to locate a running athlete on an indoor running track. Through a real-time analysis on the raw localisation data, the location results could be used to support other useful coaching support applications, such as automatic video tracking. The system was experimented against gold-standard technologies. The results show that the presented system achieves a positional accuracy within 21.959cm for tracking running athletes.**

Keywords—Application; athletes; localisation; sports; ubiquitous sensing.

I. Introduction

The use of ubiquitous sensing to support sports performance monitoring has been demonstrated in recent years. The system design principles for developing ubiquitous sports equipment were identified in [6]; whereas in [7], a wearable system that detects kicks in martial arts was reported. In [1][8][11], the use of pervasive sensing for performance monitoring of athletes (i.e., sprinters) was reported. The most interesting performance information of an athlete is speed, which is derivable from location data. Although the use of radio-based localisation systems to locate objects have been reported, however, most existing work focus on locating static objects (e.g., locating static sensor nodes in an office) or tracking (relatively) slow moving subjects (e.g., people in a hospital); also, most of the reported work were carried out in indoor and (relatively) confined environments (e.g., offices, hospital rooms, etc.). The applicability of radio-based localisation system for locating *running* subject in a *large* indoor environment, for example a sprinter running in an indoor stadium, is unknown.

It should be noted that besides the athletes' speed profile, video footage is considered as an important element in coaching support. Traditionally, coaches hold hand-held cameras to capture footage of athletes in motion. The drawback is that such manual approach distracts coaches from the coaching session. An automated solution is therefore preferred. It is possible to install multiple cameras along-side the track to capture video footages of athletes running for long range (e.g., over 60m), but the drawback of this solution is that the cost increases substantially. An alternative solution that involves fewer cameras is one that spins a camera towards the athlete. To do so, the system must be able to approximate the location of the athlete on the track in real-time. One solution is to carry out real-time image processing of the video footage to track athletes. The authors suggest that radio-based localisation systems – such as the one presented in this paper – could provide location information of a running athlete in order to drive a camera in real-time.

To investigate the applicability of radio localisation system for locating a running athlete, the custom-designed SEnsing for Sports and Managed Exercise (SESAME) [1] nanoLoc (NNL) 2.4GHz radio-based localisation system was developed and evaluated. Through experimentations, the system shows that radio-based localisation is a promising approach with an average positional error of 21.9589cm using minimal equipment setup. The accuracy of the results is promising comparing to the 0.5m to 1m positional accuracy reported in existing literature. This paper is organised as follow: firstly, related work and the design challenges will be presented; secondly, the design assumptions and the NNL system will be presented; thirdly, the experiments and the results will be presented and analysed. The paper finishes with a conclusion and future work.

II. Background

A. Related Work

Motion-capture optical-based systems [4][14] have been used in existing biomechanics research to capture 2D/3D motion data of athletes, including positional data. Although highly accurate (i.e., millimeter-level accuracy) [5], they are very expensive, have limited Field of View (FoV), and unless permanently installed, would require one calibration per setup. Also, multiple markers must be attached to the subject. Thus, to cover longer distance runs, multiple scanners would be needed which means cost would rocket. Also, since they are infrared-based systems, they could only be used indoor. The high monetary cost involved and the level of complexity in the setup process mean these systems are impractical for regular data collection. These systems are generally used for small-scale studies involving small number of sprinters over small number of trials, or used as gold-standard for system evaluation. The same restrictions apply to high speed video cameras (i.e., >2k frame rate) as well.

A split time monitoring system is reported in [10]. Split time is the time it takes for one to run for 10m. The system reports gold-standard comparable split time information of athletes using cost-effective light-sensors. But split time does not provide continuous location information. Although more light sensors could be added to improve the granularity of the information, this may create a scalability issue. The same applies to conventional Light-Gate (LG)-based systems.

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There are several other methods for continuous location tracking: GPS-based systems have been used; with a repeater, it could be a solution for indoor tracking. However, the use of repeaters is illegal in many parts of the world including the UK and Europe. Also, high precision GPS systems are expensive. An alternative would be laser range finders [9]. Coaches have been using laser range finders for continuous location tracking of athletes, however, only on an occasional basis. A laser range finder is placed at the end of the track, and emits an infrared beam to a flat subject, commonly the lower back of an athlete. The time-of-flight of the (reflected) signal is used to determine the position of the athlete relative to the laser range finder. However, laser range finders suffer from the following drawbacks: a) a laser range finder must be placed behind an athlete, and the operator (i.e., the coach) must manually adjust the finder to point at the flattest surface of the athlete (i.e., the lower back); a task which is increasingly difficult when the athlete runs further away from the finder; and b) they are expensive. Although automated laser range finders - such as Total Station - are available, they are even more expensive than conventional laser range finders.

Another approach for continuous location tracking would be to the use of on-body sensors such as inertial sensors [15]; high quality inertial sensing systems, however, are expensive. In [11], an integrated on-body and track-side sensing system which detects step/stride length was reported. Stride length is the forward displacement of on the same foot during a stride. A series of accurately measured stride length would enable one to determine the location of the subject, provided that the starting position and the direction of the run are known. An alternative approach would be radio-based localisation systems. These systems use different types of radio [12][13], each with different types of characteristics and accuracy. Radio-based systems, however, subject to noise. There are reports on radio localisation data analysis protocols, such as the Curvilinear Component Analysis (CCA) [16] for processing multi-dimensional localisation data. In [13][17], the algorithms for interference-aware radio-based localisation systems were presented. In [18], the work on locating a relatively slow moving pedestrian in an indoor environment was reported. The use of (extended) Kalman Filter for robot localisation was reported in [19][20]; however, the speed of the robots was relatively slow and the results are insufficiently accurate for the purpose of this study.

B. *Design Challenges*

Spaces available on athletes for attaching on-body sensors are limited: the authors' interviews with the coaches and athletes suggest that they would prefer to minimise the number of on-body equipment to avoid affecting athletes' performance. Athletes do have a more open attitude towards placing sensors at more static and rigid locations, such as the lower back, where motion obstruction caused by sensor attachment is negligible. Thus, care must be taken to design systems so that they are small in size and light in weight. Also, since the track is a shared environment, the number of on-track equipment should be minimised to avoid disturbance to other users.

III. System Design

A. *System Assumption*

The NNL system is deployed and evaluated in an indoor environment; this is because training commonly takes place in indoor stadiums in the UK; also, optical-motion systems, such as CODA, could be used for evaluation purpose. Since the system is portable, radio-based, and uses a small number of track-side equipment, the system is provisioned to be deployed in outdoor environment as well. As a preliminary study, the investigation will start with using the NNL radio-based localisation system for locating an athlete sprinting on a straight (i.e., a 60m straight). Energy consumption of devices is not important, as each sprint is no more than a few seconds and athletes only train for a few sprints per day training session; thus, batteries could be re-charged or replaced at the end of a training session. Since the track is a shared environment, the number of on-track and on-body equipment should be minimised. The track is assumed to be clear when the athlete runs; this is a valid assumption for safety purpose. Safety and security issues are not addressed.

Radio-based localisation systems are sensitive to changes in the surrounding environment, such as new additional infrastructure; however, it is fair to assume that during a day raining session, the surrounding environment does not change. In Section VII, provisionings in the finalised system that minimise the effect on the system's accuracy due to changes of the surrounding infrastructure will be presented.

B. *System Design*

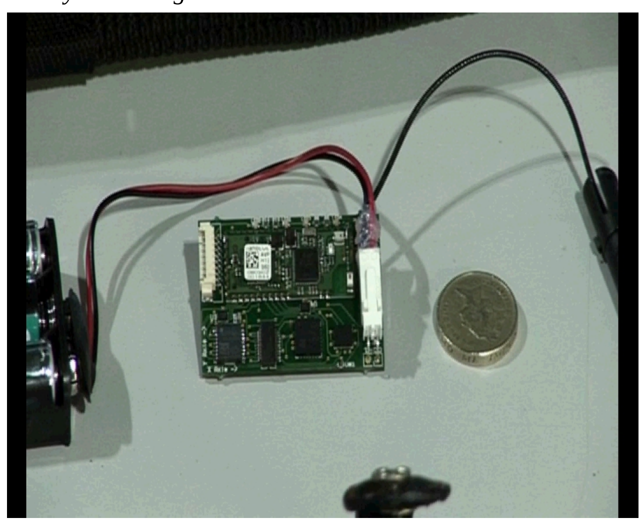

Figure 1 – The custom-designed NNL board

The NNL system has track-side anchor(s), on-body tag(s), and a track-side sink which is connected to a laptop. The on-body tag sends radio signal to the track-side anchor(s) which is(are) placed at known position(s), and uses Time-of-Arrival (ToA) to determine the distance between itself and the anchor(s). The (raw) distance value calculated by the tag is uploaded to the track-side sink. The system supports both Multiple Anchor (MA) and Peer-to-Peer (P2P) mode. The former requires multiple anchors to be placed at known positions on the track and uses triangulation to locate a subject,

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whereas the latter uses only one anchor (which is placed behind the athlete) and is therefore suitable for straight runs. Another advantage of the P2P mode was that it involves less equipment on the track, which is ideal for experimentation in a shared environment at this early stage. Thus, in this paper, the results of the system using the P2P setup are reported.

The custom-design localisation board (Figure 1) is used for implementing the anchors, tags, and sink. Thus, the only difference between the three types of nodes lies within their functionalities (i.e., software). Each board is only a few millimeter thick and half the size of a credit card, and each has a nanoLoc AVR chip from nanotron [3]. Each board is equipped with an ATmega644 processor and a 3-axis accelerometer and gyros. The boards operate in the 2.45GHz ISM band for both localisation and wireless data transmission. The effective wireless range in an indoor environment with a 12dBi directional antenna was sufficient enough to cover a 60m indoor track. The use of a directional antenna improves signal quality, hence reduces packet loss, and the range of coverage. For ranging, the system uses the Symmetric Double-Sided Two-Way Ranging (SDS-TWR) protocol. Due to space limitation, readers are referred to [3] for details on the protocol. The double-side and two-way approach of the SDS-TWR protocol enables compensation of internal hardware delays, time drifts, and wireless transmission delays; hence eliminating the need of explicit wireless synchronisation between devices. Thus, the major advantage of the protocol is that it is asynchronous, which means no synchronisation is needed among the boards involved in ranging.

IV. EXPERIMENT

A. Experiment Setup

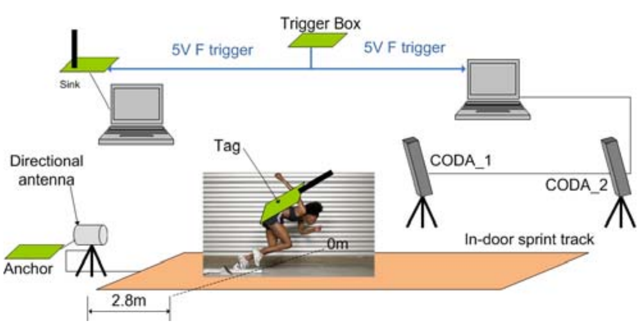

Figure 2 – Experiment equipment setup

Figure 2 shows the equipment setup. The anchor (with a directional antenna) is placed on a tripod (i.e., 0.76m above ground) and is placed at 2.8m behind the 0m line. The on-body tag is securely mounted to a belt which is worn by the subject (i.e., 1.12m above ground); thus, the tag is close to the Centre-of-Mass (CoM) (i.e., lower back) of the subject (Figure 3). Gold-standard passive optical motion tracking system, CODA from CODAmotion, was used for evaluation. CODA was chosen because of its well-documented high accuracy (i.e., millimetre-level). The CODA scanners were placed horizontally to the track, each has a viewing FoV of ~7m; thus, the total FoV was ~13m (with some overlapping between the scanners). A CODA marker is placed on the right side of the tag, so that the marker is within direct line-of-sight with the track-side CODA scanners in order to track the forward displacement of the tag (i.e., CoM of the subject). CODA was set to sample at 400Hz.

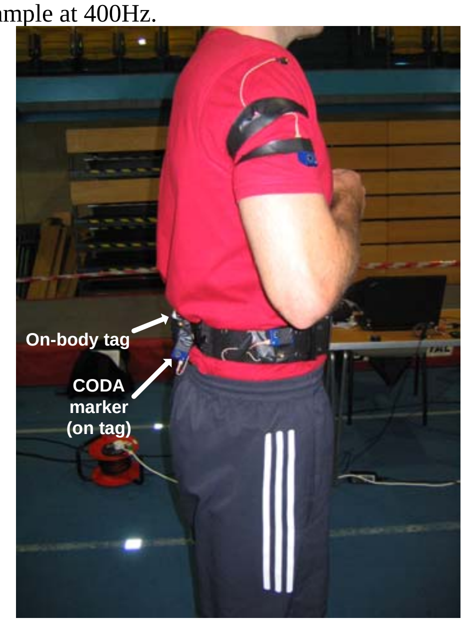

Figure 3 – On-body equipment

It should be noted that a unique feature of sprinting experiment is that the experiment runtime is very short and there is no need to capture positional information beyond each sprint. Since crystal clocks drift linearly and the experiment runtime is very short, the effect of clock drift is minimal. TRIG IN was therefore chosen as the cross-subsystem synchronisation method between CODA and NNL: a 5.5V falling edge trigger was delivered to both systems through a BNC cable. An alternative method to TRIG IN is SYNC IN, in which all systems are driven to sample by the same clock. CODA provides a SYNC OUT function which could be used to drive other systems to sample. However, SYNC IN is currently not supported in NNL because NNL was designed operate independently. Note that for longer experiment, multiple triggers could be sent to synchronise the systems to address clock drift: this is possible because both NNL and CODA logs the incoming trigger signal in a separate ADC channel from their data channels. A series of common triggers could be generated as square waves by a signal generator. This arrangement facilitates for continuous and concurrent data sampling and trigger signal sampling (i.e., continuous synchronisation through multiple triggers).

B. System Calibration

It is well known that radio-based localisation systems are subject to noise and bias. The question is the repeatability of these parameters. Calibration is needed to address bias in the system. To calibrate the system, the subject was asked to stand at different known positions on the track for 30s (i.e., at every 5m away from the 0m line, up to 60m). The raw distance values reported by the NNL system at each known position are averaged to determine the bias value associated with that position.

Note that two sessions of the experiments were conducted. This is because, even though radio subjects to noise, calibration is only needed *per experiment setup*, or *per infrastructural change* (i.e., major constructional changes in the surrounding environment), but not per repetition (rep.). Repetition is the term used by coaches to refer to a sprint. This argument is justified by carrying out the experiments over two sessions: the calibration on the second session reports a similar bias.

V. Results and Analysis

A. *Low-Pass Filtering and Correction*

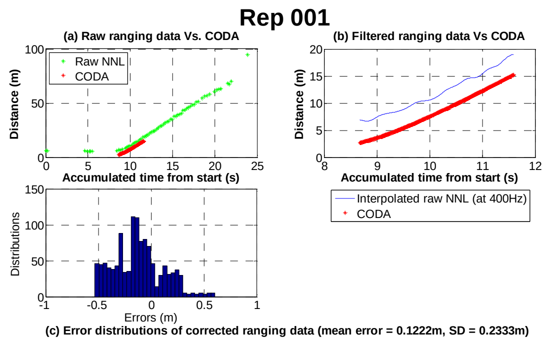

Figure 4 – Error distributions of corrected ranging data (rep. 1)

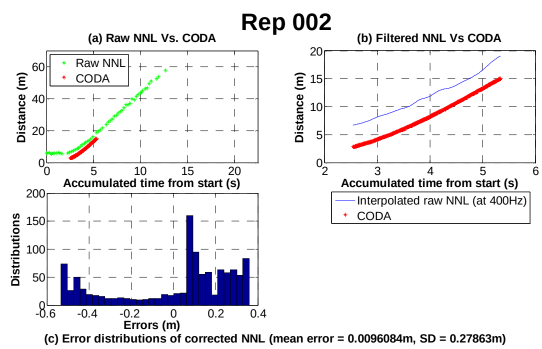

Figure 5 – Error distributions of corrected ranging data (rep. 2)

One approach to correct bias in the data is through modeling. However, given the level of variability caused by a relatively significant change in pace (i.e., acceleration) at the start-up phase of a run, a modeling approach would be difficult, as reported in [2]. In this section, the raw ranging data are first low-pass filtered, then corrected using the calibration data collected as described in Section IV.B. Fast Fourier Transform (FFT) was used to determine a suitable cut-off frequency (i.e., 1Hz), and the filtered ranging data are corrected using a piecewise linear model and the calibration data. The corrected ranging data are then compared with CODA data for error analysis. Some of the selected results are shown in Figure 4 to Figure 8 respectively. Note that because the NNL ranging data and CODA data were sampled at different rates, the corrected NNL ranging data are interpolated at 400Hz for error analysis.

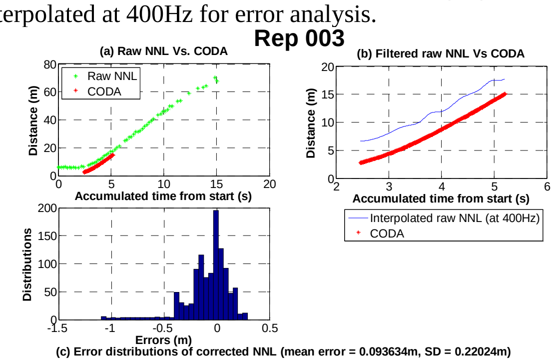

Figure 6 – Error distributions of corrected ranging data (rep. 3)

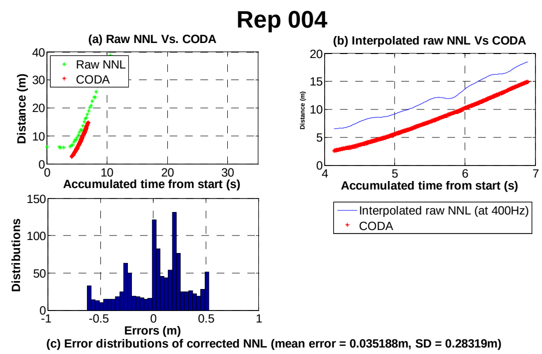

Figure 7 – Error distributions of corrected ranging data (rep. 4)#

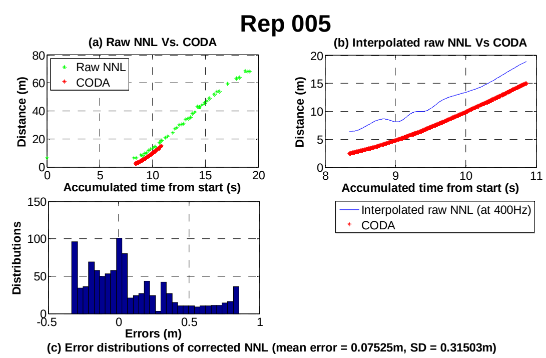

Figure 8 – Error distributions of corrected ranging data (rep. 5)

The averaged positional error of all reps. is 6.7172±26.6078cm (mean±SD), which gives an overall positional error of 20.0211cm. There were a number of factors which would have contributed to the error: a) mean error and SD were useful to evaluate systematic error and noise; but the lower the cut-off frequency, the smaller the SD, the estimated trajectory is smoother. To justify this point, the analysis process was repeated but with a higher cut-off frequency at 4Hz, the mean error was reduced but the SD was increased (i.e., 6.03248±31.138cm); b) it was assumed that the direction of movement of the tag is along the forward plane only. This is a valid assumption because sprinters are trained to run in a straight line (to maximise their speed) and lane crossing is strictly prohibited; in reality, however, sprinters could drift slightly off the centre of their assigned lane, and each lane has a width of 1.21m; c) track-side equipment's positional measurements were done manually; which could contribute to the error; and d) because NNL and CODA has a different sampling rate, corrected NNL data are interpolated at 400Hz for error analysis; should some of the corrected values were out-of-range, interpolation would contribute to the error as well.

B. *Real-time Approximation*

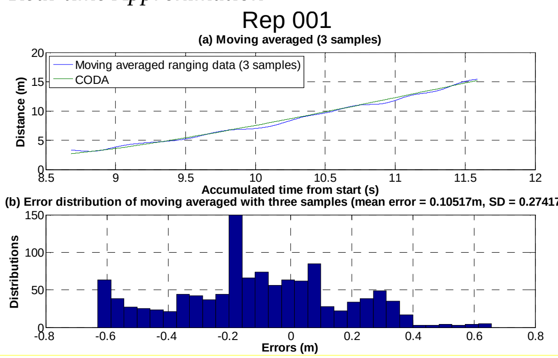

Figure 9 - Error distributions of the moving averaged data (rep. 1)

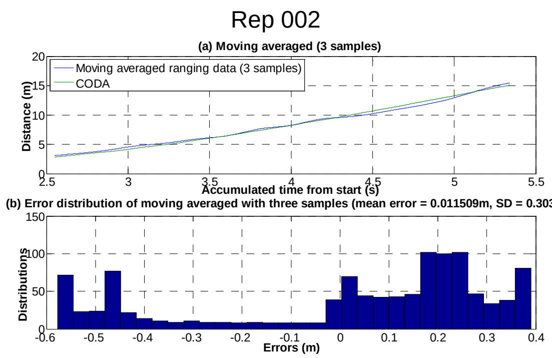

Figure 10 - Error distributions of the moving averaged data (rep. 2)

It should be noted that, a light-weight localisation protocol for approximating the location of an athlete in real-time would be preferred; one that is sufficiently accurate enough for spinning the camera at the athlete. Note that a typical camera placed on the track side has a FoV of ~5m (dependent on size of lens used). The FoV increases when the camera is placed further away from the track, which is the likely scenario (i.e., permanently installed cameras in a sport stadium – such as photo-finishing cameras - are usually installed in the roof or somewhere high on the side walls). Thus, one could tolerate a relatively larger error in the localisation system if the data were used for driving a camera. It should be that the design of the mechanical mechanism to spin a camera is out of the scope of this paper.

Thus, the use of an alternative light-weight algorithm for approximating the location of a running athlete in real-time is investigated in this section. The algorithm involves moving average and correction in which three consecutive raw ranging data are averaged (i.e., a raw ranging data is averaged with its neighbouring value immediately before and after itself). The averaged value is subsequently corrected using the known calibration data. Since the typical FoV of camera is ~5m, the delay incurred by waiting for three samples is therefore acceptable. It should be noted that this is a proof-of-concept experiment, which means the presented system is not restricted to a moving average of three samples. Figure 9 to Figure 13 shows the error distributions of the selected reps. (i.e., interpolated NNL results against CODA). Note that interpolation is not needed to spin the camera, but needed for error analysis only.

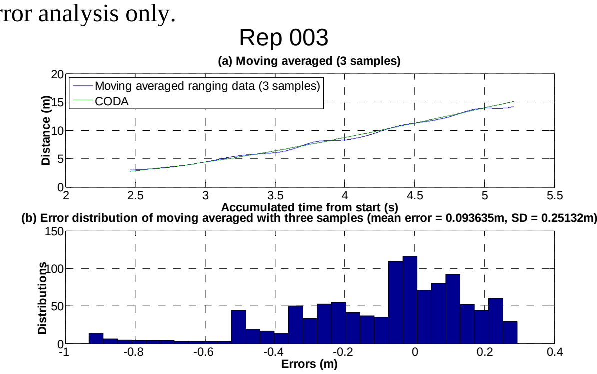

Figure 11 - Error distributions of the moving averaged data (rep. 3)

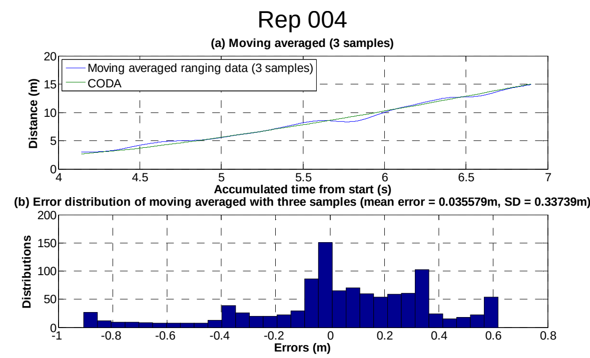

Figure 12 - Error distributions of the moving averaged data (rep. 4)

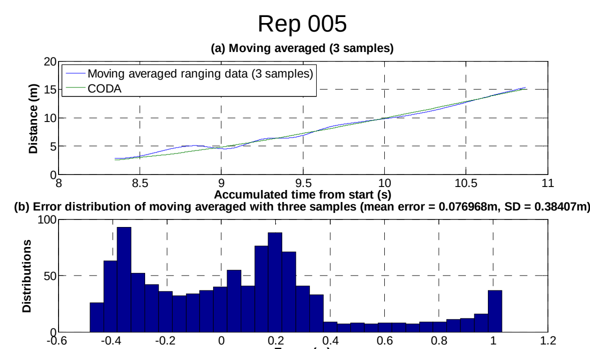

Figure 13 - Error distributions of the moving averaged data (rep. 5)

The results show that the error is 6.4574±31.003cm (mean±SD); thus, an average error of 21.9589cm. Both the mean error and SD are higher than the results using filtered and corrected approach reported in Section IV.A. This is expected because of the presence of noise due to the decision to compensate accuracy for performance (i.e., a faster response time for spinning a camera). Consider the typical FoV of a camera is in excess of a few meters, the authors

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argue that this level of accuracy is sufficiently enough for spinning a camera to follow an athlete in motion.

VI. Conclusion

In this paper, a radio-based localisation system that is capable of accurately locating a running athlete on an indoor running track was presented. The system operates in the 2.4GHz band and uses ToA as the ranging protocol for localisation. The system supports either a multi-anchor mode, which includes multiple anchors placed at known positions on the track, or a P2P mode, in which only one anchor would be needed. A range of experiments using the system in P2P mode were conducted and the results show that radio localisation technique is a promising approach with an average positional error of 21.9589cm. The authors suggest that such level of accuracy is sufficiently enough for supporting an automated camera-based video tracking system to track athletes.

VII. Future Work

It was discussed in Section II.B that the presented system is not limited to indoor but also outdoor. With a directional antenna, the range of coverage in an outdoor environment could reach over 130m. To evaluate the system's performance in an outdoor environment, a light-weight GPS board is being developed. Part of the future work is to develop a spinning motor what spins a camera at an athlete based on real-time localisation data from the NNL system using a gumstix computer. Gumstix was chosen because of its wide range of functionalities, although the system will not be restricted to gumstix. Another part of the future work includes installing the anchors in the roof of the stadium. The purpose of doing so is to avoid the need of placing equipments on the track, hence minimising the level of disturbance to other users. Also, calibration would be needed only when there was a substantial infrastructural change to the system's location. This arrangement would also enable one to experiment with the multiple-anchor setup of the NNL system, which would allow one to do 2D tracking via triangulation (i.e., for oval track localisation).

With regard to the on-body equipment, the authors' observation is that coaches and athletes prefer tiny, light-weight on-body equipment. This requirement means three further areas of work: a) a new version of the on-body sensor board is underdevelopment, the new version of the board is the size of a one-euro coin; b) the omni-directional antenna of the on-body tag must be replaced; probably by a chip-antenna on the NNL AVR chip; and c) currently, the sensor is attached to a belt which is worn by the subject; the sensor must be firmly attached to the subject's body for safety reason as well as reducing the fluctuation of orientation of the antenna; thus, a better, less intrusive, user-friendly sensor attachment will be investigated.

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