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Original Contribution

SOFTWARE MODEL OF MOBILE INTERACTIVE USER DEVICE IN UWB NETWORK

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Abstract: *The present paper represents a subsequent step in the modeling phase of the new software model for a UWB wireless interactive sensor system, presented in a previous study, which employs precise local positioning for spatial orientation. Using tools, a software model of a key component of the considered wireless interactive sensor system is developed. The program constructs presented below provide, in a generalized form, an approach to the synthesis of a logical model of a Mobile Interactive User Device (MIUD), which is a component of the aforementioned system, during the design phase following its mathematical modeling. The fundamental principles of the MIUD model defining its functionality are presented.*

Key words: *UWB, Mobile, Wireless, Interactive, Positioning, System.*

1. Introduction

The advantages of wireless technologies, such as Ultra-Wideband (UWB), have facilitated the development and advancement of interactive sensor systems [3, 4]. The characteristics of this class of interactive sensor systems overcome a number of limitations identified in other systems serving a similar purpose, such as camera-based interactive systems.

In terms of its nature, principles, and underlying approaches, UWB is a technology for developing network models. In this context, a relevant issue in research related to “network architecture design” is the level of performance, and, in particular, the need for calculations determining end-to-end delay [2]. Considering the main approaches to the development of interactive sensor systems, the present study highlights, as key arguments, the advantages of UWB sensor networks over optical (camera)-based sensor networks. The key advantages of UWB include:

- Precise localization;
- High signal processing speed;

- Higher performance at the software processing level;
- Lower latency at the physical level, i.e. less end-to-end delay;
- Larger sensor network coverage area;
- A wide range of interfaces with programmable logic;
- Low cost of integrated components based on RFID technology;
- Fewer integrated components, resulting in a higher degree of reliability of the sensor system;
- Higher degree of ergonomics.

2. Related work

This paper presents a continuation of the work based on the proposed architecture of a UWB wireless sensor-based interactive system, which comprises four main subsystems: The Interactive Simulation Server, the UWB Positioning System, the Mobile Interactive User Device, and the Projector System. Thus, the above-mentioned rationale was a determining factor in the selection of UWB technology and the engineering approach adopted for the synthesis of a software model for a Mobile Interactive User Device (MIUD), which constitutes a key component of the system architecture. The architecture in question was presented in a previous publication [1], which introduced a new prototype model for a UWB wireless interactive sensor system employing precise local positioning for spatial orientation (Fig. 1).

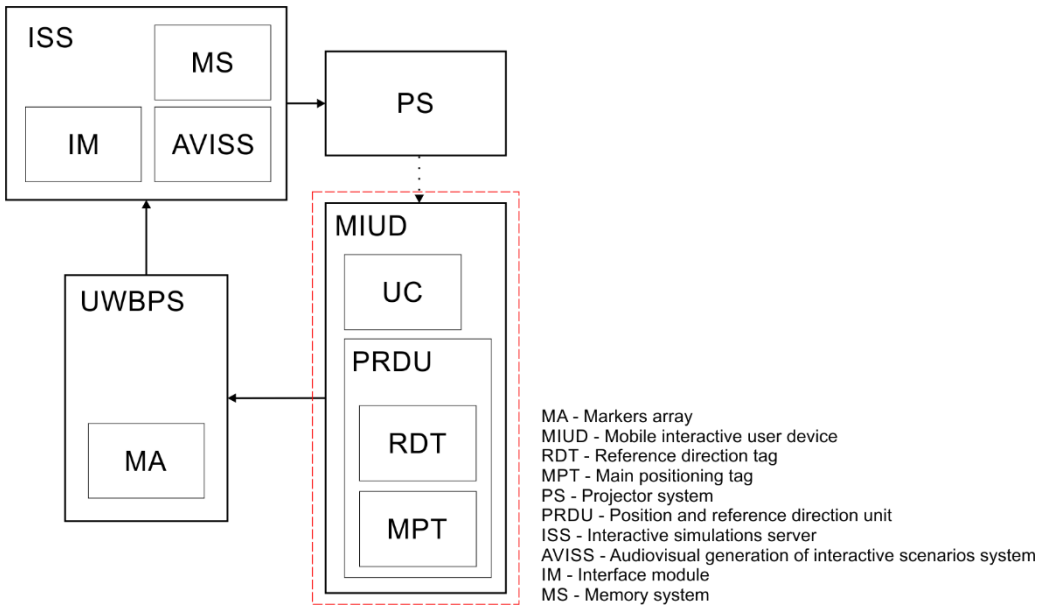


Fig. 1. An architecture of UWB wireless sensor-based interactive system [1]

The subject of the present study is the synthesis of a software model of the system component represented by the Mobile Interactive User Device (MIUD), highlighted by a red dashed line on the diagram above.

3. Basics and constraints

Following established engineering practice, mathematical modelling [1] is followed by the development of a simulation environment for collecting model data, which are subsequently subject to analysis [5, 6, 7]. In this context, this process can be regarded as an investigation of the behavior of the model under consideration. By relating the scientific

understanding that there are two fundamental approaches to describing a model qualitative and quantitative to the methods used for collecting model data, two questions can be addressed. The first refers to the qualitative aspect of the model, namely, "how will this model" exhibit its behavior, whereas the second, representing the quantitative aspect, concerns "to what extent" this behavior will be manifested.

It should be noted that, according to researchers, a key aspect is the answer to the qualitative question, whereas the answer to the quantitatively oriented question provides the researcher with an understanding of the model's behavior under specific conditions and within defined circumstances [6]. In addition, the model under consideration can be classified as stochastic, given the unpredictable behavior of the user operating the modelled device. This classification implies a broader range of possible model behaviors and therefore places greater emphasis on its qualitative description [6].

Based on the above considerations, the fundamental principles governing the behavior of the model should be formulated as follow:

- The positioning of the modelled MIUD will be based on the coordinates calculated for its two integrated tags;
- The modelled device will operate within an affine coordinate system;
- Data will be collected through simulations performed in an interactive 3D simulation environment for the future statistical processing.

At this stage, it is necessary to formulate a set of constraints applicable to and valid for the modelled device, while taking into account the holistic aspect of the entire UWB wireless interactive sensor system. It should be noted that the references to the elements, components, characteristics, descriptions, and constraints of the system represent a logical continuation of the first phase of the modelling process presented in [1].

Following this approach, the following fundamental constraints are defined:

a) The modelled MIUD shall operate exclusively within a confined indoor space;
b) The confined indoor space is represented as a parallelepiped with dimensions of $10 \times 10 \times 2.5$;
c) The housing of the modelled MIUD has a length of 10 cm;
d) The Main Position Tag (MPT) and Reference Direction Tag (RDT) are positioned at opposite ends of the device housing;
e) The roles of the MPT and RDT tags are defined by the system model of the MIUD, represented using UML diagrams;
f) The effective interactive working surface is assumed to be orthogonal;
g) The effective interactive working surface is defined within an affine coordinate system using the X, Y, and Z axes, with the origin at $(0,0,0)$;
h) For the purposes of the software simulation, three predefined static markers—$M_{initial}, M_{width}$, and M_{height} —are assumed to lie on the effective interactive working surface;
i) The coordinates of these markers are defined as $M_{initial} = (0,0,0), M_{width} = (7,0,0)$, and $M_{height} = (0,2.5,0)$;
j) The MIUD enters the active phase only when the line defined by its direction vector intersects the effective interactive working surface and the proximity condition $MPT(Z.0) < RDT(Z.0)$ is satisfied.

4. Software modelling

An interactive 3D simulation environment implemented using HTML, CSS, and JavaScript is used for the modelling process, with Three.js employed for 3D visualization. Its primary purpose is to model the behavior of the Mobile Interactive User Device in a three-

dimensional space and to mathematically determine whether the direction defined by the device intersects the Interactive Projection Area (EIWA).

The simulation is based on a geometric model comprising:

- a virtual three-dimensional space $V = \{X, Y, Z\}$;
- a Mobile Interactive User Device (MUID) with six degrees of freedom (6-DOF):
- translation along the X, Y, and Z axes;
- rotation about the X, Y, and Z axes;
- two virtual UWB tags:
- MPT — green;
- RDT — red;
- an Interactive Projection Area;
- calculation of the direction from RDT to MPT;
- calculation of the intersection point Q between this direction and the EIWA plane;
- verification of whether Q lies within the permissible interactive area.

Therefore, this is not a physical UWB simulator in the sense of modelling the radio channel, ToF/TDoA, multipath propagation, NLOS conditions, or noise. Rather, it is a geometric and kinematic simulation model of the MUID behavior and its spatial interaction with the EIWA.

The simulation defines a virtual room with the following dimensions:

$$X = 0 \dots 10$$
$$Y = 0 \dots 2.5$$
$$Z = 0 \dots 10.$$

Thus:

$$width: 10$$
$$height: 2.5$$
$$depth: 10$$

These dimensions are defined in the code as follows:

$$const\ ROOM_WIDTH\ =\ 10;$$
$$const\ ROOM_HEIGHT\ =\ 2.5;$$
$$const\ ROOM_DEPTH\ =\ 10.$$

The interactive surface is positioned in the plane: $z = 0$

This is a key aspect of the simulation, as the entire interaction verification process is reduced to determining the intersection point between a defined spatial direction and this plane.

The MUID is modelled as a kinematic object represented by the MUID class, which defines its position and orientation through the this.position and this.rotation parameters, respectively in the code. Consequently, the model has six degrees of freedom, As described by the mathematical model (6-DOF), comprising translation along and rotation about the X, Y, and Z axes [1].

The initial position of the MUID is defined as $PMUID = (5,3,4)$, while its initial orientation is $(\theta x, \theta y, \theta z) = (0,0,0)$. This configuration enables the investigation of how changes in the device's position and orientation affect its ability to interact with the EIWA. A key element of the model is the representation of two integrated virtual tags, MPT and RDT, defined in the local coordinate system of the MUID as $MPT = (0,0,0.5)$ and $RDT = (0,0,-0.5)$, respectively. Thus, the distance between the two tags is fixed at $|\ MPT - RDT\ |$

$= 1$ conditional unit. The MPT and RDT are positioned along the same axis of the device and are not independently positioned; consequently, any translation or rotation of the MUID results in a corresponding transformation of both tags.

The system determines the validity of the interaction based on three main conditions:

First, the projection direction must not be parallel to the EIWA plane. This condition is verified by checking whether $| dz |< 10 - 9; if\ dz \approx 0$, the direction is considered parallel to the plane $z = 0$, and no valid intersection can be determined, resulting in an $INVALID - PARALLEL_TO_SCREEN$ status.

Second, the calculated intersection point must lie in the forward direction from the MPT, which requires the parameter $t \geq 0. If\ t < 0$, the interaction is classified as $INVALID - REVERSE_ORIENTATION$.

Third, the intersection point Q must lie within the boundaries of the EIWA, defined by $2 \leq Qx \leq 8$ and $0 \leq Qy \leq 2$. If Q lies outside these limits, the system returns $INVALID - OUTSIDE_EIWA$. The interaction is considered $VALID - OK$ only when all three conditions are simultaneously satisfied.

The mathematical core of the software simulation model can be summarized as a sequential process that determines the validity of the spatial interaction between the MUID and the EIWA. Starting from the MUID pose, the global coordinates of the MPT and RDT are determined, followed by the calculation of the direction vector $d = MPT - RDT$. The projection half-line is then defined as $L(t) = MPT + t_d$, and its intersection parameter with the EIWA plane $z = 0$ is calculated as $t = -MPT_z/d_z$. The interaction point is subsequently determined as $Q = MPT + td$. Finally, the conditions $t \geq 0\ and\ Q \in EIWA$ are evaluated to determine whether the interaction is $VALID$ or $INVALID$.

The complete mathematical sequence can be represented horizontally as follows:

$$MUID\ Pose \ \rightarrow\ Global\ MPT,\ RDT \ \rightarrow\ d = MPT - RDT \ \rightarrow\ L(t) = MPT + t_d \ \rightarrow\ t = -\frac{MPT_z}{d_z} \ \rightarrow\ Q = MPT + t_d \ \rightarrow\ t \geq 0 \ Q \in EIWA \ \rightarrow\ VALID\ or\ INVALID$$

This sequence represents the mathematical core of the software simulation model and provides a concise basis for generating model data and performing subsequent analysis.

The software simulation provides functionality for user-controlled manipulation of the MUID in a three-dimensional space with 6 DOF (Fig. 2.). The process can be visually monitored by the user in real time.

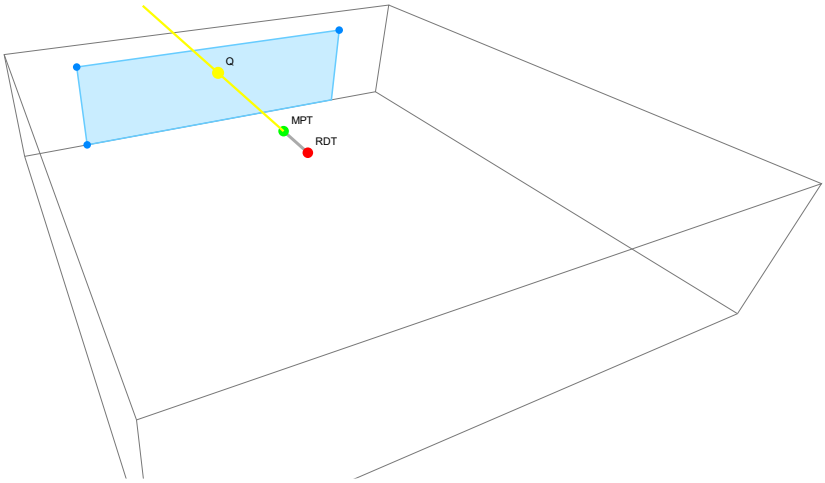


Fig. 2. Visual representation of MUID 3D space

5. Conclusion

The developed environment represents a three-dimensional geometric software simulation model of a UWB-based Mobile Interactive User Device, designed to investigate the spatial interaction between the device orientation and an Interactive Projection Area. This characterization more accurately reflects the scope of the developed model than describing it as a complete simulation of the UWB communication system, as the current implementation focuses primarily on the geometric and kinematic aspects of the MIUD and its interaction with the Interactive Projection Area.

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