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INDOOR POSITIONING METHODS FOR SMALL AUTONOMOUS VEHICLES

Abstract. The estimation of their position by unmanned vehicles is crucial for successful reconnaissance, procurement and rescue missions in autonomous mode. Determining goals and mission checkpoints allows the platform operator, and also the decision-making algorithms, to take appropriate actions. The paper presents popular positioning methods in spaces where GNSS navigation signal is not available. The potential of using such technologies as UWB, US, INS or SLAM algorithms based on readings from LiDARs or cameras is discussed in the context of small land platforms that can perform specific tasks in an automated manner. The paper also discusses the solutions described in detail in the cited literature related to the subject of data fusion from various types of sensors, which ensures greater accuracy and reliability of the readings obtained.

Keywords: vehicle positioning, Indoor Position System (IPS), Ultra-Wideband (UWB), Ultrasound (US), Simultaneous Localization and Mapping (SLAM), Inertial Navigation System (INS), Unmanned Ground Vehicle (UGV).

1. INTRODUCTION

Universal access to GNSS satellite navigation and positioning systems has certainly made many processes much easier, for example those in the field of logistics and land, sea or air transport. GNSS operation is based on radio waves from artificial satellites placed in Earth orbits, which are used to determine the location of objects (receivers). Various techniques are used in the process of determining the position of a receiver, such as measuring the time of signal propagation or the phase shift. These methods render satisfactory results in many cases of use in open spaces. However, none of them is able to eliminate or at least reduce the error of position estimation of an object caused by wave absorption phenomena, excessive noise level, multiple wave propagation paths that occur in confined spaces. Therefore, it is not possible to obtain an exact location in a restricted and/or indoor environment. In addition, even under outdoor conditions, with a good satellite signal, GNSS precision may be unsatisfactory in the case of specific small UGVs (Unmanned Ground Vehicle) which execute tasks in a relatively small spaces.

In order to reduce the gap that is created by the lack of satellite signal continuity caused by excessive absorption of electromagnetic waves by obstacles, or its multi-directional propagation or other disturbances inside the rooms, many tests and experiments have been carried out. That research led to the creation of an area of interest within which computerized methods of indoor positioning could be developed, mainly without the presence of a direct satellite signal. That domain is referred to as IPS (*Indoor Positioning System*) or sometimes RTLS (*Real Time Location System*), indicating thereby that these systems operate in near real time. Solutions developed within this area are often used by robotics specialists who implement commercial solutions or conduct research on small unmanned autonomous or automated vehicles. The methods of indoor positioning described in the literature can be briefly divided into those that determine the absolute position in the map of a building or the

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relative position, which is actually a shift from the starting point of the algorithm's operation. This, in turn, means that, depending on how the position is determined, a robot provided with autonomous functions is capable of performing tasks of different characteristics.

It is worth noting that some of the systems described by the keyword IPS also operate in outdoor environments as a support, or in some cases even as a substitute, for the GNSS system. Fusion of these systems leads to improved precision and accuracy of the positioning process. The combination of the GNSS system with the ultra-wideband (UWB) positioning technology in [1], whereas the combination with the ultrasonic wave based system (Ultrasonic, US) was described in [2], which provided the opportunity to construct a system for continuous positioning in mixed environments.

Parallel to the attempts to combine positioning technology based on satellite signals with technologies of the IPS area, numerous works and studies are conducted that focus on individual IPS components which could potentially find application in the positioning of mobile robots. Those include, among others, the aforementioned ultra-wideband RF (Radio Frequency) UWB [3] and other that belong to the RF group, e.g. Wifi, RFID, BLE [4,5], as well as systems based on: vision [6], infrared [7], or inertial sensors [8]. Fig. 1 shows the presented systems in the context of key criteria functions. Each of the above-mentioned technologies is characterized by different parameters (including accuracy or scalability of the system - Fig. 1), thus giving various possibilities of application under various conditions. This gave rise to concepts that use the potential of two or more technologies in parallel (sensor data fusion).

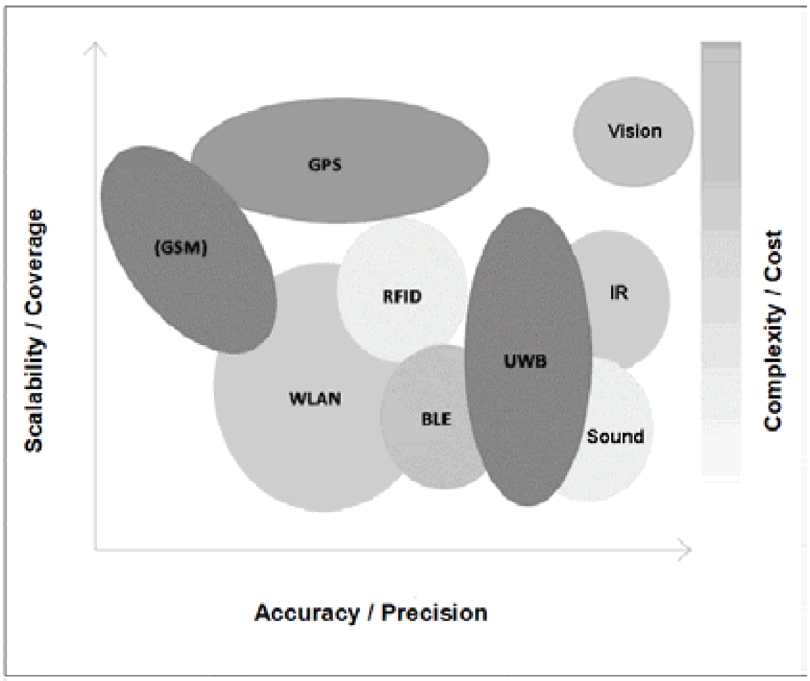


Fig. 1. Comparison of positioning technologies, as a function of the following criteria: accuracy/precision, scalability/coverage, and complexity/cost [9]

This paper aims to discuss the available solutions in the area of positioning of small autonomous vehicles in confined spaces and is arranged in the following way: section 2 discusses selected methods of positioning small autonomous vehicles in relation to key parameters which include, among others: accuracy/precision, scalability, energy efficiency, cost and their potential and challenges related thereto. Vision-based systems (section 2.1), systems using inertial sensors in the positioning process (section 2.2) and radio and sound systems of positioning within restricted spaces (section 2.3) are discussed in sequence. Section 3 discusses the potential for combining previously discussed technologies in the context of increasing the accuracy and precision of IPS, as well as overcoming the limitations of using only one of these technologies, with account taken of the complexity of the solution, operating speed, scalability and cost. Section 4 summarizes the work. And finally section 5 lists the literature reviewed for the preparation of this paper.

2. REVIEW OF THE SOLUTIONS

Numerous indoor positioning methods have been described in the literature. The main area of application for this type of techniques is robotics. There are several groups of algorithms based, among others, on vision-based systems, inertial sensors, radio systems, as well as complex systems using data provided by various sensors. In addition, the solution to the problem of positioning varies depending on the area of operation, i.e. other algorithms are applied in an unknown environment, and other where a priori knowledge about the environment is available.

2.1. Vision-based systems

In the case of positioning small vehicles having certain autonomy of operation, one of the most popular techniques is the use of vision-based systems. These include standard single-lens cameras, stereoscopic cameras and even complete sets of imaging devices.

Fig. 2. Stereolabs ZED 3D camera (photo by OBRUM sp. z o.o.)

Apart from cameras, the other optical sensors often used in robotics are active LiDAR (*Light Detection and Ranging*) detectors by means of which the so-called point clouds are obtained. In addition to measuring the intensity of reflected light, LiDAR also enables distance measurement. The principle of operation is based on the emission of precisely metered laser beams (class 1 laser - safe for people and eyesight; the wavelength of LiDARs used in robotics is usually ca. 905 nm). By measuring the time between sending and receiving a laser pulse, it is possible to determine the distance to the point of reflection of the light beam. [10] There are two types of such devices: 2D and 3D LiDARs. The former, usually comprising a single emitter and detector, rotating around its own axis, make measurements in one plane. The latter have a more complex structure that allows measurements to be taken not only horizontally, but also vertically, which also translates into an increased amount of data returned.

Fig. 3. 3D LiDAR from Velodyne (photo by OBRUM sp. z o.o.)

The basic positioning technique using vision-based systems are the algorithms of simultaneous localization and mapping (SLAM). The solution to the SLAM problem involves creation of an environment map with simultaneous use thereof for positioning purposes. In this case, the platform operates in an unknown environment in which both the approximate locations of the landmark characteristic points and the trajectory of the robot movement are calculated [11]. A drawback of this solution is the inability of determining the absolute position in the environment, only the relative position can be acquired. The first mention of the SLAM problem dates back to 1986 [12]. Since then, there has been a significant development in this field, many methods have been implemented to solve this problem, as shown by the openslam.org website where researchers can make their algorithms available for the community. The main driving force behind the research is the desire to build fully autonomous vehicles, for which it is necessary to determine their position with high, even centimetre level accuracy. Therefore, many implementations of the SLAM algorithm that use different configurations of vision-based systems have been created up to date [13].

One popular solution, particularly in mobile vehicle systems operating in enclosed spaces, is the use of a single camera. The first step in determining the position is to find characteristic points in a given image frame. Various algorithms can be used for this purpose, such as Fast Corner Detection [14], SURF [15] or SIFT [16]. These points must then be determined repetitively and correlated with each other. Thanks to such tracking of features, the position of a given point can be unambiguously determined on two image frames which, based on triangulation and known camera parameters, makes it possible to determine the shift and consequently the position of the camera relative to the beginning of the measurement [17]. Examples of the solution to the SLAM problem are papers [18, 19], where filtering based on the Extended Kalman Filter or particle filtering is applied. One of the more advanced methods is ORB-SLAM which uses the so-called Bundle Adjustment in the calculations [20].

The 3D camera in a way extends the possibilities of positioning and mapping, providing depth information. The constant distance between two images allows to determine the distance to individual characteristic points, provided that they are visible for both sensors at the same time. Examples of these solutions are given in the literature [21, 22].

The principle of SLAM operation using a 2D or 3D laser scanner is similar to that of a camera. In this case, however, the input for the algorithm is a point cloud rather than a signal form an imaging device. Whereas here the features which will be used for positioning and mapping can also be extracted. However, when using LiDAR, there are also solutions based on matching individual laser scans, which is executed, for instance, by the ICP (*Iterative Closest Point*) algorithm [23] or by various variants thereof. Simultaneous positioning and mapping on 2D LIDAR data using the SLAM implementation is presented, for example, in [24], where the Google Cartographer algorithm is discussed.

A slightly different example of using a vision-based system and the SLAM algorithm is positioning on a 3D map created beforehand. This approach reflects the recent trend that is promoted by manufacturers in the autonomous systems developed for cars driving on public roads. It is based on precise scanning of the road network by specialized vehicles fitted with LiDARs. The scan is then processed into a very detailed 3D map containing information about the road profile, curbs, sidewalks, signs, traffic lights and other characteristic points [25]. Data prepared in such a way allow locating the car using a cheaper and simpler laser scanner [26], or even just a standard single-lens camera [27]. This approach can also be applied for smaller unmanned vehicles [28], although due to the generally milder accuracy requirements and, at the same time, greater expected versatility, this is a less popular solution. However, the unquestionable advantage in this case may be the ability to calculate the absolute position relative to the world.

2.2. Inertial sensors

A completely different approach to the issue of positioning and thus to the localization in space is the use of inertial sensors and inertial navigation INS (*Inertial Navigation System*). As was the case with SLAM, it enables the determination of the position relative to the starting point of the algorithm's operation.

The inertial sensor, also known as the Inertial Measurement Unit (IMU), is a MEMS (Microelectromechanical System) system with 6 degrees of freedom. It comprises two components: a 3-axis accelerometer and a 3-axis gyroscope. They allow for accurate tracking of the object's orientation, but only in two axes, as the azimuth measurement is carried out by calculation, which makes it susceptible to drift due to accumulation of errors of both sensors. Some complement to the IMU is the AHRS system (Attitude and Heading Reference System) which measures the Earth's magnetic field by means of a 3-axis magnetometer, which allows much more accurate determination of orientation in the space in all three axes, provided that the environment is magnetically homogeneous. It appears that readings of the magnetic field strength may be susceptible to substantial disturbances.

Dead reckoning originates from the sea transport and consists in computing the current position on the basis of the last known determined position, and the current course and speed data. At present, the INS inertial navigation is used extensively in automotive applications, in particular in the context of autonomous cars being developed. A development of dead reckoning, thanks to the use of modern IMU sensors, it supports the GNSS (Global Navigation Satellite System), which warrants high measurement precision and uninterrupted availability of positioning data in areas where satellite signals are inaccessible, such as tunnels or underground car parks. Similar solutions are used, for example, in pedestrian navigation inside buildings, which also uses IMU sensors and knowledge about the specificity of human movement [29]. However, it must be remembered that, similarly to the methods using the SLAM algorithm, it is the position related to the starting point of the navigation that is determined here.

Determining the position using a gyroscope that provides angular velocities and an accelerometer that provides acceleration requires several mathematical calculations. If a perfect indication of the gyroscope is assumed, it becomes possible to determine the orientation by integrating the values of the time (Fig. 4). In turn, a position can be determined using the indications of a perfect accelerometer by double integrating the individual components of the acceleration value (Fig. 4) [30].

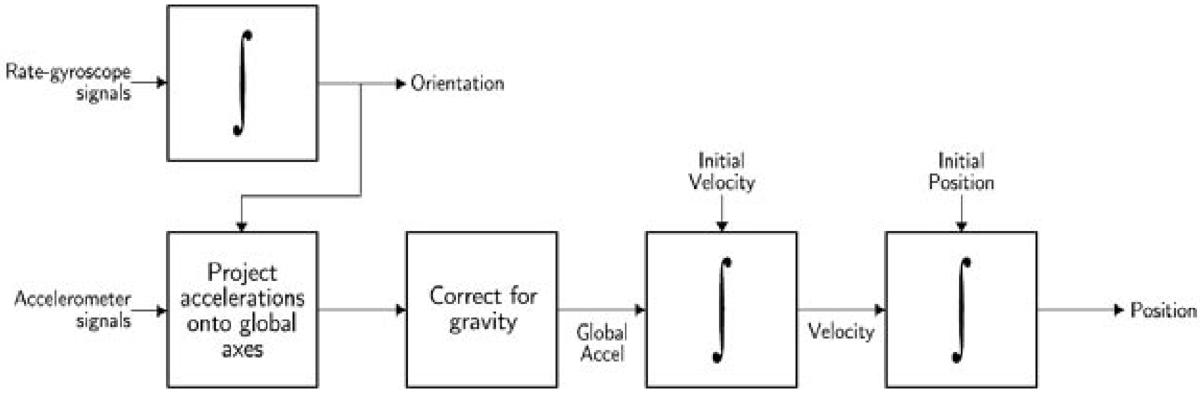


Fig. 4. Schematic diagram of positioning based on accelerometer and gyroscope data [30]

However, due to the fact that the sensors are not perfect, it turns out that the calculations are prone to errors, which are difficult to correct during algorithm execution. On the one hand, the gyroscope is susceptible to the so-called drift, mainly in the vertical axis, and the error can build up over time. On the other hand, the accelerometer data are noisy and cause errors in calculations. It is necessary to use appropriate filters, the widely used Extended Kalman Filter (EKF) [31, 32, 33] or other filter algorithms [34]. Also noteworthy is the issue of using a magnetometer to eliminate the gyroscope drift. This allows for deviation correction with the help of additional reference points. Unfortunately, the magnetic field sensor is also subject to considerable disturbances, e.g. in the vicinity of metal objects or radio wave sources, which can also affect measurement accuracy.

2.3. Radio and acoustic systems

The interest in radio and acoustic positioning systems has recently increased in both research as well as commercial circles. Particularly noteworthy is the industrial sector, where numerous attempts are made to implement radio or acoustic positioning systems as part of the new industrial revolution (Industry 4.0), in order, among other things, to optimize WIP (Work in Progress) or to improve safety in the target area. Brands such as Volkswagen [35], IBM [36] or the Fargo medical centre in Stanford [37] already benefit from the solution. Since 2014, Microsoft has been organizing a competition in the annual cycle called Microsoft Indoor Localization Competition (IPSN), in which participants compete in the discipline of indoor positioning using various technologies. Since the beginning of the competition, the UWB and US technologies [38], have been the leaders in the context of the number of applications and the best results regarding the accuracy of position estimation, which also confirms that there is a deep interest in the above-mentioned technologies as compared to other positioning technologies. In addition, UWB and US results in the competition compared with the other technologies indicate greater opportunities and performance in minimizing measurement errors, the order of which is several to a ten odd centimetres while, for instance, a technology that makes use of sounds in the 16 Hz to 20 kHz range generates errors of several dozen centimetres [38].

Analyzing the available radio and acoustic positioning systems in terms of precision, accuracy, low cost of application, scalability, energy efficiency or relatively low complexity, the following solutions of the highest potential are discussed further in the text:

1. Ultra wideband radio technology (UWB).
2. Ultrasonic (US) in the context of technology providing information on the absolute UGV position in a previously defined environment.

Implementation of the above positioning systems is based on general architecture resting mainly on two modes of operation, centralized or decentralized (Fig. 5), alternatively called unilateral and multilateral. Under the decentralized (multilateral) architecture, measurements of signals originating from the searched for mobile object are made by receivers of constant spatial coordinates, while the centralized (unilateral) method transfers the burden of calculations onto the mobile receiver whose position is sought. Both schemes present some limitations or cause increased complexity of the system. In both cases it is necessary at least to synchronize infrastructural devices, however in the case of a decentralized solution, where a larger number of objects are localized, it is necessary to additionally use receiver access schemes, which increases the complexity of the entire system. In the centralized case, the need to perform position calculations has a real impact on the higher power demand, although on the other hand it does not cause any limitations in the number of parallel localizations or does not have a significant effect on the electromagnetic compatibility of the object being localized, as it consists only of the receiver. Still both methods allow exploitation of the following data for position estimation: ToA (Time of Arrival), ToF (Time of Flight), or TDoA (Time Difference of Arrival) [39].

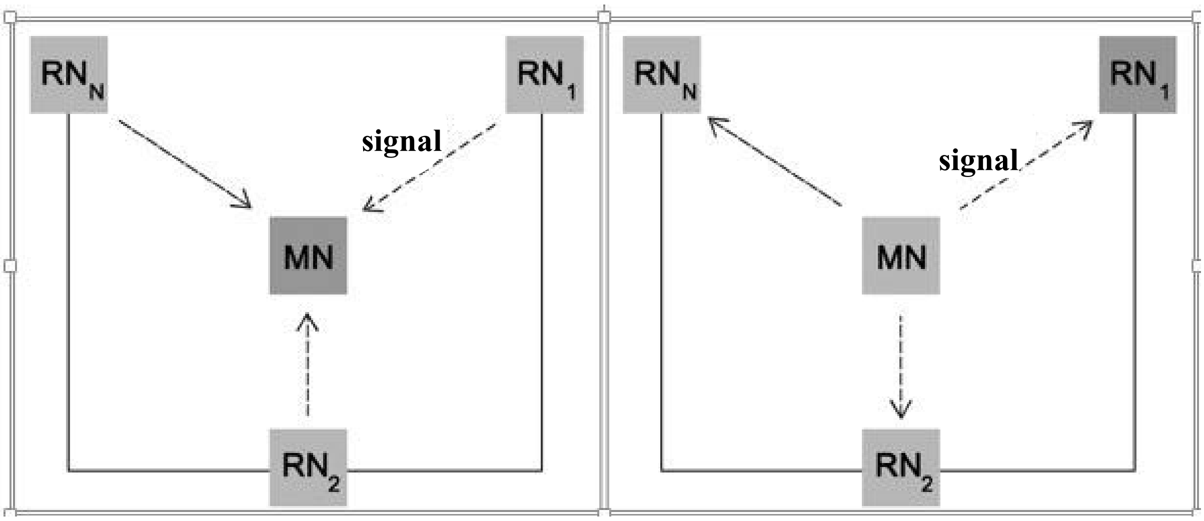


Fig. 5. The centralized (left) and decentralized IPS architecture (right). In the centralized architecture the position is estimated in the mobile node (MN), while in the decentralized architecture it can be estimated in one of the reference nodes (RN)

2.3.1. Ultra Wideband

Since the FCC (Federal Communications Commission) in the US (February 2002) and ETSI (European Telecommunications Standards Institute) together with CEPT (European Conference of Postal and Telecommunications Administrations) in Europe have defined the categories of admissible commercial applications of UWB technology (communications, mobile radars, imaging) and have permitted the use of devices within the unlicensed band (Fig. 6), the UWB technology has attracted close attention of researchers and engineers. Strong interest of that group was additionally caused by the unique characteristics of UWB. UWB technology, unlike other RF (Radio Frequency) technologies, such as, for instance, Narrowband technology, is characterized by occupancy of a large spectrum of frequencies (3.1 GHz - 10.6 GHz) through the spectrum of electromagnetic waves (Fig. 7). This aspect enables fast emission of very short (nanosecond) waveforms described as impulses [39]. Hence, UWB is often described in the literature as an IR (Impulse Radio) system. UWB impulses, due to their low spectral density, are perceived as noise in other systems, which allows simultaneous operation with narrowband devices, such as Wifi or BLE, without mutual interference, and additionally they are difficult to detect by accident. Good time resolution of UWB impulses measured in the time domain allows the use of this technology to potentially precisely measure the distance between the transmitter and the receiver, while having a real effect on the mitigation of multipath effect. UWB is also characterized by its high potential in penetration of materials, of which the previously mentioned narrowband radios are devoid, which makes the technology also applicable in radar systems [40].

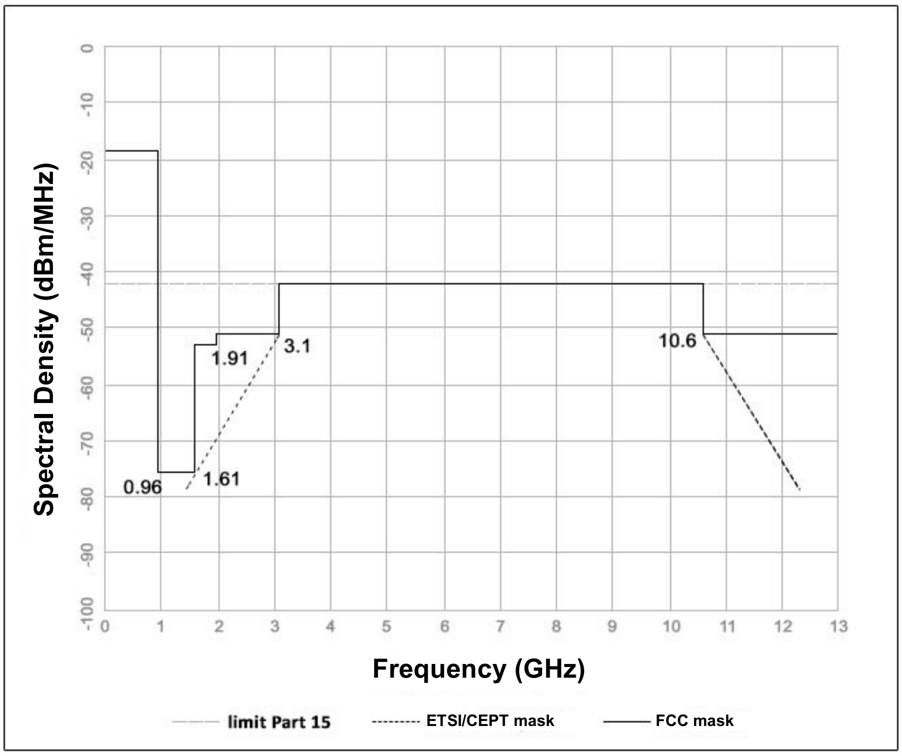


Fig. 6. UWB radiation limits (FCC - USA and ETSI/CEPT - Europe)

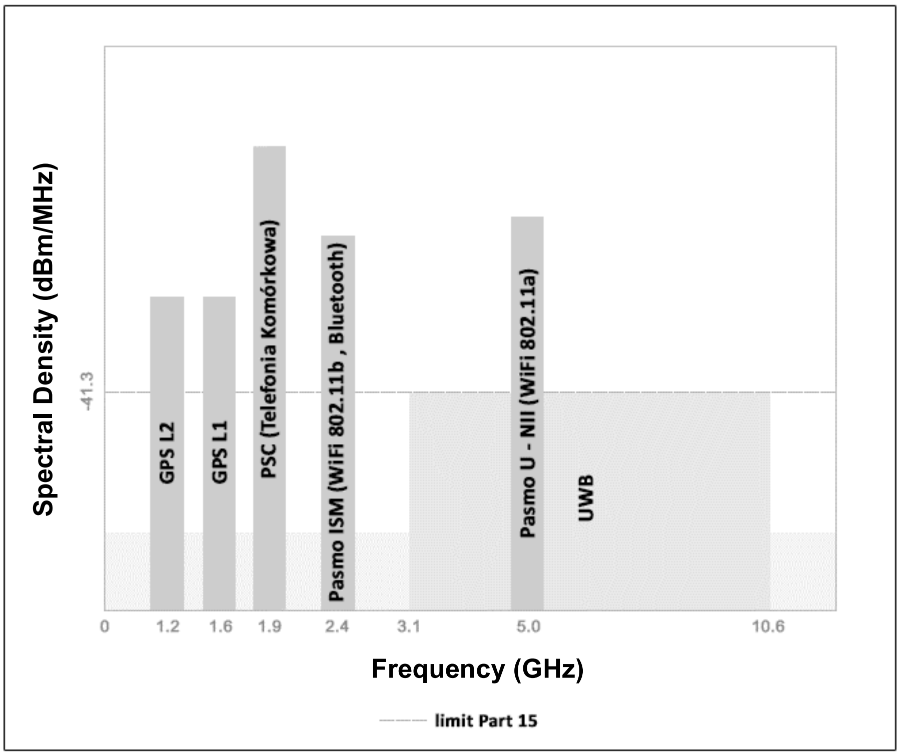
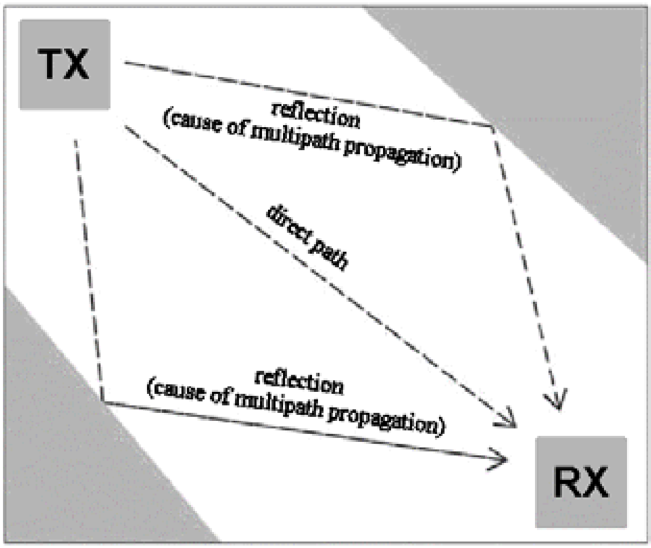


Fig. 7. UWB frequency spectrum and narrowband frequencies

Regardless of the many of its advantages, UWB also poses several challenges, which are relatively often described in the literature [41]. Certainly one of them, and probably one of the most important, is the multipath problem, which deepens along with the change of environment from LoS (Line of Sight), where UWB is doing well, to NLoS (Non Line of Sight). If mobile devices installed in a UGV and the reference nodes are mutually completely out of sight, it is highly probable that copies of the same signal, differing in strength, will reach the receiver at a different time. Such signals will require further processing thereof to determine which signal is the original, and this highly affects the correct determination of the signal's transit time (ToA, ToF), which is the basis for position estimation. There are several methods used to minimize the negative effect of the multipath problem. These include the use of the MUSIC algorithm or the use of Impulse Response-UWB or MultiBand-OFDM UWB [42]. Despite the fact that these methods address this problem to some extent, it is still categorized as difficult and challenging. The problem in an NLoS environment is shown in Fig. 8.



Figs. 8. Multipath propagation of waves between a transmitter and a receiver

In addition to the multipath problem, there is also the need for time synchronization of the devices included in the IPS topology. Also indicated [43] is the high cost of devices and greater complexity of the highly precise system (e.g. antenna arrays in AoA technology).

2.3.2. Ultrasonic

Ultrasound is characterized by higher wave frequencies (40 kHz) than audible sounds (16 Hz to ~ 20 kHz) and is not audible by humans. In contrast to electromagnetic waves propagating at the speed of light, on which RF systems are based, the velocity of the sound wave propagation is much lower, as it is approximately 343 m / s, and is variable depending on the temperature and humidity of the propagation medium. In [44] the velocity of a sound wave is given by the formula:

$$\mathbf{V}_{us} = \mathbf{20.05}\sqrt{\mathbf{T}}$$

where temperature (T) is expressed in kelvins. Temperature change of one degree and causes a change in the speed of sound by approximately 0.18%. Changes in the speed of the sound wave are so important in position estimation that temperature sensors are used to compensate for the negative impact of temperature change on the accuracy of calculations. [44]

The problems are aggravated by high continuous environmental noise which also affects the calculations. Contrary to RF, the signal does not penetrate thin walls [45], which in some cases is an advantage in the context of the possibility of using the system inside one room only, and in other cases it is a disadvantage for exactly the same reason.

Most of the ultrasonic positioning methods studied require an additional RF channel in order to synchronize ultrasonic transmitters and receivers, which disqualifies the implementation of the system at some locations, such as hospitals. This model is often described in the literature [45] and implemented. Nevertheless, there are also attempts to simplify the system by eliminating the RF module and using only the time of receipt of ultrasonic pulses [46] the measurement of which is enabled by the use of periodic interruptions in transmission. This, however, limits the possibility of using positioning techniques to TDoA [47].

The localization process itself is mainly based on the previously mentioned schemes and positioning techniques, in particular ToF or RSS, and despite some limitations, IPS based on ultrasounds is potentially able to offer an accuracy of above ten centimetres [45] or even of a few centimetres [47] at low energy consumption and low cost. For comparison, no reports have been found on computational error of less than a decimetre in the case of IPS based only on UWB.

3. SENSOR FUSION

Indoor positioning can be effected with the aid of many different sensors. Each of them offers different operating parameters and has its advantages and disadvantages. Therefore, a popular solution is the so-called sensor fusion, that is parallel use of several data sources. This approach allows to increase the accuracy and precision of measurements and results obtained, in this case information on vehicle location. Currently, many solutions based on the fusion of various sensors combined in many configurations can be found in the literature. Fig. 9 presents examples of the use of different data sources to increase positioning accuracy. Further the paper discusses the use of the most common data fusion cases reported in the literature, which concern previously discussed issues.

One such example is [48], which describes the fusion of inertial data with a camera image. Such a combination with the use of a UHF (Unscented Kalman Filter) provides, according to the authors, an accurate movement estimation. Thus, this method potentially enables determination of the position relative to the starting point, and therefore it can be used in both outdoor and indoor locations. It is also worth mentioning self-calibration, the principle of operation described in that paper improves the functioning of the algorithm and guarantees a certain versatility of application.

Another paper [49] shows the integration of LiDAR with an IMU sensor for the purposes of the UAV (Unmanned Aerial Vehicle) positioning in indoor environment. With the use of 3D laser scans and inertial data, the position is determined in two dimensions, while the third dimension is calculated owing to 2D LiDAR and line extraction. Finally, the Kalman filter is used for data smoothing.

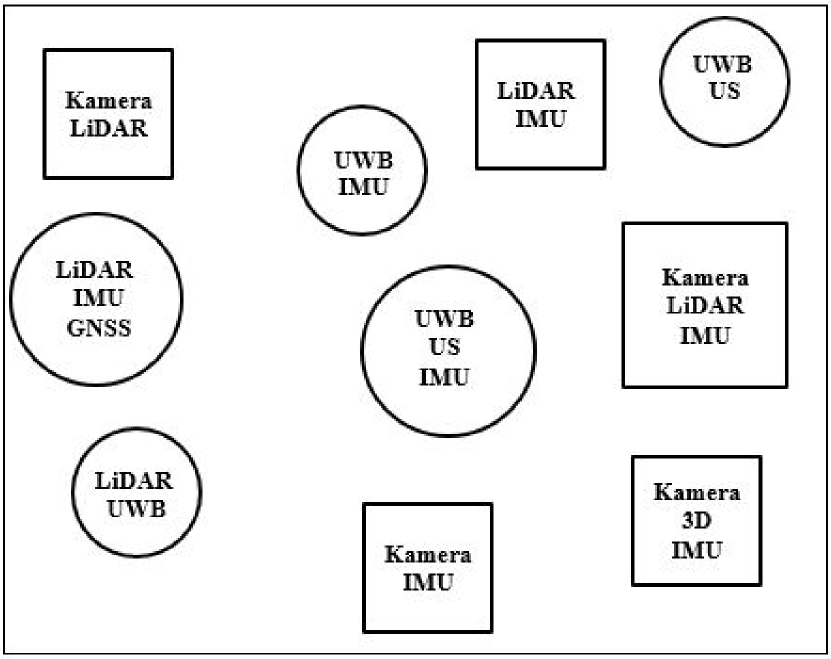


Fig. 9. Examples of sensor combinations used for data fusion which improves the accuracy of indoor positioning

a) ○ absolute positioning, b) □ relative positioning

Another paper [50] deals with the combination of data from a laser scanner with camera image. According to the authors [50], this combination provides high accuracy of movement estimation and drift error at below 1%. An evident advantage is the fact that this solution works well both under outdoor as well as indoor conditions.

In the case of using UWB or US, the most common integration of many data sources that enable precise indoor positioning of objects is undoubtedly the combination of these systems with IMU/AHRS sensors [52, 53]. Due to the fact that IMU sensors are insensitive to multipath propagation under LoS or NLoS conditions, they constitute a potential complement to the above-mentioned technologies. UWB, for its part, can provide information on the initial position, which will be used to pre-calibrate the IMU sensor and can later be used to correct the drift error by periodically estimating the position under LoS conditions, when accuracy is the greatest. In this way, both subsystems can complement each other and determine the absolute position, which is not possible when an INS system is used solely. The mechanism of IMU and UWB fusion has been described, for instance, in [52]. An accuracy and performance improved by 100% has been reported there using a 9-axis IMU and an Extended Kalman Filter (EKF) used for the continuous estimation and correction of the systematic IMU error under simulation and laboratory conditions. A further step was taken in [51], where the author proposes using the latest versions of the EKF algorithm, Sigma Point Kalman Filters (SPKF), as well as Cubature Kalman Filter (CKF) as an alternative to standard algorithms, or in [53] where IMU and UWB data fusion was tested at various stages of the EKF algorithm, showing the best results in the update phase and a general improvement of position estimation accuracy with the use of multiple data sources.

The presented techniques and algorithms are technologically independent, which means that they can be used equally when switching between UWB and US as data sources. Certainly many other, though less popular, sensor fusion models based on various combinations of almost all of the available sensors are used in robot positioning. Furthermore, data from GNSS can be also be used in data fusion, for instance in Kalman algorithms, enabling thereby continuous indoor and outdoor UGV positioning.

4. SUMMARY

Depending on the environment in which an autonomous vehicle performs its tasks, a different approach to the issue of positioning is required. The paper discusses popular methods that may support the implementation of two main cases of the use of mobile robots in enclosed spaces: recurring operations within a known environment and spontaneous activities in an unspecified environment. The use of sensor fusion is very popular and there is a great abundance of scientific publications dealing with this issue. Logically, it turns out that despite the greater complexity of algorithms that combine different data sources, the benefits, such as increased accuracy or precision of results, are worth making efforts to continuously improve the available technologies and to search for new ones.

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