Tracking Wireless Bio-Medical Sensors: Result Validation with the Bland-Altman Plots

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Outline

Abstract

In this paper, we present a series of experimental results of tracking an embedded sensor object similar in physical characteristics to telemetry capsules in the gastro-intestinal (GI) tract using radio frequency (RF) signals.

A fair description of implementation detail is given in the body of the paper while focus is on analyzing the experimental results.

Experiments were based on a test capsule transmitting radio frequency (RF) signals pulses at 433MHz (Centre Frequency of Free Band in Europe).

Primary focus is a unique and practical way of achieving the task of dynamically identifying the location of the capsule in real-time as it traverses the experimental duct.

Tracking results for experiments in liquid simulating the electrical behavior of the lower portion of the intestines yielded an average error of about 18.9%.

These results were validated with the Bland-Altman plots using manual measurements as gold standard.

Overall analysis shows that the end result of the algorithm is quite suitable for tracking ingestible telemetry capsules in the GI tract.

Introduction

VARIOUS technologies have been used to implement wireless positioning systems including ultrasound and radio frequency (RF) identification (RFID).

These positioning implementations require specialized hardware and infrastructure and are often expensive. However, in medical application, a wireless positioning implementation with non-specialized, relatively inexpensive hardware is desirable.

Within the GI tract for example, traditional methods of radio localization based on time or/and angle based methods (Time Of Arrival, Time Difference Of Arrival and Angle Of Arrival) are not feasible due to the dense multi-path characteristics of the digestive organs.

Such a positioning problem is worsened by non-line-of-sight (NLOS) conditions due to intestinal shifting, routing, filling and emptying, resulting in intermittent total signal loss.

To accurately determine the position of an object in the GI tract, simultaneous RSSI measurements from several access points (AP) are needed.

Most of these works incorporates devices with radio transmitters, camera, and in some case, storage.

Usually, the device is capable of delivering medication to an identified location in the GI tract.

It could identify a specific location based on pictures taken by the camera and consequently, it could deliver medication or take samples from such identified locations.

Other capsules are developed with a facility to measure pH level temperature and pressure changes inside the GI tract.

With the incorporated camera technology most of the products are able to transmit pictures of the intestine to a base station.

However, these devices have no way of determining the physical position of the capsule in real-time, and consequently, their passage through the GI tract are not easily reproducible.

Considerable efforts around the world have been devoted to exploring the application of micro and nano-technology to issues broadly related to human health.

There is ongoing research in analyzing more complex biological system such as living cells by combining micro-fabrication and microfluidic technologies.

Various types of embedded cores and miniaturized hardware are gaining significance in clinical medicine for disease diagnosis applications.

The potential applications for an indoor wireless positioning system are many.
For example, such a system could be used for an indoor navigation system, or to enable resource management by tracking physical assets and people or to provide a multitude of location based services.

Various technologies have been used to implement wireless positioning systems including ultrasound, infrared and Radio-frequency identification (RFID).

These positioning implementations require specialized hardware and infrastructure and are often expensive.

In medical device application however, a wireless positioning implementation with non-specialized, relatively inexpensive hardware is desirable. As presented in this paper, positioning was implemented by using RSSI signals.

RSSI are a measure of the power received by a radio receiver from a radio transmitter and provides information as to the proximity of the transmitter.

Method Comparison - THE BLAND-ALTMAN PLOTS

The Bland & Altman plot is a statistical method to compare two measurements techniques x1 and x2. In this graphical method the differences (or alternatively the ratios) between the two techniques **(x1 - x2)** (are plotted against the averages **(x1 + x2)/2** of the two techniques.

The Bland-Altman method was employed in this analysis because of the failure of the old methods of error measurements (regression, correlation, etc.) tells us whether the results of manual measurements and that obtained from the tracking algorithm can be considered equivalent.

A Regression Approach

Linear regression is probably the most popular approach in method comparison studies.

Based on that approach, the regression of test method to reference method should yield a straight line non significantly different from the equality line.
The equality line is determined by two parameters:
Slope =1 and intercept = 0.

Deviation from the equality line indicates a lack of agreement between the two methods. Because error is always present in the statistical tests for regression, the parameters provide a test for agreement between the methods. The least-squares technique is usually used to fit the regression data and to estimate the parameters.

B Correlation Coefficient

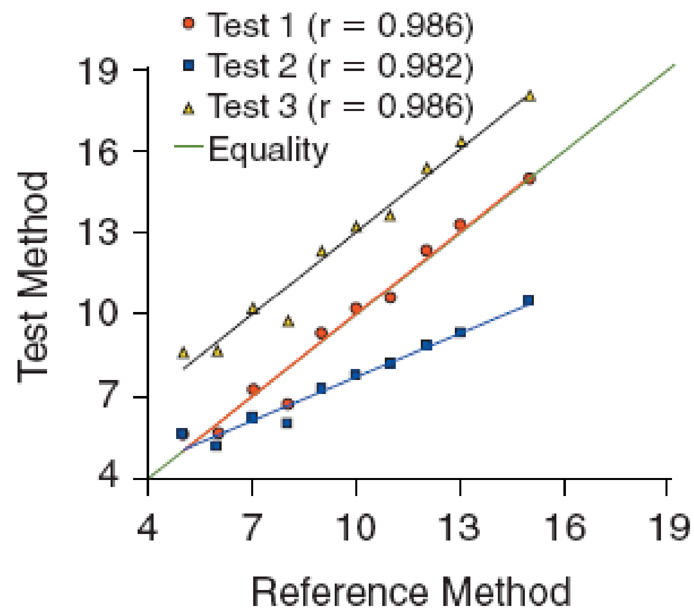
Sometimes when the results of the two methods have high correlation coefficient values, it is interpreted as an indicator of agreement.

However, high correlation does not necessarily mean agreement between methods.

The correlation coefficient measures the strength of the relationship, and it is incorrect to interpret it as a measure of agreement.

The methods agree when their scatter lies along the equality line, although high correlation can be obtained if the scatter lies along any straight line.

Simulated data for three test methods compared with the same reference method are presented in the next figure.



Correlation coefficient fails to measure agreement between the two methods

The three test methods have very high correlation with the reference, but only Test 1 agrees with the reference.

Test 2 does not lie along the equality line, whereas Test 3 exhibited a constant bias (CB) in comparison with the reference. Of course, the presence of constant bias does not change the value of the correlation coefficient.

Therefore the use of correlation coefficient to assess agreement in this case would be misleading.

Statistical testing of the correlation coefficient is irrelevant to the question of agreement because two methods designed to measure the same substance are expected to be related.

Really, the values of the correlation depend on the range of the data and also on the precision of measurements. Concordance coefficient and the gold standard correlation are two improved versions of the correlation coefficient. References abound on this subject in the Statistics libraries.

Two analytical methods can agree on average but exhibit biases in particular ranges of measurements.

Those are proportional biases (PB). PB is usually related to the range of measurements, but it can be related also to the quality of measurement.

In the Bland-Altman model, PB is regarded as a significant difference between two methods that exceeds the amount of CB for each subject. PB can be present for several reasons.

The test method may measure lower than the reference in the lower range of measurements and higher than the reference in the upper range.

Test methods can also be more sensitive to the measuring environment or less discriminative to related substances. Sometimes it is important to interpret PB as a source of disagreement between the two methods.

Construction and use of Bland-Altman plot

The key aspects of the appropriate construction and use of the Bland–Altman plot are the following:

The x axis should be constructed by the mean of the methods and the y axis in a way that is most sensible to the range of the x data (absolute: small range; percentage: medium range; log-scale: large range).

The 95% limits of agreement should reflect the actually observed nature of the differences (whether or not there is a relationship between difference and magnitude).

Most important, interpretation of the data should be done by comparison of the observed limits of agreement with a priori ones.

By using this comparison method, we want to know by how much the new method is likely to differ from the old; **if this difference is not enough to cause problems in clinical interpretation** we can confidently replace the old method by the new or use the two interchangeably.

Ideally, such difference variable should be defined in advance to help in the interpretation of the method comparison and to choose the sample size.

The basis for correlation will then be to investigate whether the upper (UCL) or lower (LCL) 95% confidence limit of 1.96 SD of the differences between the methods was equal to or smaller than a predefined limit for total error.

The reason why this strategy is seldom applied may be that the Bland-Altman plots does not present neither of the acceptance limits nor the confidence intervals (CIs) in the graphic plot.

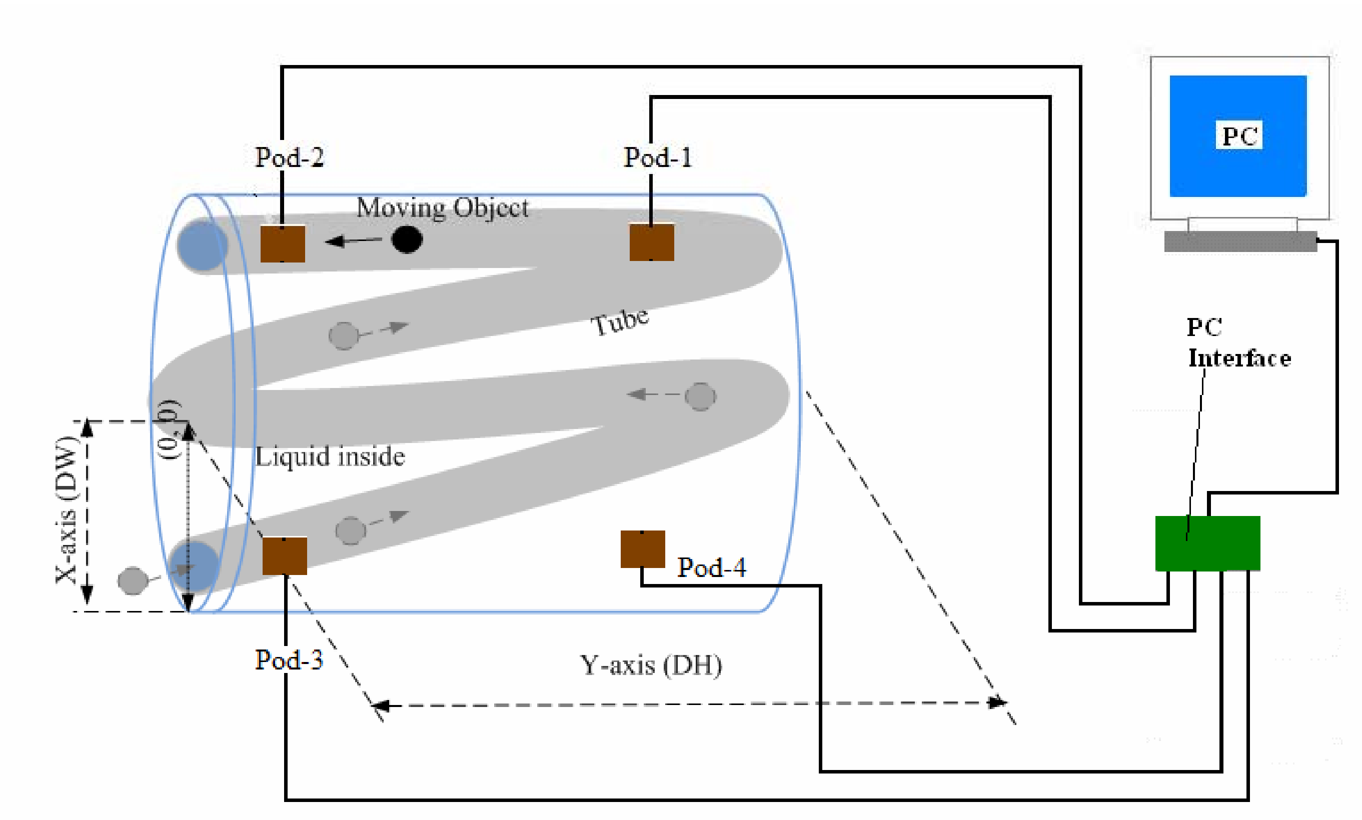
However, a generally accepted way of interpreting the plot in order to confirm agreement is to determine that the cluster of points are close around the zero line, and to examine the percentage of points outside the confidence interval.

Analysis And Solution Method

The following section gives a full detail of how we solved the tracking problem with experimental reference to the human gastro-intestinal tract.

As shown in the next figure, four receivers (Pods) are placed on a pre-determined positions on the patient's abdomen. In this setup, the Pods are wired onto an industry standard Data logger with adequate memory to save location data coming from the microprocessor over the time range of investigation.

Consequently at the end of investigation, the saved data are uploaded to a PC running custom software (algorithm) where necessary computation, approximation and compensations are made.



Capsule tracking with RSSI output

As stated above, the location of capsule are estimated from the voltage strengths at the receivers (pods). The voltages are translated into distance in the relevant section of the custom algorithm.

An integral part of this work is a fully developed C++ algorithm consisting of four major interrelated programs for achieving capsule triangulation [15].

The approach was not to solve for object position based on the intersection of 3 circles, but we used the linear approximation techniques on the data received from RSSI conversion process to predict the position of the object. Based on the initial prediction, final position of the object can be computed.

One main assumption in this method is the eliminating the third Cartesian axis *(z-axis).* This consequently reduces the problem to a 2-D analysis problem.

Capsule position is determined by considering the magnitude of the received RSSI signals at the four APs respectively located inside the four quadrants of the cylindrical volume representing the abdomen.

Using the translated distances from the RSSI voltages at the Pods, the algorithm is able to determine the approximate value of r_{ni}.

- While n 0 and for i = *1...4;*

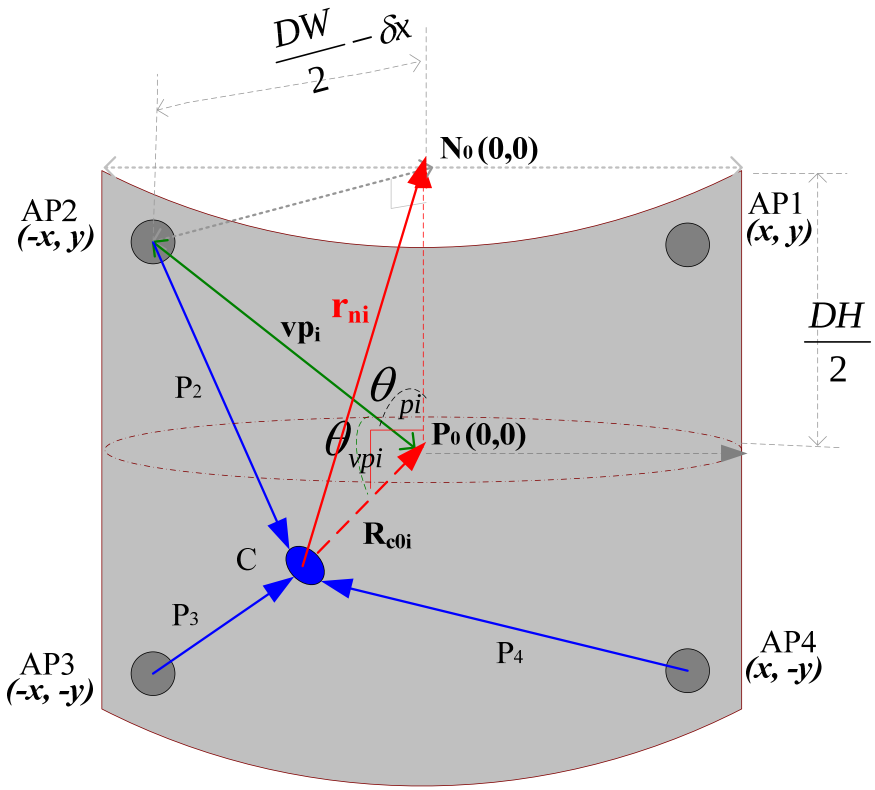
- The fixed position Pods for collecting data are labelled AP*i* and are represented by (*xi, yi, zi*).

- The approximate distance between any access point and the capsule is represented by the vectors *ri.*
- The knowledge of P_{n-1} and that of P_n are combined to tract the trajectory of the capsule within the period of examination.

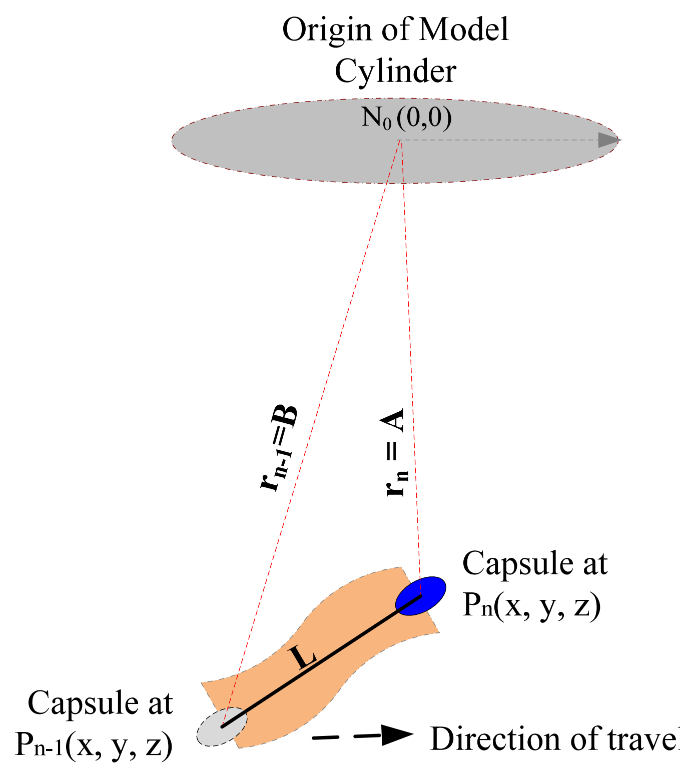
- The coordinates of the capsule is denoted as *x, y, z.* (from any arbitrary reference origin (0, 0, 0))

As shown in the following figures, it is possible to use the cosine rule to compute the length of intestinal segment which the capsule have traversed between the time periods $\mathbf{t_i}$ and $\mathbf{t_{i-1}}$.

The end result of all data collection, transformation and manipulation is a final human readable version of the data which can be displayed graphically on the computer screen for the physician to interpret.



Determination of Capsule position relative to N_0 (0, 0)



Intestinal Length computed within the algorithm

Results

- As shown in the previous slide, Intestinal length can be computed piece-wise by linearly following the curve of the trajectory with respect to time.
- The tracking data processing was performed by a local processor on a host computer (PC).
- Finally, a human readable version of data is generated and displayed on the computer screen for the physician to visually locate a particular section of the intestine based on real-time computed length of intestines.
- The Bland-Altman plot was used to validate the results obtained. Since there was no standard/reference with which such tracking results could be benchmarked, a manual measurement was used as a standard.
- The next set of figures show the graphs of object tracking (for three different experiments).
- Figures of the average of tracking experiments in liquid at 433MHz (algorithm) and the corresponding Bland-Altman plots for the average of above experiments are also shown in the next slide.

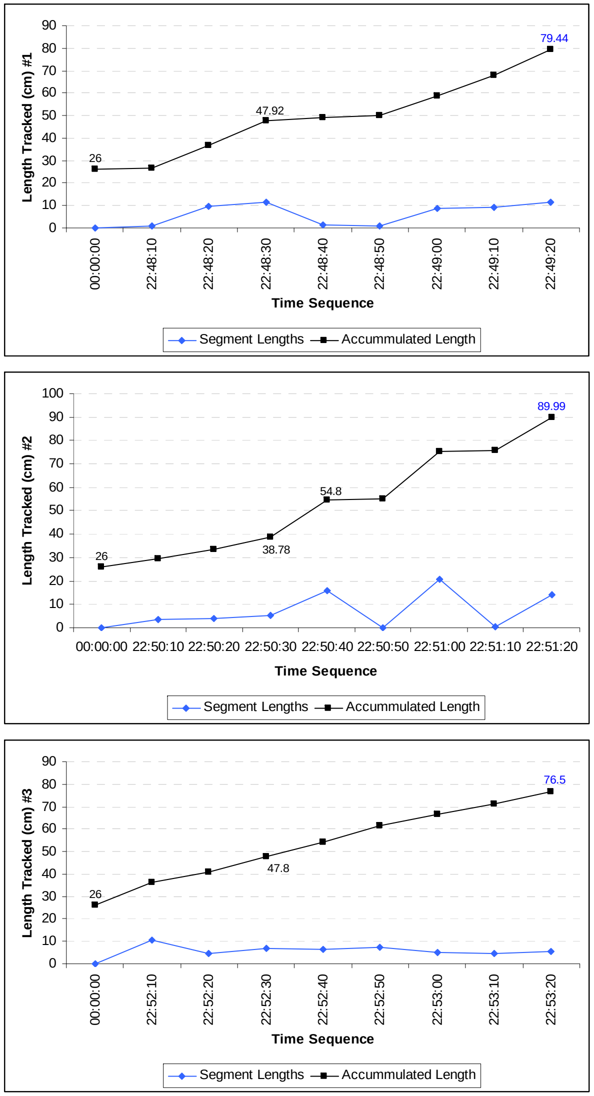


Fig. (a, b, c) Real Trajectory of object

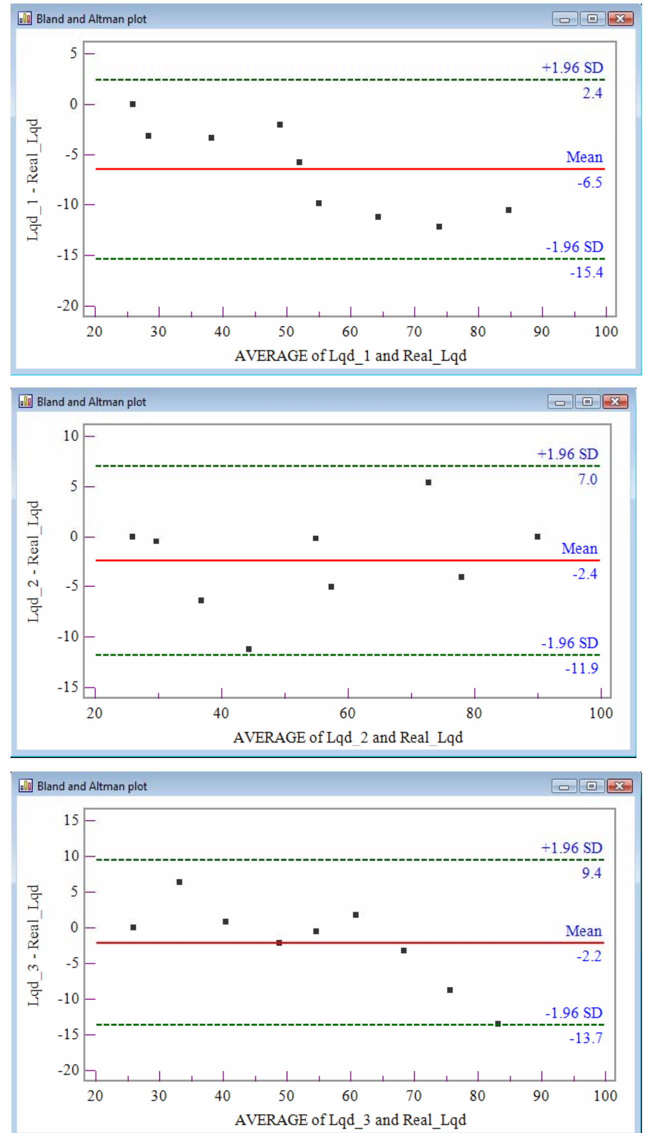
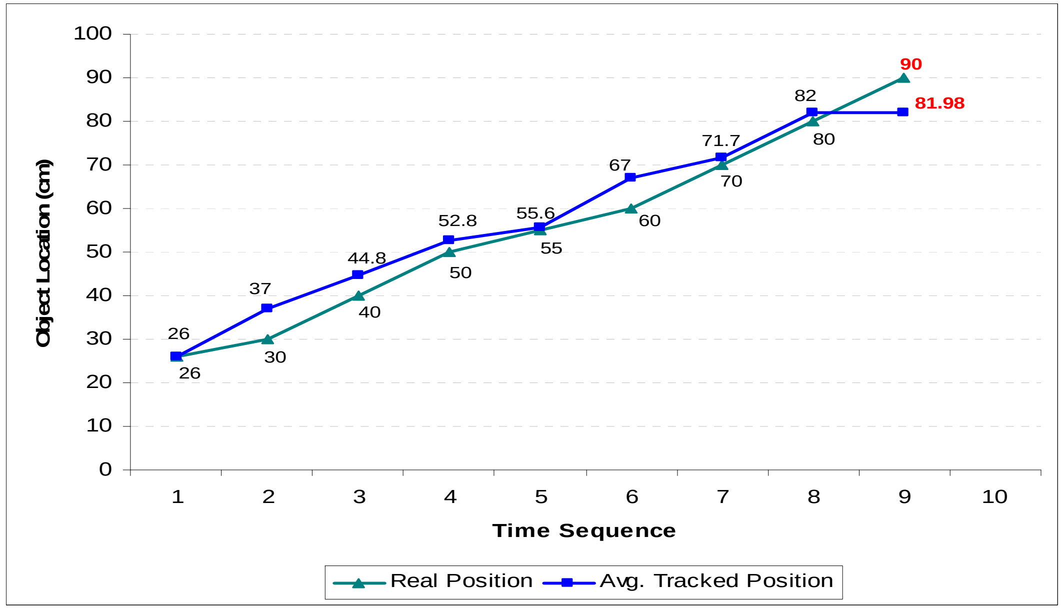
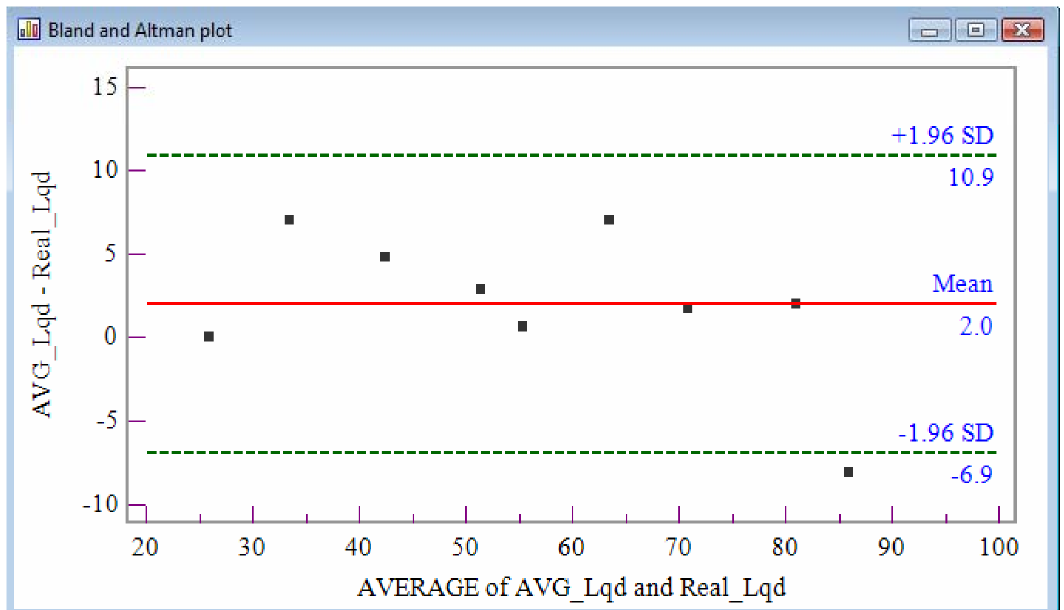


Fig. (a, b, c) The Bland-Altman plots for the three experiments with respect to the reference method

Real Trajectory of object vs. Average Trajectory of object



The Bland-Altman plots for the average of three experiments with respect to the reference method



Discussion

- As mentioned in earlier sections, the error in Liquid tracking experiments could not be represented intelligently as a ratio. Therefore another way of quantifying the error in tracking must be used.

- None of the classical way of error measurement (regression, correlation, etc.) could tell us whether the results of manual measurements and that obtained from the tracking algorithm can be considered equivalent. In that case, the Bland-Altman plots were employed for comparative analysis.
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- The segment length and total final tube lengths produced by the algorithm compared quite reasonably with the record obtained by physical measurements with less than 19% error.

- As shown here, the two methods of object tracking in a fairly small cylindrical volume was confirmed to be interchangeable.

- It is obvious though that both the manual data and those obtained from the RSSI-to-algorithm have constant bias even though all data points are well inside the confidence interval.

- Of course, the methods are interchangeable since there is no instance of PB in the results.

- **Conclusion**

- The results presented in this paper follow from our previous publication on tracking.

- It is to be noted that although the range of position results obtained conforms to theoretical expectations, practical implementations inside the human GI tract will introduce some unforeseen variations in the final results due to the effects of noise, organ-interface reflection, hardware and true nature of the human tissue.

  This was not accounted for in the results presented in this paper.

- Future works will involve the FDTD simulation of the antenna in layers of tissue representing the human organs, validating the radiation pattern with more path-loss variables and validating the tracking algorithm under loaded scenario.

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Thank You…