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The use of RFID Transponders Equipped with Built-in Sensors in Navigation Systems

***Abstract**. The authors' research in the subject of sensors integration with IC of RFID transponder has been presented in this paper. A deployment of some number of such equipped identifiers in a particular region gives the opportunity to determine precisely the parameter values describing ambient conditions. Selected problems connected with memory organization of the transponders and also with an implementation in autonomous navigation systems of static and mobile objects inside of the defined space have been analysed in details.*

***Streszczenie.** W artykule autorzy zaprezentowali badania związane z możliwością integracji czujników z układem scalonym identyfikatora RFID. Rozmieszczenie pewnej liczby tak wyposażonych identyfikatorów na określonym obszarze daje możliwość precyzyjnego wyznaczenia wartości parametrów opisujących warunki środowiskowe. Szczegółowo zostały przedstawione wybrane problemy związane z organizacją pamięci takiego identyfikatora jak również z jego wykorzystaniem w autonomicznych systemach nawigacji statycznych lub mobilnych obiektów wewnątrz określonego obszaru. (**Wykorzystanie identyfikatorów RFID z wbudowanymi czujnikami w systemach nawigacji**).*

Keywords: RFID, transponders, intelligent sensors, autonomous localization.
Słowa kluczowe: RFID, identyfikatory elektroniczne, czujniki inteligentne, lokalizacja autonomiczna.

Introduction

The navigation of mobile object is connected with such issues as determination of actual localization and position of possible static or moving obstacles, estimation of motion path and evaluation the easiest efficient routes to the selected destination. In most cases these tasks are provided thanks to implementation of several different systems cooperating and supporting each other [1]. Each system is usually responsible only for a one particular task. For example, a system GPS is used for current object localization, laser scanner – for obstacle detection, analysis of camera images – for recognition of objects, etc. The above mentioned solutions give the orientation in a limited extent, due to their inherent principles of operation. It is the reason why there are navigation systems with doublet units for realization the same sense task (e.g. laser scanner and sonar). In this manner, the units complement each other, providing the expected perception and thus increasing an efficiency of operation in different environmental conditions. Untypical use of RFID (Radio Frequency IDentification) technique in the process of navigation allows designers to eliminate the need for implementing functionally diverse solutions and overcome some barriers limiting the mobility of contemporary systems.

RFID technique is generally used in processes of object identification. An electronic transponder with built-in antenna (called also tag) is the main element of the system. It responds to the inquiry from a RWD (Read/Write Device) [2] by conveying its own unique identification code. Since the tag is connected inseparably with object, the code allows users to identify unequivocally this assembly. The transponder is very often equipped with additional memory (for writing or reading extra data). Its capacity, logical and technological structure depends on the type of tag. Contemporary integration of solutions from different fields of the electronics, in a single hybrid structure, allows for a significant increase in a functionality of electronic systems [3]. The hybridization of a RFID (Radio Frequency IDentification) IC (Integrated Circuit), sensors of various physical quantities and a data memory of environment parameters on a one shared substrate (usually flexible but also ceramic, PCB, etc.) is a great example of this achievement. The achievement of greater functional quality in the single element enables a realization of innovative applications in the area of artificial intelligence.

Aspects connected with the multi-functionality of sensor tags (a tag equipped with sensors of any physical quantity) are presented on the example of a navigation system of static or moving objects within a given space – the system has been built on the basis of RFID technique with appropriate configuration of sensors and distributed memory of navigation data. Such a system called ACRNM (Autonomous Robinson Crusoe Navigation Method) was proposed in [4] and its idea is presented in the Fig. 1.

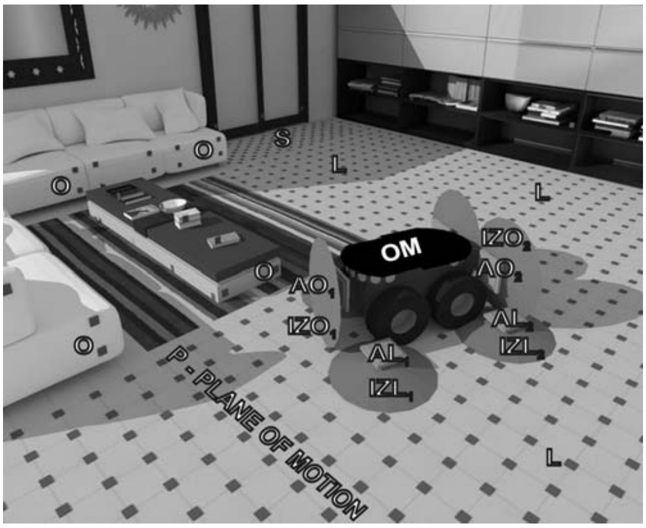

Fig.1. Idea of ACRNM navigation system

In the ACRNM system, RFID tags are placed according to a given structure on a plane or in space and serve as position sensors, and in addition, as sensors of other local environmental parameters (temperature, humidity, pressure, stored information about load-carrying capacity, surface roughness, gradient, dimensions of zone etc.). Such a defined network of sensors provides required information to realize the location process of a moving object and its autonomous navigation without necessity of implementing any other intelligent detectors (e.g. cameras, ultrasonic and strain gauge, etc.) [5].

RFID transponder in navigation system

According to the analyze of contemporary trends in the navigation world, the RFID technique is mainly used in determination of mobile object localization or position of other obstacles in specified space. In this solution, a control system connected with the read/write device reads unique serial numbers from dispersed transponders which appear in the interrogation zone (IZ) generated by RWD's antenna. On the base of gathered data, the localization in a map of particular area is estimated by using adequate algorithms in control software. These numbers can be unequivocally assigned to particular grid nodes describing a moving area of object in the navigation system. The map of surroundings and points-tags assignment has to be known and implemented in control system [6].

The accuracy of objects positioning mainly depends on two factors: the size of interrogation zone and the density of points with transponders in established lattice. The size and shape of the interrogation zone can be dynamically changed in output circuit of RWD. It can be made by designing appropriate construction of antenna but usually the shape is fixed. Designers seek to obtain a circular shape in order to simplify the algorithm of position determination for mobile objects. Then the size of the interrogation zone described by a radius can be changed by adjusting the power supplied to the antenna terminals. The solution with power adjusting gives the possibility to influence the localization accuracy and speed of movement of an object. Aspects connected with selection of the adequate IZ radius are considered on the base of two regular grids: square and triangular (Fig. 2).

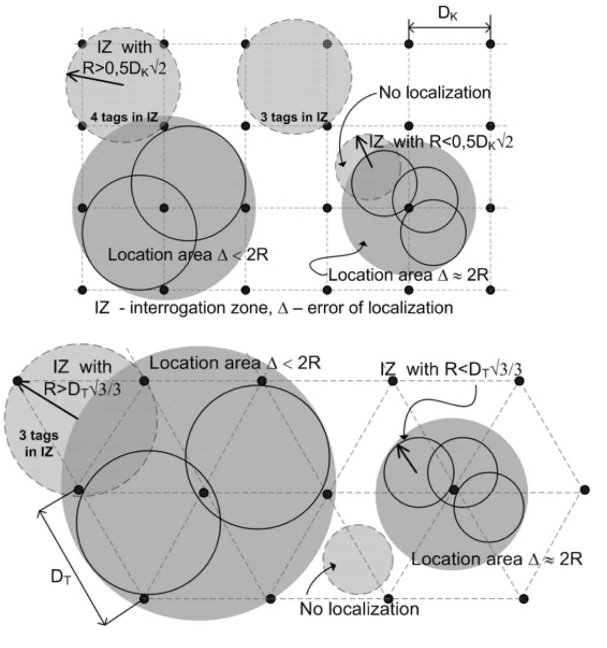

Fig.2. Accuracy of position according to radius R of interrogation zone and square grid constant D_K or triangular grid constant D_T

It is obvious that decreasing the power supply and thus an area of the interrogation zone causes reduction of the localization error. But then, an increasing of local concentration of transponders (points of grid describing the area – for example S zone in the figure 1) is required what influence the amount of transferred data and thus the speed of the object. On the other hand increasing the interrogation zone allows mobile object to increase the speed in the situation when there is not necessity for high precision movement, then the number of tags can be reduced.

It would seem that decreasing the radius R of IZ without reduction of the grid constant should also result in better accuracy. Although it is then equal 2R but if $R < 0,5\, D_K\sqrt{2}$ for square grid or $R < D_T\sqrt{3} / 3$ for triangular grid, there are places where there is not possible to identify the localization (there is not any transponder in interrogation zone). This causes the necessity to implement in control software extra algorithms for estimating positions or paths of movement. If the size of the interrogation zone is expanded to the value of $R \approx 0,5 D_K\sqrt{2}$ or $R \approx D_T\sqrt{3}/3$, the accuracy decreases (it is still equal 2R) but there are at least four active transponders (1, 2, 3 or 4) in the detection range of RWD antenna. In this case, the permanent actualization of the object position is possible. There are also places where localization can be calculated very precisely (4 transponders simultaneously active for square grid or 3 – for triangular grid) with the accuracy which depend only on the regularity of IZ circuit. It would be useful to increase only the radius R (or decrease only grid constant D_K, D_T) but it requires to use some more sophisticated navigation algorithms. It also leads to huge telecommunication traffic connected with anticollision procedures and ID numbers exchange between RWD and transponders while appearing simultaneously in the interrogation zone.

It should be noticed that the localization error is maximal only for the situation when in the interrogation zone is visible one active transponder. It does not depend on a path of mobile object. Since a few tags are usually active in the IZ, the effect of the localization is more accurate. However, comparing the two structures of tags deployment in terms of the error value, it should be noticed that the square grid provides a better localization because there are fewer places where only one transponder is recognised.

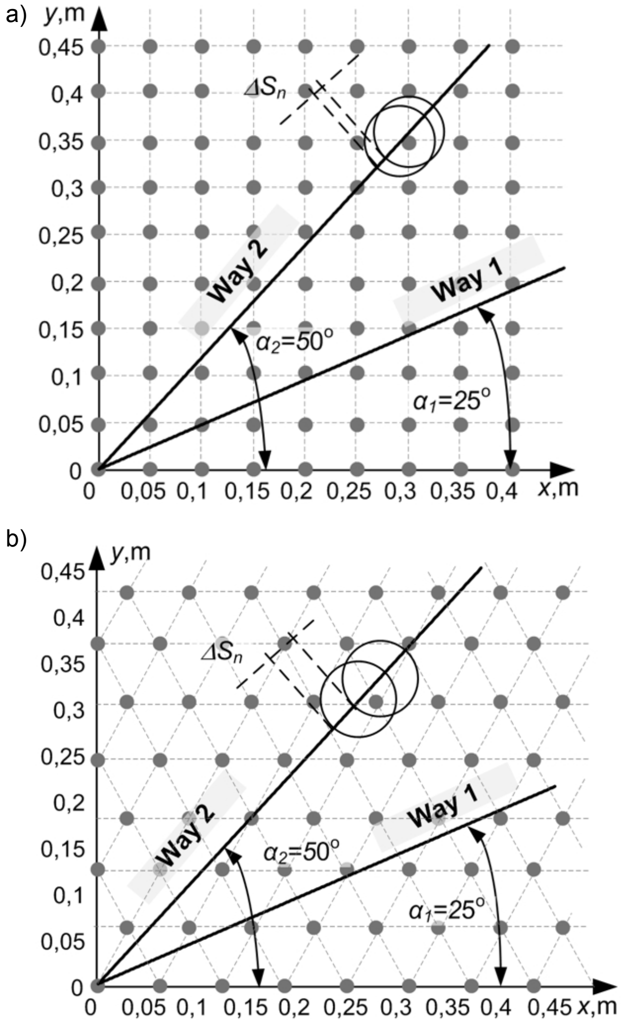

Fig.3. Considered trajectories of motions for different configuration of lattices: a) square, b) triangular (ΔS_n means path along which the number of tags is constant)

It is clear from the foregoing discussion that the aspect of tags deployment in an area of movement is very important in the navigation process. On the base of previous works considered in other papers [7, 8, 9], the two regular structures of transponders distribution have been selected. The square and triangular arrangements and trajectories of robot motion (Way 1, Way 2) are presented in the Fig. 3.

The numbers of identifiers being in the interrogation zone of the RWD antenna moving along the trajectories have been obtained on the base of numerical simulation (Fig. 4). The calculations have been made with assumptions that there is at least an one transponder in the interrogation zone and maximal number of active nodes is four or three according to considered structure of lattice (R>0,5D$_K$√2 square grid or R>D$_T$√3/3 triangle grid).

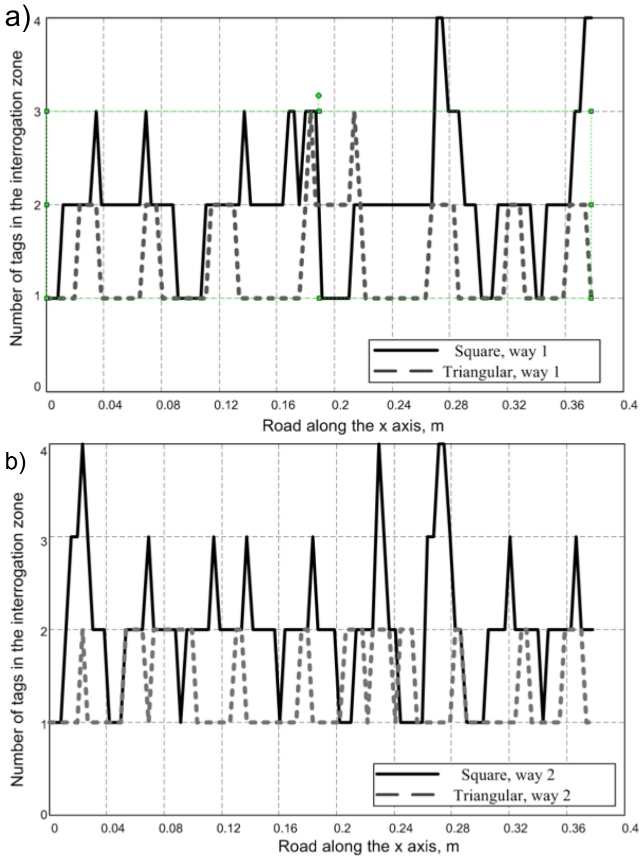

Fig.4. Number of RFID transponders in the interrogation zone for Way 1 – a) / Way 2 – b) and square / triangular lattice

An arrangement of tags deployment has a significant impact on the number of active transponders being in the detection range of RWD. It also influences the dynamic of the number fluctuation. For comparative purposes, the statistical analysis has been performed according to the formula:

(1)
$$Sr_{KwTr} = \frac{\sum_{k=1}^{100} \frac{l_{IdKw_k} - l_{IdTr_k}}{l_{IdKw_k}}}{100} \cdot 100\% = \sum_{k=1}^{100} \frac{l_{IdKw_k} - l_{IdTr_k}}{l_{IdKw_k}}, \%$$

where: k means step of mobile object (interrogation zone) along the x axis, l_{IdKw}, l_{IdTr} – number of transponders in the interrogation zone of RFID system for square and triangular grid correspondingly.

In any case, the number of transponders is greater for the square grid by an average of over 20%.

Changing the size of the interrogation zone so that a significant number of transponders (an average of a dozen points) was identified by the RWD at any its position, gives the results shown in the figure 5.

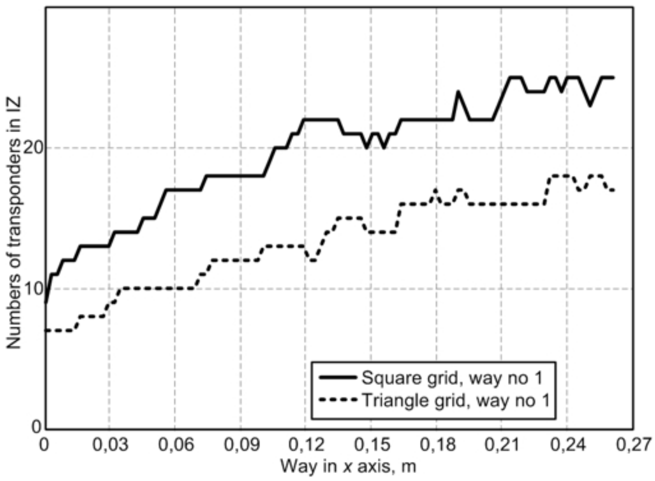

Fig. 5. Number of RFID transponder in the interrogation zone of radius r = 4R

In any case, the number of active tags is greater for the square grid by an average of over 30%. The rapid increase in the number of transponders that is observed in the first phase of movement is caused by reaching the place where there is full coverage of the IZ area by points of grid.

Trajectories have been chosen to take into account possible strong dynamic of changes and the fluctuation of the number of identifiers. The data transferring from the transponders in the network takes place at the time when the tags are in the interrogation zone of the RWD antenna which is localized on the mobile object. Thus, important information for the current location of the object is delivered locally and at the time of passing the particular zone.

These results lead to the conclusion that the higher constant grid with reference to the interrogation zone causes the necessity to pass significant more information in the case of square grid. It affects a throughput of the telecommunication transmission and a computing capacity of the control system. In order to decide the next step while moving the mobile object, it is necessary to compute more data and thus to reduce the maximum speed according to the formula:

(2) $$V = \Delta S_n / t_s$$

where ΔS_n (see the Fig. 3) means path along which the number of tags is constant in the interrogation zone (the path of movement is consistent with one of n trajectories), t_s is duration of the data exchange with tags located in the interrogation zone.

The time needed to exchange data with transponders currently situated in the interrogation zone is equal:

(3) $$t_s = t_{AC} + \sum_{1}^{k} \{ t_{Pk}, t_{READk}, t_{WRITEk}, \ldots \}$$

where k∈[1, 2, 3, 4], t_{Pk} means duration of signal processing from sensor (sensors) and data writing in the memory of k–th transponder, t_{AC} – duration of handling non-collision procedure, t_{READk} – duration of data reading from k–th transponder, t_{WRITEk} – duration of data writing in k–th transponder. t_{READk} and t_{WRITEk} depend on the amount of data exchange and rate – $BitRate$ parameter [10].

A special application for computer simulation of selected structures of transponders has been developed in Mathcad environment. In the programme there is possibility to choose the shape and dimensions of grid, the size of constant grid and interrogation zone or the range of number of simultaneously active tags.

A passive radio frequency identification system with inductive coupling, working on the frequency of 13,56MHz has been used in the proposed navigation task. Such a system is inexpensive in compare with other RFID solutions. It uses near field communication so the RWD and active transponders have to be in close proximity to each other usually by no more then few dozen centimetres [2]. It is very important for the accuracy of position determination. Since it operates by direct inductive coupling between antenna sets, the magnetic field produced around antenna loops of read/write device determines the power condition for supply passive tags [10]. It is also necessary for the proper performance of writing and reading information stored in the transponder memory.

The effectiveness (and also accuracy) of the system depends mainly on the quality (in respect of shape and size) of the interrogation zone. The Q-factor is a crucial parameter in the synthesis of this zone. During designing of an antenna output, the maximal value of this parameter can be reach by adjusting an inductance (or indirectly – loop resistance) of the winding according to the shape and size of a tag. This value determines the proper operation of a supply unit in transponders. But energy determinants of the RFID system are in conflict with the communication conditions. The need to transfer data with an appropriate bit rate is associated with ensuring adequate bandwidth for the loaded circuit of transponder antenna. Reaching required data rate is connected with reduction of the Q-factor and thus the energy efficiency of system. All aspects connected with above mentioned problems of determining the interrogation zone is detailed described in previous works [10, 11, 12].

RFID sensor tag – sensor in navigation system

The simplest solutions of navigation systems with the possibility of informing mobile object about the environment characteristics can be constructed by using common identifiers equipped with data memory. Depending on the needs, the memory can be programmed in the design stage or modified in the process of message exchange with RWD. In this case, the stored data characterize local parameters which describe e. g. the type, slope and drop of substrate, sizes, shapes and properties of another object or fixed obstacles. This information can be used to self-localization of a mobile object, build its own maps of the environment, update the information in points of grid, and ultimately to the autonomous navigation [13, 14].

There is also possibility to build general sensor tag platform by using commercially available transponders and additional digital switch (Fig. 6.) for connecting different kind of transducers. This device can receive and transmit signals from any sensor [15] by sampling the voltage value from the transducer and then activating selected antenna or whole transponder and broadcasting in real time a combination of different ID codes. Each combination of transmitted serial numbers corresponds to a different level of sensor output.

The similar solution could be made by using MCRF202 (Microchip Technology) tag which contains a 1-bit sensor port that can be used to invert the bit stream associated with the ID code, and a Vcc port for powering external electronics (10μA/2V) [3].

Using commercially available passive RFID transponders equipped with a sensor of a physical quantity called sensor tag (there are tags with embedded temperature or humidity sensors, but also it is possible to find prototype solutions with other detectors), the significant increase in the visibility of environment properties is feasible. Moreover, the intelligence of a navigation control system is not necessarily more sophisticated. The main disadvantage of this solution is that it is not possible to connect user's sensors.

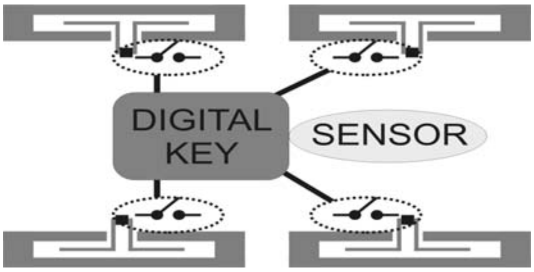

Fig.6. General purpose RFID tag platform with 4-bits output for connecting different kind of sensors

The usage of a passive (powered by energy supplied by the antenna system) intelligent RFID platform with inputs for digital or analogue signals (from e.g. sensor) would seem the best solution for navigation system (like ACRNM). The idea of such a solution is shown in the figure 7. Feasibility of this type of tags is possible thanks to the emergence of the ICs (microprocessors and ASICs) with very low power consumption. Moreover, it was confirmed in laboratories of Intel Labs Seattle, where the so-called platform WSIP (Wireless Identification and Sensing Platform) was developed [16].

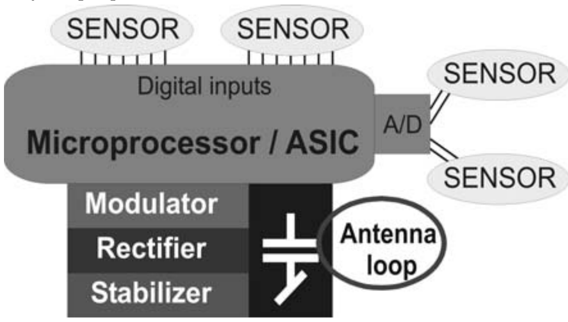

Fig.7. RFID tag platform for sensor – model under consideration

It can be immediately noticed that such a circuit should be made in hybrid technology and taking into consideration its applications, elastic and polymer materials should be used in its technological process. In order to set up the assumed functionality, elements made in monolithic technology (e.g. RFID control system, memory, and also – in some solutions – sensors) have to be integrated with conventional thick-film structures (e.g. antenna, transducers of physical quantities into electrical signal, passive and matching elements, system of roots) [2, 17]. However, the integration of different kind of physical quantity sensors with transponders enables to store information about local environment in built-in memory [18]. The quantities (temperature, humidity, pressure, light intensity, vibration, etc.) can be measured with different frequency and in time periods with various duration, and the data gathered by the tag can be read at any time by superior control system. A deployment of some number of such equipped identifiers in a particular region gives the opportunity to determine precisely parameter values describing ambient conditions. This knowledge is very valuable during routing processes of mobile robots especially with high autonomous intelligence.

Whatever solution someone would want to use there is always a problem with the memory capacity and rate of exchange data between IDs and RWD. The general idea of a sensor tag with hypothetic memory organization is presented in the figure 8.

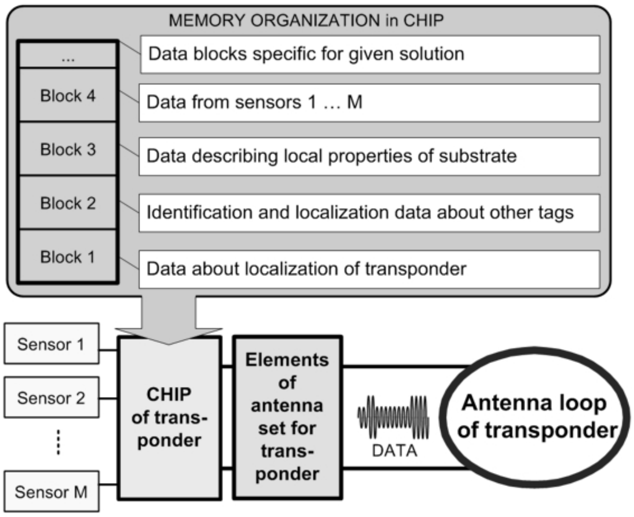

Fig.8. General idea of the intelligent tag with sensors

The data transferring from the transponders in the grid nodes takes place only at the time when the tag is in the interrogation zone of the RWD antenna localized on the mobile object. Moreover, a few transponders may be present simultaneously in the interrogation zone and all off them may try automatically to answer an enquiry from the RWD. It causes the necessity to transmit a huge number of bits connected either with serial ID as well with anticollision procedure. This process takes a significant amount of time and influences the speed of mobile object with RWD antenna [1, 2]. Now, since there is the need to send extra bits from the built-in memory connected with data from sensors, the speed of the object has to be even more limited in considered grid of navigation system. So, the problem is how to meet requirements for proper transmission and for intention of ambient data gathering.

Since the transponder has its own unique serial number consisted of a few dozens of bits, the reading process of this identifying information is a significant part of the whole transmission. On the other hand, a position of the given tag with reference to others is sufficient to determine coordinates of the autonomous object movement in the navigation system. So, there is possibility to code the relative position (for example according to eight neighbours) by using a few bits (for example one byte) which can replace more precise but long specific ID number (Fig.9).

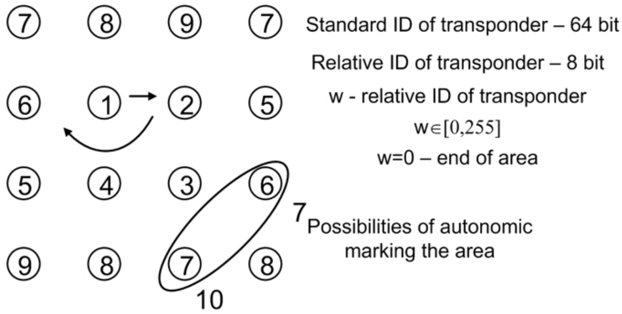

Fig.9. General idea of coding the relative position

Of course this new dynamic code system has to ensure that all items in the group of neighbours interrogated by the RWD will have a different allocated number. This approach greatly reduces the amount of transmitted data and increases ability of the mobile object to move at higher speed. Besides this, the mobile object can alone label the points with the relative IDs (by writing number $w \in [0,255]$ in tag memory) using a simple procedure (for example numbering tags with the smallest free ID).

Further simplification of data stream is possible by dividing the whole data which are designed for transmitting to RWD into two main groups presented in the figure 10 and 11. The ”basic information” is obligatorily transferred to control system every time, whereas the “supplementary information” will be read only on the base of writings in the “status information” record and adequate operation algorithm implemented in the control system. The algorithm can decide what part of additional information should be read depending on realised task. Of course this data block (“supplementary information) can be completely omitted. It means that the minimal number of data bits which are necessary to read from each identifier equals 10 bytes.

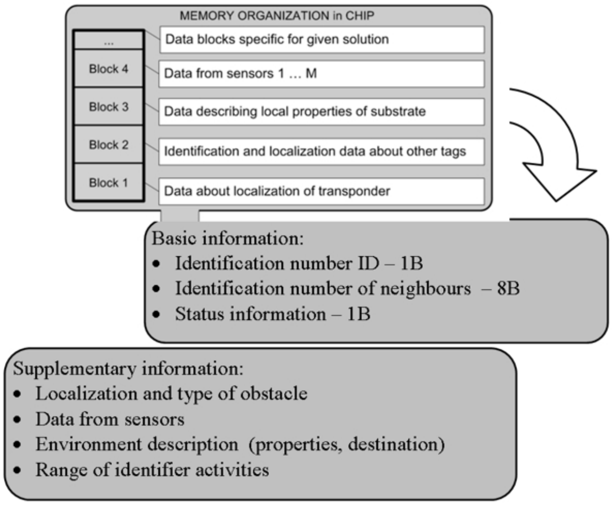

Fig.10. Functional partitions in transponder memory

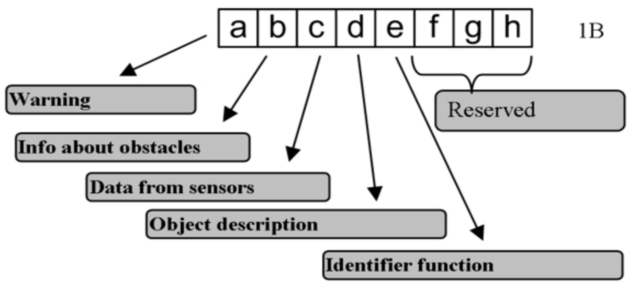

Fig.11. The meaning of “status information” bits

If there is requirement to make analysis of other setups it is possible to use the following dependence:

$$LD(t) = \sum_{i=1}^{k} \left(10 + \sum_{j=1}^{8} status(j) * data(j) \right) \quad (4)$$

where LD means current range of data designed to read, k is number of transponders in the interrogation zone and j means bits of “status information” byte. If $status(j)$ bit is true (Fig. 11), it means that there is possibility to read extra bytes $data(j)$ which describe the navigation environment.

The total number of transferred data is not constant and depends on the inquiries that are necessary to rout the path in navigation process realized by superior control system. This solution makes possible to increase the velocity of autonomous robot in not demanding environment.

Practical verification

The appropriate laboratory stand presented in the figure 12 has been developed in order to practical verification of the Mathcad calculation and possibility to creation of the implementation in RFID technique.

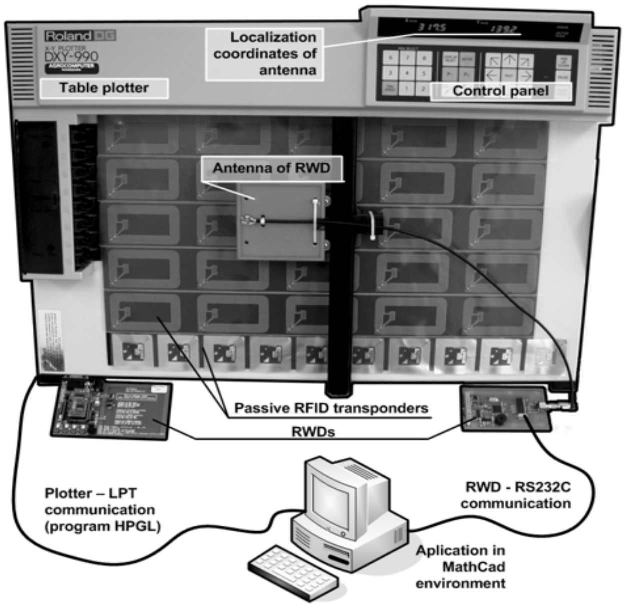

Fig.12. Laboratory stand

Since the stand is constructed by using a typical table plotter, the plane of the RWD antenna motion is limited to its working area. The tags are arranged according to the assumed shape and size of the considered square and triangular grids. The size and shape of the interrogation zone is adjusted by adequate selecting a type of the RWD antenna, its point of fixation (the distance between the RWD antenna, and the plane with tags) and power supply of antenna provided by the RWD output circuit. The system works under the PC controller. It allows researcher to implement advanced algorithms for motion control, navigation and localization taking into account dynamic conditions. Additionally, it is possible to manually control the RWD antenna movement

Summary

The usage of tags equipped with special systems of sensors gives a new quality in the process of building navigation systems. This allows both the location of the mobile object as well as the construction of cognitive knowledge base about the environment. Unfortunately, increasing the universality of markers (sensor tags) the necessity of reading vast amounts of data affects the speed of movement of the mobile object. In extreme cases $\Delta S_n \rightarrow 0$, that means too rapid change in the number of transponders (or replacement of identifiers) in the interrogation zone. This situation leads to faults in processes of data transferring and thus – in an extreme cases – to losses in information from specific tag (sensor). The maximum speed should be a compromise between the required rate of movement of the mobile object and assumed level of losses in data gathering.

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