Drone Localization using Ultrasonic TDOA and RSS Signal – Integration of the Inverse Method of a Particle Filter

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This paper will present an overview of indoor and outdoor drone localization methods. Outdoor scenarios almost always use a GPS with IMU. Indoor systems are using short-range sensors that are sensitive to the external conditions of the environment. Mostly used methods are optical flow and stereovision, while an ultrasonic transceiver system optimizes and provides high precision and orientation of the drone. An ultrasonic preceptor is integrated into a listener/beacon and can be used with referenced beacons inside a WSN. The Crossbow Cricket hardware platform, which is based on TDOA and RSS principle, is used for simulations and code development. The researched direction is the localization of referent nodes (beacons) concerning the listener which is mounted on a flying drone. For that purpose, a probabilistic approach is used, based on a Bayes filter, where the positions of the beacon can be observed like random variables. Considering that these distributions significantly vary from a Gauss distribution, it is appropriate to use a particle filter.

Keywords: *WSN, TDOA-RSS method, Indoor localization, Probabilistic model, Particle filter.*

1. INTRODUCTION

Wireless sensor networks have become the main protocol of every home, commercial, and industrial automatization application with a special purpose. Hardware platforms of (Wireless Sensor Network) WSNs are separated in commerce [1-3] and for developments [4-6]. Development platforms are fully open for programming, but they have a disadvantage because of scalability when considering the hardware environment.

At the beginning of the development in WSNs (or nodes), until now, a wide range of applications have been found with sensors and monitoring devices to measure values. These types of microcontroller embedded systems, on a low level, can communicate with peripheral analog inputs and outputs. They can also communicate with digital interfaces that use communication protocols. Digital communication systems are divided into parallel and serial hardware interfaces. WSN radio interfaces are based on telecommand radio devices, which in the past started using improved modulation, demodulation, encryption, and coding with developed algorithms in high-level applications. With issues of routing [7] and localization in these kinds of networks, the areas for exploration include the field of security and implementation of higher and more advanced protocols on the network layers (IPv6, 6LowPAN) [8]. WSNs with an adequate number of nodes that are independent of applications are suitable for the use of sending small packets of data to the monitoring and controlling systems.

The predefined scene in this paper is set for a mobile robot platform used in an indoor environment. A hybrid option (indoor and outdoor) is considered and will be explored in future papers. Localization in an outdoor environment has different scientific methods that lead to different scientific research in an outdoor environment localization. As an example, the Global Positioning System (GPS) principle of localization in an outdoor environment is often used as a method. Because of the disadvantages of this principle, it is necessary to compensate and optimize it with additional hardware, as well as additional software implementation methods. Using inertial GPS receivers, it is possible to achieve high precision of an object, but still, there has been demand for a more precise and more reliable solution [9-11]. For that purpose, the developed inertial GPS system, with a geostationary node is connected with another GPS receiver. This is then mounted on a mobile robot platform. Further consideration of this problematic trend was that it is a single physical device where everything will be integrated. Some developed GPS receivers already have an integrated mechanism like Attitude and Heading Reference System (AHRS) and this is proven to be very accurate [12]. It is an open question on how to make and use this technological hardware available as a more cost-effective solution.

The localization of a drone in an indoor environment is divided into systems with stereovision, optical flow, and ultrasonic hybrid methods and can be considered as case scenario for mobile robotic platform. These measure the intensity of a high frequency (HF) signal. Stereo vision is divided on 2D and 3D cameras while the optical flow uses one camera. With a 3D camera, the depth of the

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picture is better approximated, because it uses laser projection for scene analytics. With a laser dot field module, e.g. “Kinect”, better analytics and measurements can be achieved inside the infra-red (IR) spectrum with proper accuracy of its depth [13-15]. Once the depth is precise, the distance can be recalculated to make an algorithm for object avoidance. In our test scenario, using ultrasonic methods of localization Time Differential Of Arrival (TDOA), the positioning and orientation of a drone were explored. The analog measuring Receiver Signal Strength (RSS) on a microcontroller can improve accuracy when the signal is provided by an HF radio chip [16]. The accuracy of localization algorithms, including RSS signals, depends on the propagation model of the indoor area [17-19]. The integrated hardware technology in a node depends on the frequency of the radio module. Therefore, Crossbow as a node producer provides the ZigBee solution on 2.4GHz suited to the European market [20]. A possible development kit for our testbed is the Crossbow Cricket based on an HF radio chip of 418 MHz [16]. These wireless sensor nodes do not have an integrated ZigBee stack, but a Tiny OS firmware on the microcontroller’s high-frequency radio which can be operated instead [21, 22].

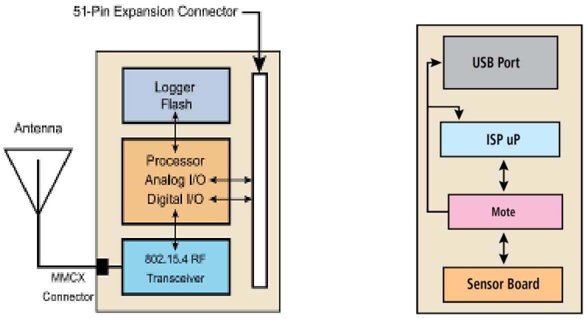
The difference between a deterministic and a probabilistic approach is that in a deterministic procedure all values are treated as certain. That kind of value is entered earlier in a coordinate system within the model. In this way, the symmetrical or asymmetrical position of an ultrasonic generator (beacons – nodes) is defined in advance. A probabilistic approach uses basic values of variables and it is always supplied with random values. Through this kind of approach, for further research, the Bayes filter will be used. This is where the positions of the referent nodes (beacons) will be considered like random values based on the position of the drone (listener). Distributions in this case significantly vary from normal (Gauss) distribution and for this reason, a Particle filter has been chosen to be used [23-25]. The ultrasonic perceptional sensor (listener) located on the drone is then predicted to be the coordinator. It can provide information through an embedded Linux system of the main controlling loop of the drone [26]. An inertial drone system, by using an Extended Kalman Filter (EKF) [27], will ensure a qualitative measured and processed result. This is essential to further the application and optimization of an inverse hybrid TDOA-RSS method for object localization. Qualitative processed results from a Particle filter and EKF are based on the background of the probability theory with statistics, which needs to be done in real-time. With a defined hypothesis set with isolated variables, and the influence/control of external factors, such as the propagation of an electrical wave in RSS or air properties, the ultrasonic method has an entirely empiric approach.

2. ARCHITECTURE OF SUGGESTED WSN PLATFORM NODES

The qualitative architecture of wireless sensor nodes is based on the main microcontroller which is connected with an HF radio transceiver chip. The microcontroller periphery has analog and digital inputs and outputs where sensors and control units have been connected. The HF radio chip is classified by frequency on the platform and complies with technology standards. With the regular power supply of nodes, it uses the external possibility to upgrade and optimize consumption. Optimization can be done in this field by controlling the low level of layers such as a network layer, a physical layer, or even a higher layer such as transport or application layer [28].

The architecture of the wireless sensor nodes contains standard blocks like a CPU system with integrated memory, a communication system with radio, a module chip interface, a peripheral interface for sensors and control circuitry. A power unit block has the option for an external source while the node is a covered subsystem for localization and mobility. The considered platform, Crossbow Cricket Tiny OS, can change the carrier frequency with program functions within the microcontroller [16]. Based on the defined frequency, it needs a specific antenna to be designed with a calculated input impendency. The favorable external frequency is chosen (418 MHz), while it is possible to use an internal microstrip antenna designed on a Printed Circuit Board (PCB). For communication between the HF radio module and the microcontroller Serial Peripheral Interface (SPI) protocol should be used.

Except for the adduced platform, which is based on an ultrasonic transceiver, a serial RS 232 interface and an expansion connector, as in earlier research, the Crossbow ZigBee MICAz/MICA2 platform [20] can be applied. MICAz/MICA2 uses the same expansion 51 pin compatible connector as the Cricket system, which then opens up possibilities to upgrade the firmware of the wireless sensor nodes. During the first stage of research, which covered the WSN field, an extended board MTS310 [16] was used. That kind of board has integrated hardware peripherals, such as a thermometer, a sensor for brightness, a tone detector and a tone generator. A very important component integrated on an MTS310 board is a magnetometer, which can be used for orientation calculations of a drone with redundancy based on optical flow. The optical flow will be determined with a WLAN camera and middleware integration inside LabView; National Instruments environment. Crossbow WSN technology has the same standard block structure as described before. With an expansion connector, the WSN node can be individually programmed remotely by using a coordinator.



a) b)

Figure 1. a) Block diagram of sensor node – Crossbow rev.1, b) USB programmer and interface for forwarding data to API [20]

Figure 1 a) shows a block diagram of the first ZigBee generation platform, while Figure 1 b) presents a USB programmer (MIB520CB), which is used for the upload of firmware individually or remotely via a coordinator.

The USB connection is based on a serial TTL converter to RS232 interface [33], which uses full-duplex communication with the In-System Programming microcontroller (ISPuC) based on ATMega16. That kind of microcontroller has a function as a programmer or as the coordinator between API and other nodes. The sensor node can use different types of external boards, such as boards with temperature, humidity, brightness, noise level detection, acceleration 2D (two-axis), and orientation with magnetometer [16].

The research fundamentally focusing on the localization of a drone is based on the Crossbow Cricket platform, where an integrated irreversible hybrid TDOA-RSS method will be applied. With the main microcontroller ATMega128 and HF radio chip CC1000, communication support is ensured by a Tiny OS and NesC compiler. Hardware upgrades consist of the serial interface on a basic Cricket board and its integrated ultrasonic transceiver circuitry for controlled generator and detection of the remittent signal [21]. The block diagram of the Crossbow Cricket system is presented in Figure 2.

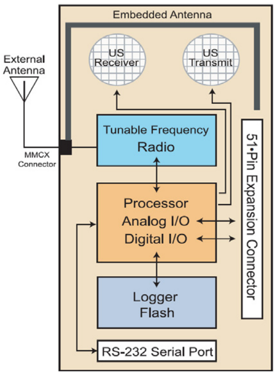


Figure 2. Block diagram of the Crossbow Cricket system

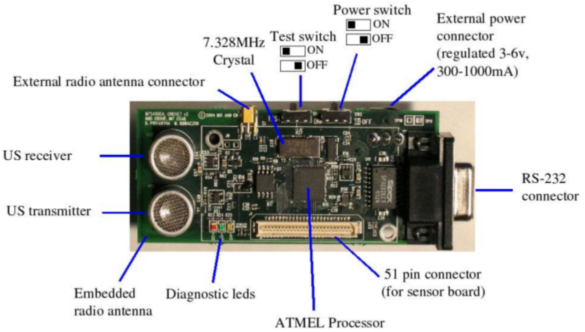


Figure 3. The Crossbow Cricket platform of a wireless sensor node

In addition to the battery power supply, the system has a corresponding stabilizer for an external power supply with an adequate connector, see Figure 3. During testing, while the microswitch is enabled, there is an option for a programmable function. In case a mode only for ultrasonic generator (beacon) has been activated, the receiving circuitry, which is connected via a converter on a serial interface, will be without power supply. This results in high energy efficiency and longer battery lifetime [29-35]. The programming possibilities of this wireless sensor node are ensured by a serial programmer MiB510CA. An additional connector interface onboard supports Joint Test Action Group, IEEE 1149.1 and 1149.7 (JTAG), which is useful during programming inside the compiler. In this way, we can monitor the program flow step by step with a registered status overview.

3. LOCALIZATION OF DRONE IN INDOOR AREA USING CROSSBOW CRRICKET PLATFORM – TDOA-RSS METHOD

The localization of drone in an indoor area can be achieved by using various methods in the research field. The method type and the approach are determined by the technical solutions and the sensor selections. One solution is based on a camera stereo system (stereovision) [14], while another technical solution is a laser projection system – Kinect (which has a more precise picture depth of scene). The most popular indoor technical solution, however, is based on grey-ball, reflective referent points, which is easy to track with infra-red (IR) cameras.

According to some research [36-43], using helicopters and later Unmanned Aerial Vehicle (UAV); researchers focus is on mathematical models, the Fuzzy Logic application, and neural networks. The integration of a control algorithm used with most of the sensor technical solutions focused mostly on an outdoor localization environment. Researchers with high h-index rankings and classifications are selected and considered for this specific exploration [44].

Some publications and testing in laboratory environments [45, 46, 49], are more focused on an indoor area of localization by using laser technical solutions with a limited distance measurement. Researchers describe the methodology of aggressive maneuvers and estimative conditions by using stereovision. The mathematical background of standard maneuvers is explained with models and simulations. Integrated algorithms, methods for aggressive flight, connecting parts with mobile robots in formation, creating a 3D formation, trajectory planning with short distance and avoiding dynamic obstacles are just some elements of the research within this group [47]. This kind of localization methods requires additional odometry, which is realized with an inertial module.

The research of WSN integration in drones [48] opens up much space for new scenarios, such as an algorithm integration and optimization of control on a high level and low level. The above, mentioned researchers obtain measurements based on the SunSpot technical solution and JavaME platform. The same precision of this technical solution is ±3 cm, which is adequate to the Crossbow Cricket platform. The only difference is that this system uses the ZigBee platform on 2.4 GHz.

The available platform, Crossbow Cricket, is based on a hybrid principle of two subsystems in parallel work. The first system is based on the RSS method, which, as a single system, is very imprecise [32]. The accuracy of that kind of system depends on the area where the localization of a drone is needed. With predefined mathematical models (propagation models) its defined the spreading of the electromagnetic wave inside a considered environment. In spreading the case of HF electromagnetic waves, the speed of light is considered. To be more precise, it can be integrated with a redundancy system based on the ultrasonic principles of time measurement, TDOA. From the time, which is measured from the moment of sending to the receiving of a signal, it calculates the distance between the listener and the beacon. The mathematical model presented in Figure 4 describes the working principle of one listener and several beacons. The initial conditions, which are symmetrical or defined and fixedly mounted in the environment, are described in [26]. In this case, a 2D analysis is used, while real drone scenarios will be presented in a 3D coordinate system.

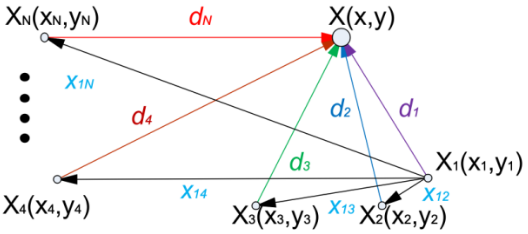


Figure 4. TDOA-RSS localization method – mathematical model

The measuring of the beginning of a sequence focuses on the beacon, which starts by sending two signals, an ultrasonic and a radio signal, where the message is integrated. Based on the measured time between the two received signals, the listener calculates the distance and defines the position. According to [26], the system-measured time difference starts at 50 ms to 250 ms. The Cricket platform does not have fixed intervals during the measurement, and results are stochastic because of nonlinearity. The EKF because of that kind of intervals needs to be integrated at the end. Research is focused on the TDOA-RSS method based on the appliance of the Bayes and a Particle filter [23-25]. The inverse sequence of direction can result in a couple of iterations for the listener's position. Iterations are related to the small shifts of the listener, where beacons can be mounted and placed asymmetrically, at random, and initial conditions are not required. One exception is the positioning of a drone, which is a very important parameter in orientation. In this case, it is necessary to use an additional listener. The specific case scenario shown by Figure 5 with P3-DX [26] may aim to perform orientation differently with another odometry system based on optical flow. An integrated compass inside the drone, Inertial Measurement Unit (IMU) system is sensitive and can cause deviations in measurement due to electromagnetic environmental influence. Taking into consideration the hypothesis that the scene of a moving drone is unknown when high quality and accurate done measurements are needed, the SLAM technique can be used for better performance [47, 50-54]. Drone or mobile robot autonomy, in this case, is realized by using a method like TORO (2D and 3D), which is derived from the Olson algorithm [15]. The SLAM principle is based on the Olson algorithm, which works on optimization during the process. The drone used for this testbed is the Parrot AR Drone 2.0 [1]. The TDOA-RSS method for localization is mostly used for mobile robots in 2D environments, while [55] paper describes the possibilities to be used in a 3D drone environment. According to research [56], it can have integrated algorithms with the benefits of more precise and accurate localization of a drone by using a compass for orientation in a specific area.

What is common in all these papers is the TDOA – RSS problem of the synchronous coming of HF and TDOA signal to the listener. To solve this issue, researchers use filtering methods. For this testbed case scenario, the Bayes/Particle filter was used with an emphasis on EKF, which will be used in future research.

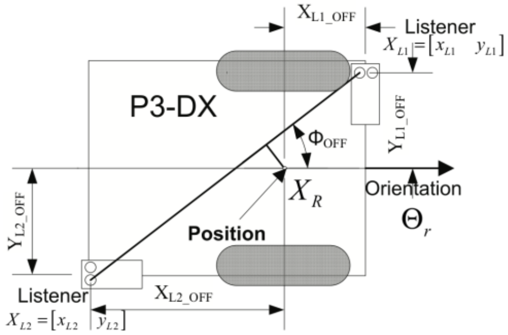


Figure 5. The position of listeners for position and orientation calculations

4. PROBABILISTIC APPROACH TO THE INVERSE METHOD OF DRONE LOCALIZATION IN INDOOR AREAS USING THE BAYES/PARTICLE FILTER

The probabilistic approach is based on values of base variables, which are treated during measurement as random variables. In this way, the size of the security zone is predestined stochastic, where the uncertainty is described by random variables or a random field. The field value generation of a suggested inverse method of localization is exactly a random field defined by a circle and standard deviation. With minor movements of the listener system from one set of solutions, it has a created second set of possible solutions, as shown in Figure 6.

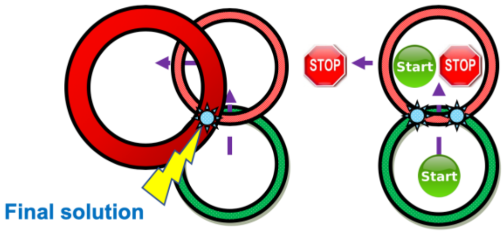


Figure 6. Listener minor movement principle – convergence to solution

While moving the drone/listener during the flight, two bundles or two zones of possible solutions are created. The isolation of a real solution can be given by applying the Bayes filter based on the numeric approximation methods [57, 58]. These methods are divided based on [23], while in this case the approximation on discarding samples are chosen. The real solution from two proposed solutions in simulation is given by a minor additional shift of the listener. The convergence of that kind of sequence brings us to a final solution of an accurate position. The processing speed of random variables must be very high to eliminate all the wrong possible dots and to re-process and calculate new samples. The optimal solution is to apply the Monte Carlo algorithm for the listener localization. Applied methods are based on a Particle filter where the sequence is based on a previous position of a listener. With an applied dynamical model for prediction of a current position it is used by the Bayes filter algorithm with corresponding roles and sequence, according to (1), [23, 57-59]. The second and third steps represent the prediction while steps 4, 5 and 6 are the correction. In step 3, there is a case where a sub integral value of probability, if we take generalized Bayes filter, can be a Particle filter or Kalman Filter.

```
1: Bayes filter algorith $\left(bel\left(x_{t-1}\right),u_t,z_t\right)$:
2: for all $x_t$ do
3: $\overline{bel}\left(x_t\right)=\int p\left(x_t\middle|u_{t-1}\right)bel\left(x_{t-1}\right)dx$
4: $bel\left(x_t\right)=\eta p\left(z_t\middle|x_t\right)\overline{bel}\left(x_t\right)$          (1)
5: endfor
6: return $bel\left(x_t\right)$
$bel =$ probability
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In the case when there is only one nonlinear component the EKF can be used. Step 4 describes the correction while the step 6 is re-sampling. In the present case of unimodal distribution, the Gauss or normal distribution can be used with Matlab "*randn*" function.

A discrete form (2) is extended to the form with more variables (3). The following steps will describe the creation of a mathematical model for a 2D scene of a drone. An initial simulation start requires a position vector of a beacon (4). With a specific case where we have six beacons, a distance-vector is used (6). With a shifting listener or the minor moving of a drone, the position is changed according to the odometry of SLAM. In this case, it is presupposed that odometry is based on IMU and visual (optical flow) data.

The assignment of the position and measuring of the distance (7) is based on conditional probability (8) where and are the last measurement and is everything except the last measurement. With that kind of substitution, we have the distance probability of each beacon along with the known position of the listener $p\left(z_t\middle|x_t\right)$.

In the specific case of (3), where the probability of the listener position $p\left(x_t\middle|x_{t-1},u_t\right)$ along with the previously known position of listener and known shift according to odometry there is a relation (9). Simulation of the scenario also requires some rules with steps.

$$p\left(x\middle|y\right)=\frac{p\left(y\middle|x\right)p\left(x\right)}{p\left(y\right)} \tag{2}$$

$$p\left(x\middle|y\right)=\frac{p\left(y\middle|x\right)p\left(x\right)}{p\left(y\right)} \tag{3}$$

$$x=\begin{bmatrix} x \\ y \end{bmatrix} \tag{4}$$

$$u=\begin{bmatrix} \Delta x \\ \Delta y \end{bmatrix}=\begin{bmatrix} u_x \\ y_y \end{bmatrix} \tag{5}$$

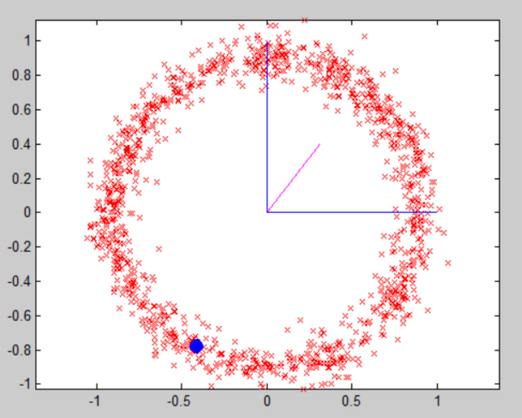
$$z=\begin{bmatrix} r_1 \\ r_2 \\ r_3 \\ r_4 \\ r_5 \\ r_6 \end{bmatrix} \tag{6}$$

$$\begin{aligned} x &= x_t \\ y &= z_t \\ z &= z_{1:t-1},u_{1:t} \end{aligned} \tag{7}$$

$$bel\left(x_t\right)=p\left(x_t\middle|z_{1:t-1},u_{1:t}\right) \tag{8}$$

$$p\left(x_t\middle|u_t,x_{t-1},z_t\right)=\frac{p\left(z_t\middle|x_t\right)p\left(x_t\middle|x_{t-1},u_t\right)}{p\left(z_t\right)} \tag{9}$$

In the simulation process, step 1 is the generation of a 2D particle zone or belt. In step 2 the listener is shifted, while in step 3 the shifting of the listener and resampling of particles is included. Already in step 4, the process convergence can be seen, as in Figure 7. One beacon scenario is presented in the simulation, where the purple line defines shifts, while the blue marker represents the beacon position which is known only to us but is not in the process.



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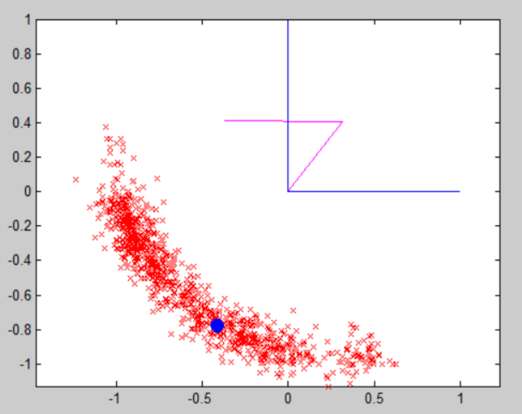

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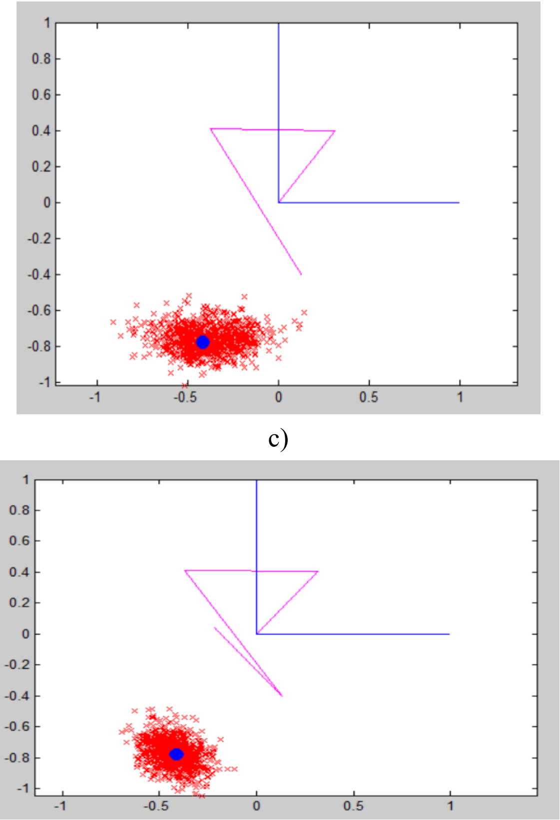

c)

d)

Figure 7. a) 2D generation of particle belt, b) listener shifting, c) listener shifting and resampling of particles, d) process convergence

5. CONCLUSION

Through the survey of the research area, drones and mobile robots localization systems are presented for indoor areas. Mobile robots are presented as vehicles with two wheels and a drone which are moving in a 2D environment. The used research methods are specific and they are based on the selection of sensors. Similarly, an indoor and outdoor area environment can be examined. Common methods can be used in outdoor and indoor localization. The laser IR method can be a kind of a hybrid solution for mapping an area. According to scientific papers, the most often used technique is an IR system with cameras. The principle is based on reflective balls which are recognized with cameras that instantly apply SLAM with the known position and orientation. The method is suitable for the formation of drone flights with command rules defined by the program. The main advantage of this method is multi-drone localization, while the disadvantage is mounting all systems in a predefined environment.

The indoor TDOA-RSS method can also be considered as a common method for the near field of an outdoor area when the drone is approaching a building. The outdoor influence of noise can be disturbing for the technical solutions integrated on sensor boards. The developed platform for the drone uses a 22 kHz transmitter sensor system for landing, while the beacon-listener ultrasonic frequency is 44 kHz. In this way, there is no interference which can cause an issue, but any other signal on this frequency can influence an echo signal and disturb or jam our signals. With stereo vision, 3D sensor technique and adequate odometry, the intensively researched method is SLAM which can be optimized easily with new technical solutions. The integration of this proposed method can be integrated into a Linux service on an AR Drone where odometry and the whole SLAM approach can be optimized on a higher level. The reduction of time is done by initial conditions where there is no need to know the position of beacons. Belt or cloud generation of particles can be easily generated from the board circuitry of beacons while the listener can send RSS signals to other beacons with service interrupt. Random variables can be generated and with the Particle filter discarding the sample principle can be applied. In addition to the 2D-belt simulation approach, a 3D cloud generation of particles is also considered. Future work will be focused on the cloud generation of particles where beacons could be nonsymmetrical and distributed in 3D space. Based on 2D simulations, the conclusion of this process has a faster convergence to unique unimodal solutions, when movements of a listener/drone are shifted at the beginning to an unknown location of beacons. The upgrading of the presented system can be even more precisely done in a way of integration of a fuzzy-partition model element in a dynamic model (later drone firmware) [59, 60-75]. Original scientific contributions are based on precise measurements in the localization method technique. IMU gyro drift can be compensated which will be presented in future work, while this approach with particle filter is a direction to edge and randomize distribution in Range-Only SLAM preparation for test scenarios of a mobile robotic platforms. The general idea would be to provide a hybrid indoor and outdoor system, which could be considered as one single field in RnD [76-86]. Such a development requires a flight simulator tool that can change the control algorithm. Fine-tuning of the control algorithm can be verified and applied in real experimental systems [60].

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КОПТЕР ЛОКАЛИЗАЦИЈА КОРИШТЕЊЕМ УЛТРАЗВУЦНОГ ТДОА И РСС СИГНАЛА - ИНТЕГРАЦИЈА ИНВЕРЗНЕ МЕТОДЕ ЧЕСТИЧНОГ ФИЛТРА

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Овај рад ће представити преглед локализацијских метода у унутарњем и вањском простору. Вањски сценарији готово увијек користе ГПС са ИМУ. Унутарњи сустави користе сензоре кратког домета који су осјетљиви на вањске увјете околиша. Најчешће кориштене методе су оптички проток и стереовизија, док ултразвучни примопредајни сустав оптимизира и пружа велику прецизност и оријентацију коптера. Ултразвучни рецептор инте-гриран је у слушатеља /бикон и може се користити са референцираним чворовима/биконима унутар WSN. Crossbow Cricket хардверска платформа која се темељи на принципу ТДОА и РСС користи се за симулације и развој кода. Истражени смјер је локализација референтних чворова (beacons) у вези са слушаоцем који је постављен на летећи коптер. У ту сврху користи се приступ вјеројатности заснован на Bayesovom филтру при чему се положаји чворова могу проматрати као случајне варијабле. С обзиром да се те расподјеле значајно разликују од Gaussove дистрибуције, прикладно је користити честични филтер.