Deutscher Luft- und Raumfahrtkongress 2010
DocumentID: 161172

DESIGNING AND EVALUATING A LOCATION DETECTION SOLUTION FOR THE AIRCRAFT CABIN WITH MODEL BASED SYSTEMS ENGINEERING

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Abstract

Aircraft systems have to integrate more and new functions. Self configuration is such a new function. With self configuration the aircraft cabin can be reconfigured faster than with the technologies that are used today. The cabin communication architecture can be adapted dynamically depending on the installed systems and the location and maintenance mechanics can find components faster. In this paper an integrated location detection system for the aircraft cabin is designed with model based engineering. The design uses a hybrid signal location detection technology to locate a tag in the cabin. The distance to a tag is measured with RFID and ultrasonic sound using the Time Difference of Arrival (TDoA) technique. Simulation results show that an accuracy of less than 10 cm is achieved. Model based systems engineering and simulation is successfully used to evaluate different designs early in the system development.

1. INTRODUCTION

Development of new concepts and the verification of designs during the development process are not easy, but they are often required by development processes. Traditionally experiments are performed and prototypes are built late in the development process [1]. This approach has the disadvantage of high costs and an additional development effort for prototypes. Model Based Systems Engineering (MBSE) is a concept that originated in the software world and was adapted quickly by other engineering areas. The goal is to verify concepts and designs during the development and to have one unique description language for different systems. Models in combination with simulation tools are used to test processes, performance and integration concepts without the need to create a prototype. Models are lifted to a central and governing role in the specification, design, integration, verification and operation of the system [2]. UML (Unified Modeling Language) and SYSML (Systems Modeling Language) are two description languages for models that have been designed by the Object Management Group (OMG) [3].

The PAHMIR project (Preventive Aircraft Health Monitoring for Integrated Reconfiguration) investigates methods to improve the reconfiguration of the cabin. Changing the class layout of the cabin and affected systems is one aspect of reconfiguration. Reconfiguration can be improved by giving the cabin configuration management system the ability to detect which configuration is installed. The cabin management system can adjust the cabin networks and addresses of system by itself with the knowledge of the installed configuration. Location detection of components is one method to detect, which configuration is installed.

Locating and tracking objects in buildings or rooms has been a topic for some years. The topic received new inputs with the development of Wireless Local Area Networks (WLAN) and Radio Frequency IDentification (RFID). New solutions have been developed as a result. Goal of the location detection design is to have a position detection system in the aircraft cabin with a maximum error of 10 cm. The cabin environment has special restrictions, such that a system is not allowed to interfere with any local regulation concerning signals and that it should not interfere with other systems and aircraft. E.g. RF (Radio Frequency) should not use any frequencies that are used by aircraft systems and it should not be so powerful enough to reach another aircraft on the ground or in the air. This limits the available technologies for a solution significantly. Most RF technologies are not available, including WLAN and GSM (Global System for Mobile Communications). Usable technologies are RFID, GPS (Global Positioning System), infrared and ultrasonic signals.

On the positive side, components cannot be installed in any place in the aircraft. They can only be installed in places defined by the design and for which the aircraft is certified. A location detection algorithm can use these position restrictions to improve the accuracy of location detection.

2. METHODS AND CONCEPTS

The Model Driven Architecture (MDA) by the OMG defines multiple models for designing a system. MDA is a specific implementation of MBSE that uses concepts of UML. For the concept design three different models are used: the Platform Independent Model (PIM), the platform model and the Platform Specific Model (PSM) [3]. The PIM describes the functions of the system independently of the hardware architecture. Functions and processes in a PIM have no implementation details, as the name implies. A model of the physical architecture of a system is called a platform model in MDA. The platform model is the opposite of the PIM. It does not contain any information about functions. The PIM and the platform model together define the Platform Specific Model (PSM) where the functions of the PIM are mapped on a hardware architecture.

2.1. Platform Independent Model

Today many different concepts for indoor localization exist. The design in this paper is based on the “Active Bat” project and uses RF and ultrasonic sound.

Active Bat was developed at the University of Cambridge in 1997. The concept uses ultrasonic sound and radio frequency for location detection. Users wear a device called “Bat”. This device is equipped with an ultrasonic transmitter and a radio frequency (RF) receiver. The receivers request a “Bat” via RF to send an ultrasonic impulse called a “chirp”. All receivers that record the “chirp” transmit the signal travel time to a central server, where the position of the “Bat” is calculated. This concept needs to know the exact position of the receivers. The accuracy of Active Bat is about 3 m [4].

The difference of the PAHMIR location detection and “Active Bat” is that PAHMIR uses RFID, because a higher location detection accuracy is needed (10 cm) and tags are not requested to emit an ultrasonic signal. Instead, they work independently and have to organize the location detection themselves.

RFID is used because it is not restricted in any country and its low power ensures that the signal stays within the aircraft. Distances in the aircraft cabin are small and the clocks in the receivers need to be very accurate, especially if radio waves are used. A small fault in the signal travel time can produce a big fault in the calculated tag position. An accuracy of 10 cm is required to identify the position of a seat. Radio waves need clocks with a resolution of 0.3 ns and a very fast processing infrastructure due to a very high propagation speed of radio waves (see Equation (1)). A simulation showed the effects of less accurate clocks on the location detection.

$$(1) \qquad \frac{0.1\,\text{m}}{300\,000\,000\,\text{m/s}} = 0.3\,\text{ns}$$

If ultrasonic sound is used then only a clock resolution of 0.3 ms is needed (see Equation (2)). The downside is that the whole location detection process takes longer then with RF.

$$(2) \qquad \frac{0.1\,\text{m}}{300\,\text{m/s}} = 0.3\,\text{ms}$$

Tag positions are calculated with the Time Difference of Arrival (TDoA) technique. TDoA uses the signal travel time to calculate the distance to the sender [5]. Figure 1 shows an example of how TDoA works. The idea is that the distance to a tag is measurable, but not the angle or any other information about the position of the tag. With only one receiver and a known position of the receiver a tag may be located on a circle around the receiver with the distance as the radius. If the distance to a second receiver is known then the intersection of both circles limits the position of the tag to two locations. A known distance to a third receiver can be used to calculate which of the two possible locations is the correct one (Figure 1).

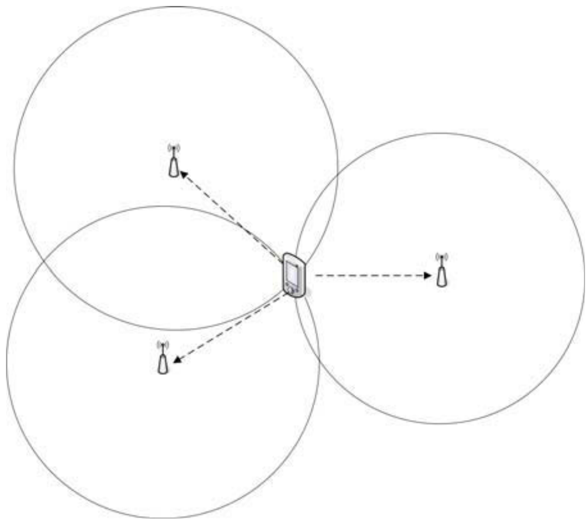

Figure 1 Time Difference of Arrival

The distances can be calculated from the signal travel times (T_a, T_b and T_c) and the signal speed (s):

$$(3) \qquad d_a = T_a \cdot s$$

$$(4) \qquad d_b = T_b \cdot s$$

$$(5) \qquad d_c = T_c \cdot s$$

With the distances it is possible to write down the three circle equations, which form the basic system of equations for multilateration. The systems of equations (6) and (7) show the mathematical problem. d_a,

d_b and d_c are the distances to the three receivers a (x_a, y_a), b (x_b, y_b), c (x_c, y_c) with coordinates x and y of the unknown location of the object to be located.

$$\left.\begin{aligned} d_a^2 &= (x - x_a)^2 + (y - y_a)^2 \\ d_b^2 &= (x - x_b)^2 + (y - y_b)^2 \\ d_c^2 &= (x - x_c)^2 + (y - y_c)^2 \end{aligned}\right\} \Rightarrow \tag{6}$$

$$\begin{aligned} d_a^2 - d_b^2 = &- 2x \cdot (x_a - x_b) - 2y \cdot (y_a - y_b) \\ &+ x_a^2 + y_a^2 - x_b^2 - y_b^2 \\ d_a^2 - d_c^2 = &- 2x \cdot (x_a - x_c) - 2y \cdot (y_a - y_c) \\ &+ x_a^2 + y_a^2 - x_c^2 - y_c^2 \end{aligned} \tag{7}$$

x_a, y_a, x_b, y_b, x_c, y_c, d_a^2, d_b^2 and d_c^2 are the coordinates of the receivers and the distances of the tag to the receivers these are all known values.

TDoA needs at least three receivers for a 2-D problem and four receivers for a 3-D problem. If more receivers are used than an over determined equation system needs to be solved and propagation errors can be reduced.

The advantage of using two signals with different propagation speeds is that no knowledge of the absolute time is needed [6]. An RF signal is used to start a timer at the receiver and an ultrasonic signal is used to measure the distance. Thus the problem of synchronizing clocks between tag and receiver and between the receivers does not exist.

The location detection process uses three architecture components (tags, receivers and a central computer) to locate an object in the cabin. Figure 2 shows the location detection process. A tag has an ultrasonic transmitter and an RFID transmitter. Basically the tag first emits its identification data via RF and emits an ultrasonic impulse at the same time. The receivers then measure the ultrasonic signal travel time. Position of a tag can be calculated based on the signal travel time. Receivers need only one ultrasonic and one RFID receiver and no transmitter to do the location detection.

It is assumed in the design that the infrastructure components (receivers and computer) are turned on and are available. The process is also only performed on activation of a tag. It is not intended that tags request a location detection at any other time. Of course it is easy to modify the design so that a location detection can be performed not only on power-up, but also when an RFID command is sent to a tag.

- **Power Up** happens when the tag is connected to a power supply. The receiver and the configuration management computer have to be running at this time to ensure that location detection can be performed.
- Tags **listen for 2 s to the RFID channel**. This ensures that the newly activated tags do not interrupt any locating process. When a tag receives a location detection request from another tag then it waits again for 2 s until it can freely transmit.
- A Location Detection Request is sent (**Send Location Detection Request via RF**) by a tag as a broadcast message to all other tags and receivers. It contains the unique identification of a tag and informs other tags and receivers that this tag is now attempting a location detection.
- After the RF signal with the Location Detection Request has been transmitted, a tag **sends an ultrasonic signal** to all receivers. This ultrasonic signal is an impulse signal. After the ultrasonic signal is sent the location detection process stops for the tag.
- Receivers **wait for a Location Detection Request** of a tag. When a Location Detection Request is received an internal clock is started that measures the time until the ultrasonic signal arrives and the receiver saves the identification of the tag, which was transmitted with the RF signal.
- Receivers **wait for an ultrasonic signal**, when an ultrasonic signal arrives, then the internal clock is stopped and the signal travel time of the tag is recorded.
- Now a receiver has all information and **sends the location information** (signal travel time and tag identification) together with its own identification to the configuration management computer. After the information is sent the receiver waits for the next location detection request.
- The configuration management computer **waits for location information** from any receiver. It saves the location information in an internal database.
- As soon as all location information for a tag are available, the configuration management computer starts to **calculate the position of the tag** in the cabin.

The system can locate nearly any number of tags in the cabin, if enough time is available.

2.2. Platform Model

The system architecture consists of three basic components:

a) a tag, which should be located,

b) receivers that are located in the cabin and receive any signals,

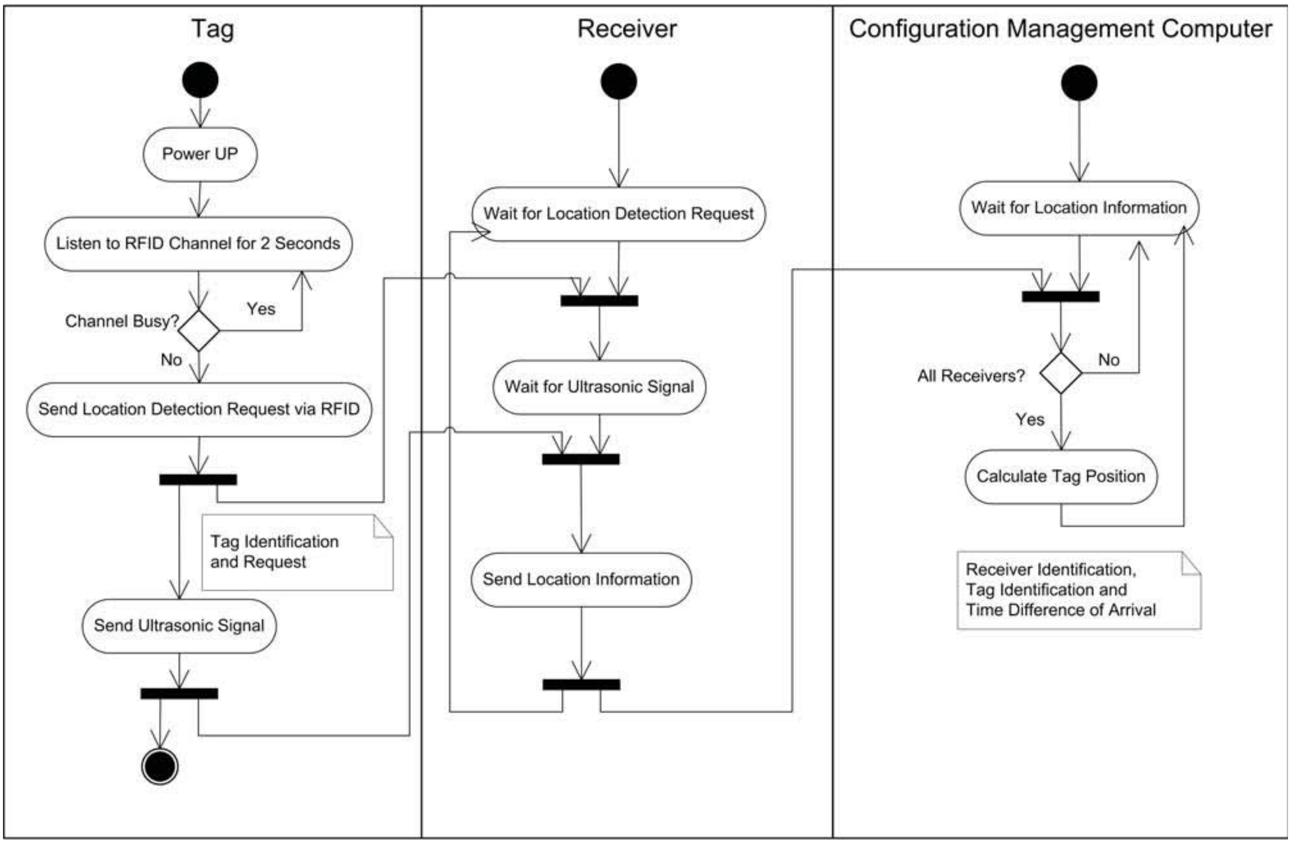

Figure 2 Location Detection Process

c) an infrastructure for the calculation of the position of tags (configuration management computer).

Memory and computation power is needed for calculations and processes. Position and number of the receivers depends on the placement layout (see below).

During the simulation five different placement layouts will be evaluated: a grid layout, a line layout, a square layout, a cross layout and a mixed layout (a mixture between the square and the cross layout). Figure 3 to 7 show the different layouts with up to 16 receivers in an A320 similar cabin (3.7 m cabin width, 30 m cabin length). The black dots in the figures are the positions of the receivers, green circles mark positions of tags in the cabin environment.

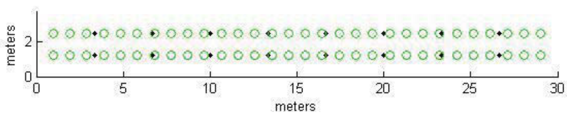

Figure 3 Receiver Line Layout

In a line layout the receivers are placed in two rows along the cabin with equal space between the receivers of each line.

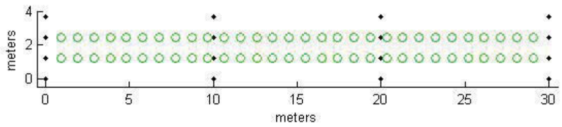

Figure 4 Receiver Grid Layout

The grid layout resembles the line layout, but receivers are arranged in more than two horizontal lines as seen in Figure 4.

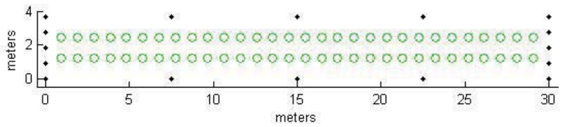

Figure 5 Receiver Square Layout

A square layout is achieved, if the receivers are placed along the borders of the cabin environment.

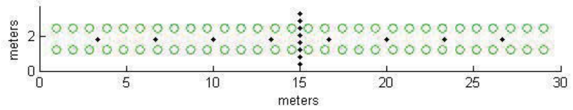

Figure 6 Receiver Cross Layout

The cross layout consists of one vertical and one horizontal line of receivers that meet in the middle of the cabin.

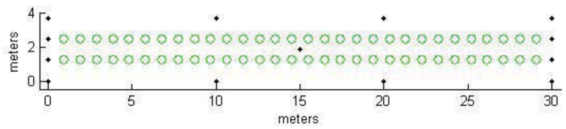

Figure 7 Receiver Mixed Layout

A mixed layout is achieved, when a square layout is taken and an additional receiver is placed in the middle of the cabin.

2.3. Platform Specific Model

The PSM contains the functions specified in the PIM onto the platform model and implemented on a certain platform. A PSM is not a prototype, but a description of the system in a software or in a description language. Function mapping is used to map the PIM onto different platform models and thus to create different PSMs. In this paper simulation is used to evaluate the different PSMs. Let PM be the platform model then

(8) $$PSM = PIM \oplus PM$$

describes the definition of the PSM. Where the $\oplus$ symbol denotes a mapping function, which maps the PIM onto the platform model. The PIM contains the location detection process and a few physical variables. Platforms will be represented by different receiver layouts and specific tag positions, other aspects like seats and walls will be neglected. A PSM is then a combination of the PIM and a specific platform. Simulation is not specified in the MDA. It is possible to simulate a process and the PSM with executable UML (xUML) and standard simulation software.

3. SIMULATION

The simulation of a PSM was done with the software MLDesigner by Mission Level Design. MLDesigner is a tool by Mission Level Design for modeling and simulation. It resembles MATLAB Simulink and supports different domains in the same model [7]. It was used to design and test a system with different parameters. The simulation first generates a platform model (the cabin layout, receivers and tags) then the location detection process is simulated. The simulation run until all tags are located or a defined time span has passed. The output of the simulation is a MATLAB file with the layout and location information. MATLAB is then used to calculate the positions of the tags and the average and maximum absolute error. Figure 8 shows the complete simulation run as a diagram.

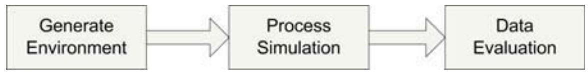

Figure 8 Simulation Process

Nine different parameters are used to customize the simulation.

- **Number of receivers and receiver layout** (see Section 2.2).
- **Cabin layout** is the parameter that controls generation and placement of receivers and tags. This parameter contains information about the dimension of the cabin (number of rows of tags and distances between tags).
- **Signal speed** describes which signal is used for the localization impulse. A choice exists between ultrasonic sound and RF.
- **Clock resolution** defines the smallest time difference that the clock is able to measure. A “normal” clock has a resolution of 1 s and stop watches normally have a resolution of 10^{-2} s.
- **Waiting time between location requests** is the time that a tag waits after detecting that the transmission channel is busy. The time depends on the signal speed and can be modified to simulated protocol errors.
- **Seat rail simulation** means that the location of the tags is limited. The position of tags resembles that of the seats in a cabin. Seats can only vary in their position along the seat rail (x-axis). The location detection can be modified to limit the possible location of a seat to achieve a higher accuracy.
- **Installation fault** is a parameter that can be used to introduce uncertainty and randomness in the location of the receivers. The parameter is given in meters and varies the position of a receiver up to that value.
- **Noise** is a delay in the signal speed that varied with each receiver/tag pair and can be used to simulate reflections or physical barriers for the signal (multi path signal propagation).

The first four parameters were used to generate a platform model and to create different PSMs. “Waiting time between location requests” and “Seat rail simulation” were used to modify the PIM. The remaining two parameters were only used to modify the simulation for evaluation. The following list shows the available parameters.

Installation fault and noise fault parameters defined the maximum possible fault. The simulation generated a random value between 0 and the parameter value. Six different simulations were performed to evaluate the design. Two simulations were used to verify the process and technology. The remaining four simulations verified the accuracy of the concept for different parameter variations. An average and maximum error were calculated for every simulation and used for the evaluation. For all simulations the same simulated cabin was used. The cabin layout parameter simulated a cabin that was 30 m long and 3.7 m wide. Four rows with tags were placed in the cabin with a distance of 1 m between the tags. The following simulations were performed to evaluate the design:

Signal speed/clock resolution

In this simulation the hybrid-signal concept was evaluated by varying the signal speed (ultrasonic sound or RF) and the clock resolution of the receivers. The clock resolution had the following values during the simulations: 10^{-3} s, 10^{-6} s and 10^{-9} s. A grid layout with 16 receivers, 300 ms between location requests, seat rail simulation, no installation fault and no noise in the signal transmission was used.

Waiting time between location requests/signal speed

This simulation tested the process and the system behavior if a new impulse was sent before the location detection process was finished. Both signal types were tested. A grid layout with 16 receivers, 10^{-9} s clock resolution, seat rail simulation, no installation fault and no noise in the signal transmission was used. The waiting time between location requests could be 10 ms, 50 ms, 100 ms or 200 ms and signal speed was 343 m/s or 300 000 000 m/s.

Number of receivers/receiver layout

During this simulation the number of the installed receivers and the layout of the receiver placement were varied, while the other parameters were fixed. Goal of this simulation was to evaluate the influence of the number of receivers for the different layouts on the location detection error. A signal speed of 343 m/s, 300 ms between two location requests, seat rail simulation, no installation fault and 1 % noise in the signal transmission were used. Simulated were 4, 8, 12, 16 or 20 receivers and a line, grid, square, cross and mixed layout.

Seat rail simulation/receiver layout

The influence of the seat rail simulation for the different receiver layouts was evaluated in this simulation. A parameter set with a signal speed of 343 m/s, 300 ms between location requests, 16 receivers, no installation fault and 1 % noise in the signal transmission was used. All five receiver layouts were simulated with seat rail simulation turned on or off.

Installation fault/receiver layout

In this simulation the influence of an absolute error depending on the receiver layout was tested. A parameter set with a signal speed of 343 m/s, 300 ms between location requests, 16 receivers, seat rail simulation and no noise in the signal transmission were used. The installation fault had the following values: 0.001 m, 0.01 m, 0.1 m and 1 m.

Noise/receiver layout

Effects of a relative error were evaluated by varying the time that the signal needed from a tag to the receiver. The following parameters were used: a signal speed of 343 m/s, 300 ms between location requests, 16 receivers, seat rail simulation and no installation fault. Noise had the following values: 0.01 %, 0.1 %, 1 % and 10 %.

4. RESULTS

This section shows the most significant results of the different simulations.

4.1. Signal speed/clock resolution for grid layout

It was possible to gain a high accuracy with ultrasonic signals, if the clock resolution was finer then 1 ms (see Table 1). If RF signals were used, the clock resolution needed to be finer then 1 ns to get any results at all. In the simulation it was assumed that the signal was perfectly transmitted. These results confirmed the calculated values in Section 2.1.

Table 1 Mean error for signal speed/clock resolution

	Ultrasonic signal	RF signal
1 ms	0.2864 m	7.5821 m
1 µs	0.0001 m	7.5821 m
1 ns	0.0000 m	0.2983 m

4.2. Waiting time between location requests/-clock resolution for grid layout

Locating a position was possible with a waiting time of 10 ms between two location detection requests and an RF signal (see Table 2). The waiting time needed to be significantly higher when an ultrasonic signal was used and thus the system needed longer to detect components. In Figure 2 is the waiting time 2 s.

Table 2 Mean error for layout and seat rail simulation

	Ultrasonic signal	RF signal
10 ms	7.6747 m	0.2983 m
50 ms	8.6508 m	0.2983 m
100 ms	0.0000 m	0.2983 m
200 ms	0.0000 m	0.2983 m

4.3. Number of receivers/receiver layout

The cross layout had the lowest mean error in the location detection (Figure 9). When 8 or more receivers were used, the cross layout is the only configuration in which an accuracy of less than 10 cm was achieved.

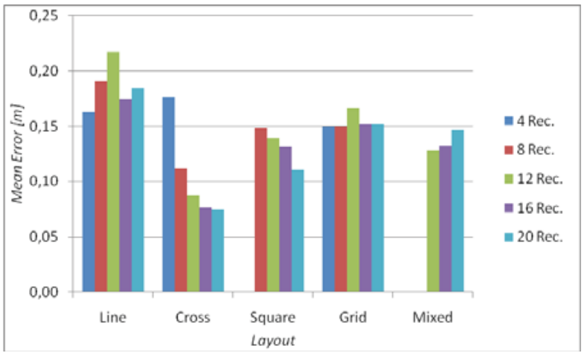

Figure 9 Mean error for layout and receiver variation

Other layouts were in the range of an accuracy of 15 cm. The maximum errors (Figure 10) showed that the cross layout was the best layout, but the maximum error was more than 10 cm in all tested cases.

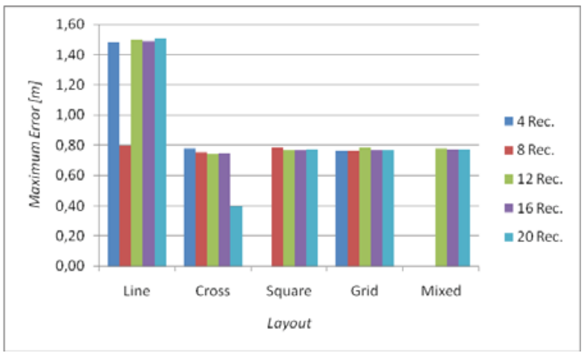

Figure 10 Maximum error for layout and receiver variation

4.4. With seat rails/receiver layout

The seat rail option was introduced into the algorithm to limit the solution space and thus reduce the errors.

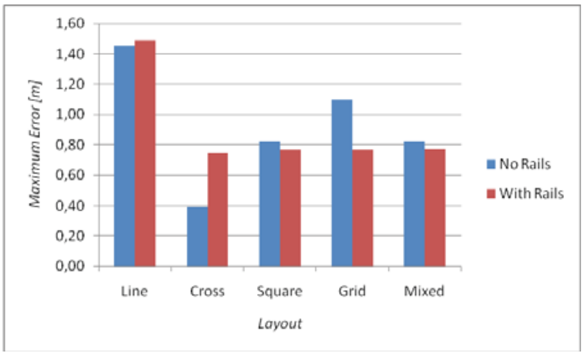

Figure 11 Maximum error for layout and seat rail simulation

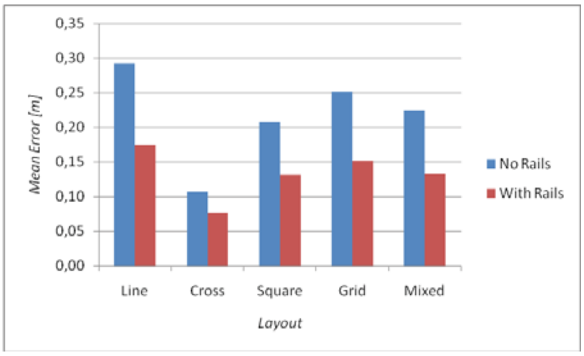

Figure 12 Mean error for layout and seat rail simulation

Figure 12 shows that the mean error with seat rails restriction was significant lower (about 60 % of the error, when no seat rails are used) compared to using no seat rail simulation. The maximum error stayed at nearly the same level (Figure 11). This was because of the algorithm of the seat rail simulation. The algorithm detected a seat on the wrong seat rail.

4.5. Installation fault/receiver layout

This simulation showed the effect of an absolute error in the system. The error simulated a wrong installation of receivers.

Table 3 Mean error for installation fault/receiver layout

	0.001 m	0.01 m	0.1 m	1 m
Line	0.0005 m	0.0049 m	0.5688 m	1.3293 m
Cross	0.0008 m	0.0076 m	0.1741 m	1.3562 m
Square	0.0004 m	0.0039 m	0.1624 m	1.0249 m
Grid	0.0004 m	0.0039 m	0.3282 m	1.1406 m
Mixed	0.0003 m	0.0026 m	0.2642 m	1.0480 m

As expected, the mean value of the error was lower when the error value was small (see Table 3). Up to a fault of 1 cm the effect on the location detection was small, but it increased significantly for bigger faults and sometimes could be more than the original fault. This underlined that receivers should be installed at the accurate position, because their position defines the dimensions of the space.

4.6. Noise/receiver layout

Table 4 shows the error, when the signal was delayed. It is visible that the behavior of the system was quite good until the noise reached a level of about 1 %. Above this level the disturbance was too much, so that the algorithm could not decide correctly on which rail a seat was located.

Table 4 Mean error for noise/receiver layout

	0.01 %	0.1 %	1 %	10 %
Line	0.0007 m	0.0068 m	0.1744 m	1.1871 m
Cross	0.0007 m	0.0071 m	0.0768 m	0.9118 m
Square	0.0007 m	0.0072 m	0.1312 m	1.1609 m
Grid	0.0007 m	0.0072 m	0.1517 m	1.2646 m
Mixed	0.0007 m	0.0074 m	0.1323 m	1.1708 m

Faults in the signal runtime and in the installation of receivers showed a similar behavior. Faults could be reduced up to a certain limit, but above that limit the error increased significantly. This effect did not happen when seat rail restriction was not used, however then the general fault was also bigger in smaller fault cases.

4.7. Cross Layout

The simulations showed that it is feasible to use the presented concept for an indoor location detection system with an accuracy of 10 cm. A receiver cross layout seemed to be the best solution of the tested layouts. To be able to evaluate this layout a bit better, an additional simulation was performed. In this simulation the number of receivers (4, 8, 12, 16, 20 and 24) and the level of noise (0.01 %, 0.1 %, 1 % and 10 %) was varied. This was done to find the performance limits of the concept. A correct installation of the receivers was assumed as well as ultrasonic sound for the location detection signal.

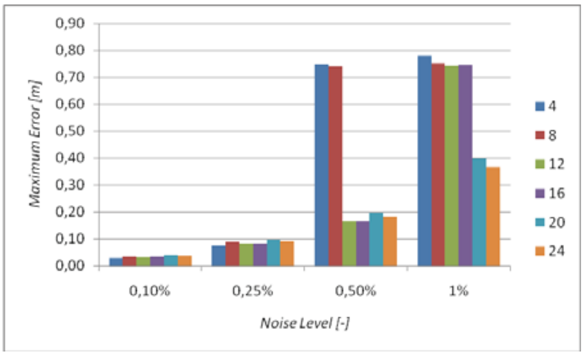

Figure 13 Maximum error for a cross layout with receiver and noise variation

The accuracy could be better than 10 cm, when the noise was below 0.25 % (Figure 13). A layout with 16 receivers delivered good results. The average position error was bigger with only 4 or 8 receivers than with more receivers (Figure 14).

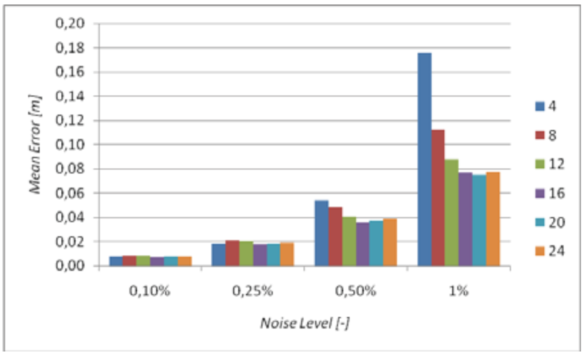

Figure 14 Mean error for a cross layout with receiver and noise variation

5. CONCLUSIONS

Goal of MBSE is to enhance specifications and to unify the design process. This paper shows, that simulation of a PSM can be used to evaluate different designs and investigate design parameters. An additional iteration would be needed to generate a more detailed platform model and to build a prototype. However, it was possible to choose a platform model for the location detection. Specific hardware and software choices for a more detailed platform model are needed to create a prototype which was not in the scope of this work.

The simulations for location detection showed that an accuracy of at least 10 cm is possible, but can not if the noise in the environment is below a certain limit of 0.01 %. A cross layout with 8 receivers showed the highest accuracy. More receivers may limit the position error effect of noise, but not eliminate them. Real world noise effects in the cabin environment were not investigated in this paper, but the limits of the concept were evaluated. However, it was possible to show the effects of different receiver layouts and technologies. A cross layout with 8 receivers is recommended for the hybrid-signal design. The total location detection time for all seats depends on the waiting time between two requests and the signal speed. It must be ensured that no location detection impulse from a wrong tag (too little time between two requests or echoes) reaches a receiver, while a receiver waits for an impulse from a certain tag.

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