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Design and Implementation of PIR sensors with Distributed Intelligence

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***Abstract*— The article analyzes the development trends of industrial systems called real-time location systems. The systems are based on various basic principles and are designed to solve problems of localization and predicting the position of mobile objects. The characteristics of the scanning information and navigation system are given. It is based on the use of infrared technologies based on PIR sensors [1]. The system consists of distributed scanning cells matrix. Computing cores of cells, implemented on the FPGA platform and represent distributed intelligence. They also perform the tasks of navigation and localization of mobile objects. The modeling of the scanning network fragment in the AnyLogic software package was carried out and the criterion of efficiency was determined. This made it possible to optimize the topology of communication links for the interaction of individual cells when transmitting messages and to determine the limiting characteristics of the network.**

Keywords—RTLS, FPGA, PIR sensor, model, AnyLogic

I. Introduction

The modern development of industrial automation systems and network ecosystems such as *IIoT* and *Internet of Robotic Things (IoRT)* [2] has set new challenges for developers. One of the tasks is related to the interaction of technological systems that have access to the network communication infrastructure. Industrial network devices, called *Functional Networking Components (FNC)* [3], are network devices that can independently solve part of a distributed technological problem and affect the surrounding physical environment. In this case, the problem of safety at production sites takes one of the first places. The second task is determined by human-machine interaction. The solution to this problem is caused by the need to ensure effective communication with a person of intelligent robotic systems, including unmanned vehicles such as AGV. In fact, AGV is a robotic device that has navigation, communication with technological equipment and security systems.

To solve these problems, a large class of positioning systems has been developed and is currently used. Systems make it possible to determine the position of physical or biological objects in space with a given accuracy. The use of positioning systems in technological and business processes is widely used to improve the quality of logistics, analyze the behavior and interaction of objects, and increase the safety of people and mechanisms. All positioning systems can be conditionally divided into global without space limitation and local, which operate in a limited area.

There is a large class of systems called real-time location systems (RTLS). These systems based on various basic principles: radio frequency technologies, infrared, ultrasonic, satellite navigation systems, etc. Different systems differ in characteristics such as positioning accuracy, polling frequency, noise immunity, etc.

The main criterion for choosing a system is determined by the task and the budget. From the point of view of the budget as a criterion for choosing the basic principle of RTLS, the use of infrared technologies gives a great advantage. In addition, Device-free localization (DFL) methods based on pyro electric infrared (PIR) sensors are actively investigated. These methods are characterized by low cost and low energy consumption. The big advantage of using the DFL method on PIR sensors is confidentiality, as opposed to the video image processing method.

In the proposed article, both passive localization systems based on the control of infrared radiation and active localization using infrared controlled beacons operating in a pulsed mode are considered.

PIR sensors are widely used as simple sensors, for example in automatic lighting systems. In particular, by changing the effective polarization of the sensing elements in the PIR sensor, it is possible to determine the relative direction of object moving in the plane of the sensor motion. This allows predicting the route of movement and turning on the corresponding lights.

The article is organized as follows. Section 2 analyzes works devoted to the use of infrared technologies in the creation of RTLS systems. Section 3 discusses the development and research results of the Scanning Information and Navigation System (SINS). The algorithm of its work is considered. Modeling of interaction between SINS cells is performed to optimize message transmission. Model building and research is presented in section 4. Presentation of research results and discussion is given in section 5.

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II. RELATED WORK

Quite a lot of publications are devoted to the use of infrared technologies in the creation of RTLS systems. The work [4] considers the developed RTLS based on infrared light in the problems of localization of internal objects. In the healthcare industry, such systems are used to track a hospital bed, monitor a patient, or locate critical equipment. The article [5] presents a method for determining the relative direction of a person's movement (in eight directions, evenly distributed) using two pairs of IR sensors. The sensing elements of them are aligned orthogonally. Based on the collected PIR signals, a classification analysis is performed using well-known machine learning algorithms. The results presented in this article show that with a set of raw data collected from two orthogonally aligned PIR sensors with modified lenses, more than 98% of the correct direction of movement can be achieved.

DFL - methods of localization without the use of devices based on the use of PIR - sensors are devoted to many publications. This method attracts with such advantages as low cost and energy consumption, as well as respect for confidentiality. In [6], a method based on deep learning technology is proposed. To improve the efficiency of localization, a network architecture is proposed. It contains two modules: one for counting the number of people on the move, and the other for predicting their location. According to the authors of the article, using the proposed method, it was possible to reduce the density of PIR deployment by about 76%, while maintaining the accuracy of localization.

The method of using people localization in PIR sensor system is presented in article [7]. The PIR sensor generates binary information indicating the presence of a person in the area of his detection. Deploying several PIR sensors and taking their detection areas partially overlap. Then a person in different places will launch different sets of PIR sensors. In Fig. 1 it can be seen that a person enters the area of the PIR1 and PIR3 sensors. Therefore, vector '101' can represent the current location. By continuously collecting the vectors of these PIR sensors, the trajectory of a person's movement can be obtained.

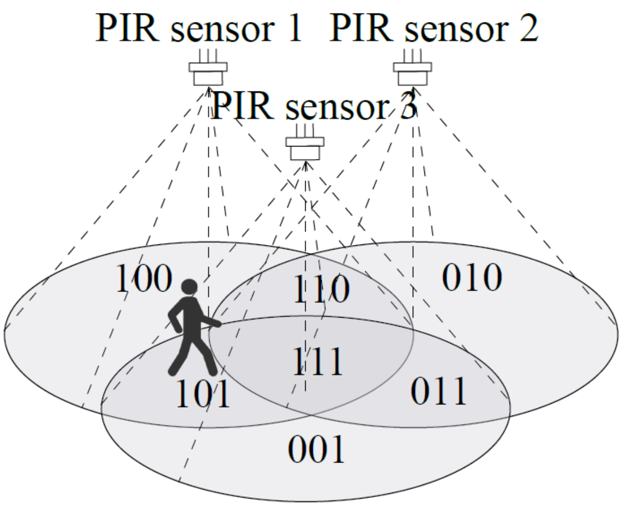

Fig. 1. Basic idea of PIR-based localization systems [7].

Thus, from the output signal of the PIR sensor, it is possible to extract a change in the azimuth of a moving person containing localization information. The disadvantage of this method is the ability to localize only one person.

The article [1] proposes a model of a scanning information and navigation system (SINS), consisting of distributed scanning cells (SCs) matrix developed on the Field-Programmable Gate Array (FPGA) platform.

According to its structure, SINS is a matrix of SCs. SCs are located in those places of production facilities where the routes of movement of autonomous mobile devices and personnel - scan objects (SOs) - pass. Each SC has a specific area of responsibility and interacts with the nearest cells.

The computing cores of the cells, which are distributed intelligence, perform the tasks of navigation and localization. Based on the information transmitted from each cell to the central computer, it is possible to track mobile devices and personnel and visualize their positions on the map.

The SC operation is based on the principle of monitoring the thermal radiation of SOs objects using passive PIR sensors. The scanning system makes it possible to implement in real time the tasks of route planning by mobile autonomous devices. In addition, SINS allows providing the necessary assistance in real time to all traffic participants in their area of responsibility in emergencies. As a result it ensure safe man-machine interaction.

The results of the further development of the SINS system in the direction associated with the optimization of information interaction between individual SCs will be presented. It is necessary to reduce the response time to events and increase the intellectual abilities of the entire network..

III. CASE STUDY

As noted in [1], the SC device is based on two elements: a passive PIR sensor and a digital matrix based on the FPGA platform.

In the SC computing core, a digital nonvolatile FPGA matrix of the MAX 10 family of INTEL company was used [8]. The choice of a device from the family was determined by the required number of inputs and outputs with LVDS levels and the required capacity for logical elements. In communication links, connecting individual cells, at the signal level, Data - Strobe coding (DS) is used. In addition, it is used in the IEEE 1355 - 1995 standard [9]. The advantages of DS - coding include the possibility of independent coding and the choice of data transmission rates in various links. In addition, there is no need to negotiate bit rates, since DS coding is self-synchronizing.

When analyzing and selecting routes of a communication network for data transmission between individual SCs, the following requirements are formulated:

- The number of links should be minimal;
- Each SC must be included in one or more local closed circular loops. This is necessary to control the transmitted information and determines the one direction of data transmission;
- The routes of the communication network should be located in such a way that in the event of any link or cell failure, it would be possible to transmit messages to the designated addressee.

Fig. 2 shows a SINS fragment of 9 SCs (SC1-SC9). Cell SC5 communicates with other cells (SC1-SC4, SC6-SC9) through four circular loops with unidirectional data transfer. Consider the contour formed by cells SC2, SC3, SC5, and SC6. To transfer data from cell SC5 to SC6 it is necessary to route through two cells: SC5 → SC2 → SC3 → SC6 (maximum route when interacting with cells directly surrounding SC5). To transfer data from SC5 to SC3, you need to go through SC2 (route: SC5 → SC2 → SC3). To control the validity and transport time, any message transfers from cell SC5 must end in the same cell.

Each cell of the circuit under consideration can transmit and receive messages. Thus, messages from each cell of the loop can circulate in this loop at any time, always transmitted in one direction.

Simulation of the SINS communication circuit to assess the effectiveness of the proposed link configuration.

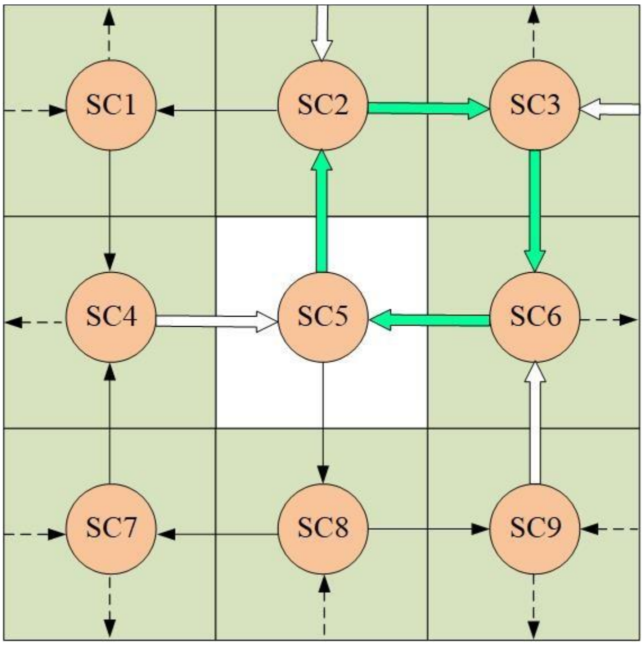

Fig. 2. SINS fragment of 9 SCs.

IV. Development And Testing Of The SINS Communication Curcuit Model

A communication network as a kind of network system can be attributed, from the point of view of building a model, to a queuing system. This allows choosing a simulation method as a model. Such model has a number of advantages over the analytical method of modeling. When creating and testing a model of a SINS fragment, it was the simulation method of modeling. Since this approach most accurately reflects the structure of the communication circuit and the relationship of individual cells. Let choose the SINS fragment formed by the contour from the cells SC2, SC3, SC5 and SC6 as the object of modeling. To build the model, the software package AnyLogic 8.7 [10] will be used.

A. Formalization of SINS Structure and Cell Interaction Algorithm

As noted earlier, in SNIS, objects of scanning can be both people and mobile devices such as AGV. Each AGV must carry a pulsed infrared beacon on board. Using this beacon, the SINS localizes the device in the cell and starts the exchange of messages. Thus, in the developed model, it is necessary to take into account the receipt of data from a localized SO for transmission to other SINS cells. Let assume that the set of functional blocks is the same in all cells.

Each of the cells of the selected contour has two input and two output links. That is, if we talk about the input and output streams of messages, then the computing system of each cell must process three input streams (taking into account data from the PIR) and two output streams. Let assume that the messages transmitted along the circular loop (that is, between the cells of the selected loop) have the highest priority. Messages arriving from other input streams (for example, from cells of another circuit - SC4, SC9, etc.) are distributed to queues with FIFO drives and are transmitted cyclically around the ring with equal access.

In the process of studying a fragment of the SINS network [1], experimental data were obtained for the distribution of input messages arriving at the cells. Analysis of the time intervals between messages showed that the message flow has three features of the simplest or stationary flow with a Poisson distribution (that is, the flow is stationary, ordinal and without aftereffect). An important characteristic of a Poisson stream is the distribution law of the interval duration between adjacent messages. It was shown in [11] that this law corresponds to an exponential (exponential) distribution law. Therefore, to build a model, as an input stream, we take a stream with an exponential distribution. To simplify the calculation of the total flow rate, let assume that all input flows are stationary flows with a Poisson distribution. This allows you to find the superposition of all input streams using the simple addition method.

B. Model Development and Research

The main purpose of a simulation model building (Fig. 3) of a SINS fragment is to assess its limiting capabilities as an open system. The model research program includes:

- Determination of the maximum throughput of the selected network contour for a given number of switching and routing nodes (multiples of the number of cells), maximum intensity and fixed processing time for messages in each cell;
- Determination of the maximum number of switching nodes (the possibility of increasing the structural units of the SINS) with a fixed number of input messages;
- Investigation of the messages delay time in switching nodes at different input intensity.

The structure of the model, built from library elements of the AnyLogic package. Structure reflects the ring topology of the SINS fragment and consists of the following functional blocks:

- *Sen <SCnumber>* - a source of information from sensors, where *<SCnumber>* corresponds to the SINS cell number (Fig.2) with an exponential distribution of the incoming messages intervals;

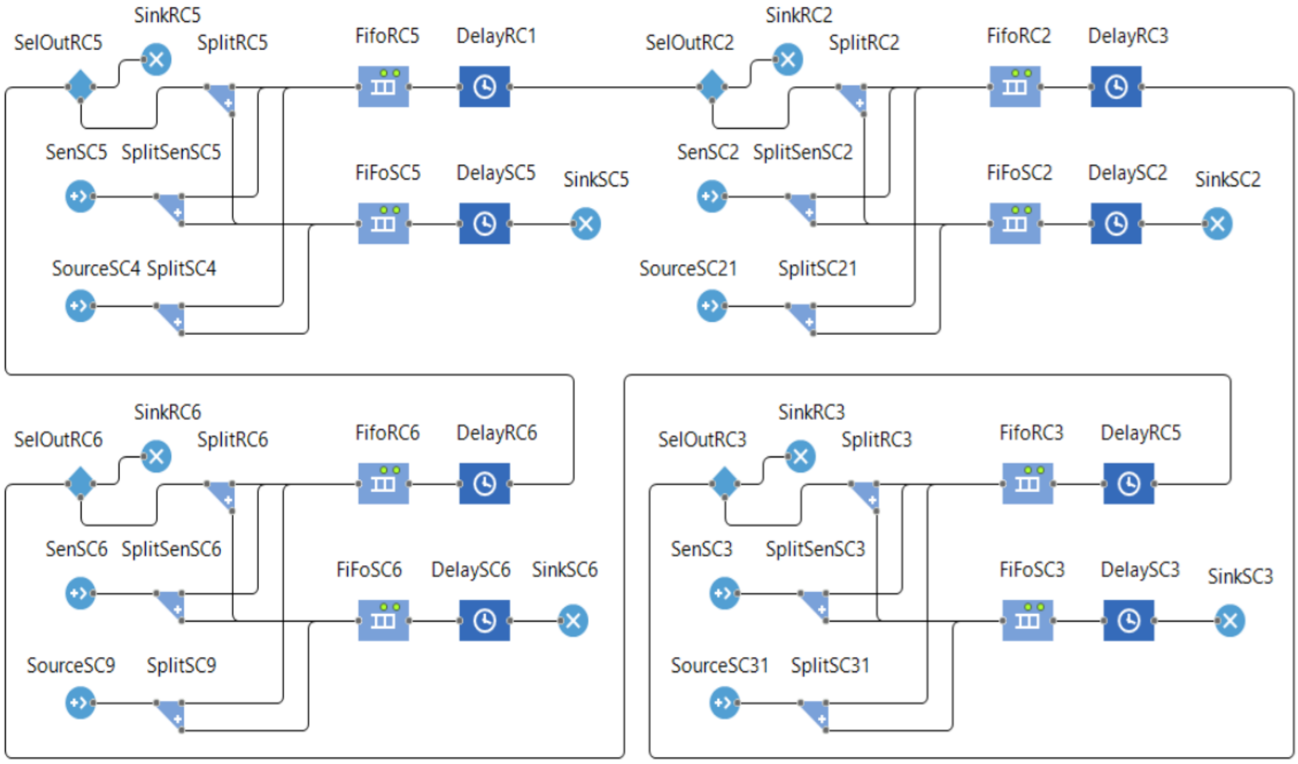

Fig. 3. Cells interaction model of a circular contour SC5 →SC2→SC3→SC6

- *SinkRCN* is a block that destroys messages which have returned along a ring circuit *(Ring Contour)* to their "own" cell (N is the ordinal number of the cell);
- *Sink<SCnumber>* is a block that destroys all post-processed messages that arrive in this cell;
- *SplitRCN* creates copies of messages entering the cell from the network (the whole copy operation is performed during zero time);
- *SplitSen<SCnumber>* creates copies of messages, broadcast to the ring network and for processing to the cell with the current number;
- *SelOutRCN* accepts messages from the network, and then chooses actions, depending on the specified condition ("own" messages - to destroy, "others" - to skip);
- *FifoRCN* simulates a FIFO type accumulator for messages coming from cells of the selected network loop, from a cell of an adjacent loop and from sensors of this cell (with priority for messages from the loop network);
- *Fifo<SCnumber>* simulates a FIFO drive for messages coming from the sensors of a given cell and from the network;
- *DelayRCN* is transport delay (fixed time) for transmission between cells over the network, the same for all links;
- *Delay<SCnumber>* delay for processing messages in the cell with the current number (from the network and from the cell sensors).

Let's denote the cells not shown in Fig. 2 as SC21 and SC31, transmitting messages to cells SC2 and SC3, respectively. Simulation options while running experiments:

- A random seed number of messages at the inputs of any cell on each run (unique experiments);
- The simulation time in each experiment is 10 model units (can be equated to seconds);
- The rate of messages receipt from *Sen <SCnumber>* is set for each experiment;
- Number of runs in each experiment is 10.

The paper [12] discusses the criteria for the timing (synchronization) systems effectiveness of various technological systems. Efficiency in this case depends on a large number of factors and conditions: the bandwidth of the backbones, the speed and performance of the message processing equipment, the network topology, etc. The main parameter for evaluating the effectiveness of a timing systems model can be considered the reliability of the messages used. The reliability of messages, in turn, is determined by the transport delay, the processing time in each cell, and the losses in case of overflowing data storage devices. With an increase in the depth of the buffer memory of drives, losses are reduced, but the reliability of transmitted messages also decreases.

The delivery time of any message between cells can be expressed as:

$$T_{SC\text{-}SC} = (P - 1) * DelayRCN + Delay\langle SCnumber\rangle \quad (1)$$

where P are cells number in curcuit. Time of processing is $Delay\langle SCnumber\rangle = D*T_{PROC}$, where D is memory fill depth

FiFo, T_{PROC} is fixed processing time for one message, determined only by the hardware capabilities of the cell calculator.

Based on the requirements for SINS, determined by the speed of movement of SO's (people and autonomous mobile devices) and the throughput of links, the total delivery time of T_{NET} should not exceed the time corresponding to the processing of 6 messages, and $T_{PROC}/DelayRCN = 3$. The last ratio is determined by the speed of the communication network and performance of message processing. For this problem these requirements should not change. Even when changing network capabilities, changing hardware platforms of calculators and message processing algorithms. Based on the above requirements, the depth of the buffer memory capacity D (*FifoSCN*) should not exceed 6 ($D \leq 6$). Let's make a substitution in relation (1) taking into account the requirements and relations presented above

$$T_{SC\text{-}SC} = (P - 1) * (T_{PROC} /3) + D * T_{PROC} \leq 6 * T_{PROC} \qquad (2)$$

The fulfillment of relation (2) during model runs determines the efficiency of the communication network. Simplifying expression (2):

$$P - 1 + 3\, D \leq 25 \; (P, D > 0) \qquad (3)$$

From expression (3) it can be seen that with $P = 4$, the *FifoSCN* memory depth should not exceed 5 (($D \leq 5$), and with P = 10, the *FifoSCN* memory depth should not exceed 3 ($D \leq 3$). Fig. 4 shows a time diagram of the storage devices operation at the maximum intensity of input message flows, $P = 4$ and with strict observance of the relation (2)

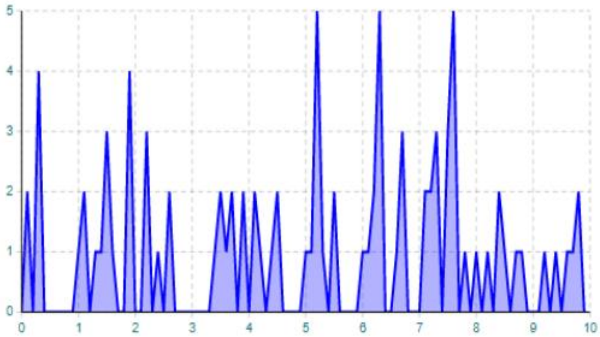

Fig. 4. Timing diagram of the *FiFoSC5* operation drive: along the X-axis - model time, along the Y-axis - the depth of the drive memory filling.

V. Discussion and Conclusions

The results of the experiments on the model are presented in Tables I and II. In each cell of the table, the maximum values of filling the buffer memory depth are indicated, separated by commas, for experiments with the following conditions:

- $P = 4$, intensity of 1.2 messages per unit of model time (default intensity);
- $P = 4$, the total number of messages processed in the computational core of each cell during the model time at the maximum intensity (10 times higher than the default intensity);
- $P = 10$, default intensity.

TABLE I. Memory Filling Depth *FiFoRCN*

Memory filling depth D_k k =1, . . ,10	***FIFO* drives for messages arriving at cell inputs from the network**			
	FiFoRC5	***FiFoRC2***	***FiFoRC3***	***FiFoRC6***
D_1	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
D_2	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
D_3	1, 2, 1	1, 1, 1	1, 1, 1	1, 2, 1
D_4	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
D_5	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
D_6	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
D_7	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1
D_8	1, 1, 1	1, 2, 1	1, 1, 1	1, 1, 1
D_9	1, 1, 1	1, 1, 1	1, 1, 1	1, 2, 1
D_{10}	1, 1, 1	1, 1, 1	1, 1, 1	1, 1, 1

TABLE II. Memory Filling Depth *FiFoSCN*

Memory filling depth D_k k =1, . . ,10	***FIFO* drives for messages arriving at cell inputs from the network**			
	FiFoSC5	***FiFoSC2***	***FiFoSC3***	***FiFoSC6***
D_1	1, 4, 3	1, 3, 2	1, 4, 3	1, 4, 2
D_2	1, 3, 3	1, 4, 3	1, 3, 3	1, 3, 2
D_3	1, 4, 3	1, 4, 3	1, 4, 3	1, 5, 3
D_4	1, 2, 2	1, 3, 2	1, 3, 2	1, 3, 2
D_5	1, 2, 2	1, 3, 3	1, 3, 3	1, 3, 3
D_6	1, 4, 3	1, 4, 3	1, 4, 3	1, 4, 3
D_7	1, 5, 4	1, 5, 3	1, 4, 3	1, 5, 3
D_8	1, 5, 4	1, 5, 4	1, 4, 4	1, 4, 3
D_9	1, 5, 4	1, 5, 3	1, 4, 3	1, 5, 3
D_{10}	1, 2, 2	1, 3, 2	1, 3, 2	1, 3, 2

Analysis of the simulation results draw the following conclusions. Simulation model (Fig. 3) running of the SINS fragment correspond to the performance indicators both. Firstly, when the values of the input messages intensity are significantly exceeded, set by default, and when the network configuration is changed, that is, when the number of SC's in the loop increases to 10 (P = 10).

The article discusses the algorithm of the optimized SINS operation. The simulation of the network ring circuit in the AnyLogic software package made it possible to optimize the topology of communication links for the interaction of individual cells of the SINS during message transmission and to determine the limiting characteristics. The use of a scanning network makes it possible to provide the necessary assistance in real time to all traffic participants in their area of responsibility in case of emergencies. It ensures safe man-machine and machine-machine interaction *(Machine-to-Machine).*

Further development of SINS is associated with determining the direction of SO's movement. It will allow the cells distributed intelligence to predict more accurately the route of mobile objects movement.

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