Next-Generation Landing System Based on Combined Passive Radar

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Abstract

The paper presents a newly-created aircraft landing system based on passive radar positioning principles and proposed to enhance the performance of existing systems of traffic control at local airport areas. The proposed system is built as a distributed one consisting of central processing station and several receiving stations equipped with complex three-dimensional phased array antenna which possible configuration of eight concentric rings with heptagonal allocation of antenna elements is discussed. The accurate estimation of landing aircraft position is achieved by joint digital processing of signal acquired from all the receiving station by means of one-stage angle of arrival (AOA) and combined AOA/TDOA (time difference of arrival) maximum likelihood estimators. The potential accuracy is evaluated as simulation results obtained for the deployed prototype of the system for the case of the particular stations allocation along a runway and some assumption made about the form of transmitted signal spectra and noise level.

1. Introduction

The existing classes of instrument landing systems (ILS) were developed several decades ago and the relative simplicity of the underlain operational principles determines their wide-spreading and sustains their leading position on the market. Deployed ILS typically consists of two separate ground based transmitting subsystems – localizer and glide slope system. Both subsystems function similarly, they are forming several (usually two) narrow beams slightly shifted in the opposite directions from the desired landing trajectory. Each beam transmits the space-modulated waves which are detected by onboard receiver; the receiver performs the estimation of the deviation from the plane course by means of difference in the depth of modulation technique.

But some limitations are bound to exist due to the technical complexity of ILS localizer and glide slope systems. Thus, localizer systems are sensitive to obstructions in the signal broadcast area like large buildings, hangars or other aircrafts that makes it a common practice to establish a local airport regulation of ground aircraft maneuvers to prevent the accuracy decreasing of localizers. Glide slope systems are also affected by the terrain in front of the glide slope antennas. If the terrain is sloping or uneven, reflections can dramatically influence on the entire structure of electromagnetic fields, causing unwanted deflections. The radiation pattern will also suffer in the area rich with mineral resources especially metal ores. Besides, since the signals generated by ILS permanently are pointed in one direction by the positioning of the antenna arrays, glide slope can support only a straight-line approach with a constant angle of descent. In addition to it, the installation of ILS is usually costly because of siting criteria and the complexity of the antenna systems used by a localizers and glide slope systems. Moreover, in some regions such as high mountains, it is particularly difficult to find appropriate locality to place ILS facilities optimally.

However, increasing intensity of loading the existing airport infrastructure and a deliberate deployment of new airports in arbitrary terrain with severe climate nowadays raise back the problem of designing the next generation of landing systems. This paper describes the model of autonomous landing system based on passive positioning principles [1]. The core feature of the system under developing is that its functions are redistributed between on-board and ground components in a favor of the latter. The ground part plays the prime role in evaluating the position of the aircraft while the onboard part works as just a consumer of those evaluated coordinates and possible instructions for the pilot and electronic systems of particular aircraft. To make the passive radar effective, an aircraft has to be equipped with microwave transmitter sending the noise-like signal in narrow frequency band permanently during the landing approach.

The rest of the paper is organized as follows. The essential details of the landing system design are considered in Section 2. Section 3 describes the passive radar antenna system assembled as three-dimensional phased antenna array. The potential accuracy of aircraft coordinates estimated along its typical glide path obtained by the radar with certain antenna system is presented in Section 4. The paper ends with the conclusion where the current results and further development are shortly discussed.

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2. System Design

The proposed system is designed as a distributed system which uses the directed scheme of the interaction between ground services and aircraft on-board equipment. The system interaction diagram is shown in fig. 1. The ground-based part of the system consists of several separate receiving stations allocated near the runway facility of airport and central control and processing station (CPS) which is wire-connected to those antenna stations.

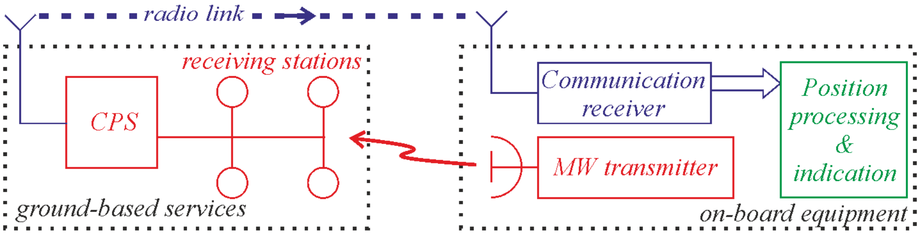

Fig. 1. Distributed landing system interaction diagram.

A landing aircraft is assumed to be equipped with the microwave transmitter sending predefined narrow-band signal at a certain carrier frequency. The values for the carrier are 1.5 GHz and 2.5 GHz but some testing scenario with 50 MHz carrier is also proposed at current developing stage to perform measurements in calibration mode. The transmitted signal is received by the antenna stations, then sampled and undergone the digital processing to extract the coordinates of the transmitter. The mutual correlation technique based on maximum likelihood estimation procedure is at the core of the signal processing. The essential idea of the likelihood algorithm for time delay estimation is proposed in [2] and thoroughly extended to the applied one-stage procedures in [3]. This approach allows one to build both angle of arrival (AOA) and time difference of arrival (TDOA) passive location technique by the systems with the same installation and hardware by means of appropriate signal processing algorithm.

The implementation of two-step AOA-only estimation technique suggests that each antenna system realized the estimation of angle with high accuracy. Then the position of the aircraft can be evaluated by some scheme incorporating least mean square estimation or some of its modification [1]. The more preferable one-step technique means that estimated parameters extracted from the sampled data are coordinates themselves that deliberately decrease the probability of abnormal errors at cost of computational resources. Uniting AOA with TDOA for signals measured by different stations increases the accuracy of obtained estimators but leads to more sophisticated processing algorithm.

The more accurate estimation of position location, especially in further cases of simultaneous aircrafts landing, requires a lot of computational resources. It would be reasonable to assign most of the necessary calculations to high-performance ground computer complex which is not affected by the boundaries of limiting weigh and power consumption that are critical for on-board electronic equipment. Such heavy computations carried out by the specialized ground-based computing center can be significantly accelerated by well-developed achievements supporting essential parallel-computing such as multithreading, multiprocessor execution, cluster processing, etc.

The on-board system receives back the information about the calculated position of the aircraft through the radio linked communication channel. This information should be transformed in the form friendly for the pilot to percept. As a possible option, the interface of the omni-bearing indicator is implemented with the LCD screens in a pilot cabin. This allows the pilot to control the aircraft during its landing. In addition to human-controlling landing scenario, the artificial intelligent landing system performing landing approach can be also viewed as a sink for the positioning data.

3. Antenna System Implementation

Each receiving station of the on-ground part of the distributed system includes the complex antenna system assembled on the phased-array principles. The certain geometry of the antenna array should provide the desired accuracy of aircraft positioning which can prevent the pilot or automatic landing system from unacceptable risks. The following configuration was proposed as a working prototype ready for further investigations. It consists of several concentric rings [5] allocated on the mast with spacing between the rings from 0.3 to 1.2 meter. Radii of the rings can vary from one ring to another as well as be the same for all of them for cost-reducing at manufacturing steps. The radii assumed to be equal from 0.8 to 2.0 meter but there is no principal limitation to make them larger or smaller at further optimization steps. Each ring supports basic antenna elements which are uniformly distributed on the circle – at the radius distance from the mast as the center of each ring. The number of basic elements is preferably to be chosen as a prime number, seven and thirteen are considered to be the best candidate. Choosing the same antenna systems for all the stations is preferable since it will increase their manufacturability which leads to reducing the costs and makes followed-up maintaining easier to perform.

The initial configuration that allows obtaining appropriate characteristics is shown in fig. 2 a). This system contains 8 rings placed on the top part of the 9-meter length mast uniformly as scheme in fig. 2 b) explains. Each ring has the same configuration like others which includes 7 antenna elements placed at the vertex of a regular heptagon as depicted in fig. 2 c). Total 56 elements mutually implements receiving points of the phased antenna array. Each point is equipped with the digital receiver based on quadrature demodulator circuit. The sampled acquired data is transmitted then to the central station by high-speed network where the main processing steps are performed.

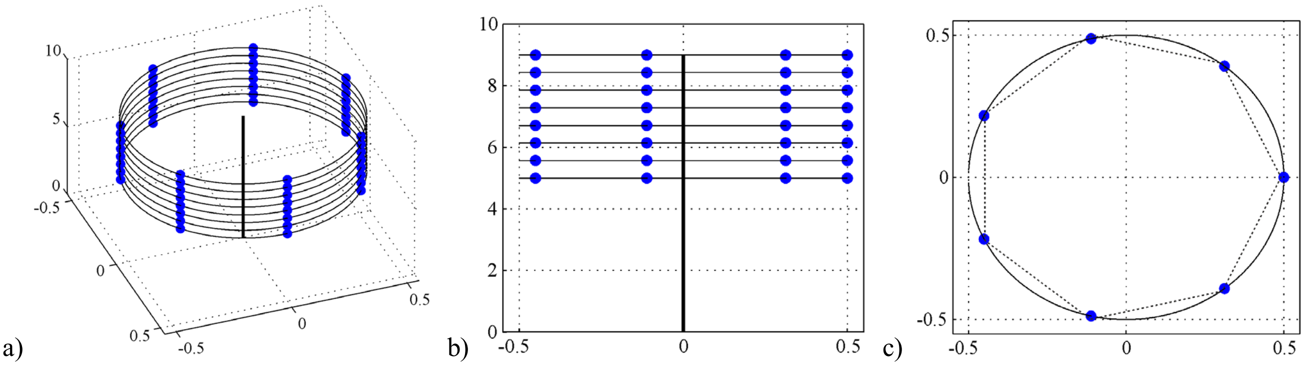

Fig. 2. 56-element antenna array configuration: a) isometric, b) vertical projection: the mast with 8 rings c) horizontal projection: a ring with elements heptagonal distributed on the circle. All dimensions are measured in meters.

4. Potential Accuracy

The potentially achievable accuracy of coordinate estimators can be evaluated by Cramer-Rao Lower Bound (CRLB) in the closed-form of a matrix **K** (of 3-by-3 size) inversed to the Fisher information matrix (in curly braces):

$$\mathbf{K}=\left\{P_\tau \mathbf{B}_\tau^T\left(N\mathbf{I}_{(N-1)}-\mathbf{1}_{(N-1)}\right)\mathbf{B}_\tau+P_\varphi\sum_{n=1}^{N}\mathbf{B}_{\varphi n}^T\left(M\mathbf{I}_{(M-1)}-\mathbf{1}_{(M-1)}\right)\mathbf{B}_{\varphi n}\right\}^{-1}, \qquad (1)$$

where N is number of stations, M is number of antenna elements for each station (assumed to be equal for all stations); **I** is identity matrix of the size mentioned in their indices, **1** is the similar matrix containing one for all its elements, P_τ and $P_{\varphi n}$ are constant for TDOA and each station AOA components correspondingly, they depends on received signal parameters, e.g., carrier frequency, bandwidth, signal-to-noise ratio, etc.; $\mathbf{B}_\tau$ and $\mathbf{B}_{\varphi n}$ are matrices determined by the allocation of receiving stations and antenna array geometry correspondingly. The examples of evaluation P_τ, $P_{\varphi n}$, $\mathbf{B}_\tau$ and $\mathbf{B}_{\varphi n}$ are presented and discussed in papers [3, 4, 5].

The glide path of the landing aircraft is generally sophisticated curve in three-dimensional space which is affected by plenty of factors. Some of them are principal such as the type of the aircraft or airfield traffic pattern individual for the airport while others are acting at particular moment of the landing e.g. wind strength and direction. Here the simplified landing is analyzed with the case where the glide path, as a curve in 3D-space with the lading point as points of origin and axes referred to the runway, stays constant for cross-length coordinate and varies in the plane built on the axes of length and height (altitude). The third-order polynomial approximation [6] is used (shown in fig. 3) where the initial altitude is given to be 500 meters and the initial length is 10 kilometers far from the expected landing point on the runway. That corresponds to about averaged 3 degree glideslope in the middle of the glide path.

The simulation was performed for the system consists of three antenna stations equipped with antenna arrays described above. The placement scheme of those antenna systems near the runway are shown in fig. 4. The central processor implements combined positioning technique; estimations are performed in series where each takes about 80 milliseconds of recorded data. On-board MW transmitter is assumed to send wide-stationary Gaussian noise-like signal in the band of 10 kHz width at the carrier frequency of 1.5 GHz. The PSD of this process is considered to be uniform.

The potential accuracy of each coordinate measured as mean-squared error (MSE) is shown in fig. 3, below the draw of approximated glide path. The signal-to-noise ratio was assumed to be 5 dB in the band of analysis. The results allows to examine that the MSE for the vertical and cross-length coordinate are not greater than 1 and 15 meters correspondingly while the accuracy of length estimation is significantly diluting as the distance from the landing point increases. The result is tractable mathematically and although the length MSE looks large enough there’s no reason for it to be considered as a defection. Firstly, the proposed system takes it main part at the ending part of landing final approach; secondly, one should notice that the proposed system is no way realized as the only one and it would be used for correcting the position of the aircraft obtained with other positioning systems, e.g., global navigation satellite system (GNSS).

5. Conclusion

The system proposed in the paper is now at the stage of its developing. Although the prototype is already deployed for field testing facility but the overall technological process of its creating is at the very beginning. There is a lot of follow-up tasks to be accomplished for making sensible progresses in it. One of the most challenging consists in the implementation of multichannel antenna station that inevitably requires specialized solution for accurate synchronization between their channels to avoid getting extra error. Thus, the technical complexity is dramatically increasing and it causes the promising task of antenna structure optimization in order to achieve the appropriate working characteristics with lesser number of elements. Another kind of problem to be solved some later is the integration of the newly-created system with the existing ones that will require unification of the information exchange protocols. Successful solution of above-mentioned problems opens the road to airports equipped with low-cost all-weather landing systems immune to the certain landscape features and surrounding facility allocation.

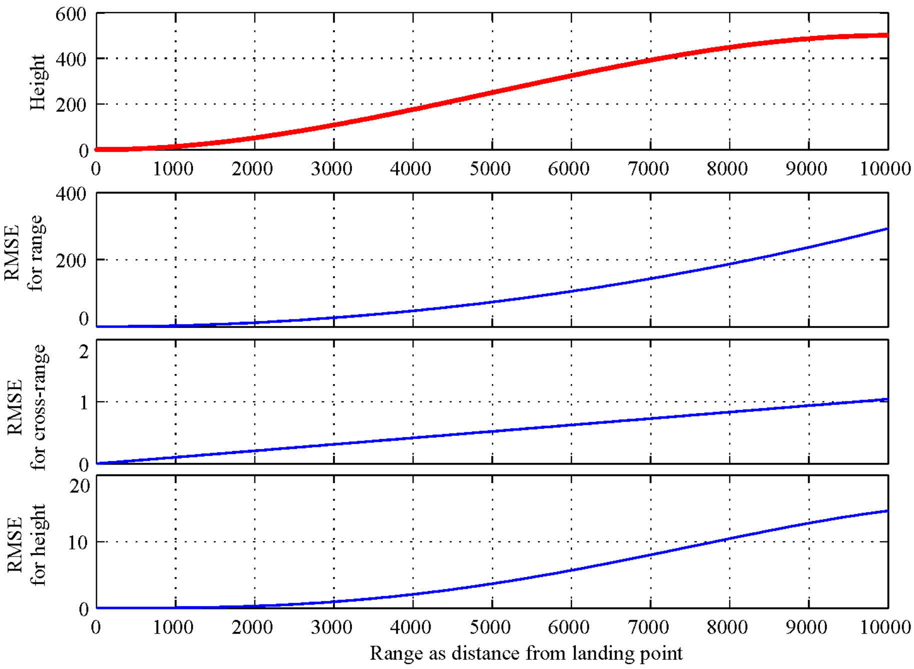

Fig. 3. Glide path and potential accuracy of coordinates estimators for *SNR* = 5 dB.

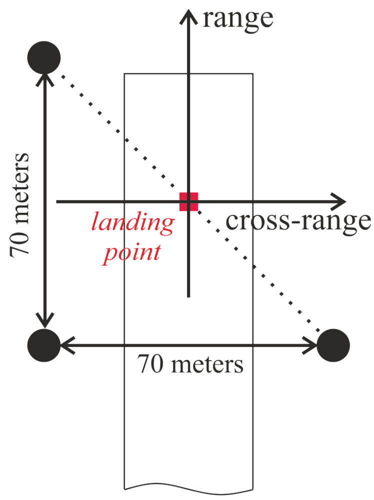

Fig. 4. Antenna stations placement.

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