Active access card and non-blocking access gates

Semester Project

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Introduction

In the frame of an Innosuisse project [1] the Integrated Actuator Laboratory is collaborating with an industrial partner (e-liberty) and some research groups of He-Arc to the development of a new approach to perform access control to facilities offered by ski resort. The system is based on active access cards for customers. With an autonomy of one month, the card must allow the positioning of the customers on the domain, the achievement of micropayments, the opening, and closing of electronic locks, the communication with the company's servers and the non-blocking access to facilities. The most ambitious aim is the development of the gates carrying out the non-blocking access control. That is to say, detect people passing the gates and reliably automatically determine whether they are in possession of the appropriate access pass or not.

For positioning the access card around an access gate, the idea is to use modulated magnetic fields. One advantage of this approach is to use magnetic fields to wake-up the card for a sleep mode [2]. Then, it is conceivable to position the card with an accuracy of a few centimeters [3][4]. For this project, we propose to first study the literature about positioning based on the magnetic field [5][6] to well understand the constraints of this approach. The next step is to evaluate whether the circuit currently implemented on the last version of the card can be used to perform positioning. The last step is to implement such a positioning, i.e. create the necessary fields and perform the measurement.

Figure 1: Overview of the access card.
Work description and project schedule

To perform positioning by a magnetic field, one possibility is to generate multiple fields (figure). Ideally, these fields must be orthogonal, i.e. generated by antennas in such a way that the fields are orthogonal by each other. In the case of this project, the idea is to place the different antennas in the same place. These are what we call transmitting antennas. At this level, there are no energy constraints. It is also possible to modulate the fields in different ways to distinguish them.

Positioning techniques based on magnetic fields are not new. But the development of electronics, i.e. integrated circuits, nowadays makes it possible to design low cost and low power systems. On the receiver side, there may be different antennas to receive the fields emitted by the different transmitters. This is what has been implemented in the developed card. It is thus possible to analyze these fields in order to deduce the relative position and orientation of the receiver, i.e. the access card.

In this project, the first step is to study what has already been done in order to have a clear idea of the different methods that have already been developed or implemented into products. In a second step, it is asked to implement a positioning of the access card using the chosen AMS circuit.

The project tasks are summarized in the following list:

- Study the literature about positioning based on magnetic fields
- Summarize the technological constraint and the equations
- Develop a system to perform positioning the access card
  - strategy to perform the positioning
  - magnetic field multiple-antenna transmitter
  - implementation of the magnetic field detection
- Evaluate the limit of this positioning system

Instructions for the conduct of student projects can be found on the laboratory website (https://www.epfl.ch/labs/lai/studentprojects).

Table I: Summary of main dates and deadlines

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start of project</td>
<td>16.09.2019</td>
</tr>
<tr>
<td>End of project</td>
<td>20.12.2019 (14 effective weeks)</td>
</tr>
<tr>
<td>Report submission</td>
<td>10.01.2020 (16h00)</td>
</tr>
<tr>
<td>Intermediate presentation</td>
<td>TBD (mid-term)</td>
</tr>
<tr>
<td>Final presentation</td>
<td>TBD (last week of the semester)</td>
</tr>
</tbody>
</table>

Literature Review

Traditionally there are 2 different ways to classify the magnetic tracking systems depending on the type of the generated magnetic field. This magnetic field can either generated by an Alternating Current (AC) or it can only be a static magnetic field using coils with pulsed Direct Current (DC). [9,10]. In 1979 Raab [5] introduced tracking and positioning and tracking system using 3 axis magnetic dipole sources and 3 axes magnetic sensor. Later in 2001 Paperno et al. [11] uses 2 axes a quasi-static rotating magnetic field as source and 3 axes magnetic sensor. In this way they increased the speed and reduced the magnetic interference. Some tried to optimized sensor positions [12], and some tried to change the generating magnetic field source [13].

Summarize Magnetic Technology

To get the best result for the proposed application, we have to find the appropriate method to use the same concept in the existing positioning problem. Now we have to get an overview of the existing magnetic systems and their properties to choose the proper method for this project. An overview of the existing technologies in this field will create the sketch to choose between them. This requires a good technical understanding.
Providing an overview of magnetic field antennas the applicable system can simply be chosen. Knowing the properties of antenna which can provide the required electromagnetic field is critical for the whole project.

System development
A system which enables 6DoF should be used to give the exact position of a moving object in 3D area. As proposed the system must be accurate enough to be able to track people in an un-structured queue in the ski lift. This system should also be able to 1) wake-up the card as soon as it is in the magnetic field while using the built-in wake-up feature in AMS3933. 2) Give us the exact position of the card in the field. Following the default wake-up/sleep protocol in AMS can be a good starting point.
The power consumption is another factor that one should take into account. As a result, the card should be in the deep sleep mode once it is out of the scope of the magnetic field. It can turn into the shallow sleep mode when moving and occasionally send signal to notify its position.

Evaluation
No system is perfect. A video positioning system parallel to magnetic tracking system is used to visualize the whole project. These two systems are complementary. It is critical for both technologies as accurate as they can. Once these two systems are merged together, one should be able to accurately allocate each card to each specific customer and to determine the position.
Also, it is important to know the limits of the card. We should be able to understand the limits of accuracy of the sensor (card) for positioning. When the card is not accurate? How to validate the card in the first place? What are the minimum requirements for the card to function as proposed? And finally, what is the efficiency of the whole system?

References
[1] Innosuisse project, application # 32823.1 IP-ENG, «Active access card and non-blocking access gates», 2018.

Neuchâtel, 28th of August 2019

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1 Introduction

In the frame of Innosuisse project, the Integrated Actuator Laboratory collaborates with an industrial partner (e-liberty) and some research groups of He-Arc to the development of a new approach to perform access control to facilities offered by ski resort. An active access card will be used to satisfy the positioning. The based idea is to use modulated magnetic fields. The best advantage of this approach is that the modulated magnetic fields can perform a wake-up system as well as positioning. In addition, by using those fields, one can conceivably know where the active cards are with an accuracy of few centimeters [5].

To delete the blocking access gate, we need to know where the cards are in 3D and which client of the ski resort has one. The position of the card in 3D is compute by using magnetic field and we correlate this position with image processing to know which client has a card. In the following schema, there is an overview of how it will work.

![Schema of the positioning system](image)

Figure 1: Schema of the positioning system

We know the position of the 3 receivers behind the gate and by image processing, we localize that individual 3 has no card. Then, an agent fine this individual to default paying the subscription.

First, let’s look at existing papers who already spoke about this question to understand how to compute positioning by using RSSI and magnetic field (look at Section 3).
2  Hypothesis

2.1  Specifications of the Demo Kit

The Demo Kit [6] AMS3933 is a wake-up receiver which is basically used to wake up the system.

![Image of Demo Kit]

Figure 2: Left side: Transmitter  Right side: Receiver

On one side, we have the transmitter that has a frequency of 125kHz and one antenna. In addition, there are buttons to switch the mode of the transmitter. The functions of the mode are:

1. Pattern/Data: The transmitter continuously sends the wake-up pattern plus data (01010101).
2. Single Pattern: The transmitter send a single wake-up pattern.
3. Automatic Pattern: The transmitter sends a wake-up pattern every 1s
4. STOP: The transmitter stops transmitting

On the other side, we have the receiver which has 3 antennas (one for each axis) and some leds that show which antenna receives the strongest signal. There is also a USB-connector which will be used to collect the data of the received signal. The values that we can get from the receiver are RSSI values (look at Section 3.2 for more details).

2.2  Description of the problem

Obviously, to know the position and the orientation, we need at least 6 variables:

<table>
<thead>
<tr>
<th>Position X</th>
<th>Position Y</th>
<th>Position Z</th>
<th>Rotation $R_x$</th>
<th>Rotation $R_y$</th>
<th>Rotation $R_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X$</td>
<td>$Y$</td>
<td>$Z$</td>
<td>$R_x$</td>
<td>$R_y$</td>
<td>$R_z$</td>
</tr>
</tbody>
</table>

Table 1: Table of the variables needed to know the position

But, we have to find a way to identify those variables. This is the starting point of the problem. After looking at the documentation of the AMS Demo kit 3933 [6], one can notice that three channels
enable us to get some values from the antenna of the receiver. The values that we can get are the Receive Signal Strength Indication (RSSI) which give an approximation of the magnetic field intensity received by the card. That’s exactly what we need to find the variables of the Table 1.

Now, how to translate the RSSI values into coordinates or rotation angle around an axis? The report oncoming is all about this fundamental question.

### 2.3 First look

Previous readings about the RSSI told that we will get an approximation of the distance between the transmitter and the receiver. Somehow, to find the position and the orientation of the card, we will need an algorithm to transform norm of vectors to coordinates. In addition, because the RSSI gives only an approximation of the distance, we will have to optimize it to be as much accurate as possible.
3 State of the art

3.1 Magnetic positioning and orientation tracking

The idea is to have a two-axis generation of a quasi-static rotating magnetic field and three-axis sensing. The sensor position is given by the distance $r_{x,y,z}$, the azimuth $\theta$ and the elevation $\psi$. (look Figure 3).

Figure 3: Excitation field at an arbitrary position. [2]

On the source, we have two mutually orthogonal coils fed with phase-quadrature currents. Because of that phase-quadrature, we have a resulting excitation field rotates elliptically at any position in the near-field region. Then the sensor sees a rotating field which will be using to compute the position. The excitation ellipse has a single set of parameters (aspect ratio, size, phase and orientation) that gives us enough information to know the distance between the source and the sensor. Look at this paper [2] for more informations.
3.2 RSSI

The RSSI ranged based localization algorithm is simple and cost effective. It relies on measuring the Receive Signal Strength Indicator (RSSI) and gives a good distance estimation. RSSI is a unit less metric used to measure the intensity of the received signal. In our case, we have 5 bits to encode it then the values will be in the range 0 to 31. The power received by the sensor follows this equation:

\[
P_r = RSSI + \text{OFFSET}
\]  

(3.1)

where the offset is a calibration constant that we can find empirically.

If we work under ideal conditions, the RSSI values could be used to compute approximately the distance between the transmitter and the receiver. We compute the power received by the antenna with:

\[
P_r = P_t G_t G_r \left( \frac{\lambda}{4\pi d} \right)^2
\]  

(3.2)

where \( G_t \) is the gain of the transmitting antenna, \( G_r \) the gain of the receiving antenna and \( \lambda \) is the signal wavelength. But we can’t use this equation on terrestrial indoor or outdoor environments because the power of the transmitted signal attenuates with distance.

There is a better solution to correlate the RSSI with the distance which use the log-distance path loss model. This model predict the path loss a signal encounters in an indoor environment to the distance. The equations [4] are the following:

\[
P_r(d) = P_{r}(1) - 10n_p \log_{10}(d) + X_{\sigma}
\]  

(3.3)

\[
P_r(d) = -\eta \log_{10}(d) + C
\]  

(3.4)

Where \( P_{r}(1) \) is the received power in dBm at \( d = 1m \), \( n_p \) is the path loss exponent, \( X_{\sigma} \) is a normally distributed random variable with zero mean and \( \sigma \) standard deviation and finally \( C = P_{r}(1) + X_{\sigma} \). By using the equation (3.4), we compute the distance with:

\[
d = 10^{-\frac{P_r(d) - C}{\eta}}
\]  

(3.5)

We will discuss about the constant and this equation more deeply in the section 5

3.3 Use of RSSI for positioning

3.3.1 Distance between the transmitter and the receiver

According to Jinze Du thesis [3], there is an empirically way to find the constant that we need to compute the distance as a function of the RSSI. Looking at the equation 3.4, if we replace \( \log_{10}(d) \) by \( X \), we obtain:

\[
P_r(d) = RSSI = -\eta X + C
\]  

(3.6)
which is linear. \( \eta \) and \( C \) are determined a linear regression analysis of the equation 3.6 where \( \eta = -m \) and \( C = h \). Knowing these two constants, we express a new function which will give us the distance by knowing the RSSI:

\[
d = 10^{-\frac{RSSI-h}{m}}
\]  

Graphically, with (3.6) we have the Figure 4 where we identify a linear curve that fit approximately the points.

With this method, we know the distance between the receiver and the transmitter. But, this is in a linear case. That means that we only know at which distance is the receiver but we can’t express the variables (table 1) of the system.
### 3.3.2 Trilateration algorithm

The trilateration algorithm describe in the same paper [3] allows us to compute the position $X,Y$ and $Z$.

![Figure 5: Trilateration](image)

As shown in Figure 5, the relationship between the unknown nodes and three anchor nodes becomes:

\[
\begin{align*}
(x - x_1)^2 + (y - y_1)^2 &= d_1^2 \\
(x - x_2)^2 + (y - y_2)^2 &= d_2^2 \\
(x - x_3)^2 + (y - y_3)^2 &= d_3^2
\end{align*}
\]

(3.8)

where $(x, y)$ are the coordinates of the unknown node and $(x_1, y_1), (x_2, y_2), (x_3, y_3)$ are the coordinates of the known anchor nodes. By substracting the first equation to the others, this system can be transformed into a matrix system like:

\[
Q \mathbf{x} = \mathbf{b}
\]

(3.9)

where $Q$ is a 2 X 2 matrix, $\mathbf{x}$ is the coordinate vector and $\mathbf{b}$ is a 2 dimensions vector.

\[
Q = \begin{bmatrix}
2(x_1 - x_2) & 2(y_1 - y_2) \\
2(x_1 - x_3) & 2(y_1 - y_3)
\end{bmatrix}
\]

(3.10)

\[
\mathbf{x} = \begin{bmatrix}
x \\
y
\end{bmatrix}
\]

(3.11)

\[
\mathbf{b} = \begin{bmatrix}
b_1 \\
b_2
\end{bmatrix} = \begin{bmatrix}
x_1^2 - x_2^2 + y_1^2 - y_2^2 - d_2^2 - d_1^2 \\
x_1^2 - x_3^2 + y_1^2 - y_3^2 - d_3^2 - d_1^2
\end{bmatrix}
\]

(3.12)
then, by choosing well the anchor position, we can make sure that $Q$ is invertible and:

$$x = Q^{-1}b \quad \text{where} \quad x = \begin{bmatrix} x \\ y \end{bmatrix}$$  \hspace{1cm} (3.13)

Finally, we can define a matrix $M$ 2 X 2 to have:

$$\begin{bmatrix} x \\ y \end{bmatrix} = M \begin{bmatrix} x^2 - x_2^2 + y_1^2 - y_2^2 + d_2^2 - d_1^2 \\ x_1^2 - x_3^2 + y_1^2 - y_2^2 + d_3^2 - d_1^2 \end{bmatrix}$$  \hspace{1cm} (3.14)

and the matrix $M$ has elements defined as follows:

$$M = \begin{bmatrix} \frac{1}{2C}(y_1 - x_3) & \frac{1}{2C}(y_2 - y_1) \\ \frac{1}{2C}(x_3 - x_1) & \frac{1}{2C}(x_1 - x_2) \end{bmatrix}$$  \hspace{1cm} (3.15)

$$C = x_1y_2 - x_2y_1 - x_1y_3 + x_3y_1 + x_2y_3 - x_3y_2 \hspace{1cm} (3.16)$$

### 3.4 Technological constraint and summary of the different equations

According to the fact that the RSSI values depends on the pass loss exponent, if there are obstacles between the transmitter and the receiver, this term will increase and, in the equation 3.6, the slope will increase as well. In other words, more obstacles stand in the magnetic field translate less precision in term of positioning. In the Figure 1, if we want to read the values of the individual 2, there are persons (obstacles) between his card and the transmitters. It will be a great idea to look at the accuracy’s limitations of the final system (not in this project) linked with this problem.

In addition, to perform a trilateration algorithm, we need to modulate in time the signal from each transmitter. Knowing that the receivers in our case have only 3 slots for the RSSI, we have to measure the RSSI from each antenna separately and it creates a problem because the system becomes time dependant so we have to optimize it (see Section 4.2.3).

The equations that we will keep in this project are:

$$P_r(d) = RSSI = -\eta X + C$$  \hspace{1cm} (3.17)

and

$$d = 10^{-\frac{RSSI - h}{m}}$$  \hspace{1cm} (3.18)

### 3.5 Amfitrack

Amfitrack created a high precision and low cost electromagnetic tracking system. The AmfiTrack system positions an object in 3D, outputting the absolute position (XYZ) and rotation (pitch/yaw/roll) of the system components relative to each other, making it a true six degrees of freedom electromagnetic tracking system. In addition, the output can be used in a python script for grabbing real time values on Windows or Mac. Ideally, this is what we wanted for this project. But unfortunately, we can’t use this technology because the receiver (the one you can see on the web site [5]) needs to be use as define and we’re not able to grab only the positioning part. It means that we need to create our own system with the AMS wake-up receiver.
4 AMS positionning

4.1 Redefine the problem

Before goes into 3D, we need to identify the best parameters to optimize the system and make its accurate considering the huge number of parameters which can be tuned in the software 4.2.1. We will discuss about this part in Section 4.2.3. In addition, the equations to compute the RSSI change when we’re in near field region. According to the fact that the frequency of the system is 125kHz, the wavelength is around 2.4km which bring us into near field region. But fortunately, which equation 3.6, the linearization of the RSSI as a function of the distance bypass this obstacle.

4.2 Demo kit receiver positioning

4.2.1 Software: AS393x EvalSW

By using the software AS393x EvalSW, we can tune parameters on the receiver and on the transmitter. After some research on the Demo kit Manual, we saw that a lot of parameters on the receiver are adjustable. Here is a picture of the GUI of the receiver:

![Figure 6: Gui of the receiver. [6]](image-url)
4. AMS POSITIONNING

4.2.2 Positioning in 1D

To perform positioning in 1D, we need to shift the receiver on a line perpendicular or parallel to the transmitter. The figure below shows the two direction available on the plane of the ground. There is also the Z axis who is not shown there. Furthermore, with a ruler, we know the desired distance between the transmitter and the receiver.

![Figure 7: Plane of displacement](image)

4.2.3 Optimization

1. Stability and precision:

   What we mean by stability is the fact that the RSSI’s values that we get as output need to be the same if we don’t change the position of the receiver. We observed that without any optimization, the values range from +-2 dB around the desired measurement. We want to eliminate that as much as possible.

   (a) Resonance frequency of the antennas:

   We know that the frequency of the transmitter is 125kHz therefore if we haven’t the same frequency on the antennas, we will lose informations and data on the output. In the software, antennas’ resonance frequency are tuneable with an input capacitor bank. Each antenna has its own specific parameters so the input capacitor bank will not be the same for each of them. Experimentally, we find those values to have a frequency around 125kHz:

<table>
<thead>
<tr>
<th>Input capacitor bank</th>
<th>Antenna X</th>
<th>Antenna Y</th>
<th>Antenna Z</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>14pF</td>
<td>8pF</td>
<td>0pF</td>
</tr>
</tbody>
</table>

   Table 2: Table of the input capacitor banks
(b) Frequency detection:
The frequency detection is successful if in two consecutive time windows the zero threshold counter detects M zero crossing, where M depends also on the operating frequency range (look at the datasheet for more details [7]. The frequency detection criteria can be tighter or more relaxed. This parameter doesn’t change that much the precision. Let’s use Medium.

(c) Antenna Damper:
The antenna damper consists of internal resistors which can be connected in parallel to the external resonator. In this way the resonator sees a smaller parallel resistance (in the band of interest) which degrades its quality factor in order to increase the linear range of the channel amplifier (the amplifier doesn’t saturate in presence of bigger signals).

(d) Antenna gain reduction:
The antennas gain reduction able the receiver to reduce the magnitude of the received signal. It allows to increase the precision because the step between each values of RSSI becomes smaller. In contrast, the range becomes smaller (look at Section 6.1 for more details). Furthermore, the minimum RSSI value is equal to the gain reduction. For example, if the gain reduction is $-4\, dB$, the minimum value that we have in output is $-4$. Knowing that the RSSI slots are designed as 5 bits registers, the number of different values that we can get is 32 if the gain reduction is 0 but it decrease to 28 with a gain reduction of $-4\, dB$

(e) Result of the optimization of the precision and stability parameters:
By experimenting pairs of parameters for antenna damping and gain reduction, we obtain the following table:

<table>
<thead>
<tr>
<th>damping factor/Gain</th>
<th>0 dB</th>
<th>-4 dB</th>
<th>-8 dB</th>
<th>-12 dB</th>
<th>-16 dB</th>
<th>-20 dB</th>
<th>-24 dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 kΩ</td>
<td>14</td>
<td>14</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>16</td>
<td>17</td>
</tr>
<tr>
<td>1 kΩ</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>10</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>3 kΩ</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>9 kΩ</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>14</td>
</tr>
<tr>
<td>27 kΩ</td>
<td>17</td>
<td>17</td>
<td>17</td>
<td>19</td>
<td>19</td>
<td>16</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 3: Table of RSSI get at 1 meter for different parameters

The best parameters for the antenna damper to have stable values are highlighted in gray. Arbitrarily, we take damping factor = 9kΩ and reduction gain = $-4\, dB$.

2. Demodulator’s performances:
The signal is encoded as a Manchester code and the demodulator is a Manchester decoder. The demodulator’s performances are crucial because we need to have a low time response to increase the speed of the system. The performance of the demodulator can be optimized according to bit rate and preamble length. Below, the Figure 8 shows us how the system works during a cycle:
Figure 8: Wake-up protocol of the system

The principle of the demodulator is to take the signal to base-band and to recover two signals from the amplifier RF signal; a fast and a slow envelop. Those two signals are fed to the data slicer. At the output of this one, digital received bits are streamed.

(a) Symbol rate of the transmitter and the receiver (fast envelop):

The fast envelop’s time constant needs to be adjusted to a desired symbol rate. Here are the possibilities:

<table>
<thead>
<tr>
<th>Symbol Rate [Manchester Symbols/s]</th>
</tr>
</thead>
</table>
| 4096 | 3276 | 2730 | 2340 | 1820 | 1638 | 1489 | 1365 | 1260 | 1170 | 1092 | 1024 | 963 |...

Table 4: Possible symbol rate for the fast envelop (keep orange value)

However, decreasing the fast envelop’s time constant is traducted as more noise injected due to the wider band. In contrast, if we decrease the time constant, we consume less energy. The card will have to work for a whole day which means that we have to make some trade-off between energy consumption and noise inclusion.

(b) Envelope detector(slow envelop):

The slop envelop acts as an average of the incoming data. For that reason, the bigger its time constant is, the better will be the noise rejection. In contrast, if we increase the envelop
detector’s time constant, we will need to increase the preamble length as well. As before, we have to choose a values between the following one:

<table>
<thead>
<tr>
<th>Symbol Rate [Manchester Symbols/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4096</td>
</tr>
</tbody>
</table>

Table 5: Possible symbol rate for the slow envelop (keep orange value)

The following Figure 9 explain graphically how the slow and fast envelop work together.

![Figure 9: Envelop detector signal - Dynamic threshold](image)

(c) Preamble length:

The Preamble length needs to be greater than a constant which depends on the envelope detector. The equation to set the minimum preamble length ($P_t$) is:

$$P_t > \frac{1}{\text{symbol rate}}$$  \hspace{1cm} (4.1)

which gives us $P_t = 2.3\text{ms} > 1.3\text{ms}$ with a symbol rate $= \frac{1638}{s}$

3. The correlator (pattern detection):

In order to prevent that the AS3933 wakes up the host system (MCU) from noise or disturbers, the internal correlator checks that the bit sequence delivered from the data slicer corresponds to stored pattern. After some research on the datasheet of the system [7], it doesn’t affect the time respond but only the complexity of the encoded data.
5 Experiences

5.1 Experiences without optimization

What is meant by no optimization is the fact that we try to get result without taking into account the Section 4.2.3. The idea is to know the accuracy, the range and the limits of the system without any optimization.

First, we need to set the environment of the experience. We choose a wood table to have no interference with any metal piece. Second, we need to be sure that the receiver move into a straight line along one axis and to always orientate the receiver such as the Y antenna is in front of the transmitter (just to be sure to have the same configuration for each axis). Third, we need to set some values on the receiver and the transmitter. As we want no optimization, the gain reduction is set to 0 dB, the antenna damper is set to 0 kΩ as well. For the demodulator parameters, as we’re only looking at the precision of the system, we don’t care about the values of those parameters. The only things that we need is to have the same fast envelop (symbol rate) on the transmitter and the receiver. Obviously, we need to respect the rule for the preamble length to avoid loosing any data during the experience. Finally, we use the capacitor bank to have the same frequency on the receiver’s antennas and the transmitter.

Now that the experience is set, we need to get the values and store them somewhere. To get the values, we have to open the register map on the software and refresh it about 5 times per position. We do that to be sure that we have the good values because we don’t take into account the time response. As we don’t have a lot of bits to encode the RSSI, let’s start the experience at 20 cm and move by 10 cm to 10 cm.

Here are the values that we received from 20 cm to 3 m in x direction (look at Figure 7 to know which axis it is).

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>31</td>
<td>28</td>
<td>24</td>
<td>21</td>
<td>18</td>
<td>16</td>
<td>14</td>
<td>12</td>
<td>11</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Y</td>
<td>31</td>
<td>31</td>
<td>29</td>
<td>26</td>
<td>24</td>
<td>22</td>
<td>20</td>
<td>18</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>12</td>
<td>11</td>
<td>9</td>
</tr>
<tr>
<td>Z</td>
<td>24</td>
<td>21</td>
<td>16</td>
<td>15</td>
<td>13</td>
<td>11</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>160 cm</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>170 cm</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>180 cm</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6: Table of RSSI get without optimization in x direction (values are in dB)

As we can see, after 2.3 m and 2.4 m, the antenna X and Z respectively don’t receive any signal. Which means that this is the maximum range for these two antennas.
Now, by using the Equation 3.7, we can compute the distance as a function of the RSSI get for each antenna and take the mean of the three of them:

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>23.83</td>
<td>28.02</td>
<td>38.70</td>
<td>46.57</td>
<td>56.75</td>
<td>67.27</td>
<td>79.76</td>
<td>88.44</td>
<td>96.26</td>
<td>107.26</td>
<td>113.44</td>
<td>126.45</td>
<td>129.77</td>
<td>137.22</td>
</tr>
<tr>
<td>160cm</td>
<td>170cm</td>
<td>180cm</td>
<td>190cm</td>
<td>200cm</td>
<td>210cm</td>
<td>220cm</td>
<td>230cm</td>
<td>240cm</td>
<td>250cm</td>
<td>260cm</td>
<td>270cm</td>
<td>280cm</td>
<td>290cm</td>
<td>300cm</td>
</tr>
<tr>
<td>150.04</td>
<td>159.40</td>
<td>159.40</td>
<td>173.08</td>
<td>186.64</td>
<td>197.17</td>
<td>202.41</td>
<td>220.16</td>
<td>233.23</td>
<td>239.30</td>
<td>245.84</td>
<td>245.84</td>
<td>252.90</td>
<td>260.51</td>
<td></td>
</tr>
</tbody>
</table>

Table 7: Table of the distances as a function of the RSSI

and finally the error that we have in output at each distance is given in the following table:

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error</td>
<td>3.83cm</td>
<td>1.98cm</td>
<td>1.30cm</td>
<td>3.33cm</td>
<td>3.25cm</td>
<td>2.75cm</td>
<td>0.24cm</td>
<td>1.56cm</td>
<td>3.73cm</td>
<td>2.74cm</td>
<td>6.56cm</td>
<td>3.55cm</td>
<td>10.23cm</td>
<td>12.78cm</td>
</tr>
<tr>
<td>160cm</td>
<td>170cm</td>
<td>180cm</td>
<td>190cm</td>
<td>200cm</td>
<td>210cm</td>
<td>220cm</td>
<td>230cm</td>
<td>240cm</td>
<td>250cm</td>
<td>260cm</td>
<td>270cm</td>
<td>280cm</td>
<td>290cm</td>
<td>300cm</td>
</tr>
<tr>
<td>9.96cm</td>
<td>10.60cm</td>
<td>20.60cm</td>
<td>16.92cm</td>
<td>13.36cm</td>
<td>12.83cm</td>
<td>17.59cm</td>
<td>8.94cm</td>
<td>5.77cm</td>
<td>10.70cm</td>
<td>20.70cm</td>
<td>24.16cm</td>
<td>34.16cm</td>
<td>37.10cm</td>
<td>39.49cm</td>
</tr>
</tbody>
</table>

Table 8: Table of the errors between the output and the desired distances

The RSSI values have an exponential curve theoretically which explains why the farther we go the higher becomes the error. In conclusion, without optimization, the range is about 3m and the error as a mean of 9.6cm.

Because of the fact that the idea of this project is to optimize the system, we won’t show there the values get in the two other directions but, in Y direction, the values get really quickly to 0 dB because of the magnetic field who has less strength in this direction and in the Z direction, the values are roughly the same but the error is higher (the mean is around 13cm).

5.2 Experiences with optimization

Looking at the performance of the receiver, it would be a great idea to decrease the error because 39.49cm is too high for the final application. According to the Section 4.2.3, we will tune the parameters to improve the accuracy but, unfortunately, it will decrease the range.

We will use the same setup as before but this time, we will get further on the analysis by choosing the best axis of displacement and with which receiver’s antenna it’s better to get the values because the mean of the three of them is not that accurate.

But first, we need to set the parameters on the software. For that, we will use the results found in the optimization part. The following Table 9 shows them:

<table>
<thead>
<tr>
<th>Antenna Damper</th>
<th>Frequency Detection Tolerance</th>
<th>Gain Reduction</th>
<th>Preamble length</th>
<th>Envelop Detector Symbol Rate</th>
<th>Symbol Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>9kΩ</td>
<td>Medium</td>
<td>−4dB</td>
<td>1.55ms</td>
<td>1400</td>
<td>1638</td>
</tr>
</tbody>
</table>

Table 9: Parameters after optimization

5.2.1 How to choose the best antenna to get the values?

By intuition, the best antenna should be the one which in parallel to the transmitter because the magnetic field goes through this antenna like shown in the Figure 10.
5. EXPERIENCES

(a) Picture of the antennas on the receiver

(b) Magnetic field

Figure 10: Magnetic field with the receiver in it. The red square schematize the receiver’s antennas

To be sure that our intuition is true, we store the results and we display them on the three following table (one for each axis). In addition, We always put the LY antenna in front of the transmitter to have the same configuration on every single axis.

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>28</td>
<td>22</td>
<td>19</td>
<td>15</td>
<td>12</td>
<td>9</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Y</td>
<td>31</td>
<td>29</td>
<td>27</td>
<td>23</td>
<td>21</td>
<td>19</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>12</td>
<td>11</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>Z</td>
<td>16</td>
<td>11</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 10: Table of RSSI get with optimization in X direction (values are in dB)

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>31</td>
<td>31</td>
<td>29</td>
<td>27</td>
<td>24</td>
<td>22</td>
<td>21</td>
<td>19</td>
<td>18</td>
<td>16</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Y</td>
<td>31</td>
<td>27</td>
<td>23</td>
<td>21</td>
<td>18</td>
<td>16</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>7</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Z</td>
<td>21</td>
<td>19</td>
<td>17</td>
<td>15</td>
<td>13</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 11: Table of RSSI get with optimization in Y direction (values are in dB)

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>31</td>
<td>25</td>
<td>20</td>
<td>17</td>
<td>17</td>
<td>11</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Y</td>
<td>31</td>
<td>29</td>
<td>25</td>
<td>23</td>
<td>21</td>
<td>19</td>
<td>18</td>
<td>17</td>
<td>15</td>
<td>14</td>
<td>13</td>
<td>11</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Z</td>
<td>31</td>
<td>21</td>
<td>19</td>
<td>17</td>
<td>12</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 12: Table of RSSI get with optimization in Z direction (values are in dB)

What we see there is the fact that the RSSI in the LY antenna is the one who receive the signal at the higher range.

The last observations bring us to the result that the best antenna to compute the distance is the one which is parallel and in front of the receiver.
5.2.2 How to choose the best axis of displacement?

To choose the best axis of displacement, the easiest is to look at the output and compare the results obtain on X, Y and Z. Again, we start at 20cm until we find $-4dB$ (the minimum with this gain reduction) on the three antenna. The setup of the experiment for each axis is shown below:

Figure 11: The three axis (line) on which we do the displacement
5. EXPERIENCES

Like the previous part, we store the results to know what is the maximum range and we display them on the three following table (one for each axis). Knowing that the best antenna is the one in front of the receiver, we only keep the values of this one and we directly compute the distance as a function of the RSSI (see Equation 3.7 and values of RSSI are in row y of the Tables 10,11,12).

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>24.23cm</td>
<td>28.71cm</td>
<td>34.01cm</td>
<td>37.74cm</td>
<td>36.55cm</td>
<td>31.39cm</td>
<td>29.37cm</td>
<td>94.02cm</td>
<td>102.34cm</td>
<td>111.39cm</td>
<td>121.23cm</td>
<td>131.96cm</td>
<td>143.63cm</td>
<td>156.33cm</td>
</tr>
<tr>
<td>Error</td>
<td>4.23cm</td>
<td>1.29cm</td>
<td>9.99cm</td>
<td>2.27cm</td>
<td>3.45cm</td>
<td>3.01cm</td>
<td>0.63cm</td>
<td>4.02cm</td>
<td>2.34cm</td>
<td>1.35cm</td>
<td>1.24cm</td>
<td>1.96cm</td>
<td>3.63cm</td>
<td>6.33cm</td>
</tr>
</tbody>
</table>

Table 13: Values for X axis

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>24.23cm</td>
<td>34.01cm</td>
<td>47.74cm</td>
<td>56.55cm</td>
<td>72.92cm</td>
<td>86.39cm</td>
<td>94.02cm</td>
<td>102.34cm</td>
<td>111.39cm</td>
<td>121.23cm</td>
<td>131.96cm</td>
<td>143.63cm</td>
<td>156.33cm</td>
<td></td>
</tr>
<tr>
<td>Error</td>
<td>4.23cm</td>
<td>4.01cm</td>
<td>7.75cm</td>
<td>6.55cm</td>
<td>12.92cm</td>
<td>16.38cm</td>
<td>14.02cm</td>
<td>12.34cm</td>
<td>11.39cm</td>
<td>21.96cm</td>
<td>23.63cm</td>
<td>55.20cm</td>
<td>98.80cm</td>
<td>88.80cm</td>
</tr>
</tbody>
</table>

Table 14: Values for Y axis

<table>
<thead>
<tr>
<th>Distance</th>
<th>20cm</th>
<th>30cm</th>
<th>40cm</th>
<th>50cm</th>
<th>60cm</th>
<th>70cm</th>
<th>80cm</th>
<th>90cm</th>
<th>100cm</th>
<th>110cm</th>
<th>120cm</th>
<th>130cm</th>
<th>140cm</th>
<th>150cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output</td>
<td>3.83cm</td>
<td>1.98cm</td>
<td>1.30cm</td>
<td>3.43cm</td>
<td>3.25cm</td>
<td>2.73cm</td>
<td>6.24cm</td>
<td>1.56cm</td>
<td>3.74cm</td>
<td>2.74cm</td>
<td>6.56cm</td>
<td>3.55cm</td>
<td>10.23cm</td>
<td>12.78cm</td>
</tr>
</tbody>
</table>

Table 15: Values for Z axis

Looking at the Figure 10b, we could say before that the values on the Y axis would be worst than the others. Both X axis and Z give good approximations and the maximum error is significantly smaller than the ones we get without the optimization. As the purpose is to have the best situation, we will keep the X axis for the direction of displacement. The maximum range of the optimized system is 1.5m and the mean of the error is 3cm.

Finally we compare the distance that we obtain on the output with the expected values in the following Figure 12.
Figure 12: Plot of the output and the expected values
In addition, the following graphs confirm that the linear regression who suit the best the curve is the one in the X direction.

(a) Linear regression of the RSSI values on X axis

(b) Linear regression of the RSSI values on Y axis

(c) Linear regression of the RSSI values on Z axis

Figure 13: Linear regressions of the RSSI values on each axis
6  Limits of the system

6.1  Range and Accuracy

According to the result that we got in Section 5, the range depends on the input’s parameters of the receiver. There is clearly a trade-off between the optimization of the accuracy and the range. The range without optimization is around 3 meters because after this values, the antennas don’t receive any signal anymore. The experiments gave us the following values around 3 meters:

<table>
<thead>
<tr>
<th>2.3m</th>
<th>2.4m</th>
<th>2.5m</th>
<th>2.6m</th>
<th>2.7m</th>
<th>2.8m</th>
<th>2.9m</th>
<th>3.0m</th>
<th>3.1m</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 16: Maximum range before optimization

which confirm that the maximum range is 3 meters with this demo kit.

The range will diminish as the precision of the system increase. Knowing that the optimization enhance the precision, we should see a diminution of the range with the optimized system. Looking at the following table, we can confirm that the previous statements are true:

<table>
<thead>
<tr>
<th>1.5m</th>
<th>1.6m</th>
<th>1.7m</th>
<th>1.8m</th>
<th>1.9m</th>
<th>2m</th>
<th>2.1m</th>
<th>2.2m</th>
<th>2.3m</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 17: Maximum range after optimization

What is important there is the fact that after 1.5m the receiver starts to store one value of RSSI for different distances which means that the accuracy goes down after this range. Furthermore, the maximum range where the receiver still acquire a signal is 2.1m. Finally, we can say that the absolute range after optimization is 2.1m but to have accurate values, the maximum range diminish to 1.6m.

6.2  Encoding of the RSSI

After looking at the documentation of the demo kit, we see that the RSSI values are encoded on 5 bits:

<table>
<thead>
<tr>
<th>R10</th>
<th>n.a</th>
<th>RSSI1</th>
</tr>
</thead>
<tbody>
<tr>
<td>R11</td>
<td>n.a</td>
<td>RSSI2</td>
</tr>
<tr>
<td>R12</td>
<td>n.a</td>
<td>RSSI3</td>
</tr>
</tbody>
</table>

Figure 14: Map of the registers
which means that the resolution is not that big because we only have 32 different values to encode the position. In addition, when the system is optimized this number decrease by the value of the gain reduction (as explained in Section 4.2.3). After all, this limitation is the reason why we took values every 10cm because if we took a smaller interval, the precision would be smaller.

6.3 Angle of the receiver

All the experiences done before were taking into account that the receiver has no rotation on Y and Z axis. Which means that the output will change if we change the orientation of the card because the receiver’s antennas will receive others RSSI than the ones discuss in Section 5. It must need further experimentation to know how the system react with the orientation but in a 1D system, if we compute the mean of the RSSI values get by each antenna after a small rotation around the Y and Z axis, the output of the system gives similar values than the ones we got before.
7 Conclusion

First of all, the goal was to perform a 3D positioning system. After some weeks, we decide to change the purpose of the project to the optimization of the parameters because it was necessary to have an accurate system before trying to position the receiver spatially. Furthermore, the optimization of the parameters adds a reduction of the system’s range which is a problem in our case because we need a large gate for the second phase of the project. However, it’s too soon to make conclusion about this point because we can tune the range and the accuracy by changing the parameters which means that when the gate will be designed, one can tune the parameters to have the most suitable system.

At the end, we have some good results and we improve the precision by more than 6cm according to the mean of the error. We know yet the best orientation of the transmitter and in which axis is better to fix it to the gate.

After the optimization, we can pursue the analysis to perform the desire 3D positioning expected. The results of this report will surely help the next person who will work on the positioning because now, we know the limitation of system as well as how to configure it to have the best results. I suggest now to test the response of the system with different transmitter and try to perform the positioning with the trilateration algorithm (Section 3.3.2). In addition, if the range after the optimization is too short, one can reduce the gain reduction to increase a bit the range but it will unfortunately increase the error.

Finally, the demodulator performance were optimized but in this project, we used only one transmitter therefore we couldn’t see any impact in a 1D system. If we use 3 transmitter to perform the algorithm, the time response will have an impact and then some parameters about the demodulator can change according to the result obtain.
References

[1] Innosuisse project, application # 32823.1 IP-ENG, «Active access card and non-blocking access gates», 2018.


[8] More papers: \laisrv3.epfl.ch\Mohaghegh\e-liberty\State of the Art


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