BIOSCIENCES BIOTECHNOLOGY RESEARCH ASIA, December 2014. Vol. **11**(3), 1741-1748

Software Implementation of Autonomous Short-range Radio Navigation System

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doi: http://dx.doi.org/10.13005/bbra/1579

(Received: 30 October 2014; accepted: 05 December 2014)

In the presented paper problems of a software implementation of a ground-based and on board part of an autonomous system of short-range radio navigation of aerial vehicle are discussed. Operation stages of a ground-based part of the system are described, the most important of which is a selection of aerical vehicle (AV) flight trajectory correction points, which are controlled by on-board inertial navigation system. The final result produced by a ground-based part of the system is a flight plan for on-board module. In the last part of the paper problems of range measurements' filtering and monitoring of navigation field integrity are discussed. A control flow schemeis presented,which is implemented for a single processor computer.

Key words: Autonomous system short-range radio navigation; Correction of trajectories; Fault tree; filtering of range measurements; autonomous integrity monitoring; OS2000.

The modern technology of objects' position locations are based on use of global satellite-based radio navigation systems (GPS, GLONASS, Galileo, Beidou), long-range navigation systems (LORAN, WAAS, "Marshrut", "Tropik", "Mars-75"), systems short-range navigation (VOR, LAAS, Bras-3, GRAS, Krabik-BM, PRS, RSBN, RMA, RMD, DVOR-2000, DME-2000) and landing systems (ILS, MLS, SP, PRMG, MLS) (RPRF, 2008, IRP, 2001, FRP, 2012). As an alternative to existing radio navigation systems (RNS) with an aim to solve a problem of prospective unmanned aerial vehicles (UAV) at final section of a trajectory of flight and landing of AV an autonomous system of short-range radio navigation (ASSRRN) is undergoing development.

ASSRRN provides a capability for a location (correction) of AV position using a system of range measurements from AV to ground-based supporting navigation devices – radio beacons (RB), which form an artificial navigation field with a known geometric configuration (Khusainov, 2007; Khusainov and Shcherbinin,, 2009). The key advantage of ASSRRN as compared with known systems of short-range and local navigation is a potentially the highest consumer's location accuracy due to use of range measurements (Groves, 2008; Parkinson and Spilker, 2006; Kaplan and Hegarty, 2006). In comparison with global satellite navigation systems,ASSRRN possess certain advantages, such as a complex solution of problems related with a provision of high accuracy and reliability of positioning in a case of a violation of an integrity of a navigation field (including multiple failures of RB) and high speed of navigation measurements, which is required for

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high-speed AV. Additional factors, ensuring effectiveness of ASSRRN for military and civil application are secrecy of the functioning of RB and their activation by AV signal, low power consumption in standby mode, ease of deployment and "curtailing" of navigation field, low cost of equipment.

The presented paper discusses the main stages of software functioning of ground-based and on-board parts of ASSRRN. Ground-based part is developed using C++ programming language, on-board part uses C language for build-in"BAGET-83V" series computers, which are operating under RV BAGET (OS2000) operating system.

Software implementation is based on algorithmic fundamentals of short-range radionavigation system development, described in following works (Khusainov, 2013; Kravchenko *et al.*, 2010; Khusainov, 2010).

Design of ground-based part of the ASSRRN

Ground-based part's main purpose is to estimate accuracy of navigation tasks and prepare flight data for an on-board module. The software of a ground part consistently performs the following steps.

Preparation of data for a calculation

In a case of an installation of N beacons, their coordinates are captured in a spherical coordinate system (SCS): The distance from a RB to a touchdown point, azimuth angle between north direction and the direction to a touchdown point, measured at a sensor's position and angle between horizontal plane and the radius-vector. The software converts those coordinates into rectangular coordinates, taking into account calculation accuracy of measuring instrument at the same time.

The program generates an array of all combinations of an artificial navigation fields for a number of RB from 3 to N. The lowest value is related with the fact that the further analysis implies a location of AV coordinates with an implementation of ranging method using 3 RB, ranging-difference method using 4 RB and least-squares method for more than 3 RB. A list of combinations is formed as combinations of RB numbers without repetitions.

From that list the combinations are excluded, in which there are RB located in straight line. Such "degenerate" combinations cause low accuracy of a location of AV position, which is obtained using already mentioned methods. To determine whether combination is "degenerate" or not, equation of straight line for two RB is composed, then, distances for the rest of RB, which are the part of the analyzed a combination, are determined. If for all beacons, which are the part of a combination and are not included in the straight line equation, the measured distance is different from zero for no more than a predefined value, the combination is considered to be the "degenerate" into line. And it cannot be firmly stated that the combination is not "degenerate", if the straight line equation was composed using only first 2 RB in the combination. For example, if for a combination, consisting of RB under the numbers 1, 2, 3, check for "degenerated" combinations gave negative result for an equation corresponding to RB 1 and 2, this combination will be considered "not degenerate". However, if single line equations are composed for RB 2, 3, and 3, 1, that combination may prove to be "degenerate". Therefore, a check for "degenerate" combinations implies making lines for all combinations without repetition of two RB, which are the part of a checked combination.

Range method and range-difference method, which are used for a location of AV position, give a low accuracy not only for a combination of "degenerate" in line, but also in those cases, when four or more RB belong to the same plane. To prevent such instances "degenerate" combinations for plane are checked in the same manner as "degenerate" combinations for line. At the following stages of a ground-based part of ASSRRN operation "degenerate" combinations are not used. The main result of that phase is an array of "working" combinations of RB.

Creation and analysis of ASSRRN operation field

At that stage operation field of ASSRRN is analyzed, which is a rectangular parallelepiped, length of rib of which is proportional to a range of on-board radio range finder of AV. An obtained parallelepiped is converted into a three-dimensional grid with a step for each coordinate, which is designated by an operator of ground-based part of the system. Coordinates of a grid's node are coordinates of center of a corresponding parallelepiped.

The result of an analysis of an operation is weighted average of *DOP* geometric factor'svalues for each of grid's nodes. DOP describes in arbitrary units a degree of accuracy reduction of object coordinates location in a corresponding node of a grid, depending on geometric factor, relating coordinates of RB from "locally working" combination and a position of AV (Langley, 1999)."Locally working" combinations include all combinations of four and more RB and only those combination from three RB, which distance to center node is less than or equal to resulting dispersion error of AV in a touchdown point. The probability of each "locally working" combination is normalized relatively to sum of probabilities of all the "locally working" combinations of a node. After that, for each combination from a list of "locally working" DOP parameter coefficients are calculated. That procedure is the most labor-intensive and takes up to 80% of ASSRRN ground-based part's operation time.

DOP coefficients for the entire operation field of ASSRRN are presented to an operator in tabular or visual form, and can be used to select a position of AV launch point or to select parameters of AV flight in such a way that its trajectory in final section is "passed" through areas with minimal values of the coefficient.

Determination of AV correction points

At this stage correction points' position on a trajectory is determined, which is necessary to be carried out jointly with an inertial navigation system of AV (Khusainov, 2013).Correction may be single or multiple. In a case of a single correction, one point of a trajectory is determined, in which measurements of a distance of AV from RB are performed, and a position of AV is corrected using that data; in a case of multiple – several of those points are determined. Correction points are determined in an interval from beginning of an operation of on-board part of the system t_{start} until its ending $t_{finish.}$

An algorithm of a selection of optimal correction points' for AV position was implemented on a basis of analysis of three types of errors, values of which depend on a position of AV:

-error "known" on board, which is compensated by an automatic control system of AV, which is capable to compensate significant deviations from a designated trajectory with a maximum speed of response (Kravchenko *et al*., 2014);

Error "unknown" on board, which is caused by an accumulation of departure of inertial navigation system;

Error "unknown" on board due to errors ASSRRN (Kravchenko *et al*., 2010).

The sum of all those errors constitutes predicted dispersion error of AV at a touchdown point. A problem of a compensation of other constituent of error (dynamic control error, error of survey control establishing, error of RB positioning, etc.) are not taken into account in a context of that problem's solution (in other words, such errors are considered to be permanent).

For a single correction by means of regular enumeration search, one of AV radio range finders contact points with RB is selected, in which predicted error has the lowest value. For a multiple correction, a search for "the best" combination of points is conducted with a consideration of errors in previous points. In order to do that,the algorithm of enumerative search is used, in which in each following iteration value t_{start} is increased for a certain discreet and sufficiently small step (about 0.1-0.5 sec) and a position of t_{finish} point doesn't change. For a new value of t_{start} the calculation of predicted error is repeated. An increase of t_{start} value is conducted until the condition $t_{finish} - t_{start} > 0$ is satisfied.

Fault tree creation

Fault tree is a structure in a form of several related tables, which is created for each correction point and which main task is a rapid selection of a combination of RB combination and an algorithm of coordinates determination, which gives the less possible error in a location of AV position.

Created in a ground-based part of ASSRRN, fault tree is located in an on-board module of ASSRRN. Numbers of RB, which integrity unit of an on-board module considered doubtful (failed), are coming in an input of a structure. Only "working" combinations of RB are recorder in a structure and each combination is accompanied by a priori evaluation of accuracy of AV coordinates location. In fault tree a combination is selected, which doesn't have failed RB and which has the least minimal error of accuracy of AV coordinates location.

The main tool for fault tree creation is statistical simulation of a navigation task's solution. For each "working" combination of RM using normal distribution law three random values are generated with expected value equal to coordinates of correction points. Those values are used further for a determination of presumed coordinates of AV, which are based on solving system of equations of following form (Shebshaevich *et al.*, 1993; Balabanov & Balabanova, 2007):

$$(x_i - x)^2 + (y_i - y)^2 + (z_i - z)^2 = D_i^2 \quad ...(1)$$

where x, y, z – AV coordinates, x_i, y_i, z_i – coordinates of RB i in a local coordinates systems with center in a designated touchdown point of AV; D_i – distance to RB i.

The most widely-spread approaches to a solution of that system of equations, based on iterative and terminal mathematical algorithms are discussed in details in following studies (Kravchenko *et al.*, 2010; Khusainov, 2010). As it was mentioned before, the software uses four algorithms: algebraic (range and range-difference) for 3 and 4 RB and iterative (the least squares method) for more than 3 RB.

A generation of random values and a solution of the equation (1) is conducted L times (value of L is designated before) for each pair <combination, algorithm>, then, for each combination the least for all used algorithms standard deviation of error of AV position location is calculated. If in a certain combination at least one of algorithms returns "no solution", that combination is excluded. As a results, fault tree for one correction point consists of nodes, where each node corresponds to failure of 0..*N*-3 RB. If there are several correction points, each point corresponds to its own fault tree.

Creation of a flight plan

A flight plan is a binary file, which is transfered into on-board part of the system before the flight and contains corresponding constants, an array of RB coordinates, correction point's coordinates and fault trees.

A software implementation of discussed algorithms is developed using C++ programming language without use of classes, but with a wide use of vector-type containers.

Design of on-board module of ASSRRN

The purpose of on-board module of ASSRRN is a calculation of coordinates on final part of AV trajectory. Calculations are conducted using a system of instantaneous distance measurements between on-board radio range finder and RB with use of a flight plan, created in a ground-based part of ASSRRN. In order to increase accuracy and reliability of AV position location, on-board module of ASSRRN uses distance measurements preprocessing (filtration) functions and functions of autonomous control of an integrity of navigation field. In following, analysis of a sequence of processing on each of stages of ASSRRN on-board module operation and features of its software implementation for built-in computer of "Baget" series is discussed.

Distance measurements and their filtering

As a basis of existing version of "multiple range finding" system, the principle is used, which implies time division of communication sessions during an operation at one carrier-frequency of "AV" – "ground" and "ground" – "AV" communication links. Ground transponders (N of RB) in an initial stage are in a stand-by mode and operating in receiving mode. An on-board transponder (radio range finder) begins operation on demand from ASSRRN equipment of AV. Radio range finder transmits radio-frequency pulse repeatedly with a designated period. A transmission starts with code group "Start of request" (SRq), then it is followed by N single impulses "Distance request" (DRq), which moments of transmission are rigidly connected with a moment of SR transmission. Each transmitted signal DR is addressed to a specific transponder. Thus, each of transponders is responsible only for its "personal" DR signal. "Distance response" (DRp) signal, transmitted by each transponder", includes "Start of response" (SRp) code group and a single response measurement impulse. Using received DRp signals on-board radio range finder conducts alternate measurement of distance to each of N transponders and with a same sequence sends measured values to secondary processing unit using RS-232 serial interface.

Filtration of distance measurements form RB is aimed to decrease an influence of measuring noise and to cut off impulse noise. Software filter conducts linear filtration of measurements, coming in from each RB, with slot of -M to +M readings according to known relationships for nonrecursive linear filters, base on the least squares method.

Each filter operates in two modes: accumulation and capture. In accumulation mode, an accumulation of (2M+1) measurements is carried out and first output value is produced with a reception of (2M+1) input value. After that filter works in capture mode, producing filtered values right after receiving an input measurement. If a reading comes in a filter's input, which value is significantly differ from the previous one and the reason for that is, with high probability, is an impulse noise, it is flatten. Several impulse noises entering a slot of a filter can lead to a significant distortion of filtering results. Therefore, in a case an unacceptably high number of impulse noises entering a slot of a filter (limiting values is one of parameters of a filtration algorithm in a flight plan), they are removed from entering sequence and a filter starts to work in accumulation mode again.

After receiving and processing of one measurement from all RB, a filtration unit creates two vectors:

a) Elements of first vector are filtered values of distances;

b) Elements of second vector are flags "0" and "1", depends on whether corresponding filter is in accumulation mode or

In the first case, corresponding RB can be used for further calculations. RB with flag equal to 1 are considered active.

Verification of integrity of an artificial navigation field (ANF)

Integrity verification unit provides a verification of active RB in order to detect possible changes of their actual coordinates as compared to a flight plan. RB, which changed coordinates of its position, is considered failed. The essence of the algorithm is as follows. From N numbers of active RB C_N^4 combinations are formed. For each of four RB "basic" integrity control algorithm is carried out, which is based on one of standard approaches for a detection of single failure in N measurements (MSS, RCM, MCM, LSR methods) (Ober, 1998; Perov & Kharisov, 2010). A foundation of "basic" algorithm constitutes repeated solutions of equation system (1) using the least squares method. Therefore, from calculation perspective, integrity control procedure is the most labor-intensive stage of ASSRRN on-board module stage of operation and it seriously depends on a number of combinations of four active RB (i.e. number of active RB).

Detection and isolation of multiple failures requires special analysis of results of all combinations of four active RB for a presence of failure in each of them. Software implementation is carried out with use of the algorithm, which is described in details in the study (Khusainov & Shcherbinin2009), where following relationships between maximum ratio of detected/fixed error q and number of active RB N is proved:

$$N \geq 2 * q_{isolation} + 3$$

$$N \geq q_{detection} + 3$$

According to that relationship, integrity verification unit can detect, for instance, 1 failed RB among 4 and more active RB.

The main result of that stage is vector of active RB, which was considered not failed by an integrity verification of ANF.

AV coordinates calculation

From RB, that were checked in integrity control unit, fault tree selects combination with minimal error in accuracy of AV position detection and corresponding algorithm. That algorithm is used to obtain coordinates of AV in correction points. Calculated coordinates are used in AV control system.

Feature of software implementation of ASSRRN on-board calculator

All software constituting ASSRRN on-board part are developed using C programming language and are designated for operation under RV Baget operation system (OS2000). That real-time system is aimed at operation as part of hardware-software solutions, which are working in rigid real-time conditions. Operation system meets requirements of a standard for POSIX (OS, 2014) mobile operation systems.

On-board part of ASSRRN is based on single-processor computer in a form of two control flows: coordinates and filter. The first flow includes blocks for verification of ANF and coordinate calculation. In the second flow receiving of data from radio range finders and their filtration are conducted. Flows interact through common buffer, in which created flow places vector of filtered values and filtered flags, from which coordinates flow calculate them (fig.1). Buffer blocking is conducted by means of mutex; flow synchronization is conducted by means of semaphore and filter flow has higher priority. That scheme prevents loses of changes, which are possible, when total time of integrity control and coordinates calculation in coordinates flow exceeds time between changes, obtained via radio range finders: coordinates flow is suspended, filter flow is started and filtered data is recorded in common buffer in order to substitute values for new ones after their use in coordinates flow.

That kind of flow interaction doesn't significantly slow down coordinate's calculation, because, as it was experimentally proved, that filtration time is by far lower than integrity verification time.

RESULTS

Results of experiments concerning software implementation of ground-based part of ASSRRN are presented in table 1. In the experiments, distance from start point to touchdown point of AV is 248724 m and maximum flight altitude is 171282 m.

From the data presented in the table it is clear, that single and multiple correction considerably decrease error of AV position location; when comparing single and multiple correction, one should keep in mind, that several coordinates of correction points and, therefore, several fault trees increase size of storage for a flight plan on board of AV and, thus, increase time of correction.

Experiments with software implementation of on-board part showed following results: duration of full cycle of data processing form receiving distance measurements to entering AV coordinates into on-board control system of AV for "Baget-83M" computer was from 0.01 sec (for N=4) to 0.05 sec (for N=8). It allows to state about considerably higher speed of navigation data determination in comparison with known estimations for satellite navigation systems (about 1 sec).

Table 1. Results of experiments with ground based part of ASSRRN.

Number of RB	Number of failed RB	Presence of "degenerated" beacons	Type of correction	Error of AV position location (m) without correction/with correction
8	0	no	single	154 / 34
8	0	no	multiple	154 / 29
8	1	yes	single	336 / 35

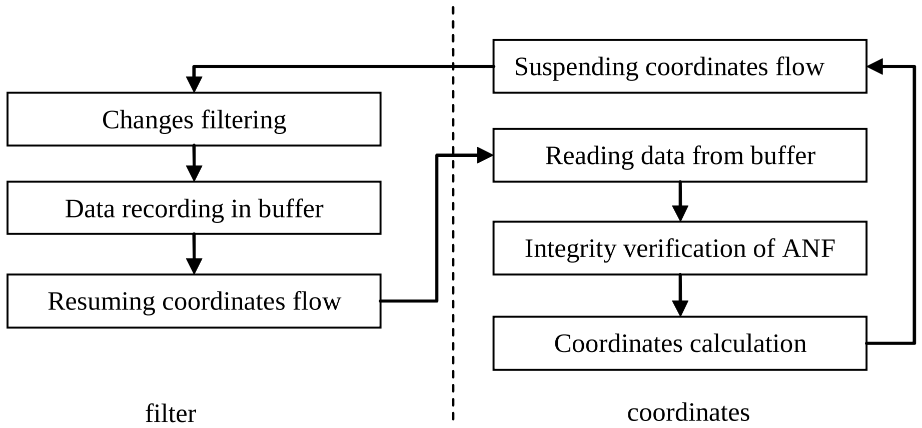

Fig. 1. Interaction scheme of control flows of on-board part of ASSRRN

CONCLUSION

Software implementation of ASSRRN discussed in the presented paper and presented experimental data allow to state that information and algorithmic justification of ASSRRN operation has necessary basis for an implementation in AV with an aim for coordinates correction on ending part of a trajectory. In particular, system takes intro account such factors, as geometry configuration of navigation field, error of position location, probabilities of RB failures and inaccuracy of radio range finder measurements. At the same time, delivery of navigation measurements is conducted with much higher speed in comparison with contemporary global navigation systems.

ACKNOWLEDGMENTS

The presented study was carried out in a framework of a basic part of state contract on topic "Information and algorithmic support of digital control systems, autonomous high-speed navigation and machine vision for prospective aerial vehicles: development of theoretical foundations of design, algorithms, methods of effective and reliable software implementation, use of high performance computational infrastructure for experimental simulation".

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