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(54) **A method of applying soft-kill deployment, a soft-kill deployment system and a computer program product**

(57) The invention relates to a method of applying soft-kill deployment to mislead an incoming missile (12) directed to a mother platform (10). The method comprises the step of predicting a number of miss distances (M) associated with corresponding particular decoy launch parameter sets. Further, the method comprises the step of selecting a decoy parameter set having an optimal predicted miss distance (M). The method also comprises the step of transmitting the selected decoy parameter set to a launch unit (1) for launching the decoy (14). Here, the predicting step includes the use of an adjoint algorithm.

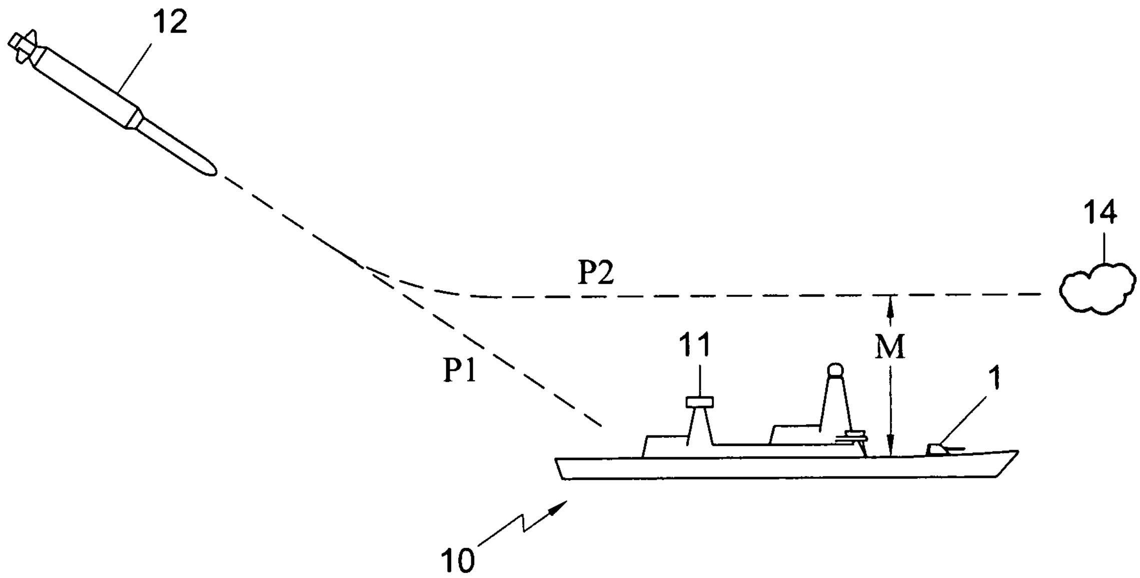

Fig. 2

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Description

[0001] The present invention relates to a method of applying soft-kill deployment to mislead an incoming missile directed to a mother platform, the method comprising the steps of evaluating a number of miss distances associated with corresponding particular decoy launch parameter sets, selecting a decoy parameter set having an optimal evaluated miss distance; and transmitting the selected decoy parameter set to a launch unit for launching the decoy.
[0002] In combating an antiship missile threat, soft-kill measures are an advantageous means, especially when coping with attacks that may not be fully averted by hard-kill means. There are some advantages that soft-kill has over hard-kill. Soft-kill deployment systems have quicker reaction times than most hard-kill systems, are cheaper and their use is not associated with the risks of collateral damage, or friendly fire that may characterize the use of hard-kill systems. There are also disadvantages in using soft-kill systems. As their effects are less localized than those of hard-kill systems, they may affect negatively the sensor and weapon systems of other ships in a task force. Also, the planning of soft-kill systems and evaluating their success/failure is a rather complex task.
[0003] Obviously, improving the effectiveness of soft-kill by taking the correct decisions during deployment is a relevant aspect. Besides the obvious consequences of incorrect deployment, or deployment of insufficient rounds, an overkill, or the deployment of too many rounds is highly undesirable. Apart from wasting limited ship resources, overkill may add an additional strain on other sensor and weapon systems on board of the ship and diminish their performance. However, improving the effectiveness of soft-kill is not an easy task due to the complexity in taking correct decisions combined with the uncertainty in information that might be available, e.g. regarding the path that the missile follows.
[0004] Advanced computing power has been a proven recipe for solving complex problems in combat decision making. For the purpose of deciding when and how to launch a soft-kill decoy, it might be relevant to predict effects of the decoy on the attacking missile. Thereto, a number of miss distances associated with corresponding particular decoy launch parameter sets may be predicted so that an optimal decoy parameter set having an optimal evaluated miss distance can be selected. The selected decoy parameter set can then be transmitted to the launch unit for launching the decoy. However, when modeling and/or simulating the combat scenario, much data has to be processed, e.g. data concerning the threat, ship, soft-kill component and the environment.
[0005] Obviously, the quality of the prediction will have an immediate effect on the performance of the soft-kill deployment. Computational time constraints will necessarily limit the complexity of the effect prediction, so many factors that may influence the effect of the soft-kill measure will need to be approximated, thereby deteriorating the predictions and rendering the decision process less effective.
[0006] It is an object of the invention to provide a method of applying soft-kill deployment to mislead an incoming missile directed to a mother platform according to the preamble wherein one of the disadvantages identified above is reduced. In particular, it is an object of the invention to provide a method according to the preamble wherein a desired accuracy of the miss distance prediction may be obtained in a relatively short computation time. Thereto, the predicting step in the method according to the invention includes the use of an adjoint algorithm.
[0007] By including the use of an adjoint algorithm, computations may be simplified, thus leading to fast, accurate solutions. As a result, the computational effort dramatically improves, thereby enabling that a relatively large number of decoy launch parameters sets can be evaluated, eventually leading to an effective choice for an optimal decoy launch parameter set.
[0008] In an embodiment according to the invention, the method further comprises the step of computing uncertainty data corresponding with a predicted miss distance, so that an estimate of the inherent uncertainty in the prediction can be taking into account in the decision process of an optimal decoy launch parameter set, thereby further improving the effect of the soft-kill deployment.
[0009] In a further embodiment according to the invention, the method further comprises a step of validating the effect of the launched decoy, the validation step comprising the substeps of predicting a zero-effort miss distance, under platform lock on condition and/or decoy lock on condition, measuring incoming missile data, comparing the measured data with the predicted zero-effort miss distance or distances, and deducing, from the comparison results, on which entity the incoming missile is locked. By using the adjoint algorithm to perform the zero-effort miss distance predicting step, an effective way of carrying out a validating step can be obtained, so that the effected of a launched decoy can be evaluated. In a particular embodiment, the deducing step includes the use of computed uncertainty data corresponding with a predicted zero-effort miss distance, thereby using the benefits of the adjoint algorithm another time.
[0010] The invention also relates to a soft-kill deployment system.
[0011] Further, the invention relates to a computer program product. A computer program product may comprise a set of computer executable instructions stored on a data carrier, such as a CD or a DVD. The set of computer executable instructions, which allow a programmable computer to carry out the method as defined above, may also be available for downloading from a remote server, for example via the Internet.
[0012] Other advantageous embodiments according to the invention are described in the following claims.
[0013] By way of example only, embodiments of the present invention will now be described with reference to the

accompanying figures in which

Fig. 1 shows a schematic view of a soft-kill deployment system according to the invention;
Fig. 2 shows a schematic perspective view of a ship equipped with the soft-kill deployment system of Figure 1;
Fig. 3 shows a time line; and
Fig. 4 shows a flow chart of an embodiment of a method according to the invention.

[0014] It is noted that the figures show merely a preferred embodiment according to the invention. In the figures, the same reference numbers refer to equal or corresponding parts.

[0015] Figure 1 shows a schematic view of a soft-kill deployment system 1 according to the invention. The system 1 is provided on a mother platform, such as a ship, and comprises a launch unit 2 for launching a decoy to mislead an incoming missile directed to the ship. The system 1 further comprises a computer system 3 provided with a processor 4 that is arranged for performing a number of steps thereby enabling a proper control of the launch unit 2. The computer system 3 has a multiple number of input ports 5 for receiving input data and at least one output port 6 for transmitting data to the launch unit 2.

[0016] Figure 2 shows a schematic perspective view of the ship 10 equipped with the soft-kill deployment system 1. The ship 10 is provided with multiple sensors, such as an omni-directional radar unit 11 for inputting data to the computer system 3 of the soft-kill deployment system 1. Figure 2 further shows a hostile missile 12 attacking the ship 10. When the missile 12 remains locked on the ship 10, the missile 12 follows a path P1 and the missile 12 will hit the ship 10. However, if the soft-kill deployment system 1 works properly, the missile will lock on a launched decoy 14 to follow another pre-determined path P2 directed to the decoy 14 thereby missing the ship 10. The missile then passes the ship 10 at a shortest distance, also called the miss distance M.

[0017] The processor 4 is arranged for performing a number of steps. First of all, the processor 4 signals an incoming missile 12. After signaling the missile 12, the processor 4 performs an identifying step of the missile 12. Such an identifying step may include determining the missile type, position, orientation, speed, path etc. In order to perform the identifying step properly, sensor data are input to the computer system 3 of the soft-kill deployment system 1.

[0018] Figure 3 shows a time line t. Here, the subsequent symbols To, Ts and T_1 denote a launch time of the missile, the signalling time instant of the missile and the identifying instant of the missile, respectively.

[0019] The processor 4 is further arranged for predicting a number of miss distances associated with corresponding particular decoy launch parameters sets. As an example, several tens of decoy launch parameter sets can be evaluated, each of them corresponding to a particular miss distance. In the predicting step, the use of an adjoint algorithm is included. The predicting step may be based on a large number of data, such as incoming missile parameter data, mother platform parameter data, the corresponding decoy launch parameter set and/or environmental data. Further, the processor is arranged for selecting a decoy parameter set having an optimal predicted miss distance M. The selected decoy parameter set is then transmitted to the launch unit 2 for launching the decoy. Further, control commands can be generated to modify the position and/or orientation of the ship.

[0020] Optionally, the processor 4 is further arranged for performing the step of computing uncertainty data corresponding with a predicted miss distance, e.g. a probability area of the path that the missile is assumed to follow.

[0021] In an embodiment according to the invention, the processor 4 selects the decoy parameter set that corresponds to the largest predicted miss distance M, thereby providing a largest offset between the ship 10 and the missile 12. Alternatively, the processor also takes into account an uncertainty in the predictions of the miss distance, thereby optionally selecting a decoy parameter set that corresponds to a relatively large predicted miss distance M having a relatively small uncertainty.

[0022] Based on the selected decoy parameter set, the launch unit 2 of the decoy system 1 launches a decoy 14 including e.g. flare for influencing any infra-red lock on device in the hostile missile and/or chaff for influencing any radar lock on equipment in the hostile missile. The decoy 14 is intended to cause the missile to deviate from the original direction, away from the ship 10.

[0023] Referring to Fig. 3, the decoy 14 is launched at a time instant T_D. Then, the missile lock on the decoy at a later time instant T_{SD}. At a further time instant Tv, it is verified or validated whether the decoy works properly and/or whether the missile 12 is now directed to the decoy 14. Thereto, the processor 4 is also arranged for performing the substeps of predicting a zero-effort miss distance, under platform lock on condition and decoy lock on condition. As a result, using the adjoint algorithm, a zero-effort miss distance is computed assuming that the missile remains locked on the ship. The zero-effor miss distance is dependent on a specific time instant and is defined as the miss distance which will result when at that specific time instant the path of the ship and the missile will remained unchanged. Similarly, a zero-effor miss distance is computed assuming that the missile changes lock on to the decoy. The processor further performs the substeps of measuring data related to the incoming missile and comparing the measured data with one or both predicted zero-effor miss distances. Then, the processor deduces, from the comparison results, on which entity the incoming missile is expected to be locked. Preferably, the deducing step includes the use of computed uncertainty data corresponding with a predicted zero-effort miss distance. After the validation has been performed, the missile enters the miss distance area, closest point of approach, at time instant T_{CPA} and moves away from the ship.

[0024] As a result, the predicting step can be used before launch of the decoy, for finding an optimal launch parameter set. Further, after launch, the effectiveness of the soft-kill can be checked by comparing the predicted effect if the anti-ship missile has been locked on the decoy or on the ship. The decision for the optimal decoy parameter set and/or the decision in the checking step can be enhanced by using uncertainty data that may be provided by the adjoint algorithm.

[0025] The adjoint algorithm, also known as adjoint method, is based on making a single simulation of a modified model called the Adjoint Model in order to determine the effect of all the perturbation sources that affect the miss distance. The adjoint model can be readily obtained from a linearization of the original model by performing some straightforward block diagram manipulations. Alternatively, the adjoint model can be obtained easily from a state-space representation of the original model. It can mathematically be proven that for deterministically analyzing guidance loops, the separate influence of the initial condition and of the input of the time-varying system on the final value of the output, it is enough to compute one initial-value solution of the adjoint system. Expressions can be derived for assessing the final value using an initial-value solution for an arbitrary initial condition and input. Though if the Adjoint Method can be useful in the case of deterministic performance analysis, it can be used with far greater advantage in the case of stochastic performance analysis. To formulate the relevant mathematical result it can be shown that the adjoint response can be used to compute the variance of the output without lengthy Monte Carlo simulations.

[0026] As such, the adjoint method includes the steps of constructing an adjoint model and using its response for generating performance data. The adjoint model simulates the dynamical system whose response includes the input sensitivities of the system to be analyzed. The adjoint algorithm is thus suited for evaluating the performance of the decoy process, in particular when the process depends on many variables, is dynamic and time varying.

[0027] The initial configuration is represented by a guided antiship missile that heads in the general direction of the ship at low altitude, a decoy cloud that is positioned a given displacement from the ship and moves freely with the wind, and a ship that is assumed to keep a constant heading during the engagement. At the start of the scenario it is assumed that the missile is locked with its seeker on the decoy and uses the seeker data for computing guidance commands. This assumption corresponds to the use of the decoy in distraction mode. By contrast, in seduction mode, the missile is first locked on the ship itself and it changes lock to the decoy only after the decoy becomes active.

[0028] It is assumed that the missile guides towards the decoy using Proportional Navigation Guidance law until passing the decoy. Subsequently, the missile continues in unguided flight until reaching the closest point of approach with respect to the ship. During the entire engagement, the velocity vector of the wind is assumed to be constant. It is also assumed that the missile speed is constant throughout the engagement, and consequently that only the course of the missile changes as a consequence of guidance commands.

[0029] It is also assumed that the ship is performing an evasive manoeuvre after deploying the decoy and that turning the ship towards the chosen course may take some time.

[0030] According to an aspect of the invention, a non-linear model is linearized to obtain a linear model and an expression for the miss distance can be formulated depending on an adjoint response that is defined as the solution to an initial value problem. Further, the variance of the miss distance can be expressed as a function of the variances of components of the initial condition. The variances of the initial state vector coordinates in terms of original stochastic quantities can be approximated relatively easily. A post-launch validation can be performed using statistical hypothesis testing algorithms.

[0031] The motion of the decoy is described as

$$(4.1) \qquad \dot{x}_f = v_{xw} \, , \; x_f(0) = x_{of} \, ,$$

$$(4.2) \qquad \dot{v}_{xw} = 0 \, , \; v_{xw}(0) = v_{xow} \, ,$$

$$(4.3) \qquad \dot{y}_f = v_{yw} \, , \; y_f(0) = y_{of} \, ,$$

$$(4.4) \qquad \dot{v}_{yw} = 0 \, , \; v_{yw}(0) = v_{yow} .$$

[0032] The equations describing the motion of the ship are

$$(4.5) \qquad \dot{x}_s = v_{xs}(t)\ ,\ x_s(0) = x_{os},$$

$$(4.6) \qquad \dot{y}_s = v_{ys}(t)\ ,\ y_s(0) = y_{os},$$

where

$$(4.7) \qquad v_{xs}(t) = V_s(t)\cos\phi_s,$$

$$(4.8) \qquad v_{ys}(t) = V_s(t)\sin\phi_s,$$

$$(4.9) \qquad V_s(t) = \begin{cases} 0, & t \le t_{man}, \\ V_{s,max} & t > t_{man}, \end{cases}$$

where t_{man} is the time required to complete the manoeuvre of the ship.

[0033] The motion of the missile is described as

$$(4.10) \qquad \dot{x}_m = V_m\cos\phi_m\ ,\ x_m(0) = x_{om},$$

$$(4.11) \qquad \dot{y}_m = V_m\sin\phi_m\ ,\ y_m(0) = y_{om},$$

$$(4.12) \qquad \dot{\phi}_m = \frac{a_n}{V_m}\ ,\ \phi_m(0) = \phi_{om},$$

$$(4.13) \qquad \dot{a}_n = -\frac{1}{\tau}a_n + \frac{1}{\tau}a_{n,c}\ ,\ a_n(0) = 0,$$

where τ is the time constant of the missile describing the response of the missile to the guidance commands represented by the commanded lateral acceleration $a_{n,c}$.

[0034] For deployment planning purposes, it will be assumed that the missile is permanently locked on the decoy, until it passes the decoy. In this case

$$(4.14) \qquad a_{n,c} = \begin{cases} N_p V_{c,f}\dot{\lambda}_f, & V_{c,f} > 0, \\ 0, & V_{c,f} \le 0, \end{cases}$$

with N_p, the navigation constant of the missile, $V_{c,f}$, the closing velocity between missile and decoy, and λ_f, the angular rate of the line-of-sight between missile and decoy. If we use for the velocity vector of the missile the notation ($v_{xm} = V_m \cos\phi_m$, $v_{ym} = V_m \sin\phi_m$), we have

$$(4.15) \qquad V_{c,f} = \frac{(x_f - x_m)(v_{xf} - v_{xm}) + (y_f - y_m)(v_{yf} - v_{ym})}{\sqrt{(x_f - x_m)^2 + (y_f - y_m)^2}},$$

$$(4.16) \qquad \dot{\lambda}_f = \frac{(v_{xf} - v_{xm})(y_f - y_m) - (v_{yf} - v_{ym})(x_f - x_m)}{(x_f - x_m)^2 + (y_f - y_m)^2}.$$

[0035] For the purpose of post-launch testing of the deployment effectiveness, it is also necessary to consider the case that the missile remains locked on the ship. In this case

$$(4.17) \qquad a_{n,c} = N_p V_{c,s} \dot{\lambda}_s,$$

where

$$(4.18) \qquad V_{c,s} = \frac{(x_s - x_m)(v_{xs} - v_{xm}) + (y_s - y_m)(v_{ys} - v_{ym})}{\sqrt{(x_s - x_m)^2 + (y_s - y_m)^2}},$$

$$(4.19) \qquad \dot{\lambda}_s = \frac{(v_{xs} - v_{xm})(y_s - y_m) - (v_{ys} - v_{ym})(x_s - x_m)}{(x_s - x_m)^2 + (y_s - y_m)^2}.$$

[0036] To linearize the nonlinear model described in the previous section, it is convenient to introduce a new coordinate system that we call the Engagement Coordinate System, with the origin in the initial position of the missile, with the x-axis along the line-of-sight from missile to ship and the y-axis completing a positively oriented coordinate system. In Figure 3.1, the axes of this coordinate system are denoted X_E and Y_E. The transformation between East-North coordinates and engagement coordinates is defined by

$$(5.1) \qquad T_e = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix},$$

where Ψ = arctan 2(y_{os} - y_{om}, x_{os} - x_{om})

[0037] We denote by the superscript ^{e} all quantities expressed in engagement coordinates. Accordingly, we have

$$(5.2) \qquad \begin{bmatrix} x_m^e \\ y_m^e \end{bmatrix} = T_e \begin{bmatrix} x_m \\ y_m \end{bmatrix}, \quad \begin{bmatrix} v_{xm}^e \\ v_{ym}^e \end{bmatrix} = T_e \begin{bmatrix} v_{xm} \\ v_{ym} \end{bmatrix},$$

and the analogues for the ship and decoy position and velocity vectors.

[0038] Since during the engagement, the course of the missile remains close to the x^e-axis, the velocity of the missile along the x^e-axis is approximately constant. Also the range between missile and ship, and between missile and decoy can be approximated by the difference of their x coordinates, whereas the miss distances can be approximated by the difference of their y coordinates. By neglecting the course variations of the missile, we can approximate the lateral acceleration of the missile by

$$(5.3) \qquad \begin{bmatrix} a_{nx}^e \\ a_{ny}^e \end{bmatrix} \approx \begin{bmatrix} a_{nx} \\ 0 \end{bmatrix}.$$

[0039] The angular rate of the line-of-sight to the decoy is approximated as

$$(5.4) \qquad \dot{\lambda}_f = \frac{d}{dt}\left[\frac{y_f^e - y_m^e}{R_{mf}}\right],$$

where the relative range missile-decoy is $R_{mf}(t) = V_{c,f}(t_{miss,f}\ t)$. We obtain

$$(5.5) \qquad \dot{\lambda}_f = \frac{y_f^e - y_m^e + (v_{yw}^e - v_{ym}^e)(t_{miss,f} - t)}{V_{c,f}(t_{miss,f} - t)^2}.$$

In a similar fashion, the line-of-sight to the ship is approximated as

$$(5.6) \qquad \dot{\lambda}_s = \frac{d}{dt}\left[\frac{y_s^e - y_m^e}{R_{ms}}\right],$$

where $R_{ms}(t) = V_{c,s}(t_{miss} - t)$. Consequently,

$$(5.7) \qquad \dot{\lambda}_s = \frac{y_s^e - y_m^e + (v_{ys}^e - v_{ym}^e)(t_{miss} - t)}{V_{c,s}(t_{miss} - t)^2}.$$

From the condition that $x_m^e = x_f^e$ at time $t_{miss,f}$, we deduce that

$$(5.8) \qquad t_{miss,f} = \frac{x_{of}^e}{v_{xom}^e - v_{xw}^e}.$$

The time of flight to the closest point of approach with respect to the ship can be approximated from the condition that $x_m^e = x_s^e$ as

$$(5.9) \qquad t_{miss} = \frac{x_{os}^e}{v_{xom}^e - v_{xos}^e}.$$

In conclusion, the linearized model for the case that the missile is locked on the decoy has the form

$$\begin{aligned}
\dot{y}_m^e &= v_{ym}^e \ , \ y_m^e(0) = y_{om}^e, \\
\dot{v}_{ym}^e &= a_n \ , \ v_{ym}^e(0) = v_{yom}^e, \\
\dot{a}_n &= -\frac{1}{\tau}a_n + \frac{1}{\tau}a_{n,c} \ , \ a_n(0) = 0, \\
(5.10) \ a_{n,c} &= \begin{cases} \frac{N_p}{(t_{miss,f}-t)^2}[y_f^e - y_m^e + (v_{yw}^e - v_{ym}^e)(t_{miss,f} - t)], & t < t_{miss,f}, \\ 0, & t \geq t_{miss,f}, \end{cases} \\
\dot{y}_s^e &= v_{ys}^e(t) \ , \ y_s^e(0) = y_{os}^e, \\
\dot{y}_f^e &= v_{yw}^e \ , \ y_f^e(0) = y_{of}^e, \\
\dot{v}_{yw}^e &= 0 \ , \ v_{yw}^e(0) = v_{yow}^e.
\end{aligned}$$

[0040] In the case that the missile is locked on the ship, equation (5.10) is replaced by

$$(5.11) \qquad a_{n,c} = \frac{N_p}{(t_{miss} - t)^2}[y_s^e - y_m^e + (v_{ys}^e - v_{ym}^e)(t_{miss} - t)],$$

and the equations describing the motion of the decoy may obviously be skipped as they do not influence the outcome of the engagement.

[0041] In both cases, the resulting model is a linear, time-varying system on [0, t_f].

[0042] The miss distance with respect to the ship is approximated by

$$(5.12) \qquad Miss = y_m^e(t_{miss}) - y_s^e(t_{miss}),$$

which is a linear function of the state of the linearized model.

[0043] For the post-launch effectiveness assessment, we use the Zero-Effort-Miss distance that can be calculated at each time moment t during the engagement as

$$(5.13) \qquad z = y_m^e - y_s^e + (t_{miss} - t)(v_{ym}^e - v_{ys}^e).$$

Notice that the miss distance is equal to $z(t_{miss})$.

[0044] It is still necessary to modify the linearized model to suit our application. Indeed, it is easy to see that the model (5.10) is singular at time t = $t_{miss,f}$. A straightforward way to eliminate this singularity while preserving the linearity of the model, by introducing a "blind time" $t_b > 0$ that is a small interval before passing the decoy in which the missile shuts down its guidance loop. With this change, the expression of the commanded acceleration for the case that the missile is locked on the decoy becomes

$$(5.14) \qquad a_{n,c} = \begin{cases} \frac{N_p}{(t_{miss,f}-t)^2}[y_f^e - y_m^e + (v_{yw}^e - v_{ym}^e)(t_{miss,f} - t)], & t < t_{miss,f} - t_b, \\ 0, & t \geq t_{miss,f} - t_b, \end{cases}$$

A similar change is necessary for the case that the missile is locked on the ship.

[0045] Notice that the introduction of the "blind time" is not necessarily affecting the realism of the simulation. Most antiship missiles are turning off the seeker when in the immediate vicinity of the target. This is done in order to avoid confusing the seeker when the target is too large in relation to the field of view.

[0046] If we introduce the state vector $\mathrm{x} = \begin{bmatrix} y_m^e & v_{ym}^e & a_n & y_s^e & y_f^e & v_{yw}^e \end{bmatrix}^T$ the linearized model can be written in matrix form as

$$(6.1) \qquad \dot{\mathrm{x}} = A(t)\mathrm{x} + w(t),$$

where

$$(6.2) \qquad A(t) = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ c_1(t) & c_2(t) & -\frac{1}{\tau} & 0 & c_3(t) & c_4(t) \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$(6.3)\qquad w(t) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ v_{ys}^{e}(t) \\ 0 \\ 0 \end{bmatrix}.$$

with

$$(6.4)\qquad c_1(t) = \begin{cases} \frac{N_p}{\tau(t_{miss,f}-t)^2}, & t < t_{miss,f} - t_b, \\ 0, & t \geq t_{miss,f} - t_b, \end{cases}$$

$$(6.5)\qquad c_2(t) = \begin{cases} -\frac{N_p}{\tau(t_{miss,f}-t)}, & t < t_{miss,f} - t_b, \\ 0, & t \geq t_{miss,f} - t_b, \end{cases}$$

$$(6.6)\qquad c_3(t) = \begin{cases} -\frac{N_p}{\tau(t_{miss,f}-t)^2}, & t < t_{miss,f} - t_b, \\ 0, & t \geq t_{miss,f} - t_b, \end{cases}$$

$$(6.7)\qquad c_4(t) = \begin{cases} \frac{N_p}{\tau(t_{miss,f}-t)}, & t < t_{miss,f} - t_b, \\ 0, & t \geq t_{miss,f} - t_b, \end{cases}$$

and the initial condition is $\mathrm{x}(0) = \begin{bmatrix} 0 & v_{yom}^{e} & 0 & 0 & \Delta y_f^{e} & v_w^{e} \end{bmatrix}^T$. The miss distance can be written as

$$(6.8)\qquad Miss = \begin{bmatrix} 1 & 0 & 0 & -1 & 0 & 0 \end{bmatrix} \mathrm{x}(t_{miss}).$$

[0047] The adjoint response at time t_{miss} is the solution of the equation

$$(6.9)\qquad \dot{\mathrm{x}}^{adj} = A^T(t_{miss} - t)\mathrm{x}^{adj}$$

with initial condition $x^{adj}(0) = [1\ 0\ 0\ -1\ 0\ 0]^T$. Notice that since matrix B in (6.1) is the identity, the state and output adjoint responses coincide.

[0048] According to Proposition 2.1, the miss distance can be written as

$$\begin{aligned}(6.10)\quad Miss &= \mathrm{x}^{adj}(t_{miss})^T \mathrm{x}(0) + \int_0^{t_{miss}} [\mathrm{x}^{adj}(t_{miss} - \tau)]^T w(\tau) d\tau \\ &= x_2^{adj}(t_{miss}) v_{yom}^{e} + \int_0^{t_{miss}} x_4^{adj}(t_{miss} - \tau) v_{ys}^{e}(\tau) d\tau \\ &\quad + x_5^{adj}(t_{miss}) \Delta y_f^{e} + x_6^{adj}(t_{miss}) v_{yw}^{e}.\end{aligned}$$

This form is particularly interesting for deterministic performance studies. In case that the initial data contains uncertainties with a stochastic character, Proposition 2.2 can be used to estimate the variance of the miss distance as a function of the variances of the components of the initial condition

$$(6.11)\quad \sigma_{Miss}^2 = \mathrm{x}^{adj}(t_{miss})^T P_{\mathrm{x}(0)} \mathrm{x}^{adj}(t_{miss}) = [x_1^{adj}(t_{miss})]^2 \sigma_{y_{om}^e}^2 + [x_2^{adj}(t_{miss})]^2 \sigma_{v_{yom}^e}^2 + + [x_5^{adj}(t_{miss})]^2 \sigma_{\Delta y_f^e}^2 + [x_6^{adj}(t_{miss})]^2 \sigma_{v_{yw}^e}^2,$$

where $P_{x(0)}$ denotes the variance matrix of x(0). Since the input of the system (6.1) is deterministic, the integral term in formula (2.6) does not appear in (6.11). Notice that formula (6.11) contains also the term corresponding to y_{om}^e that does not occur in (6.10) since $y_{om}^e = 0$ by the choice of the coordinate system, but its variance might be non-zero, reflecting uncertainties in the track data available about the missile. Notice also that formula (6.11) in its matrix form is more general since it may also contain crossvariance terms as well.

[0049] To apply formula (6.11) in practice, it is still necessary to determine the variances of the initial state vector coordinates in terms of the original stochastic quantities. An exact solution to this question may be difficult to obtain analytically, but fortunately it is easy to write approximations for these variances that are practically acceptable. For example, let us assume that x_{om} and y_{om} are stochastic variables of mean $\bar{x}_{om}$ and $\bar{y}_{om}$ and variances $\sigma_{x_{om}}$ and $\sigma_{y_{om}}$ Then the variance of y_{om} is obtained as the (2,2) element of the matrix

$$(6.12)\qquad T_e \begin{bmatrix} \sigma_{x_{om}}^2 & 0 \\ 0 & \sigma_{y_{om}}^2 \end{bmatrix} T_e^T.$$

If the error in tracking the course of the missile ϕ_m comes with a variance $\sigma\Psi_m$, then the variance of $\bar{v}_{yom}^e$ is approximately

$$(6.13)\qquad \sigma_{v_{yom}^e}^2 = V_m \sigma_{\psi_m}.$$

This relation does not take into account the error in the tracking of the missile total velocity. If we want to examine the effect of the dispersion of the decoy cloud, and we model it as a random perturbation on the launch direction, then the variance of y_{of}^e can be approximated as

$$(6.14)\qquad \sigma_{y_{of}^e} = D_f \sigma_{\psi_f}.$$

These estimates were used for the numerical tests with good results. In general, more complicated relations might be necessary to evaluate the terms occuring in (6.11).

[0050] Let us assume now that the decoy was launched and that at a fixed moment of time t_d it is required to determine whether the deployment was successful, that is if the missile has locked on the decoy. In case of an active missile there are essentially two ways to perform this function (see [1]). The first applies to active and passive missiles as well and is based on computing the closest point of approach of the attacking missile. The second way to assess if the attacking missile is locked on the ship is based on using the ESM system indication to measure the radar signal used by the missile to track the ship. The second method is considered more reliable as it will also work if the missile performs a dogleg manoeuvre such that the apparent closest point of approach may appear to be very far away. However, as mentioned before, the first method is more widely applicable and, as reported in [1], none of the methods outwits the other in all the possible situations.

[0051] In this section we will show how the Adjoint Method can be used to refine the first method of assessing the success of launching the decoy based on the closest point of approach. The idea is to use the Adjoint Method to estimate the closest point of approach for both the case that the missile is locked on the decoy and the case that the missile is locked on the ship. By comparing the computed position based on track data with these estimates and taking into account the variances of these estimates that can equally be determined using the Adjoint Method, it is possible to decide whether the missile has indeed locked on the decoy or not.

[0052] The linearized model in the case that the missile is locked on the decoy was introduced in the previous section as equation (6.1) and the following. The linearized model in the case that the missile is locked on the ship has the same form as (6.1), with $\mathrm{x} = \begin{bmatrix} y_m^e & v_{ym}^e & a_n & y_s^e \end{bmatrix}^T$, $w(t) = \begin{bmatrix} 0 & 0 & 0 & v_{ys}^e(t) \end{bmatrix}^T$ and

$$(7.1) \qquad A(t) = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ c_1(t) & c_2(t) & -\frac{1}{\tau} & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

where

$$(7.2) \qquad c_1(t) = \frac{N_p}{\tau(t_{miss} - t)^2}.$$

$$(7.3) \qquad c_2(t) = -\frac{N_p}{\tau(t_{miss} - t)}.$$

and the initial condition is $\mathrm{x}(0) = \begin{bmatrix} 0 & v_{yom}^e & 0 & 0 & \Delta y_f^e & v_w^e \end{bmatrix}^T$. We are interested in the value of the Zero-Effort-Miss distance introduced in (5.13) at time t_d that can be written as

$$(7.4) \qquad z = \begin{bmatrix} 1 & t_{miss} - t & 0 & -1 \end{bmatrix} \mathrm{x} + \begin{bmatrix} 0 & 0 & 0 & -t_{miss} + t \end{bmatrix} w(t).$$

Clearly, the linear model has the form (2.1) with D not identical zero. To apply Proposition 2.1, let the adjoint response be defined as the solution to the initial value problem

$$(7.5) \qquad \dot{\mathrm{x}}^{adj} = A^T(t_d - t)\mathrm{x}^{adj}$$

with initial condition $x^{adj}(0) = [1 \ t_{miss} - t_d \ 0 \ -1]^T$. We have

$$(7.6) \qquad \begin{aligned} z(t_d) &= \mathrm{x}^{adj}(t_d)^T \mathrm{x}(0) + \int_0^d [\mathrm{x}^{adj}(t_d - \tau)]^T w(\tau) d\tau + \begin{bmatrix} 0 & 0 & 0 & -t_{miss} + t_d \end{bmatrix} w(t_d) \\ &= x_2^{adj}(t_d) v_{yom}^e + \int_0^{t_d} x_4^{adj}(t_d - \tau) v_{ys}^e(\tau) d\tau - (t_{miss} - t_d) v_{ys}^e(t_d). \end{aligned}$$

[0053] Since the velocity of the ship is not a stochastic variable, the presence of the *D* term in the linear model does not have any influence on the formula for the variance of the Zero-Effort-Miss distance. According to Proposition 2.2

$$(7.7) \qquad \sigma_z^2 = \mathrm{x}^{adj}(t_d)^T P_{\mathrm{x}(0)} \mathrm{x}^{adj}(t_d) = [x_1^{adj}(t_d)]^2 \sigma_{y_{om}^e}^2 + [x_2^{adj}(t_d)]^2 \sigma_{v_{yom}^e}^2,$$

[0054] In a similar fashion, the Adjoint Method can be applied to estimate the Zero-Effort-Miss distance at time t_d in case that the missile is locked on the decoy.

[0055] We denote by z_s and by σ_s the average and the variance of the miss distance assuming that the decoy launch was successful and the missile is locked on the decoy, and by z_f and by σ_f the average and the variance of the miss distance assuming that the decoy launch failed to distract the missile from the ship.

[0056] The value of the Zero-Effort-Miss distance at time t_d can also be computed based on track data, and this value is denoted $\hat{z}$. We assume that $\hat{z}$ is normally distributed around z, the "true" (based on true geometrical data) ZEMD with variance σ_m that can be evaluated based on the accuracy of measurement data that are involved in computing $\hat{z}$.

[0057] The theory of statistical hypothesis testing can be used to provide an optimal interval $Z_\lambda(z_s,z_f,\sigma_s,\sigma_f,\sigma_m)$ such that if

$$\hat{z} \in Z_\lambda,$$

then the best decision is that the missile is locked on the decoy, and if this condition is not satisfied then the best decision is that the missile is locked on the ship. The optimal interval Z_λ can be obtained from the Neyman-Pearson Lemma. For convenience, we summarize here the main notions and results of statistical hypothesis testing that we use in the sequel.

[0058] First of all, let the null hypothesis H_0 be that "the missile is locked on the decoy" and the alternate hypothesis H_1 be that "the missile is locked on the ship". In this case, the type I probability, or the probability of false alarm is that the hypothesis H_1 is accepted, whereas H_0 is true:

$$(7.8) \qquad P_{eI} = P\{\text{“}H_1\text{''}|H_0\}.$$

The type II probability, or the probability of miss is that the hypothesis H_0 is accepted, whereas H_1 is true:

$$(7.9) \qquad P_{eII} = P\{\text{“}H_0\text{''}|H_1\}.$$

The power of the test is defined as

$$(7.10) \qquad \pi = P\{\text{“}H_1\text{''}|H_1\} = 1 - P_{eII}.$$

The problem is to determine the decision interval Z_λ that maximizes the power of the test, or minimizes the probability of miss, such that the probability of false alarm takes a given value α. The following classical result can be used to determine the optimal threshold.

[0059] The Neyman-Pearson Lemma: The optimal decision that minimizes the probability of miss subject to a given probability of false alarm α is obtained by the following criterion based on the likelihood ratio

$$(7.11) \qquad \Lambda(H_1,H_0) = \frac{p(Z|H_1)}{p(Z|H_0)} \quad \begin{matrix} > \Lambda_0: & \text{“}H_1\text{''}, \\ < \Lambda_0: & \text{“}H_0\text{''}, \end{matrix}$$

where Z represents the observation, and where Λ_0 satisfies

$$(7.12) \qquad P\{\Lambda(H_1,H_0) > \Lambda_0|H_0\} = \alpha.$$

[0060] In our application, the observation is represented by the computed ZEMD $\hat{z}$. Assuming that all the prediction errors are normally distributed, with the notations introduced before we have

$$p(\hat{z}|H_0) = \frac{1}{\sqrt{2\pi(\sigma_s^2 + \sigma_m^2)}} e^{-\frac{1}{2}\frac{(\hat{z}-z_s)^2}{\sigma_s^2+\sigma_m^2}}, \tag{7.13}$$

and

$$p(\hat{z}|H_1) = \frac{1}{\sqrt{2\pi(\sigma_f^2 + \sigma_m^2)}} e^{-\frac{1}{2}\frac{(\hat{z}-z_f)^2}{\sigma_f^2+\sigma_m^2}}, \tag{7.14}$$

and therefore, the likelihood ratio is

$$\Lambda(H_1|H_0) = \frac{\sqrt{\sigma_s^2 + \sigma_m^2}}{\sqrt{\sigma_f^2 + \sigma_m^2}} e^{\frac{1}{2}\left(\frac{(\hat{z}-z_s)^2}{\sigma_s^2+\sigma_m^2} - \frac{(\hat{z}-z_f)^2}{\sigma_f^2+\sigma_m^2}\right)}. \tag{7.15}$$

After some straightforward manipulations, the condition $\Lambda(H_1|H_0) > \Lambda_0$ is equivalent to

$$\left[\left(\frac{1}{\sqrt{\sigma_s^2+\sigma_m^2}} - \frac{1}{\sqrt{\sigma_f^2+\sigma_m^2}}\right)\hat{z} - \left(\frac{z_s}{\sqrt{\sigma_s^2+\sigma_m^2}} - \frac{z_f}{\sqrt{\sigma_f^2+\sigma_m^2}}\right)\right] \times$$
$$\left[\left(\frac{1}{\sqrt{\sigma_s^2+\sigma_m^2}} + \frac{1}{\sqrt{\sigma_f^2+\sigma_m^2}}\right)\hat{z} - \left(\frac{z_s}{\sqrt{\sigma_s^2+\sigma_m^2}} + \frac{z_f}{\sqrt{\sigma_f^2+\sigma_m^2}}\right)\right]$$
$$> \ln \Lambda_0^2 \frac{\sigma_f^2 + \sigma_m^2}{\sigma_s^2 + \sigma_m^2} \tag{7.16}$$

The probability that this condition is satisfied can be evaluated using the assumption about the conditional distribution of $\hat{z}$ if H_0 is true. According to the Neyman-Pearson Lemma, this probability has to be equal to α and Λ_0 can be computed using this condition.

[0061] The solution is particularly simple for the case that $\sigma_f = \sigma_s = \sigma$. In this case, the previous condition is equivalent to

$$(z_f - z_s)(\hat{z} - \frac{z_s + z_f}{2}) > (\sigma^2 + \sigma_m^2) \ln \Lambda_0. \tag{7.17}$$

Assume that $z_s > z_f$ which is physically the most likely case, since it is expected that a successful lock on the decoy will lead to a larger ZEMD than if the missile is locked on the ship. Then the previous relation is equivalent to

$$\hat{z} < \frac{z_s + z_f}{2} - \frac{\sigma^2 + \sigma_m^2}{z_s - z_f} \ln \Lambda_0. \tag{7.18}$$

Now we can evaluate the conditional probability in the Neyman-Pearson Lemma using the conditional distribution of $\hat{z}$. We have

$$P\{\Lambda(H_1,H_0)>\Lambda_0|H_0\}$$

$$(7.19)\qquad = \int_{-\infty}^{\frac{z_s+z_f}{2}-\frac{\sigma^2+\sigma_m^2}{z_s-z_f}\ln\Lambda_0} \frac{1}{\sqrt{2\pi(\sigma^2+\sigma_m^2)}} e^{-\frac{1}{2}\frac{(z-z_s)^2}{\sigma^2+\sigma_m^2}} dz$$

$$= \mathrm{NormCDF}\left(\frac{z_f-z_s}{2\sqrt{\sigma^2+\sigma_m^2}} - \frac{\sqrt{\sigma^2+\sigma_m^2}}{z_s-z_f}\ln\Lambda_0\right),$$

where NormCDF stands for the cumulative distribution function of the standard normal law

$$(7.20)\qquad \mathrm{NormCDF}(\eta) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\eta} e^{-\frac{1}{2}\xi^2} d\xi.$$

From the Neyman-Pearson lemma, we can readily obtain the value of Λ_0 by equating the expression (7.19) to the false alarm rate α. We obtain

$$(7.21)\qquad \Lambda_0 = e^{-\frac{(z_s-z_f)^2}{2(\sigma^2+\sigma_m^2)} - \frac{z_s-z_f}{\sqrt{\sigma^2+\sigma_m^2}}\mathrm{NormCDF}^{-1}(\alpha)}.$$

Introducing this expression in (7.18), we deduce that the optimal decision criterion for accepting hypothesis H_1 is that

$$(7.22)\qquad \hat{z} \le z_s + \mathrm{NormCDF}^{-1}(\alpha)\sqrt{\sigma^2+\sigma_m^2}.$$

The power of this criterion can be obtained by evaluating the probability that this condition is satisfied in case that H_1 is true. Given the conditional distribution of $\hat{z}$, we conclude that

$$(7.23)\qquad \pi = P\{\text{“}H_1\text{”}|H_1\} = \mathrm{NormCDF}\left(\frac{z_s-z_f}{\sqrt{\sigma^2+\sigma_m^2}} + \mathrm{NormCDF}^{-1}(\alpha)\right)$$

[0062] In the general case, that $\sigma_f \neq \sigma_s$, it is impossible to obtain closed-form expressions for the optimal decision criterion. However it is possible to propose a numerical algorithm that uses the conditional averages and variances to perform the decision. We explain this algorithm for the case that $\sigma_f > \sigma_s$. With the notations

$$(7.24)\qquad z_1 = \frac{\frac{z_s}{\sqrt{\sigma_s^2+\sigma_m^2}} - \frac{z_f}{\sqrt{\sigma_f^2+\sigma_m^2}}}{\frac{1}{\sqrt{\sigma_s^2+\sigma_m^2}} - \frac{1}{\sqrt{\sigma_f^2+\sigma_m^2}}},$$

$$(7.25)\qquad z_2 = \frac{\frac{z_s}{\sqrt{\sigma_s^2+\sigma_m^2}} + \frac{z_f}{\sqrt{\sigma_f^2+\sigma_m^2}}}{\frac{1}{\sqrt{\sigma_s^2+\sigma_m^2}} + \frac{1}{\sqrt{\sigma_f^2+\sigma_m^2}}},$$

$$(7.26)\qquad C = \frac{(\sigma_s^2+\sigma_m^2)(\sigma_f^2+\sigma_m^2)\ln\Lambda_0^2\frac{\sigma_f^2+\sigma_m^2}{\sigma_s^2+\sigma_m^2}}{\sigma_f^2-\sigma_s^2},$$

it is easy to see that relation (7.16) can be rewritten as

$$(7.27)\qquad (\hat{z}-z_1)(\hat{z}-z_2) > C.$$

The problem of determining Λ_0 to satisfy the condition of the Neyman-Pearson Lemma reduces to the problem of finding C such that

$$(7.28) \qquad P\{(\hat{z}-z_1)(\hat{z}-z_2) > C|H_0\} = \alpha.$$

With this value of C, if the estimate of the Zero Effort Miss distance $\hat{z}$ satisfies (7.27), then H_1 will be accepted, and otherwise H_0 will be accepted.

[0063] Introducing further

$$(7.29) \qquad \bar{z} = \frac{z_1+z_2}{2},$$

$$(7.30) \qquad C' = \sqrt{\left(\frac{z_1-z_2}{2}\right)+C},$$

the two solutions of the second degree equation

$$(7.31) \qquad (\hat{z}-z_1)(\hat{z}-z_2) = C$$

are

$$(7.32) \qquad \hat{z}_{1,2} = \bar{z} \pm C'.$$

Notice that these two solutions are the limits of the decision interval Z_λ. Relation (7.28) is equivalent to

$$(7.33) \qquad 1-\mathrm{NormCDF}\left(\frac{\hat{z}_1-z_s}{\sqrt{\sigma_s^2+\sigma_m^2}}\right)+\mathrm{NormCDF}\left(\frac{\hat{z}_2-z_s}{\sqrt{\sigma_s^2+\sigma_m^2}}\right)=\alpha,$$

or equivalently

$$(7.34) \qquad \begin{aligned} &1-\mathrm{NormCDF}\left(\frac{\bar{z}-z_s}{\sqrt{\sigma_s^2+\sigma_m^2}}+\frac{C'}{\sqrt{\sigma_s^2+\sigma_m^2}}\right)+\\ &\mathrm{NormCDF}\left(\frac{\bar{z}-z_s}{\sqrt{\sigma_s^2+\sigma_m^2}}-\frac{C'}{\sqrt{\sigma_s^2+\sigma_m^2}}\right)=\alpha. \end{aligned}$$

This equation reduces to solving the nonlinear equation in $x = \frac{C'}{\sqrt{\sigma_s^2+\sigma_m^2}}$

$$(7.35) \qquad 1-\mathrm{NormCDF}(A+x)+\mathrm{NormCDF}(A-x)=\alpha,$$

where $A = \frac{\bar{z}-z_s}{\sqrt{\sigma_s^2+\sigma_m^2}}$ is a known parameter. This equation has a unique positive solution for every value of A and α in the interval (0, 1) since the function on the left hand side is strictly decreasing in x, takes the value 1 for $x = 0$ and converges to 0 for $x \to \infty$. Moreover, it is easy to find upper and lower bound for the solution. For example, if $A > 0$, it is easy to see that

$$1 - \mathrm{NormCDF}(A + x) < \mathrm{NormCDF}(A - x) \tag{7.36}$$

for each x > 0. Now let

$$x_1 = A - \mathrm{NormCDF}^{-1}\left(\frac{\alpha}{2}\right), \tag{7.37}$$

$$x_2 = \mathrm{NormCDF}^{-1}\left(1 - \frac{\alpha}{2}\right) - A. \tag{7.38}$$

Assume that both x_1 and x_2 are positive, which is generically true for small values of α. Remember that α is the false alarm rate and it is usually chosen to be very small. Using inequality (7.36), it becomes clear that the left hand side of (7.35) is greater than α for $x = x_1$ and it is smaller than α for $x = x_2$. Because of monotonicity, the solution of (7.35) is guaranteed to be in the interval (x_1, x_2). Using a bisection method, the solution can be easily determined. This provides the solution *C'* for the equation (7.34), which can be used to determine C from (7.30), which in turn is used to check the decison criterion to determine if the antiship missile is locked

TABLE 1. Values of the parameters used in the numerical experiments.

Source	Parameter	Symbol	Value
Target sensor	Missile initial East [m]	x_{om}	6000
	Missile initial North [m]	y_{om}	6000
	Missile velocity [m/s]	V_m	300
Estimate	σ of missile initial East [m]	σ_{xom}	46.3
	σ of missile initial North [m]	σ_{yom}	46.3
	σ of missile initial course [rad]	$\sigma_{\phi om}$	0.08
	Missile time constant [s]	T	0.1
	Missile navigation constant. [-]	N_p	3
	Missile blind time [s]	t_b	0.3
	Wind velocity [m/s]	V_w	10
	Wind course [rad]	ϕ_w	π
	σ of wind course [rad]	$\sigma_{\phi w}$	0.05
Own platform	Ship initial East [m]	x_{om}	D
	Ship initial North [m]	y_{om}	D
	Ship velocity [m/s]	V_s	15
	Ship course [rad]	ϕ_e	3π/2
	Decoy relative distance [m]	Δ_f	200
	Decoy launch direction [rad]	Ψ_f	3.927
	Ship manoeuvre delay [s]	t_{man}	5

on the ship, or on the decoy according to relation (7.27). Moreover, the power of the criterion $\pi = F'\{"H_1"|H_1\}$ can be computed as

$$(7.39) \qquad \pi = 1 - \mathrm{NormCDF}\left(\frac{\hat{z}_1 - \hat{z}_f}{\sqrt{\sigma_f^2 + \sigma_m^2}}\right) + \mathrm{NormCDF}\left(\frac{\hat{z}_2 - \hat{z}_f}{\sqrt{\sigma_f^2 + \sigma_m^2}}\right),$$

Where $\hat{z}_1$ and $\hat{z}_2$ are given by (7.32).

[0064] The prediction using the adjoint algorithm may thus be applied in two ways. Firstly, before launch, the prediction may be used to optimize the deployment. Secondly, after launch, the prediction may be used to make an assessment on the success of deployment. The latter may be realized by comparing observations and predictions of the closest point of approach under two hypotheses: that the missile is locked on the decoy, i.e. the deployment was successful, and that the missile is locked on the ship, i.e. the deployment failed. The fact that the Adjoint Method can take into account measurement and estimation uncertainties without excessive computational effort leads to advantages, especially for the success assessment.

[0065] The method of applying soft-kill deployment to mislead an incoming missile directed to a mother platform can be performed using dedicated hardware structures, such as FPGA and/or ASIC components. Otherwise, the method can also at least partially be performed using a computer program product comprising instructions for causing a processor of the computer system to perform the above described steps of the method according to the invention. All steps can in principle be performed on a single processor. However it is noted that at least one step can be performed on a separate processor, e.g. the step of identifying a hostile missile and/or the step of identifying the missile.

[0066] Figure 4 shows a flow chart of an embodiment of the method according to the invention. A method is used for applying soft-kill deployment to mislead an incoming missile directed to a mother platform. The method comprises the steps of predicting (100) a number of miss distances associated with corresponding particular decoy launch parameter sets, selecting (110) a decoy parameter set having an optimal evaluated miss distance; and transmitting (120) the selected decoy parameter set to a launch unit for launching the decoy. The predicting step (100) includes the use of an adjoint algorithm.

[0067] It will be understood that the above described embodiments of the invention are exemplary only and that other embodiments are possible without departing from the scope of the present invention. It will be understood that many variants are possible.

[0068] The soft-kill deployment system according to the invention may be provided with a single launch system or with a multiple launch system. Further, a single missile or a multiple number of missiles directed to the mother platform can be coped with by the soft-kill deployment system according to the invention.

[0069] Though in the embodiments described above the method according to the invention is applied in combating an antiship missile threat, the method can also be applied when coping with missiles directed to other mother platforms, such as missiles threatening an airplane or a ground vehicle.

[0070] Such variants will be obvious for the person skilled in the art and are considered to lie within the scope of the invention as formulated in the following claims.

Claims

1. A method of applying soft-kill deployment to mislead an incoming missile directed to a mother platform, the method comprising the steps of:

- predicting a number of miss distances associated with corresponding particular decoy launch parameter sets,
- selecting a decoy parameter set having an optimal predicted miss distance; and
- transmitting the selected decoy parameter set to a launch unit for launching the decoy;

wherein the predicting step includes the use of an adjoint algorithm.

2. A method according to claim 1, wherein an predicted miss distance are based on incoming missile parameters, mother platform parameters and the corresponding decoy launch parameter set.

3. A method according to claim 1 or 2, wherein the adjoint algorithm includes linearizing a non-linear prediction model.

4. A method according to any of the previous claims, further comprising the step of computing uncertainty data corresponding with a predicted miss distance.

5. A method according to any of the previous claims, further comprising a step of validating the effect of the launched decoy, the validation step comprising the substeps of:

- predicting a zero-effort miss distance, under platform lock on condition and/or decoy lock on condition;
- measuring incoming missile data;
- comparing the measured data with the predicted zero-effort miss distance or distances;
- deducing, from the comparison results, on which entity the incoming missile is locked.

6. A method according to claim 5, wherein the deducing step includes the use of computed uncertainty data corresponding with a predicted zero-effort miss distance.

7. A method according to any previous claim, further comprising the step of signaling an incoming missile.

8. A method according to any previous claim, further comprising the step of identifying a signalled incoming missile.

9. A soft-kill deployment system, comprising:

- a launch unit for launching a decoy to mislead an incoming missile directed to a mother platform, and
- a computer system provided with a processor that is arranged for performing the steps of:
- predicting a number of miss distances associated with corresponding particular decoy launch parameter sets,
- selecting a decoy parameter set having an optimal predicted miss distance; and
- transmitting the selected decoy parameter set to the launch unit for launching the decoy;

wherein the predicting step includes the use of an adjoint algorithm.

10. A computer program product for applying soft-kill deployment to mislead an incoming missile directed to a mother platform, the computer program product comprising computer readable code for causing a processor to perform the steps of:

- predicting a number of miss distances associated with corresponding particular decoy launch parameter sets,
- selecting a decoy parameter set having an optimal predicted miss distance; and
- transmitting the selected decoy parameter set to a launch unit for launching the decoy;

wherein the predicting step includes the use of an adjoint algorithm.

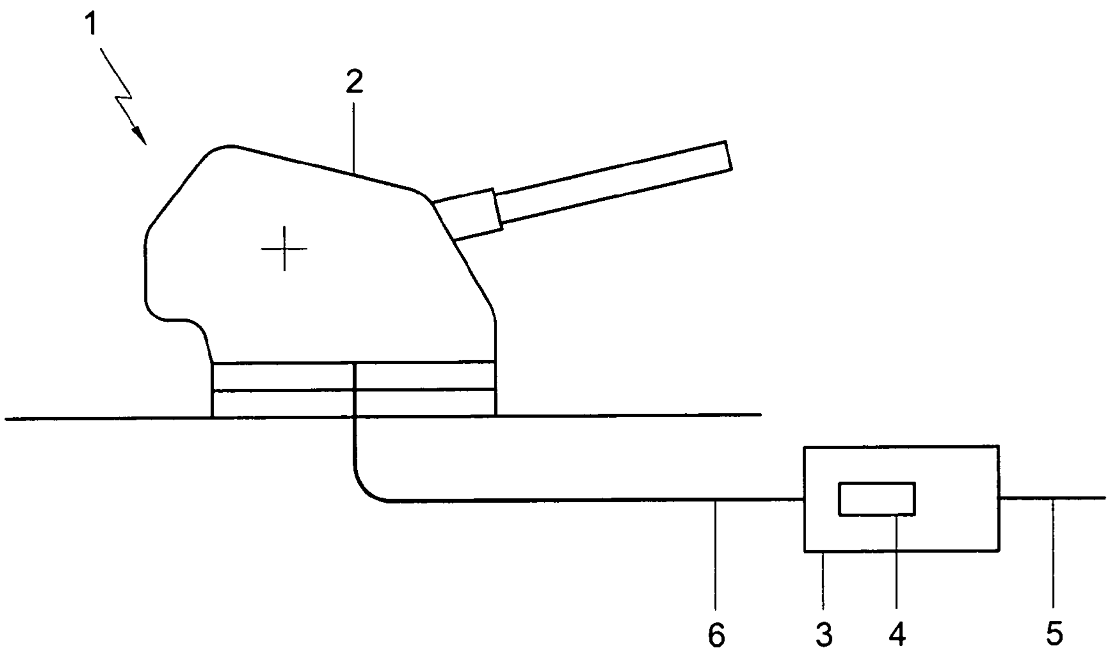

Fig. 1

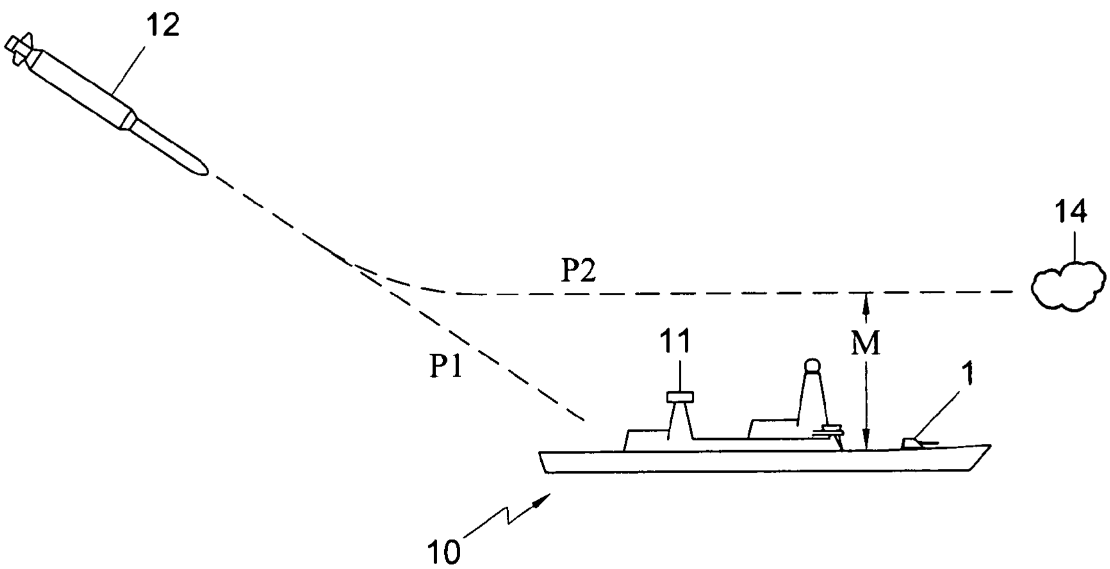

Fig. 2

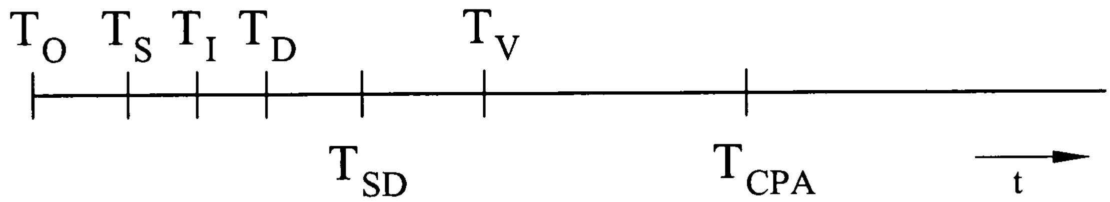

Fig. 3

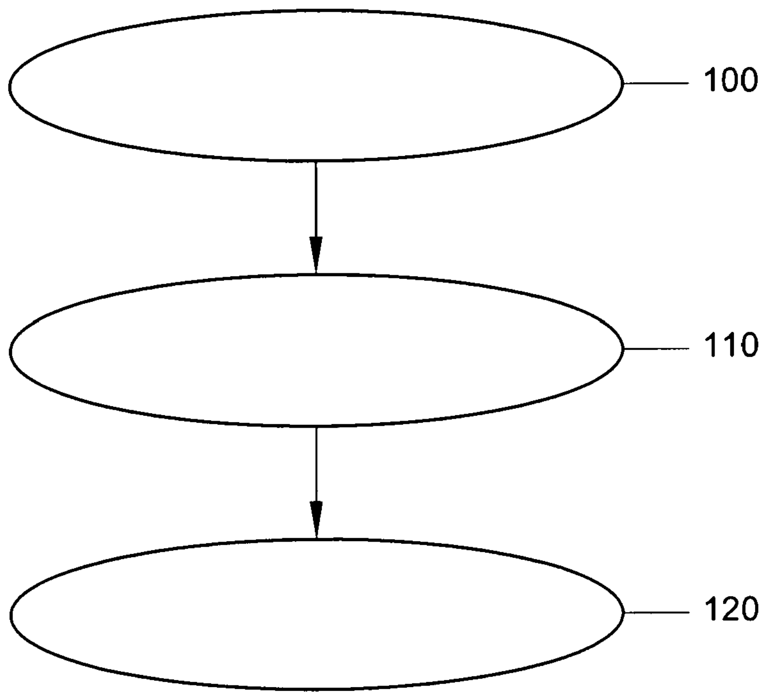

Fig. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 08 17 3134

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
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Place of search	Date of completion of the search	Examiner
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