Medical Navigation Based on RFID Tag Signals: Model and Simulation

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Abstract

Although optical tracking systems are state of the art in intraoperative navigation they suffer from some severe drawbacks like the size of the reference bases or their dependency from line of sight. In this work we present the concept of an electromagnetic based tracking device that might help to overcome these limitations. The basic elements of our prototype are regular Radio Frequency Identification (RFID) devices but in contrast to just detect presence of a tag we use multiple antennas to measure the phase differences of the returned signal. Based on this data we intend to compute the tags' position during the operation. In this work we demonstrate with some simulated data that in general the needed accuracy of about one millimeter can be reached.

1 Introduction

Minimally invasive surgery is highly preferable by patients but leaves the surgeon with almost no direct sight to the place of operation. To compensate for that, several different navigation systems have been developed over the years [3]. Most of them use preoperative images as a basis to support the visual orientation of the surgeon. This implicitly brings along the need to define specific landmarks to map those images to reality. This can be done directly on the patient or indirectly by matching intraoperative image data (e. g. from ultrasound devices) with the preoperative CT or MRI images. In either case surgical instruments in the operating room must be tracked and thus always remain visible to the tracking device i. e. a stereo camera in optical systems.

Electromagnetic tracking devices have two major advantages in comparison to optical devices. First, their detectability is tied to their signal strength and frequency but only indirectly to their actual size. Markers with a size of only a few millimeters can easily be constructed and could even be fixed to different types of instruments and inserted into a patient [2]. In addition electromagnetic waves are absorbed but not totally blocked by human bodies if the right frequencies are used. This means that the surgeon can move much more freely during operation because he doesn't have to worry about an undisturbed line of sight to the cameras anymore.

Of course these advantages are not gained for free. For ones electronic markers are more complex to construct than optical ones. The increasing use of RFID tags [1] in the recent years however has led to a rich supply of affordable devices already. The biggest remaining problem is therefore the interpretation of the electromagnetic signal. There are several different possible solutions depending on the equipment available. A measurement of the time it takes for a signal to travel from the tag to the different antennas for example needs a very precise clock. An estimation based on the signal strength on the other hand is often only usable after an extensive calibration [4]. To minimize the costs of the equipment and the time to set it up we decided to simply measure the phase differences of a signal that occur between different antennas and do the interpretation into a specific location with a more complex software solution.

2 Materials and Methods

2.1 System

Our prototype is intended to consist of eight receiving antennas, one RFID reader to activate the tags and multiple RFID tags, all working at 866.5 MHz. A standard phase detector is connected to all eight antennas and gives out the phase differences between the different antennas when a tag is emitting a signal. In our first experiments we will concentrate on locating a tag in air, thus operating at the same level an optical navigation system does.

2.2 Model for the Combination of Phase Information

Since the phase is a repeating pattern, a single phase difference usually allows for multiple different possible emitter locations even in a one-dimensional space, e. g. the connecting line between the two receiving antennas. In a two-dimensional space each of these points gives raise to a line of possible locations which we therefore call an isophase.

An isophase is characterized by the distance difference to its two antennas which must be maintained for all points of the isophase. Using the connecting line between the antennas as x-axis and the original point of the isophase on it as origin we can express this mathematically by equation (1) where l_1 and l_2 denote the distances between the antennas and the origin, x is a shift on the x-axis, h is the corresponding y-shift and Δ is an arbitrary positive number. A graphical interpretation of this is shown in figure 1.

$$\begin{aligned} h^2 &= (l_1 + \Delta)^2 - (l_1 + x)^2 \\ &= (l_2 + \Delta)^2 - (l_2 - x)^2 \end{aligned} \qquad (1)$$

By eliminating Δ from equation (1) we obtain equation (2) which directly connects the possible shifts on x and y-axis to still remain on the isophase.

$$\left(\left(\frac{l_1 + l_2}{l_1 - l_2}\right)^2 - 1\right) x^2 + \left(\frac{l_1 + l_2}{l_1 - l_2} - 1\right) 2 l_1 x = h^2 \qquad (2)$$

In three dimensions a y-axis perpendicular to the x-axis is no longer explicitly given but can be chosen freely. The y-shift therefore turns into an combination of y and z-shift meaning

$$h^2 = y^2 + z^2. \qquad (3)$$

In case all phase differences can be associated with just one isophase each, we can compute the emitter location as the intersecting point of all these isophases. To be able to do this however, equation (2) must be transformed into a global coordinate system since the given equation describes an isophase in its own special coordinate system defined by the connecting line between the two involved antennas. This results in a more complex formulation as given by equation (4).

$$\begin{aligned} a_0 = \; & a_1 x + a_2 y + a_3 z \\ & + a_4 x^2 + a_5 xy + a_6 xz \\ & + a_7 y^2 + a_8 yz + a_9 z^2 \end{aligned} \qquad (4)$$

To keep the equation readable all isophase specific constants that emerge from the factors in equation (2) during the transformation are denoted by $a_0, \ldots, a_9$.

2.3 Choice of Isophases

In most practical situations the receiving antennas will be spread over an area of several square meters, thus allowing for tens or even hundreds of isophases to fit in. Under these circumstances the main challenge of our method is to determine the isophases that will create a solvable set of equations together.

For our first experiments we use a straight forward approach that simply tries to solve every possible combination of isophases. This is of course very expansive in terms of computation time but could be greatly improved by a highly parallelized computer system. To determine the most fitting set of equations we treat all variables (e. g. x, xy or z^2) in equation (4) as independent and check afterwards how well their values match, i. e. how much $x \cdot x$ differs from x^2 and so on.

2.4 Simulations

We set up a series of simulations to test the heuristic described above as well as to determine the needed accuracy in phase differences. Each simulation used a setting of eight antennas and 100 tags, all randomly placed in a cubic area of 400 mm × 400 mm × 400 mm. The antennas were split equally into two groups and for each pairwise combination of antennas from different groups the theoretical phase differences of signals from all these tags were calculated.

The location error δ was then defined as the difference between the actual positions of a tag and the position our algorithm computed from these phase differences. Since the output of this basic version of the algorithm is rounded to the first decimal place an additional deviation of ±0.1 mm is to be considered when interpreting the statistical results.

The first simulations (S1 - S5) were done with phase differences that were accurate to the fifth decimal place. Since it is highly unlikely to get such accurate data in real experiments we conducted some additional simulations (S6 - S8) where we added some gaussian noise with mean 0 and variance σ to the phase differences and presented them to our algorithm.

3 Results

In the simulations S1 to S5 (see table 1) the basic algorithm almost always located a tag's position with a precision of about 0.1 mm or better. Additionally all major mistakes that were made in the localization could be clearly identified as such by their mismatch in variable values as discussed in section 2.3.

Once noise was added to the phase data the accuracy dropped (see table 2) and the location error even reached several centimeters for noise with a variance $\sigma \geq 10^{-4}$. Up to $\log \sigma = -6$ however the algorithm was quite tolerant against the noise, meaning it will need at least an accuracy of three decimal points in phase information in general to perform its task reliably.

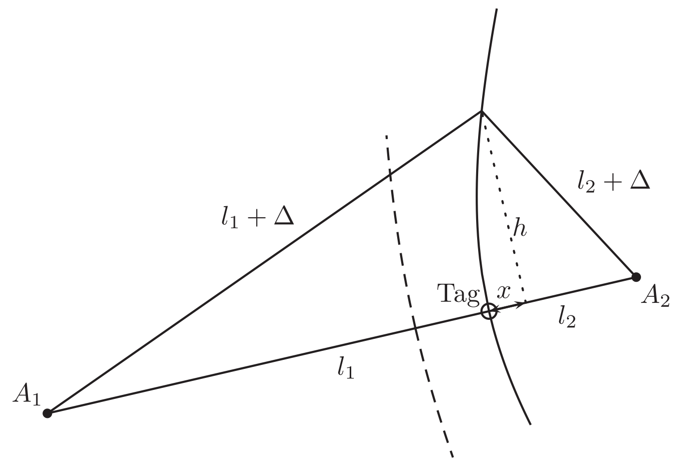

Figure 1 Draft of the RFID system showing two antennas (A_1 and A_2) and one tag. In addition to the correct isophase (straight line) another isophase with the same phase difference is drawn in (dashed line) which is created by moving the origin by $-\lambda/2$ on the line between A_1 and A_2. The remaining eight other isophases are not shown to keep the plot clear.

	Simulation no.				
	S1	S2	S3	S4	S5
Localization error δ in mm (median)	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Hits in % ($\delta \leq 0.1$ mm)	100	95	96	98	95
Misses in % (0.1 mm $< \delta \leq 1$ mm)	-	1	-	-	2
Misses in % (1 mm $< \delta \leq 2$ mm)	-	1	-	-	1
Mistakes in % ($\delta > 2$ mm)	-	3	4	2	2
Mistakes rejected in %	-	3	4	2	3

Table 1 Comparison between the localization gained by evaluating simulated phase data and the actual tag positions. All 5 simulations consisted of 100 random tag positions. For each simulation S1 to S5 the number of tags which are localized correctly (hits) is shown. The misses are divided into cases with a localization error below 2 mm and more severe mistakes.

Simulation no.	Location error δ in mm (median)						
S6	< 0.1	0.2	0.6	1.8	5.2	20.8	60.4
S7	< 0.1	< 0.1	0.1	0.3	0.2	2.5	7.3
S8	< 0.1	< 0.1	0.1	0.4	1.4	3.3	12.9
Noise level ($\log \sigma$)	-9	-8	-7	-6	-5	-4	-3

Table 2 Comparison between the localization gained by evaluating noisy simulated phase data and the actual tag positions. All simulations consisted of 100 random tag positions. For each simulation S6 to S8 the median error is shown for different levels of the added noise (described by its variance σ).

4 Discussion

The simulations showed that the basic ideas can be implemented successfully and result even without much elaboration in position estimations that achieved accuracies within the acceptable distances of less than one millimeter. To improve our algorithm further, it would easily be possible to including a tag's history to rule out positions in a great distance or use evolutionary search algorithm to select the correct set of isophases more quickly.

5 Conclusion

We presented a model for position estimation in a medical tracking system based on standard RFID devices and demonstrated with some simulated data that a general accuracy of less then two millimeters can be reached. As real data is highly disturbed, we simulated such effects by adding noise to input data and showed that up to a variance of 10^{-6} the average location error still remained below 2.0 mm. In the next step we will improve the search for the correct set of isophases, as well as evaluate the general amount of noise in real experimental data that we intend to present to our algorithm.

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