Indication of relative motion intensity of aerodynamic object and meters with different physical nature

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Abstract: The need to track the motion trajectory, of a plane for example, the parameters of a power plant, etc., requires creating meters that operate under conditions of unpredictable changes in coordinates and their derivatives. This task is done by synthesizing tracking meters, which, depending on the situation, can change both the parameters and, possibly, the structure. This is implemented by meters, which can use different combinations of state models. In accordance with the chosen method, an algorithm for indicating the intensity of relative motion - aerodynamic object – measuring system - is obtained. The intensity is indicated by the acceleration magnitude of the aerodynamic object approach to the meter, calculated on the basis of information from meters of various physical nature.

1. Introduction
The initial models for the system state (mathematical dependencies describing the temporal change of the relative motion parameters of the aerodynamic object (AO) – meter (RMAG) in the selected coordinate system) and the meter are selected taking into account the tasks solved by the tracking system and the capabilities of modern computers in terms of speed and memory capacity. The state model should provide an optimal estimation of all the relative motion parameters necessary for giving control commands.

The RMAG model should be both simple to reduce the time spent on data processing and at the same time complex enough to describe adequately the real trajectory of the aerodynamic object relative to the meter and provide the accuracy necessary for an effective solution of the measurement problem. The fact is that the computational costs increase with the rise in the size of the phase coordinates vector. When choosing a model, as a rule, they tend to simplify the modeling equations with minimal deterioration in the accuracy of the model, and, consequently, the quality of tracking. This procedure is similar to the introduction of noise, which takes into account the incompleteness of knowledge about the true process of motion and unpredictable phenomena, such as atmospheric turbulence or control effects [1, 2].

Currently, filtering algorithms use a model based on the assumption that the RMAG is rectilinear with a constant approach rate. If there is no AO maneuver (there are no deviations from the linear trajectory) or if there is a maneuver, the period of updating information about the AO is of little
importance, then the task of tracking is solved quite satisfactorily. However, the results of the analysis showed that the presence of a maneuver with a relatively long period of updating information makes the existing algorithms unsuitable for accurate tracking due to the discrepancy between the RMAG model and reality [3, 4].

To improve the accuracy of tracking the coordinates of mobile objects, it is necessary to have a follow-up system (FS) consisting of several subsystems with different structures (sets of parameters). Their purpose is to ensure operation in different modes in a changing signal-interference environment, the presence of possible violations of the tracking process, a sharp change in the behavior of signal parameters due to unpredictable reasons. Switching between the structures is performed based on the indication of the RMAG intensity, in particular, on the acceleration magnitude of the aerodynamic object approach to the meter, calculated on the basis of information from meters of different physical nature [5, 6].

2. Theory

In the process of analyzing the FS functioning, in the general case, potential errors are found first of all by applying analytical methods.

The indication of the RMAG intensity is made by the acceleration magnitude of the meter approach to the AO $a_k^{lb}$, calculated on the basis of information from meters of different physical nature. This acceleration is defined as

$$a_k^{lb} = a_k^{alo} - a_k^{ib},$$

where $a_k^{alo}$ and $a_k^{ib}$ are the algebraic projections for the acceleration vectors of the AO and the meter on the sight line (SL), respectively, at the k-th moment of time.

If $|a_k^{lb}| > a_{n_1}$, then $r_k = 1$ - a maneuver of low intensity is indicated; if $a_{n_1} \leq |a_k^{lb}| > a_{n_2}$, then $r_k = 2$ - a maneuver of medium intensity is; if $|a_k^{lb}| > a_{n_2}$, then $r_k = 3$ - an intense maneuver is. Here, the output signal $r_k$ determines the state of the indicator at the k-th moment of time.

For calculating $a_k^{alo}$, the information received from the optical system is used. For the calculation of $a_k^{ib}$, the information from the sensors of the meter’s own motion is used. The accomplishment of this approach is the advantage of the optical system in terms of jamming resistance in comparison with radio sensors. It is quite obvious that the quality of functioning the self-motion sensors of the meter does not depend on the jamming environment, and the information from them has an acceptable accuracy for solving the problem under consideration.

However, to determine the acceleration of the approach $a_k^{lb}$, information from the radar channels for the AO tracking by speed and angular coordinates is also required. Its accuracy depends both on the ability of these channels to track steadily the maneuverable AO and the jamming environment. The solution to this situation is to develop a method for determining the value $a_k^{lb}$, in which the accuracy of calculating this parameter is sufficient for the correct indication of the RMAG intensity, and the least dependence of the indicator quality on the accuracy of tracking the target in speed and angular coordinates is provided.

Thus, the problem of determining the parameters sufficient to calculate the acceleration of the approach $a_k^{lb}$ (in other words, the algebraic projections $a_k^{alo}$ and $a_k^{ib}$) arises in order to display the RMAG intensity under the conditions specified above.

* Determination of parameters sufficient to calculate the algebraic projection for the acceleration vector of the meter on the SL. It is known that the vector for the total acceleration of the meter $\vec{a}_k$ can be represented as [3]

$$\vec{a}_k = g \cdot \left( \vec{n}_{x_k}^u + \vec{n}_{y_k}^u + \vec{n}_{z_k}^u \right),$$

where $\vec{n}_{x_k}^u, \vec{n}_{y_k}^u, \vec{n}_{z_k}^u$ are the vectors for the longitudinal, normal, and lateral accelerations, respectively, in the associated meter coordinate system $OXYZ$. 

[1] Journal of Physics: Conference Series 1901 (2021) 012004 doi:10.1088/1742-6596/1901/1/012004
The algebraic projections for the acceleration vectors $\hat{n}_x^u, \hat{n}_y^u, \hat{n}_z^u$ on the axis of earth referenced coordinate system $O_X Y Z$ are defined by the following equations:

$$n_x g_k = n_x u k n \cos \phi_k \cos \theta_k - n_x u k n \cos \phi_k \sin \gamma_k + \left( \cos \phi_k \cos \theta_k \sin \gamma_k - \sin \phi_k \sin \gamma_k \right)$$  \hspace{1cm} (3)

$$n_y g_k = n_y u k n \sin \phi_k \cos \theta_k + n_y u k n \cos \phi_k \sin \gamma_k$$  \hspace{1cm} (4)

$$n_z g_k = -n_z u k n \sin \phi_k \sin \theta_k + n_z u k n \cos \phi_k \cos \gamma_k - \left( \sin \phi_k \sin \theta_k \cos \gamma_k + \cos \phi_k \sin \gamma_k \right)$$  \hspace{1cm} (5)

where $\theta_k, \phi_k, \gamma_k$ are the pitch, yaw, and roll angles of the meter, respectively.

Then the algebraic projection for the meter acceleration vector on the SL can be defined as

$$\alpha_k^{abc} = g \cdot \left( n_x u k n \cos \phi_k \cos \phi_k + n_y u k n \sin \phi_k - n_z u k n \sin \phi_k \cos \phi_k \right)$$  \hspace{1cm} (6)

The geometric meaning of the transformations is explained in Figure 1.

Information on the acceleration values $\hat{n}_x^u, \hat{n}_y^u, \hat{n}_z^u$ and pitch $\theta_k^u, \gamma_k^u$ angles of the meter comes from the meter's own motion sensors.

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**Figure 1.** The geometric meaning of the transformations

The values for the locating angles $\phi_k^e$ and $\phi_k^z$ are received from the AO tracking channel according to the angular coordinates.

Thus, the determination of the algebraic projection for the meter acceleration vector on the SL $a_k^{abc}$ is not difficult if there is complete and accurate information about the parameters of its own motion and available information about the locating angles.

**Determination of parameters sufficient to calculate the algebraic projection for the acceleration vector of the target on the SL.** The vector for the total acceleration of the target at the k-th moment of
time $\tilde{a}_k^z$ can be determined in terms of the difference between the target speed vectors at the $k$-th and $(k-1)$-th moments of time for small values of the sampling interval $T$:

$$\tilde{a}_k^o = \lim_{T \to 0} \left( \frac{\vec{V}_k^o - \vec{V}_{k-1}^o}{T} \right).$$

The modulus of the vector for the total acceleration of the target in this case is determined by the cosine law:

$$a_k^o = \frac{\sqrt{(\vec{V}_k^o - \vec{V}_{k-1}^o)^2}}{T},$$

where

$$\cos \mu_k^o = \cos \psi_k^o \cos S_k^o \cos \psi_k^{o-1} \cos S_k^{o-1} + \sin S_k^o \sin S_k^{o-1} +$$

$$+ \sin \psi_k^o \cos S_k^o \sin \psi_k^{o-1} \cos S_k^{o-1}.$$ (9)

$\mu_k^o$ is the spatial angle formed by the vectors $\vec{V}_k^o$ and $\vec{V}_{k-1}^o$.

In (8), (9), it is assumed that the longitudinal axis of the AO and its velocity vector coincide, that is, the attack and sideslip angles of the AO are zero. It can be shown that this will not cause significant errors in further calculations [2].

Modeling the motion of the AO in a number of maneuvers shows that the error in calculating the value $\tilde{a}_k^z$ rises with an increase in the values of the unaccounted attack and sideslip angles. However, large values for these angles are not typical for most cases. The average error $\overline{\Delta a}$ was 11.3 %, which is quite acceptable for this kind of indication.

It is known from kinematics that the total acceleration vector for the AO $a_k^o$ can be resolved into tangential $a_k^{o\alpha}$ and radial $a_k^{o\rho}$ components:

$$\tilde{a}_k^o = a_k^{o\alpha} + a_k^{o\rho}.$$ (10)

consequently, the modulus $a_k^o$ is defined as

$$a_k^o = \sqrt{a_k^{o\alpha^2} + a_k^{o\rho^2}}.$$ (11)

The modulus of vector for the tangential component with small values of $T$:

$$a_k^{o\alpha} = \frac{\sqrt{(\vec{V}_k^{o\alpha} - \vec{V}_{k-1}^{o\alpha})^2}}{T}.$$ (12)

Similar to the calculation of values $a_k^{o\rho}$, it is assumed that the calculation of values $a_k^{o\alpha}$ in accordance with (12) has an acceptable accuracy.

Using (11) and (12), the modulus of vector for the radial component is obtained:

$$a_k^{o\rho} = \sqrt{a_k^{o\alpha^2} - a_k^{o\rho^2}} = \sqrt{2 \cdot \vec{V}_k^{o\alpha} \cdot \vec{V}_{k-1}^{o\alpha} \cdot (1 - \cos \mu_k^o) / T}.$$ (13)

Suppose that the values of the vector moduli for the tangential $a_k^{o\alpha}$ and radial $a_k^{o\rho}$ acceleration components of the target determined on the basis of (12) and (13), respectively, are possible values of random variables (RV) $A_k^{o\alpha}$ and $A_k^{o\rho}$ statistical characteristics of which are not known.

3. Solving the problem
To determine these characteristics, a computational experiment was performed. Based on the samples of $N > 1000$ elements each, statistical probability densities for $f^o$ RV $A_k^{o\alpha}$ (Figure 2) and $A_k^{o\rho}$ (Figure 3) were constructed. The sample elements were calculated based on the actual parameters of the maneuvers.
From the curves shown in the figures, it can be seen that the RV values $a^{\alpha \tau}$ in 98% of cases are less than 10 m/s$^2$, that is $P(a^{\alpha \tau} < 10 \text{ m/s}^2) = 0.98$. In other words, the motion caused by the AO acceleration or braking is generally low-maneuvering. The mathematical expectation and the RV SD $a^{\alpha \tau}$ are equal to 2.1 m/s$^2$ and 2.8 m/s$^2$, respectively.

The probabilities of finding the RV $a^\tau_i$ in the given ranges of weak, medium and high maneuver intensity are: 0.35; 0.37 and 0.28, respectively. The conducted studies showed that the designated
volume of samples for a given reliability \( P = 0.999 \) provides the definition of mathematical expectations \( m^a_e, m^a_h \) and SD \( \sigma^a_e, \sigma^a_h \) corresponding to the RV \( a^ao_k \) and \( a^ao_k \) with sufficient accuracy to solve the problem under consideration: \( \varepsilon(m^a_e) = 0.27 \text{ m/s}^2 \), \( \varepsilon(\sigma^a_e) = 0.191 \text{ m/s}^2 \), \( \varepsilon(m^a_h) = 1.404 \text{ m/s}^2 \) and \( \varepsilon(\sigma^a_h) = 0.995 \text{ m/s}^2 \).

It should be noted that due to rather large volume of samples and the conditions of the problem to be solved, it is not necessary to approximate the obtained statistical probability distributions and the RV relationship between the RVs caused by the radial component of the AO were calculated to determine the numerical characteristics for the RV \( e^ao \) and \( h^ao \). The samples were obtained under the conditions specified above, \( N > 1000 \). The designated sample size for a given reliability \( P = 0.999 \) provides the definition of mathematical expectations corresponding to the RV \( e^ao \) and \( h^ao \) with sufficient accuracy to solve the problem.

The calculation of these statistical parameters was performed to determine the correlation coefficients \( r_{a^e}^* \) and \( r_{a^h}^* \) between the RV \( a^ao_k \) and the values \( e^ao \) and \( h^ao \), respectively. These coefficients are derived from [7]:

\[
r_{a^e}^* = \frac{\sum_{k=1}^{N} (a^e_k - m^a_e) \cdot (e^e_k - m^a_e)}{(N-1) \cdot \sigma^a_e \cdot \sigma^e_e} = -0.219 ;
\]

\[
r_{a^h}^* = \frac{\sum_{k=1}^{N} (a^h_k - m^a_h) \cdot (h^h_k - m^a_h)}{(N-1) \cdot \sigma^a_h \cdot \sigma^h_h} = 0.653 .
\]

The value of the coefficient \( r_{a^h}^* \) shows that there is a fairly strong positive linear statistical relationship between the RV \( a^ao_k \) and \( h^ao \). This means that on the base of the possible value \( h^ao \) for the RV \( h^ao \) the possible value \( a^ao_k \) for the RV \( a^ao_k \) can be judged with a high degree of certainty.

Based on the above, the equation (13) is given in the form

\[
a^ao_k = m^e_k \cdot h^ao = K_{no} \cdot \sqrt{1 - \cos \mu^ao_k} .
\]

Here, only the rotational mode parameters are used to determine the values \( a^ao_k \). The translational mode parameters are averaged on the basis of experimental data and are represented by a coefficient \( K_{no} = m^e_k \).

Identify, what is the error for motion intensity indication caused by the radial component of the AO acceleration, values \( a^ao_k \) in comparison with the indication values \( a^ao_k \). As a maneuver model the indicator state is defined in the k-th moment of time on the value \( a^ao_k = r(a^ao_k) \) and value \( a^ao_k = r(a^ao_k) \). Then the results are compared between them and compute the probability of correct \( P \left( r(a^ao_k) = r(a^ao_k) \right) \) and incorrect \( R \left( r(a^ao_k) \neq r(a^ao_k) \right) \) of the definition of motion intensity on values \( a^ao_k \). The results of the calculations are shown in Table 1.
Table 1. The probabilities of determining the intensity of the relative motion

| Event | Probability |
|-------|-------------|
| $P(r(a_{rk}^{ao*}) \neq r(a_{rk}^{ao})r(a_{rk}^{ao})) = 0.178$ | |
| $P(r(a_{rk}^{ao*}) = r(a_{rk}^{ao}))$ | $0.1746$ |
| $\pm 1|r(a_{rk}^{ao})| = 0.1$ | $0.0034$ |
| $P(r(a_{rk}^{ao*}) = 1|r(a_{rk}^{ao}) = 2)$ | $0.0096$ |
| $= 0.822$ | $0.0034$ |
| $P(r(a_{rk}^{ao*}) = 2|r(a_{rk}^{ao}) = 1)$ | $0.025$ |
| $= 0.04$ | $0$ |
| $P(r(a_{rk}^{ao*}) = 3|r(a_{rk}^{ao}) = 2)$ | $0$ |

Based on the results obtained, it can be concluded that with a high probability, the type of motion caused by the radial component of the target acceleration will be correctly indicated by the values $a_{rk}^{ao*}$. The main share of errors is made up of the ones resulting from the confusion of "neighboring" motion intensities, which does not introduce significant errors in further studies.

Thus, the modulus calculation of the vector for the radial acceleration component based on the obtained (18) is sufficiently accurate to indicate correctly the intensity of the target motion caused by this component. That is, the assumption $a_{rk}^{ao} \approx a_{rk}^{ao*}$ is quite acceptable.

In the above reasoning, the motion of the target was considered relative to the normal earth reference system $O_X Y Z$. However, neither the type of statistical distribution laws nor the numerical characteristics of the RV $a_{rk}^{ao}$ and $e^{ao}$ will not change if the reference point is moved to the mass center of the meter, that is, from the normal earth reference system $O_X Y Z$ to the radial meter one $O_{X'} Y' Z'$ (Figure 4).

![Figure 4](image-url)

**Figure 4.** Transition from the normal earth reference system to the radial meter one
The modulus value of the vector for the radial component of the target acceleration at the k-th moment of time in this case is defined as
\[ a_{r_k}^{ao} = K_n \cdot \sqrt{1 - \cos \mu_{k}^{ao/u}} , \]  
(19)
where by analogy with (8)
\[ \cos \mu_{k}^{ao/u} = \cos \psi_{k}^{ao/u} \cdot \cos \theta_{k}^{ao/u} \cdot \cos \theta_{k-1}^{ao/u} + \sin \theta_{k}^{ao/u} \cdot \sin \theta_{k-1}^{ao/u} + \sin \theta_{k}^{ao/u} \cdot \cos \theta_{k-1}^{ao/u} \cdot \cos \theta_{k-1}^{ao/u} = \frac{1}{\cos \phi_{k}} \]  
(20)
\[ \theta_{k}^{ao/u} \] and \[ \psi_{k}^{ao/u} \] are the angles of the spatial target orientation relative to the meter, the values of which are formed at the output of the image processing algorithm. They give information about both the spatial orientation of the target itself and the angle from which it is observed.

The algebraic projection of the total acceleration vector of the target on the SL is determined by the sum of the algebraic projections of this acceleration tangential and radial components:
\[ a_{k}^{ao} = a_{t_k}^{ao} + a_{r_k}^{ao} . \]  
(21)

The vector direction for the tangential component of the target acceleration \( a_{t_k}^{ao} \) depends on the presence of target acceleration or braking at the moment. Accordingly, the vectors \( a_{t_k}^{ao} \) and \( V_{k}^{ao} \) are either co-directed or oppositely directed. It is also possible that \( V_{k}^{ao} = const \) and, therefore, \( a_{r_k}^{ao} = 0 \).

Thus, the algebraic projection of the vector for the tangential component of the target acceleration on the SL can be determined based on the following conditions:
\[ a_{t_k}^{ao} = \begin{cases} a_{t_k}^{ao} \cdot \cos \delta_{k}^{ao/u} & \text{при } V_{k}^{ao} - V_{k-1}^{ao} < 0 ; \\ 0 & \text{при } V_{k}^{ao} - V_{k-1}^{ao} = 0 ; \\ a_{t_k}^{ao} \cdot \cos \delta_{k}^{ao/u} & \text{при } V_{k}^{ao} - V_{k-1}^{ao} > 0 , \end{cases} \]  
(22)
where
\[ \cos \delta_{k}^{ao/u} = \cos \theta_{k}^{ao/u} \cdot \cos \psi_{k}^{ao/u} . \]  
(23)
\( \delta_{k}^{ao/u} \) is the spatial angle formed by the vector \( V_{k}^{ao} \) and SL. Its value is defined as
\[ \delta_{k}^{ao/u} = \arccos\left(\cos \delta_{k}^{ao/u}\right) . \]  
(24)
Given that \( P\left(a_{r_k}^{ao} < a_{\eta} = 10\text{ m/s}^2\right) = 0.98 , \) \( m_{s_k} = 2.158\text{ m/s}^2 \) and \( 0 \leq \left| \cos \delta_{k}^{ao/u} \right| \leq 1 , \) it is assumed
\[ a_{k}^{ao} \approx a_{t_k}^{ao} . \]  
(25)

The vector for the radial component of the target acceleration \( a_{r_k}^{ao} \) is directed to the center of the circle approximating the target trajectory around the particular point, therefore, it is perpendicular to the target velocity vector \( V_{k}^{ao} \) directed tangentially to this circle. Thus, the vector \( a_{r_k}^{ao} \) is located to the SL at an angle
\[ \Omega_{k}^{ao/u} = \delta_{k}^{ao/u} + \frac{\pi}{2} . \]  
(26)

The algebraic projection of the vector for the radial component of the target acceleration on the SL in this case is determined by the expression
\[ a_{r_k}^{ao} = a_{t_k}^{ao} \cdot \cos \Omega_{k}^{ao/u} . \]  
(27)

The “plus” or “minus” sign in (26) is due to the advance or lag of the vector \( a_{r_k}^{ao} \) from \( V_{k}^{ao} \) and is determined by the bending side of the target trajectory relative to the meter.

The conducted studies have shown that to determine the bending side of the trajectory, it is enough to know the parameters \( \phi_{k} , \phi_{k} , \Delta \psi_{k}^{ao/u} = \psi_{k}^{ao/u} - \psi_{k-1}^{ao/u} \) and \( \Delta \theta_{k}^{ao/u} = \theta_{k}^{ao/u} - \theta_{k-1}^{ao/u} . \)
The values $\dot{\phi}_{e_k}$ and $\dot{\phi}_{g_k}$ are received from the AO tracking channel according to the angular coordinates. The parameters $\Delta \psi_k^{ao/u}$ and $\Delta \Theta_k^{ao/u}$ are calculated based on the information received from the optical system.

The results of the research are summarized in Table 2, which represents the rule for determining the bending side of the target trajectory relative to the meter.

Thus, to find the algebraic projection of the AO acceleration vector on the SL $a_{k_{lb}}^{ao}$ in order to display the intensity of the RMAG, it is sufficient to know the following parameters: $\dot{\phi}_{e_k}$, $\dot{\phi}_{g_k}$, $\Delta \psi_k^{ao/u}$, $\Delta \Theta_k^{ao/u}$, $\psi_{k-1}^{ao/u}$, and $\psi_{k-1}^{ao/u}$.

**Table 2.** Parameter values for determining the bending side of the target trajectory relative to the meter

| $\Omega_k^{ao/u} - \Theta_k^{ao/u}$ | $\dot{\phi}_{e_k} < 0$ | $\dot{\phi}_{e_k} = 0$ | $\dot{\phi}_{e_k} > 0$ |
|-----------------------------------|-------------------------|-------------------------|-------------------------|
| $\Delta \Theta_k^{ao/u}$ < 0      | $b$                     | $b$                     | $b$                     |
| $\Delta \Theta_k^{ao/u}$ = 0      | $b$                     | $b$                     | $b$                     |
| $\Delta \Theta_k^{ao/u}$ > 0      | $b$                     | $b$                     | $b$                     |
| $\Delta \Theta_k^{ao/u}$ < 0      | $b$                     | $b$                     | $a$                     |
| $\Delta \Theta_k^{ao/u}$ = 0      | $b$                     | $b$                     | $a$                     |
| $\Delta \Theta_k^{ao/u}$ > 0      | $b$                     | $b$                     | $a$                     |
| $\Delta \Theta_k^{ao/u}$ < 0      | $a$                     | $a$                     | $a$                     |
| $\Delta \Theta_k^{ao/u}$ = 0      | $a$                     | $a$                     | $a$                     |
| $\Delta \Theta_k^{ao/u}$ > 0      | $a$                     | $a$                     | $a$                     |

The table indicates: $a = +\pi/2$, $b = -\pi/2$.

The algorithm for calculating the algebraic projection $a_{k_{lb}}^{ao}$ is represented by the equations (19), (20), (21) – (27) and table 2.

**4. Conclusion**

Thus, the algorithm of functioning the RMAG intensity indicator on the basis of the developed method for determining the approach acceleration of the meter with the AO, consists of two parallel branches to calculate algebraic projections of vectors for full acceleration of the meter and the AO on SL and the general branch to calculate the value of the approach acceleration with the subsequent determination of indicator values. In general, the results of the simulation showed the effectiveness of the proposed approach.

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