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USING DELTA-TRANSFORMATIONS FOR AIRCRAFT POSITION FINDING IN LOCAL NAVIGATIN PROBLEM

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ABSTRACT

This paper presents solutions for local navigation problems using an aircraft special-purpose calculating unit. The local navigation problem formulation includes aircraft position finding from the positioning data based at relatively short distance from the local coordinate system origin of beacon quadruple groups and the distance between an aircraft and the beacons. On the basis of the available data for each group, a system of four equations standard for rangefinder navigation is formed transforming to simultaneous linear algebraic equations (linear system) of third order. Solution of this linear system with continuous running absolute terms plots the aircraft coordinates. The work considers special algorithmization aspects of local navigation problem solution with ground processing of the given problem and its solution on the board in real-time mode. A study was undertaken to apply the second order delta-transformations in linear system solution of the given problem in the context of various beacon locations. The obtained experimental results involving computer modelling substantiate linear systems solution within single iteration in a steady-state process of practical interest with a time step, and the beginning of the steady-state process is provided at a respectful distance from the origin of coordinates.

Keywords: *Aircraft Position Finding, Linear System Solution, Second Order Delta-Transformation, Aircraft Special-Purpose Calculating Unit.*

1. INTRODUCTION

Today the design problem of unmanned aerial vehicles (UAV) airborne precision integrated navigation control systems is one of the contemporary scientific research and engineering technical long-range objectives. The solution of a local navigation board problem, UAV position finding in particular, is effected in real time operation in a context of concurrent aircraft problem execution with a given time step of control discretization [1,2]. This raises the actual problem of span time and hardware cost minimization to solve the given problem within the time step, as well as to ensure minimum delayed solution with respect to the time step beginning, this owes to delay effect constraint on the control error. Application of general-purpose high performance computers in solving constrained problems of the specified character is restricted.

Thus, a special-purpose calculating unit to provide high performance and cost effective solution of the local navigation problem, aircraft position finding on a real time basis, is necessary to be created. To solve this problem may be used in many cases to calculate the coordinates of an aircraft not only iterative methods (e.g., least squares method, which is the de facto standard in the receivers of satellite navigation systems), but also the algebraic methods based on the reduction of a navigation equations system to linear system, and have a significantly lower the complexity of implementation. Within the scope of this paper, it presents the constructability of special-purpose calculating unit based on delta-transformations. Applying linear system multi-sweep procedure the delta-transformations arrange the computation process eliminating multidigit multiplications and obtaining the result within single iteration in a steady-state process [3-8]. Previous studies [7-8] have shown the benefits of this approach for the duration of the one iteration execution and iterative process as a whole compared with the implementation of the known simple iteration method [9-12] of about 1.7 times. In the design of special-purpose calculating unit using the FPGA peculiarities of algorithmic software allow to achieve the highest quality performance indicators

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to minimize the costs of resources (equipment) compared with known [13-14].

According to the efficient usage of aircraft computer resources, of special interest is computer process organization where data processing in single iteration is performed with a reasonable degree of accuracy, rapid response and a maximum time step. Under the above conditions it is possible to specify the lowest data generation frequency requirements describing changeable linear system absolute terms (for example, to frequency of distance generation between an aircraft and local navigation beacons [1,2]), as well as to computation capacity for simultaneous realization of other algorithms and programmes. Relevancy of effective solution for low-order linear systems under the described conditions rises steeply, when a large number of linear systems should be solved simultaneously, as is the case in using beacon local navigation system with simultaneous integrity control problem solution [15].

Thus, the aim is to study the design issues of special-purpose computers of high performance and low cost hardware resources intended to simultaneous solution of a large number of linear systems based on the second order delta-transformations, matched to the local navigation problem on four beacons.

Further it is considered peculiarities of the problem formulation of local navigation, in particular, the task of the local navigation on four beacon.

2. SETTING OF THE LOCAL NAVIGATION PROBLEM

One of UAV position finding problems is built on using several spaced-apart beacons located at a near short distance from the local coordinate system origin. An airborne computer receives distance value between the UAV and beacons. Relying on available beacon coordinates and the obtained distances, navigational findings can be formed in the following form standard for distance measurement navigation systems [16]:

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

where x, y, z are the UAV coordinates; (x_i, y_i, z_i) are the coordinates of the i-beacon in the selected frame of axis; D_i is the distance to the i-beacon. Solving simultaneous equations for all the beacons enables positioning the UAV (x, y, z) at air area.

The solution of the present local navigation problem on board UAV involves 2 stages.

The first stage, discussed in paragraph 1.1, is finding the current UAV position by solving simultaneous equations, where each equation is based on the location data of applicable four beacons and distances between the UAV and the beacons.

The second stage is solving the integrity problem to ensure the certainty of the obtained results with regard for hypothetical operational beacon disorder. The integrity problem original data are multiple values of the UAV coordinate formed, obtained at the first stage. The successful solution of this problem requires a great number of beacon groups capable of forming UAV coordinates for each group independently. Actually, the integrity problem is not within the scope of this paper.

2.1 Local Navigation Problem on Four Beacons

The problem considers the following:

- coordinates of four beacons in Cartesian coordinate system: (X_1, Y_1, Z_1), (X_2, Y_2, Z_2), (X_3, Y_3, Z_3) (X_4, Y_4, Z_4); the above coordinates are formed when placing the beacons by metering on the ground;

- distance between each beacon and the UAV: D_1, D_2, D_3, D_4; the above coordinates are formed in flight applying special airborne equipment.

The UAV X_P, Y_P, Z_P coordinates need to be defined.

According to (1) squared distances between 4 beacons and the UAV are as follows:

$$\begin{cases}(X_p-X_1)^2+(Y_p-Y_1)^2+(Z_p-Z_1)^2=D_1^2\\(X_p-X_2)^2+(Y_p-Y_2)^2+(Z_p-Z_2)^2=D_2^2\\(X_p-X_3)^2+(Y_p-Y_3)^2+(Z_p-Z_3)^2=D_3^2\\(X_p-X_4)^2+(Y_p-Y_4)^2+(Z_p-Z_4)^2=D_4^2\end{cases}. \qquad (1)$$

We remove parentheses and get the following:

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$$\begin{cases} X_p^2 - 2X_pX_1 + X_1^2 + Y_p^2 - 2Y_pY_1 + Y_1^2 + Z_p^2 - \\ X_p^2 - 2X_pX_2 + X_2^2 + Y_p^2 - 2Y_pY_2 + Y_2^2 + Z_p^2 - \\ X_p^2 - 2X_pX_3 + X_3^2 + Y_p^2 - 2Y_pY_3 + Y_3^2 + Z_p^2 - \\ X_p^2 - 2X_pX_4 + X_4^2 + Y_p^2 - 2Y_pY_4 + Y_4^2 + Z_p^2 - \end{cases}$$

$$\begin{cases} -2Z_pZ_1 + Z_1^2 = D_1^2 & (2.1) \\ -2Z_pZ_2 + Z_2^2 = D_2^2 & (2.2) \\ -2Z_pZ_3 + Z_3^2 = D_3^2 & (2.3) \\ -2Z_pZ_4 + Z_4^2 = D_4^2 & (2.4) \end{cases}$$

In the context of the paper with a view to creating more favorable conditions to constitute normal sufficient boundedness, passing to linear system of third order is requested to perform by the following subtraction sequence: (2.1)-(2.2), (2.2)-(2.3), (2.3)-(2.4). We find the following:

$$\begin{cases} 2X_p(X_2 - X_1) + 2Y_p(Y_2 - Y_1) + 2Z_p(Z_2 - Z_1) = \\ 2X_p(X_3 - X_2) + 2Y_p(Y_3 - Y_2) + 2Z_p(Z_3 - Z_2) = \\ 2X_p(X_4 - X_3) + 2Y_p(Y_4 - Y_3) + 2Z_p(Z_4 - Z_3) = \end{cases}$$

$$\begin{cases} = D_1^2 - D_2^2 + X_2^2 + Y_2^2 + Z_2^2 - X_1^2 - Y_1^2 - Z_1^2 \\ = D_2^2 - D_3^2 + X_3^2 + Y_3^2 + Z_3^2 - X_2^2 - Y_2^2 - Z_2^2 \\ = D_3^2 - D_4^2 + X_4^2 + Y_4^2 + Z_4^2 - X_3^2 - Y_3^2 - Z_3^2 \end{cases}. \quad (3)$$

The convergence of linear system iterative solution is achieved under fixed point iteration method conditions [9-12], formed on the data obtained from beacon allocation.

We reduce (3) to the following form:

$$\begin{cases} (X_2 - X_1)X_p + (Y_2 - Y_1)Y_p + (Z_2 - Z_1)Z_p = \\ (X_3 - X_2)X_p + (Y_3 - Y_2)Y_p + (Z_3 - Z_2)Z_p = \\ (X_4 - X_3)X_p + (Y_4 - Y_3)Y_p + (Z_4 - Z_3)Z_p = \end{cases}$$

$$\begin{cases} = \frac{1}{2}(D_1^2 - D_2^2 + X_2^2 + Y_2^2 + Z_2^2 - X_1^2 - Y_1^2 - Z_1^2) \\ = \frac{1}{2}(D_2^2 - D_3^2 + X_3^2 + Y_3^2 + Z_3^2 - X_2^2 - Y_2^2 - Z_2^2) \\ = \frac{1}{2}(D_3^2 - D_4^2 + X_4^2 + Y_4^2 + Z_4^2 - X_3^2 - Y_3^2 - Z_3^2) \end{cases}. \quad (4)$$

Next, to plot UAV coordinates (X_P, Y_P, Z_P) requires solving the obtained system of equations (4) in X_P, Y_P, Z_P.

3. ALGORITHMIZATION SINGULARITY OF LOCAL NAVIGATION PROBLEM SOLUTION

Solution of local navigation problem involves two following stages:

- ground processing of the given problem: further that all mathematical transformations are fulfilled to minimize the algorithm complexity when solving the problem aboard UAV, and groups of four beacons are selected to conform convergence conditions [9-12];

- real-time onboard solution of the local navigation problem processed on ground.

When ground processing it is worthwhile setting n>>4 beacons, as it is intimately connected with effective solution of the integrality problem, as it was noted in Section 1.

The number of combinations of n beacons taken m is calculated by the following formula:

$$C_n^m = \frac{n!}{m!(n-m)!}.$$

Suppose that n=8 beacons are found, then the number of beacon combinations used in the present algorithm will be $C_8^4 = 70$, but using all combinations is not necessarily.

This paper presents possibilities of simultaneous (parallel) solution of linear systems for 4 beacons based on special-purpose calculating unit with solution algorithmization on the base of the second order delta-transformations [7-8].

Figure 1 illustrates an enlarged structural chart of special-purpose airborne computer displaying possible implementation of the local navigation problem solution, where the section shown by hatching depicts the group of special-purpose computers to solve linear systems based on the second order delta-transformations and variable quantum, D_n is the distance between each n-beacon and the UAV.

When ground processing beacon coordinates differences and known sum values of absolute term squares (4) are downloaded into the airborne computer. In flight in real-time mode general airborne computer (the processor in Figure 1) receives the D_1^2, D_2^2, D_3^2, D_4^2 distance values, and the linear system solution based on second-order delta-transformation algorithm [7-8], the main idea of which is shown in paragraph 3, is

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effected in the section shown by hatching in Figure 1.

4. LINEAR SYSTEM PARALLEL SOLUTION ALGORITHM USING THE SECOND ORDER DELTA-TRANSFORMATIONS AND VARIABLE QUANTUM

We will consider linear system solution, containing constant coefficient matrix and variable absolute terms in general case, fulfilling convergence conditions for the fixed point iteration method [9-12], and being as follows:

$$BY^*(t) = G(t) . \quad (5)$$

We transform the system as follows:

$$Y^*(t) = AY^*(t) + D(t) .$$

We now turn to the notation introducing residual $z(t)$ and applying the iterative method:

$$z(t) = Y(t) - AY(t) - D(t) . \quad (6)$$

In the given systems $B = [b_{rj}]$, $A = [b_{rj} / b_{rr}]$ are matrices of dimensional coefficients $n \times n$; $G(t)$, $D(t)$ are column-vectors of absolute system terms (in particular for the system with fixed absolute terms $G(t) = G = [g_r]$, $D(t) = D = [g_r / b_{rr}]$); $Y^*(t)$ are column-vectors of system unknowns; $z(t)$, $Y(t)$ are column-vectors of residuals and approximate unknown values; t is an independent variable; $\det A \neq 0$.

The algorithm (7) of linear system parallel solution (5) using the second order delta-transformations and variable quantum can be depicted in the following difference form for *i*-step under initial conditions where $Y_{r01} = 0$, $\nabla Y_{r01} = 0$, $z_{r01} = -D_{r01}$, $\nabla z_{r01} = -\nabla D_{r01}$, $r = \overline{1,n}$ [3, 7-8]:

- demodulation:

$$\nabla^2 Y_{ril} = c_l^* \Delta_{ril}; \quad (7.1)$$

$$\nabla Y_{ril} = \nabla Y_{r(i-1)l} + \nabla^2 Y_{ril}; \quad (7.2)$$

$$Y_{ril} = Y_{r(i-1)l} + \nabla Y_{ril}; \quad (7.3)$$

$$r = \overline{1,n}, \; i = 1,2,..., R_l, \; l = 1,2,..., P;$$

- creation of transformed variable second order difference:

$$\nabla^2 y_{ril} = \sum_{\substack{j=1 \\ (j \neq r)}}^{n} a_{rj} c_l^* \Delta_{jil} + \nabla^2 D_{ril}; \quad (7.4)$$

- creation of residual values:

$$\nabla^2 z_{ril} = \nabla^2 Y_{ril} - \nabla^2 y_{ril}; \quad (7.5)$$

$$\nabla z_{ril} = \nabla z_{r(i-1)l} + \nabla^2 z_{ril}; \quad (7.6)$$

$$z_{ril} = z_{r(i-1)l} + \nabla z_{ril}; \quad (7.7)$$

- creation of switching function values and second difference quantum signs:

$$F_{ril} = z_{ril} + 1.5\nabla z_{ril} + (0.5\nabla z_{ril}^2 / c_l - $$
$$- 0.125c_l) sign(\nabla z_{ril}); \quad (7.8)$$

$$\Delta_{r(i+1)l} = -sign\, F_{ril}; \Delta_{ril} \in \{+1,-1\},$$
$$c_l = 0{,}75 c_l^* . \quad (7.9)$$

In the algorithm (7) c_l^* is weighting coefficient of transformation quantum magnitude in l-iteration loop ($c_l^* > 0$), P is the number of loops taken with quantum values constant in magnitude, R_l is the number of loop iterations. An additional point is that for coupling of neighboring loop segments when solving linear system with variable absolute terms the following relations are used: $Y_{r0l} = Y_{rR(l-1)}$; $z_{r0l} = z_{rR(l-1)}$.

The principle of system solution (5) based on the algorithm (7) is that the following initial data are set: Y_{r0}, ∇Y_{r0}, D_{r0}, ∇D_{r0}, $r = \overline{1,n}$ (in particular, for example, $Y_{r0} = 0$, $\nabla Y_{r0} = 0$, then, respectively, $z_{r0} = -D_{r0}$, $\nabla z_{r0} = -\nabla D_{r0}$, $r = \overline{1,n}$) and the iteration (transient) solution process is generated before entering the steady-state process, when $|z_{riP}| \leq z_{steady}$, $z_{steady} > 0$, $r = \overline{1,n}$, where z_{steady} is sufficiently small values corresponding to the assurance of required system solution accuracy. Discrete values D_{ri}, $r = \overline{1,n}$, $i = 1,2,...$ are assumed to be numerically stated at every step [3] in the algorithm (7).

The papers [7-8] develop integer estimators of algorithm parameters (7) defining the representation of variable quantum value sequence in the loops. The following relations for

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neighbouring loop quanta are suggested (s is a minimal quantum degree, $s \in N$):

- $R_{\text{int},1} = 4 \quad c^*_{P_{\text{int},1}-l} = 2^{2(l-1)-s}, \; l = \overline{P_{\text{int},1},1}$;

- $R_{\text{int},2} = 8 \quad c^*_{P_{\text{int},2}-l} = 2^{3(l-1)-s}, \; l = \overline{P_{\text{int},2},1}$.

The papers [7-8] introduce and theoretically base effective termination conditions of the iteration process in the current algorithm loop (7):

$$sign(\frac{z_{r(i+1)l}}{c^*_l}) = -sign(\frac{z_{ril}}{c^*_l}),$$

$$sign(\frac{|z_{ril}|}{c^*_l}) = -sign(\frac{|z_{ril}|}{c^*_l} - sign(\frac{|z_{ril}|}{c^*_l}) \cdot \frac{|z_{ril}|^*}{c^*_l});$$

$$r = \overline{1,n}, \; i = 1,2,\ldots,R_l; \; l = 1,2,\ldots,P.$$

4. EXPERIMENTATION AND RESULTS

We studied the application of the second order delta-transformations for linear systems solution within the local beacon navigation problem in the context of beacon allocation. Special attention was given to beacon levels, as reducing the levels increasingly resulted in disturbance effect on the iteration process error at every step.

Besides, the study accounted for two methods of computer process organization:

1. The present distance values arrive at every current step of both transient and steady-state processes; the length of all steps (iterations) is fixed.

2. The first solution time step is used to implement the transient process with fixed distance values, correspondent to this time step (the present mode is implemented if the computing resource transmission at the step for this problem is possible). After the transient process terminates, the solution is continued in the following time steps with implementation of one iteration at each step. The transient decay moment detection and the appropriate criteria formation in solving the UAV control problem to find the least transformation quantum value are assumed to be automated.

Significantly, the second method of the computer process organization implements transient processes conforming the ideas discussed in [9-12] by convergence criteria. If the above way of applying the transient process used when operating at variable absolute terms, there are possibilities to reduce the number of solution time steps (but not the number of iterations).

The research on applying the second order delta-transformations to solve linear systems within the local beacon navigation problem will be considered for separate groups in four beacons using two problem types. The first problem is position finding with the high initial UAV altitude and high speed, the second problem – with the UAV landing.

The first problem type considers three location variants for 4 beacons:

(-200, -400, 20), (450, -100, 120), (120, 400, 170), (-100, 450, 420); (8)

(-200, -400, 5), (450, -100, 25), (120, 400, 0), (-100, 450, 25); (9)

(100, -40, 1), (150, -100, 0), (10, 400, 0), (-15, 450, 10). (10)

Variant (8) differs from variant (9) in substantial level decrease of beacon locations. Variant (10) is characterized by a perfect beacon position in the XOY plane, and by critical low beacon levels.

The high initial UAV altitude is $H_0 = 17000$ м., the speed is $V_1 = 700$ m/s and $V_2 = 300$, the earth-referenced angle is equal to 60°.

The solution of all linear systems corresponding to the above beacon coordinates and composed according to the system (4) was done with assurance of the same accuracy equal to 2^{-14}, defined by 0,25 m.

Tables 1, 2 show the results characterizing time steps ∇t_2 and altitude H_2 in meters applying the algorithm based on the second order delta-transformations [7-8]. The H_2 parameter reflects the altitude from which the linear system solution within one iteration in the steady-state process with the specified common maximum solution accuracy for three variants of beacon locations (8), (9), (10) is provided. In Table 1 the computer process organization is performed on the basis of the first method, in Table 2 the computer process organization is performed on the basis of the second method. Tables 1, 2 in the parentheses show description numbers of the beacon location coordinates (8), (9), (10).

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Table 1: Experimental results of the linear systems solution for the local beacon navigation problem based on the first method of the computer process organization.

∇t_2	UAV altitude for the second order delta transformations, H_2					
	$V_1 = 700$ м/с			$V_1 = 300$ м/с		
	(8)	(9)	(10)	(8)	(9)	(10)
0,005	16357	15877	15507	16845	16277	16510
0,01	15707	13559	14764	16600	16010	15628
0,025	14363	11018	9652	15397	13847	14342
0,05	10308	3249	-	14868	12218	11722
0,075	7723	-	-	13610	6730	10322
0,1	-	-	-	12105	6084	4088

Table 2: Experimental results of the linear systems solution for the local beacon navigation problem based on the second method of the computer process organization.

∇t_2	UAV altitude for the second order delta transformations, H_2					
	$V_1 = 700$ м/с			$V_1 = 300$ м/с		
	(8)	(9)	(10)	(8)	(9)	(10)
0,005	16705	16358	16632	16938	16843	16951
0,01	15868	12887	15644	16738	16615	16692
0,025	9914	6630	9494	15667	15446	15397
0,05	-	-	-	11790	9830	11332
0,075	-	-	-	5424	5705	4433

The second problem type (whilst the UAV landing) considers the following location variants for 4 beacons:

(100, -40, 1), (150, -100, 0), (10, 400, 0), (-15, 450, 10). (11)

(100, -40, 5), (150, -100, 25), (10, 400, 0), (-15, 450, 25). (12)

We adopt that the initial UAV altitude is $H_0 = 200$, the speed is $V_1 = 20$ m/s, the earth-referenced angle is equal to 4°.

Table 3 shows the results characterizing time steps ∇t_2 and altitude H_2 in meters applying the algorithm based on the second order delta-transformations [7-8] for the first and the second methods of the computer process organization. The H_2 parameter reflects the altitude from which the linear systems solution within one iteration in the steady-state process with the specified common maximum solution accuracy equal to 2^{-13} (defined by 0,12 m.) for two variants of beacon locations (11), (12).

Table 3 - Experimental results of the linear systems solution for the local beacon navigation problem (whilst the UAV landing).

∇t_2	UAV altitude for the second order delta transformations, H_2			
	method of computer process organization			
	the first method		the second method	
	(11)	(12)	(11)	(12)
0,005	155	169	192	196
0,01	115	124	183	194
0,025	30	17	148	191
0,05			103	159
0,75				111
0,1				20

The studies present the linear systems solution without considering estimation errors in beacon location coordinates and distance measurement, the integrity problems were not considered.

5. DISCUSSION

The analysis of the data obtained in Tables 1, 2 shows that solving linear systems on the basis of the second order delta-transformations provides the steady-state process and the linear systems solution within one iteration at sufficiently high altitude with reference to the initial one with time step ∇t_2 being of practical interest. It being understood that obtaining the result for all system equations is effected within ~10 units of time with realization of the algorithm in the FPGA-based special-purpose computer. The computer process organization using either the first or the second method illustrates notably similar results, but there is an advantage of using the second method observed for the beacons located closer to the ground level.

The analysis of the data obtained in Table 3, shows that solving the local beacon navigation problem, position finding whilst the UAV landing in particular, it is reasonable to organize the computation process on the basis of the second method. In addition to the above, the first solution time step is realized with fixed distance values.

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After the transient process terminates, the solution is continued at the following time step with implementation of one iteration. The steady-state process starts from the moment of using the transformation quantum value.

For the UAV control calculated coordinates may be chosen after the steady-state process started, starting from altitude H_2.

6. CONCLUSION

The paper discusses the features of algorithmization solving the local navigation problem on four beacons for ground preparation of the proposed tasks, which describes all the mathematical transformations necessary for the application of iterative methods in general and in particular for using methods and algorithms based on delta-transformations. In addition, the paper presents the features of the problem solution on the aircraft board in real time using a delta-transformations, allowing to realize special-purpose computers of high performance and low cost hardware resources intended to simultaneous solution of a large number of linear systems based on the second order delta-transformations.

The paper undertakes a study on applying the second order delta-transformations to solve linear systems within the following local navigation problem: UAV position finding. Application of the optimized second order delta-transformations shows the possibility of linear systems solution with variable absolute terms at each time step of the steady-state process within one iteration. The obtained experimental results using computer modelling support operating on practically significant system time steps with sufficiently large distance between the beginning of the steady-state process and the origin of coordinates.

One of the directions of future research is to study the possibility of using an FPGA for the effective implementation of special-purpose computers for solving linear systems in determining the coordinates of the aircraft on the basis of the developed methods and algorithms using a second-order delta-transformations.

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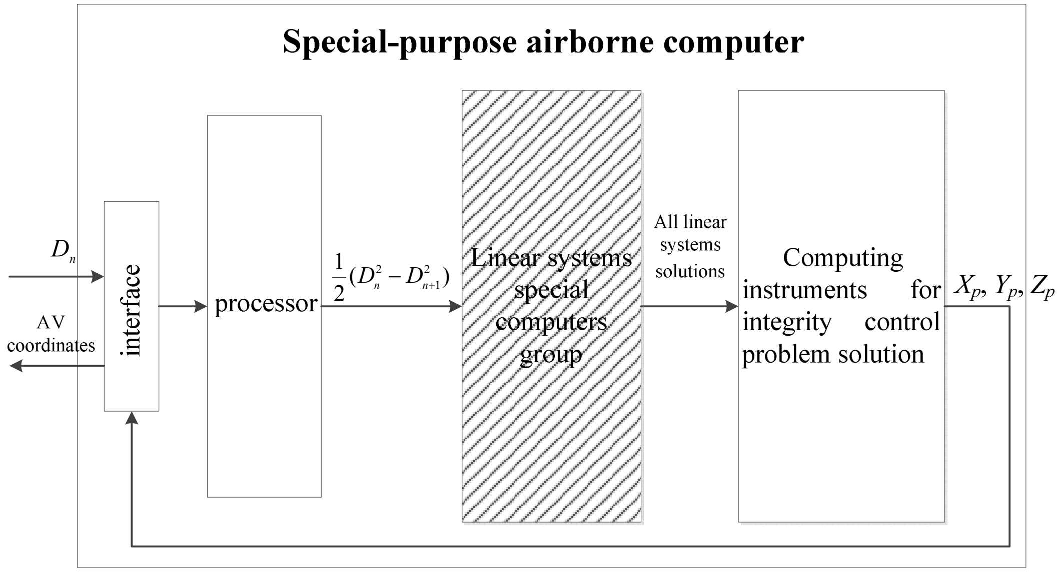

Figure 1: The Enlarged Structural Chart Of Special-Purpose Airborne Computer