Automated Data Acquisition for Indoor Localization and Tracking of Materials Onsite

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Abstract –

Considerable body of literature exits on automated site data acquisition for tracking and progress reporting of construction operations. While GPS-based solutions have been widely investigated in many studies for outdoor tracking of these operations, indoor tracking proved to be more challenging. This paper focuses on indoor material localization and investigates the use of two remote sensing (RS) technologies including ultra-wideband (UWB) and radio frequency identification device (RFID) in order to support automated tracking of indoor operations. The integrated use of these two technologies is proposed to benefit from the capabilities of each technology and to have a cost-effective and practical solution for location identification of the materials on site. The proposed methodology includes two steps. First, tracking of the items located above floor level such as plumbing and HVAC installations. This was performed using accurate identification and 3D-location information generated by an UWB system. A set of experiments were carried out using various filters to improve the localization information. The results indicate that an increase in range distance between UWB tags and receivers increases the mean ranging error from around 20 centimeters to over 50 centimeters. In the second step, an UWB tag is attached to a hand-held RFID reader and accordingly the accurate location of that reader is stored. Then, by using algorithms such as boundary condition trilateration (BConTri) and received signal strength (RSS), the objects that are labelled by RFID tags are localized. Accordingly, this integrated configuration of the sensors eliminates the need for using a large number of RFID reference tags onsite for indoor material localization. The data fusion embedded in the proposed configuration is expected to enhance automated progress reporting. Besides, it is likely to enable identification and measurement of deviations from as-planned models in a timely manner. The experimental data captured in the lab will be analyzed and presented, highlighting the advantages of the proposed method.

Keywords –

Automated progress tracking; RFID system; UWB system; Data fusion

1 Introduction

Progress reporting is a critical part of the project control in which a large amount of as-built information related to a variety of tasks onsite are provided. However, it is not a simple task due to challenges associated with data acquisition and handling a large amount of information for a variety of functions such as scheduling, construction methods, and cost management. Object tracking is an important part of a progress reporting system in which the identification and localization information of the various objects onsite are needed.

The literature reveals a wide range of studies for identification and localization of the objects, as the main parameters of a tracking system. These two types of information can enable us to track an activity in a desired time span. Tracking materials and accessing onsite information can be challenging due to dynamic nature of onsite operations including material delivery and utilization. In fact, material management was identified as one of the areas that has a great potential for improvement on sites [1].

Many researchers have proposed the application of various Remote Sensing (RS) technologies such as GPS, Radio Frequency Identification Device (RFID) and Ultra-wideband (UWB) in tracking of various objects onsite [2]. However, applications associated with outdoor tracking of the materials are mostly based on GPS-based technologies [3-9]. But, this technology is not suited for indoor environment. Besides, due to a wide range of materials and structural objects in an indoor environment, there is a need for a system in which a large number of items can be tracked efficiently.

RFID technology has been used in this respect with great capability in automatic identification and tracking of tagged objects onsite. It is applicable for both built facilities and during construction due to its non-line-of-sight capability, wireless communication and on-board data storage capacities [10]. Besides identification capability, RFID technology is also used for localization of the tagged objects onsite. There are three main methods to localize an object using RFID sensors including triangulation, proximity, and scene analysis. Range-based localization is usually based on trilateration and triangulation techniques in which the received signal strength index (RSSI), phase-based indicator and time-of-arrival (TOA) are used to measure the range distance from a tagged object. Proximity technique is based on using some reference points with known locations in order to investigate whether a tagged object is close to those reference points or no. Scene analysis uses some algorithms (e.g. k-nearest-neighbor (KNN) or probabilistic methods) to localize tagged objects based on the similarity of received signal with a prior location fingerprints collected from the environment. In the range-based techniques mentioned above, the distance value between a hand-held RFID reader and a tagged object can be measured by converting the RSSI to an experimental range value. Having said that, these received signal strength (RSS) values are unreliable since they are highly dependent on various factors in different environments. However, proximity and scene analysis techniques are not based on the range value between tag-reader, but they still rely on RSS value for localization which makes the localization not reliable enough. Besides, they face additional barriers in terms of system configuration with extra cost and deployment, computing complexity and calibration difficulties [1]. In [1], application of the RFID technology for indoor location identification of the materials was investigated. However, the individual use of RFID sensors faces some difficulties since a high density of reference tags are needed [1,11].

UWB technology is a Real-time Location System (RTLS) which has a performance almost similar to an active RFID system, however, it uses very narrow pulses of radio frequency energy which are occupied in a wide bandwidth for communication between tags and receivers. Various types of UWB sensors use different positioning techniques for localization, including: time of arrival (ToA) or time of flight, angle of arrival (AoA), time difference of arrival (TDoA), and received signal strength (RSS). AoA has some advantages over TDoA as it does not require synchronization of the sensors nor an accurate timing reference. While TDoA is less sensitive to changes in setup calibration, it still requires more cabling to have an accurate timing reference. Several researchers have investigated the possibility of using this technology for location identification of objects to track construction operations. Most of their efforts were focused on evaluating real-time tracking of workers, equipment and materials in indoor and outdoor environments [2,12-15]. Besides, some studies have investigated the effect of the UWB sensors geometry, employment of some filters (e.g. Kalman Filter, particle filters and etc.) and the possibility of using static reference tags in order to enhance the localization accuracy of these sensors [12-13,16-21].Studies have been conducted on integrated use of the RS technologies to overcome their individual limitations in order to achieve a more reliable and economical system in which a large number of objects can be tracked and localized. Examples of these integrated systems for outdoor tracking of objects include systems in which a RTLS such as GPS is integrated with Barcode and RFID to benefit the positioning and identification capability of these two technologies. In [22], a low-cost integrated system of GPS-Barcode was designed for tracking of materials on a storage yard. Furthermore, an integrated use of GPS with RFID technologies could provide better performance for tracking of the resources onsite [2,3,23-25]. For instance, in [23], a system consists of spatially distributed mobile RFID readers equipped with GPS technology was used to track a set of mobile RFID tags. Besides, boundary constraints were introduced to facilitate RFID-based localization applications to overcome the challenge associated with unknown tag-reader distance.

Applications of indoor location identification of objects in construction industry include the real-time progress reporting, safety, materials management, and productivity analysis [26]. This paper aims to introduce a new technique in which an integrated use of the UWB and RFID technologies helps to efficiently track the materials in an indoor environment. Besides, a large number of objects are localized in a more economical way which can enable us to recognize and measure deviations from planned models by having both time and location of the available objects associated with each activity. This can result in a more enhanced and timely progress reporting onsite, which is essential for an accurate earned value analysis (EVA) and project estimating.

2 Experimental Performance of the UWB System

In a set of experiments in the Construction Automation Lab. (CAL) in Concordia University, performance of the Trek1000 UWB Evaluation Kit which is an off-the-shelve product is investigated. These sensors utilizes an atomic timer embedded in their PCB board that provides a high positioning accuracy in the range of a few decimeter. This product is almost eight times less expensive than the available commercialized sensors, however, it is still not a final product with a protected enclosure.

The initial setup of the experiment includes a system of four receivers and one tag. The data rate of this setup is fixed on 110 kb/s and in Channel 2. This is the standard setting defined by the manufacturer for maximum range measurements. For calibration and measuring the accuracy of this system, a grid on the floor with tiles in size of 90 cm × 90 cm was marked in order to define the 65 ground-truth test points which covers both Line-of-Sight (LOS) and None-Line-of-Sight (NLOS) scenarios. The anchors were put at height of 1.65 m except one of them at the height of 2.15 m, and a moving tag at height of 1.35 m. The experimentation consists of moving one mobile node to 65 different ground-truth locations. For each tie point, a time interval of 30 seconds was considered, so each tests lasted 32.5 minutes (i.e. 65X30 s=1950 s). However, 10 seconds before and after each displacement was rejected in order to guarantee a good ground-truth data. Figure 1 shows the good performance of this system. As we expected, all data points are above diagonal line which indicates the positive aspect of error due to the NLOS dispersion since there should never be range measurements shorter than the real straight path.

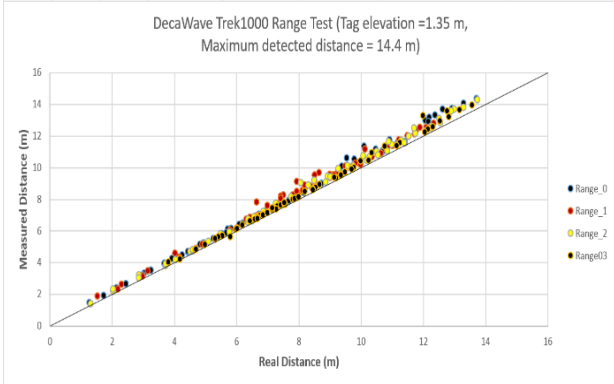

Figure 1. Real versus measured ranges.

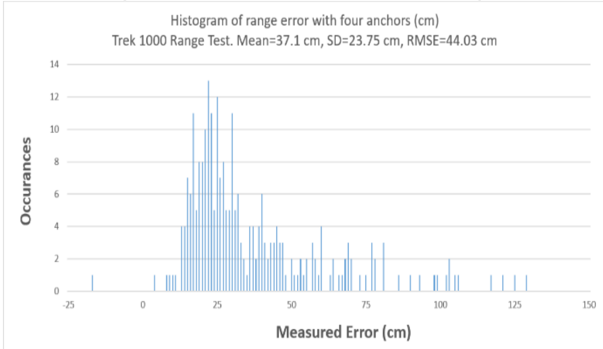

Figure 2. Error histogram in NLOS.

2.1 Range Measurement Accuracy of the UWB System

Range measurement is important since the location of the tagged objects are achieved based on their values. One way to improve ranging measurement is to remove the clearer outlier measurements from our estimation. A comparison of the methods to mitigate localization error associated with NLOS situation and the situations in which they can be employed are discussed in reference [26]. For the case of this research, there are technically two groups of objects which need to be tracked and localized by the UWB system. The first group is stationary objects which are tagged by UWB sensors. The second one is a moving RFID reader. For the first application, since the objects are stationary (or semi-stationary such as plumbing and mechanical facilities) a tailed UWB-ranging measurement model is used which is fitted to a histogram of the ranges error in NLOS situation (Figure 2). For simplicity, the same particle filter was used for the moving RFID reader.

In this experiment, first any outlier reading ranges in NLOS situation with the error value more than 0.8 m are removed from the initial data. Then, the testing ranges are split into three intervals with step of five meter (0-5,5-10,10-15). Finally, the remained reading ranges in middle of 10-second out of 30-second stop in each tie point are averaged to calculate the tag's location in each time step. Figure 3 illustrates the mean range error and standard deviation for each ranging interval with and without omitting initial outliers.

Initial Mean Error and SD values		
Range	Mean (m)	SD (m)
0_5	0.2258	0.0915
5_10	0.3259	0.21
10_15	0.5216	0.256

Mean Error and SD values without outliers		
Range	Mean (m)	SD (m)
0_5	0.2143	0.07311
5_10	0.3004	0.1426
10_15	0.4298	0.1752

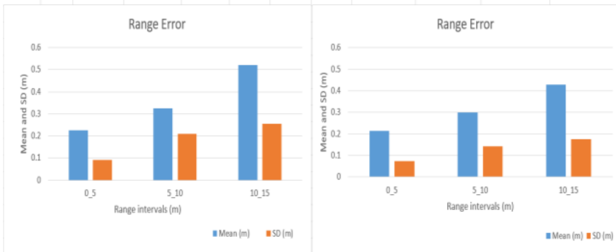

Figure 3. Mean and SD error values with outliers (left) and without outliers (right).

2.2 Localization Accuracy of the UWB system

In this research experiment the 3D location of the critical elements in elevation are tracked by UWB tags attached to these elements such as installations and critical spools in plumbing system. Besides, it is possible to localize and track the items which are tagged by RFID tags. For that, the real-time location of the hand-held RFID reader is acquired by the UWB tag attached to it (section 3.1).

From various techniques to mitigate the localization error [16,26], for tracking stationary (or semi-stationary) objects tagged by UWB sensors, a tailed UWB ranging measurement model is fitted to the experimental measurements presented in the last section. In fact, this model combines a Gaussian distribution (for the LOS measurements), a Gamma distribution (for the NLOS cases) and a constant value to cope with additional uncertainty and spurious measurements. By creating a measurement model using the error histogram in NLOS situation (Figure 2), it is possible to alleviate in-excess range measurements. Then, a particle filter with three states (i.e. X, Y and Z) is used to change the weight of each particle. Finally, the location of the moving object is obtained by computing the weighted mean location of all particles [16].

3 Proposed Methodology

There are various techniques for localization of the objects by using a RFID system. Since in this experiment a roving RFID reader (s) with known location is used, the application of a range-based technique is investigated to localize stationary tagged objects. Here an integrated system of both RFID and UWB sensors is designed. In fact, it is not economically practical to use only UWB tags for tracking objects onsite. While, the reasonable price for RFID tags make them a good choice for object identification and localization. However, the calibration of the system in this approach is problematic since the RSSI varies over time and it is highly dependent on the site environment. Plus, there is no direct relationship between this RSS value and a conventional ranging formula which results in low positioning accuracy [27].

In another approach, the tagged objects are localized by using a boundary condition-based algorithm in which the maximum reading range of a hand-held RFID reader helps to localize those objects which can satisfy the condition of appear in-out in that range limit [24,28].

Using only RFID tags for localization of the objects in an indoor environment needs to employ a large number of RFID reference tags [23]. Saying that, for outdoor tracking of materials, an integrated system of RFID and GPS-based sensors was proposed in previous literatures which eliminated the need for reference tags [23,25]. It was basically based on finding the location of the RFID reader (s) by a GPS receiver and then finding the tags location through trilateration technique. Unfortunately, in an indoor environment the performance of the GPS sensors are highly degraded since they need a direct access to the sky to receive signals from satellites. In this way, the UWB system can be replaced with GPS system to localize RFID reader in each time span.

3.1 Integrated UWB and RFID Technologies

An integrated system of the UWB and RFID sensors helps to benefit from positioning capability of UWB sensors for localization of RFID reader (s) in an indoor environment. In fact, by knowing the location of the RFID reader (s), it would be possible to localize RFID tags by using a Boundary-condition Trilateration (BConTri) algorithm or a received -based technique. In the boundary condition-based algorithm, a tag location is measured by solving three (four) lateration equations (Equation 1) in which the intersection of three circles (four spheres) for 2D (3D) localization is needed. While, the RSS-based algorithms estimate the tag location as an average weighted over received RSSI of the three (four) corresponding reader locations under the boundary condition (Equation 2) [23].

$$(x - X_{i,t})^2 + (y - Y_{i,t})^2 = r^2 \tag{1}$$

$$(\text{x,y}) = \left[\frac{\sum_{i=0}^{2} X_{i,t} * rs_i}{\sum_{i=0}^{2} rs_i} + \frac{\sum_{i=0}^{2} Y_{i,t} * rs_i}{\sum_{i=0}^{2} rs_i}\right] \tag{2}$$

Where (x,y) are unknown target tag coordinates, $(X_{i,t}, Y_{i,t})$ are the RFID reader location at time t which are measured by UWB sensor (i=0, 1, 2 for three different RFID reader locations), r is the range distance between tag and reader and rs_i is received signal strength indicator of reader i.

In BConTri technique, the initial value for r is set to the nominal range value of the RFID device (r_0). However, this value needs to be corrected until achieving an acceptable area of intersection between three circles for 2D localization. In this way, an even virtual distribution of points in all three circles is considered. If there is no common intersection area between these circles (number of the virtual points are less than a defined value), then this radius should be increased. In contrary, if the intersection area is more than a defined value, the radius should be decreased. Finally, the estimated location for each tag is calculated by averaging the points available in the intersection area.

It is worth mentioning that since here the tagged objects are static, a few number of readers would be fine for location identification of the items. However, in case of tracking moving objects, a large number of RFID readers would be required. To localize a tag, a set of acceptable boundary reader points (BRPs) should be identified. Around 10 points would be enough for an experimental assessment to localize a tag. Then, three (four) out of ten points are selected to solve the trilateration equations for 2D (3D) localization. Since selection of these three (four) points combination can affect the location accuracy, the combination with the highest value of dilution of precision (DoP) is preferred. In fact, in a GPS system the localization accuracy will increase when visible satellites are far apart which results in a higher DoP and geometry is stronger. Saying that, unlike GPS system, RFID system is not working based on clock offset (using the time difference to measure distance). In this way, a new approach to consider the effect of the RFID reader locations on the localization accuracy is needed. In fact, besides measuring the accuracy of the system to localize the RFID tag (s), a calibration model for distribution of the RFID reader (s) is also needed. Similar to the DOP factor in GPS system, this model can enable us to measure the variance for various three (four) combination of the BRPs. Each of these variances are corresponding to an average error value in localization of the tag. In this way, each combination of the BRPs is equivalent to a specific accuracy in measurement which can be used as a standard for selection of the reader (s) distribution.

3.2 Schematic Design of the RFID and UWB Data Fusion Model

Below shows a schematic diagram of the methodology to integrate the UWB and RFID systems in order to achieve a more practical and cost effective technique for indoor location identification of the materials onsite (Figure 4). This information can be used for automated progress reporting and a more timely earned value analysis.

The first part of the tracking system is based on using UWB tags to track objects above floor level. For this type of objects, the UWB tags are used to provide 3D identification-location information of the objects. However, due to high cost of UWB tags it would not be reasonable to tag all objects for tracking each activity. This issue can be addressed by tagging critical objects to track critical activities.

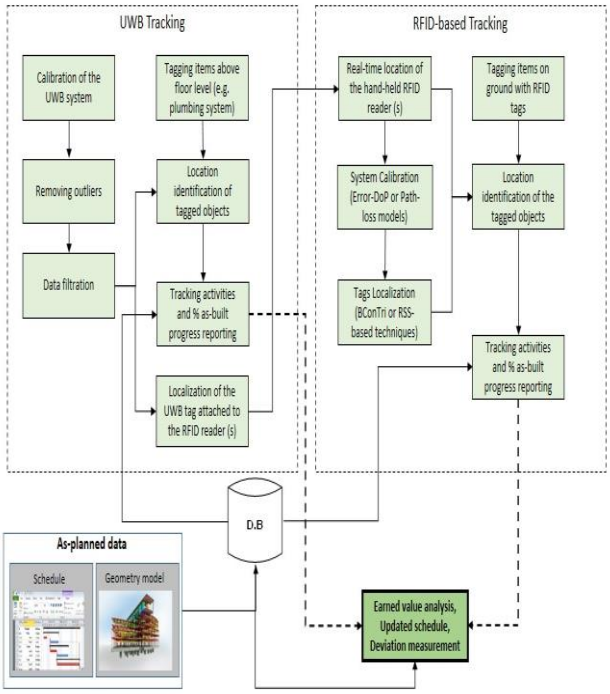

Figure 4. Conceptual overview of the location identification material tracking system.

In the second part of the tracking system, the integrated use of RFID and UWB systems is proposed to track a larger number of objects but in a cost effective manner. In fact, by attaching an UWB tag to the hand-haled RFID reader (s), it would be possible to localize the RFID reader by using the data acquired by the UWB system. By knowing location of the mobile RFID reader (s) and using a localization technique (e.g. BConTri or RSS-based technique), it is possible to localize objects with the attached RFID tags. As mentioned, system calibration should be conducted before tags localization. In the following subsections, after a brief review on some protocols for data acquisition, the calibration and localization modules are elaborated.

3.2.1 Data Acquisition protocol

The data acquired by integrated RFID-UWB sensors should be time-stamped. Saying that, the UWB system have a timer with ms accuracy, while the timer accuracy for RFID system is in second.

a) Data acquisition for system calibration: to achieve the path-loss model required for the RSS-based range measurement, the RSSI received from 10 RFID reference tags on the ground are recorded. Since the exact position of all the tie points and the 10 reference tags are known, it would be possible to measure the range distance between the reader and each reference tag. The RFID reference tags are located at the height of 1 m, while the hand-held RFID reader output is set to 22 dbm (with an approximate reading range of 3.5m). Here we move forward on the 35 tie points (the same tie points for UWB system calibration) every 30 seconds. After deducing the first and last five seconds in each step, the data read by the RFID reader are analysed. In another scenario, the real-time location of the hand-held RFID reader is estimated by the UWB tag attached on it. In this way, there is no need to move on any tie-points, however, a time-step (such as one second) should be considered for matching RFID and UWB data. To enhance the accuracy of the UWB tag in localizing the RFID reader, we should ask the surveyor to stop moving when triggering the hand-held reader.

b) Data acquisition for the RFID tags localization: in order to meet the condition required for localization based on the BConTri algorithm, some protocols for data acquisition need to be respected by the surveyor. In fact, an acceptable reading for a tag in this algorithm is based on a roving RFID reader moving to different directions in each time step. For that, we should ask the surveyor to not stop moving when pushing the trigger of the hand-held RFID reader. Plus, for better performance of the hand-held reader, it is needed to put it in rest mode every minute in which the surveyor should stop moving.

3.2.2 Calibration Module

To calibrate the system for localization of the tags by the hand-held RFID reader, first a set of acceptable readings for localization need to be selected. The acceptable reading data can be varied depending on the algorithm we use for localization. Here, both BConTri and RSS-based algorithms are tested to evaluate the accuracy of each of them for localization. For instance, in BConTri algorithm the acceptable readings are those in which the event appear in-out happens for each tie point. For the RSS-based algorithms, on the other hand, there are some factors that may affect the accuracy of the localization measurements. This includes factors associated with the RFID devices such as operating frequency, the hand-held RFID device power and distance between the tag (s) and reader. The results of an experiment showed that if the distance of the reference tags from each other is half of the device reading range (0.5RR) then a better detection rate is resulted [28]. The factors associated with indoor environment also influence the RSSI signal such as free space loss factor, multipath reflection, and interference effects [29]. As mentioned above, by putting some reference tags with known locations, it would be possible to evaluate the accuracy of the measurements. Figure 5 illustrates the various steps for the system calibration.

a) In BConTri-based technique: for this method, the combination of RFID reader locations with the highest value of Spatial Dilution (SD) is preferred in order to achieve better localization accuracy. Saying that, the SD value refers to the distribution of a number of objects in space and their geometric configuration, mostly used as an indicator of the locating accuracy for systems which are working based on the ToA and AoA positioning techniques. In fact, it is equivalent to the mathematical variance and DoP in GPS-based systems. In this case, for each combination the SD factor for hand-held RFID locations and the corresponding error in identified reference tags location are calculated. Then, the SD can be normalized into a ratio of the SD (RSD) by diving its value to the highest tag-reader distance to omit the effect of range distance in estimation. The details of the mathematical calculations are provided in [25].

After repeating the steps above for all possible combinations of the RFID locations geometry, a linear regression is assigned to the points achieved in a graph in which the error value (m) and RSD are the variables in vertical and horizontal axis respectively. This graph can be used as a standard for standard value of DoP and the corresponding accuracy. The standard value is used as a threshold for selection of the data in localization of other tagged objects. In fact, only the RFID reader location combinations with SD value more than the standard SD value are accepted.

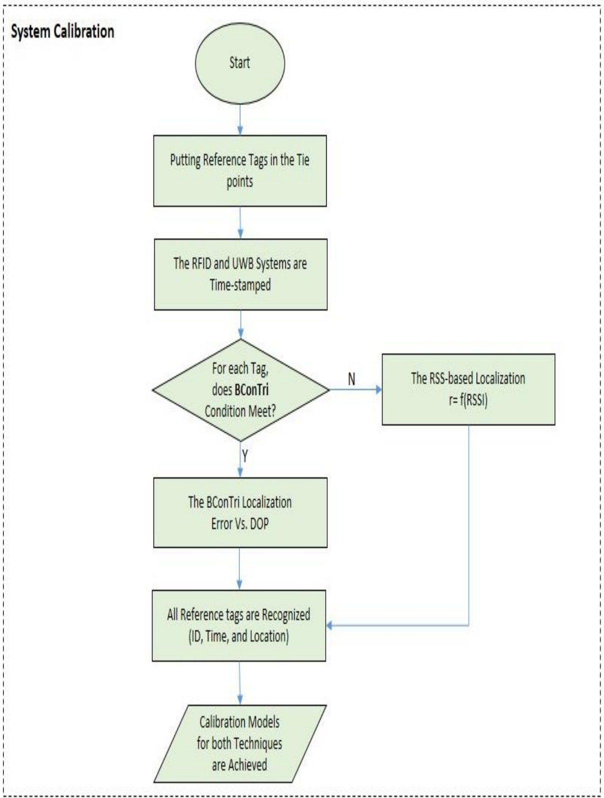

Figure 5. System calibration diagram.

b) In RSS-based technique: to use this technique for tags localization, a path-loss model is needed. In fact, based on the RSSI recorded for each reference tag and the corresponding distance range value (DRV), the model would be achieved (Equation 3). Then, by knowing the location of the RFID reader recorded by UWB sensor attached, the location of the each RFID tag is calculated by solving three distance equations (Equation 4).

$$\mathrm{DRV} = -\,0.5617\ \mathrm{RSSI} - 39.9337 \quad (3)$$

$$\mathrm{DRV} = [(x_{r\_uwb} - x_i)^2 + (y_{r_{uwb}} - y_i)^2]^{1/2} \quad (4)$$

In which (x_{r_uwb}, y_{r_uwb}) are the location of the hand-held RFID reader (s) which are acquired by UWB device attached to it. And (x_i, y_i) are the coordinates of the identified RFID reference tags with known locations. For each identified tag, an average of the RSSI values and the calculated range value are recorded.

The result of the system calibration to achieve the path-loss model is shown in Figure 6. It depicts the RSSI versus the distance between the reference tags and the reader in each tie point. In fact, the average of the RSSI for each tag identified in each tie point is calculated. Then, for assigning a regression model to the data acquired, the data are again averaged for every 5 cm increments. Details of the best regression model and their accuracy can be found in [26].

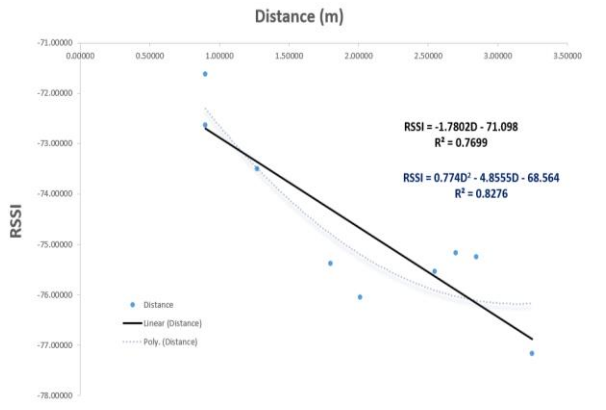

Figure 6. RFID system path-loss model.

3.2.3 Localization Module

After conducting the calibration, it is time to localize the tags location by using the standard spatial dilution (SD_{st}) or the path-loss model to localize tags in BconTri and RSS-based techniques respectively.

a) Localization through BConTri technique: to localize a tagged object, the location data achieved from the selected combinations of SD (SD> SD_{st}) for each identified tagged object are averaged.

b) Localization through RSS-based technique: to localize a tagged object, first the location of the hand-held RFID device in each time span is achieved from the UWB tag attached to it. Then, by using the path-loss model achieved in the calibration step, the range of the tagged object from the hand-held RFID is calculated. The results for the sample RSSI received from 10 target tags indicated an absolute average error of 0.94 m.

4 Summery and Concluding Remarks

This paper investigates the possibility of tracking objects in an indoor environment by doing both identification and localization of a set of tagged objects onsite. For objects in elevation, the performance of the UWB tags were investigated. However, to track a larger number of objects, the integrated use of UWB and RFID technologies was proposed. For that, a hand-held RFID reader was tagged with an UWB sensor in which the location of the RFID reader was acquired by the UWB system. A two-step algorithm developed including calibration and localization modules. In fact, the calibration was based on using some tie points with known locations in order to provide calibration models. After achieving the calibration models for both BConTri and RSS-based techniques, the tagged objects were localized in plane surface. However, the efficiency of this algorithm for 3D localization of the tagged objects need to be investigated more in future.

4.1 The Methodology Contributions

The tracking system proposed can provide identification and localization information for a set of objects in an indoor environment. The use of low cost RFID tags made it possible to track and localize a larger number of objects in comparison with systems in which the individual use of UWB tags were proposed in previous studies. The two-step algorithm developed for localization of the RFID tags would make it possible to have less missing data of the tagged objects in cases that the tagged objects cannot meet the BConTri required condition. In these cases, the object will be localized by the RSS-based technique. Besides, the integrated use of UWB-RFID technologies solved the problem of using a large number of reference tags for localization of the hand-held RFID reader that was proposed in previous studies.

4.2 The Methodology limitations

The localization algorithm provided in this experiment has some limitations. First, to localize a tag in BConTri algorithm, it is needed that at least three (four) readings happens for that tag in which the tag should appear and disappear to be considered as an acceptable reading. This condition may not be possible especially for 3D localization in an indoor environment with a cluttered distribution of the objects. To mitigate this problem, the tags were localized by RSS-based techniques in case that the BConTri requirement is not met. However, the accuracy of the RSS-based localization is still less than the BConTri algorithm.

Another limitation is the difference in reading rang of the RFID sensors in which considering a circular (spherical) profile for reading range may get biased if the direction of the hand-held RFID reader to the tag differs. Finally, the accuracy of this localization method is highly dependent on the calibration of the system in each environment. For that, an accurate positioning of the reference tags (tie points) is required.

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