INTELLIGENT MISSILE GUDANCE SYSTEM DEVELOPED FOR TRAINING AT MACEDONIAN MILITARY ACADEMY

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Abstract. We have developed a simulation model of homing-guided anti-aircraft or surface-to air (SA) missiles - SAM, suitable for research, development and testing of different guidance and control laws, obtained from synthesis process. This system was developed for the teaching and training purposes of several subjects at Macedonian Military Academy. The topics in External ballistics give cadets knowledge in guided missiles movement, which are considered as dynamic systems and controlled objects. In homing-guidance systems for SA missiles – proportional navigation is most commonly used, and also improved solutions and optimal guidance laws based on modern control theory. All systems for guidance and control of SA missiles are complex and typically non-linear. In order to provide quality process and small guidance error – we have applied fuzzy logic to obtain some parameters for the guidance law. In this paper we present results from investigation of different guidance laws for hypothetic SA missile. The results from fuzzy guidance law combined with proportional navigation are also given. Simulation programs are realized in MATLAB/SIMULINK.

Keywords: Military education and training, guidance and control systems, homing guidance, guided missiles, fuzzy logic control, training simulators.

1. INTRODUCTION

The main goal of the military sciences is to give cadets basic military knowledge for their profession and skills to assess situations and make right decisions. For the specialized branches, such as: infantry, artillery, and anti -aircraft missile units for air defense and armored mechanized units, there are separate subjects that are studied in years 3 and 4. Homing-guidance is an one of the main topics discussed in "Missile guidance and control" subject. We investigated autonomous missile guidance based only on target information, i.e. target energy detection performed by the missile devices. This energy can be radio wave, light or IR ray – reflected or emitted by the target. The system devices for this guidance concept are completely mounted on the missile and they consist of: sensor (coordinator), guidance computer, autopilot and missile as a controlled object (Fig.3.1).

In Section 3 of this paper, we present a general simulation model of the homing-guidance system, which is given in detail in (Deskovski, 1990), as well as simulation model for guidance in the vertical plane, described in (Deskovski, 1981). The guidance laws of the homing-guidance missiles are presented in chapter 4, and in chapter 5 we describe the concept of fuzzy logic control and application to our homing-guidance system. Since all systems for guidance and control of AA missiles are complex and typically non-linear, as well as the need for neutralizing of targets with high range of parameter changes

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(acceleration, velocity and height), in different shooting regimes (incoming, outgoing etc.), to provide quality process and small guidance error – we have applied fuzzy logic to obtain some parameters for the guidance law. In chapter 5 we give simulation results of the system analysis in two shooting regimes (incoming and outgoing target) and we use classic proportional navigation with and without fuzzy logic in the guidance law.

The models based on fuzzy logic can be applied in many different types of information processing, like static and adaptive control systems, process modeling, signal estimation, planning and decision etc. The reason for this is the simple development of these control systems, and their compatibility with the man-expert, aspects that are important where the process consists of non-well defined models. The common feature of these systems are the structure and homogeneity of their knowledge bases, consisted of imprecise conditional clauses, without connections, which manipulate with the same state (from the 'cause' part) and control variables (from the 'consequence' part of the rules).

2. STUDIES IN MECHANICS OF FLIGHT, MISSILE GUIDANCE AND FIRE CONTROL SYSTEMS

The model of education of the undergraduate studies at the Military Academy has been designed according to the needs and experience of the Academy, and by following the experience of some western military academies. The specific subjects are: external ballistics (mechanics of flight), automatic control systems, missile systems (missile guidance and control systems), operational research, and fire control systems.

External ballistics studies give cadets knowledge in projectile and guided missile movement, which are considered as dynamic systems and controlled objects. In order to be able to comprehend the material, cadets need prior knowledge in math, physics and computers. The program includes the following topics: Missile movement in vacuum; The atmosphere and its features; Coordinate systems Forces and moments which influence the missiles; Mathematical models of missile movement; Movement stability and missile stabilization; External ballistics tests and Special ballistics areas (Intermediate Ballistics, Terminal Ballistics, Wound Ballistics)

The subject is divided in 3 theoretical and 2 practical lessons per week. In the teaching process the simulation modules for flight simulation 6DOF are used and they are in SIMULINK, while MATLAB is used for graphical presentation and results analyses.

The subject **"Missile guidance and control systems"** gives theoretical background for the studies in guidance and control systems of guided missiles and projectiles. Besides the knowledge in math, physics, computers, electronics and external ballistics, certain knowledge in automatic control is also necessary.

The program includes the following topics: Basic notions and definitions of guidance and control systems; Mathematical models of guided missiles; Stabilization and control systems (autopilots, roll, pitch and yaw control and stabilization systems); LOS- Line of Sight Guidance Systems Homing Guidance Systems.

The subject is divided into 2 theoretical and 2 practical lessons per week. Simulation models of closed loop systems for control and guidance are used and they are in MATLAB/ SIMULINK. Also, training simulators, some missile systems and other teaching aids are used to demonstrate the functioning of the system.

The subject **"Fire control systems",** which comes after the above mentioned disciplines aims to familiarize the cadets with the structure and the process of complex artillery and missile systems of armament. The study of the targeting process, which includes detection and identification of the target, following and measuring the parameters of movement, launching and missile guidance and target destruction enables the cadets to acquire knowledge about concrete armament systems. The program includes the following chapters: Basic theory of fire; Sensors in the systems for fire control (radar, optical, OR and laser sensors, multi-sensor systems); Computers in the systems for fire control (configuration, sensor communication, A/D and D/A conversion, filtering and coordinate transformation, solving the problem of encounter); Executive components in the fire control systems (dynamics of the launchers, elevation and azimuth servo systems).

The subject has 2 theoretical and 2 practical classes. For the practical classes, concrete means from the ARM armament are used and during the classes there is a demonstration of the systems and sub-systems functioning.

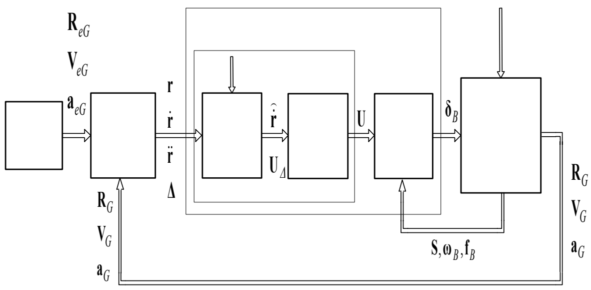


Fig. 3.1. Homing-guidance system simulation model

3. MATHEMATICAL MODEL OF THE HOMING GUIDANCE SYSTEM

The structure of the homing-guidance system of anti aircraft missiles is given on Fig.3.1. The devices of the system for guidance and control include the coordinator (target sensor) and the guidance computer, which compile the homing-guidance head and the autopilot. The block diagram that presents the system for guidance and control, and the missile as controlled object, also has a kinematics block, which presents the relative motion of the target relative to the missile. With this block we close the control loop, and some of the output variables $(r = [r, \varphi, \lambda]^T$, $\dot{r} = [\dot{r}, \dot{\varphi}, \dot{\lambda}]^T$ or $\Delta = \eta, \xi, \dot{\varphi}$, where r – distance from the missile (Pursuer – P) to the target (Evader–E), $\overline{PE}$-Line-of-sight (LOS), φ, λ-LOS angles measured in the vertical and the horizontal plane, look angle, and ξ lead angle, can be measured with sensors in order to realize the chosen guidance method. The target motion is also presented with a block, and on the output we obtain target's center of the mass (CM) motion variables (position $\mathbf{R}_{eG} = [x_{oe}, y_{oe}, z_{oe}]^T$, velocity $\mathbf{V}_{eG} = [V_{ex_g}, V_{ey_g}, V_{ez_g}]^T$ and acceleration $\mathbf{a}_{eG} = [a_{ex_g}, a_{ey_g}, a_{ez_g}]^T$ in the space).

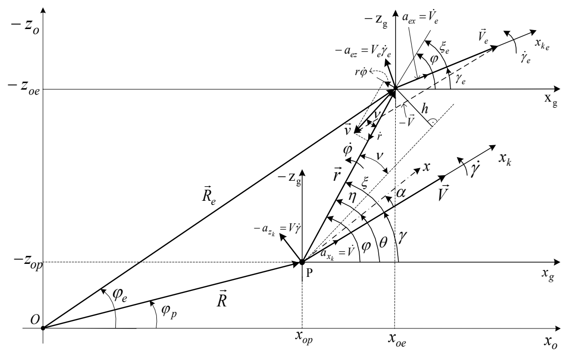


Fig. 3.2. Guidance geometry in the vertical plane

The missile motion is given with separate block, represented by dynamic and kinematics equations of the flight obtained by neglecting the earth's rotation and its curvy shape. These assumptions are valid for missiles with small range with short flying time. The obtained model is non-linear and non-stationery with time changing parameters. The input vector of the 6DOF model of the missile is determined by the deflection of the control surfaces δ_B. The output variables of the 6DOF missile model are: the position of the CM of the missile $\mathbf{R}_G = [x_{op}, y_{op}, z_{op}]^T$, $\omega_B = [p, q, r]^T$ - body absolute angular rates, body orientation $\mathbf{S}$ determined by the angles: ϕ-roll, θ - pitch and ψ - yaw, specific force $\mathbf{f}_B = [f_x, f_y, f_z]^T$, acceleration $\mathbf{a}_G = [a_{x_g}, a_{y_g}, a_{z_g}]^T$, velocity $\mathbf{V}_G = [V_{x_g}, V_{y_g}, V_{z_g}]^T$ of CM etc. All vectors are presented in adequate coordinate systems defined by ISO: *Normal-earth-fixed axis system* $G_o(P; x_o, y_o, z_o)$, *Aircraft-carried normal earth axis system* $G(P; x_g, y_g, z_g)$ and *the body axis system* $B(P; x, y, z)$ (Fig. 3.2). More detailed description of the simulation model of the homing-guidance system is given in (Deskovski, 1990).

For the needs of our investigation of fuzzy logic application in the homing guidance system, we simplified the system, to enable a homing-guidance analysis in the vertical plane. In Fig. 3.2, there is given the geometry for guidance in the vertical plane, together with all relevant kinematics variables for the mathematical model.

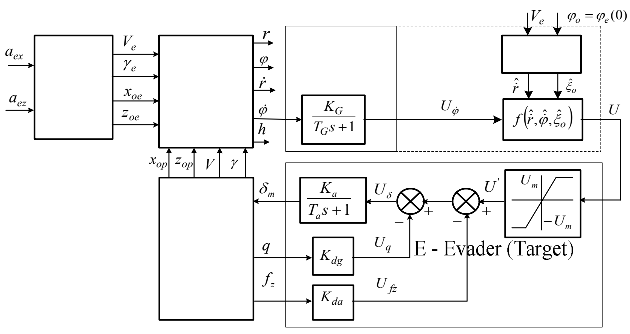
The target motion (block 1) is defined by tangential $a_{ex}(t)$ and normal $a_{ez}(t)$ acceleration as input variables, which define the target maneuvering and the initial conditions $V_e(0) = V_{e0}$, $\gamma_e(0) = \gamma_{e0}$, $x_{oe}(0) = x_{oe0}$, $z_{oe}(0) = z_{oe0}$.

The missile motion (block 2) is described with simplified differential equations and for their solving we should know the dynamic coefficients $Z_\alpha, Z_\delta, M_\alpha$ M_δ, M_q, as well as the law for velocity changing $V = V(t)$. Also we should define the initial conditions:

$\alpha(0) = \alpha_0$, $q(0) = q_0$, $\gamma(0) = \gamma_0$, $x_{op}(0) = x_{op0}$, $z_{op}(0) = z_{op0}$ and we usually take $\alpha_0 = 0, q_0 = 0,$, $x_{op0} = 0$ $z_{op0} = 0$, so only missile launching angle should be given $\gamma_0 = \gamma(0)$.

The relative motion of the target relative to the missile and the zero-effort-miss distance h(t) are calculated in the block 3.

Equations of the blocks 1., 2. and 3. are presented in (Deskovski et al. 2003).



E

Fig. 3.3. Homing guidance system simulation in the vertical plane

E'

The proportional navigation is realized by **the sensor** (block 4) which measures the LOS rate $\dot{\varphi}$, and its dynamics is given with a first order transfer function $(K_G/(T_G s+1))$.

Homing guidance laws (block 5) are described in Section 4 of the paper.

The **autopilot** (block 6) has structure typical for homing guidance SAM which includes actuator with first order transfer function $(K_a/(T_a s+1))$, feedback for the pitch angle velocity realized by speed gyroscope with gain K_{dg}, and feedback for the normal load f_z realized with an accelerometer with gain K_{da}.

4. GUIDANCE LAWS FOR HOMING GUIDANCE MISSILES

Guidance laws for homing-guidance missiles are based on classic guidance methods (direct or attitude pursuit guidance method, when the look angle should be zero $\eta = \varphi - \theta = 0$, pure pursuit guidance method when the lead angle should be zero $\xi = \varphi - \gamma = 0$, method of parallel navigation which needs the condition $\dot{\varphi} = 0$, and proportional navigation guidance method when the turn rate of the missile velocity is $\dot{\gamma} = K\dot{\varphi}$ (Fig. 3.2). These methods are described in more details in (Deskovski, 2001, Shneydor, 1998) and the method for proportional navigation is most frequently used.

For simulation of homing-guidance system (Fig. 3.3) we have applied proportional navigation (PN) for which realization – the measurement of the LOS rate $\dot{\varphi}$ is necessary. For guidance commands definition - we use the closing velocity $\dot{r}$, so the guidance law is of the form:

$$\dot{\gamma} = \frac{N\,|\,\dot{r}\,|}{V}\dot{\varphi} \quad \text{or} \quad a_{z_k} = V\dot{\gamma} = N\,|\,\dot{r}\,|\,\dot{\lambda} \qquad (4.1)$$

where N is the kinematics gain of closed homing-guidance loop (effective navigation constant) with value 3-5 (Deskovski, 2001, Shneydor, 1998), V – missile velocity and $|\,\dot{r}\,|$- absolute value of closing velocity. The classic law of PN (3.1) is realized so that the signal U is formed based on the measured value $\hat{\dot{\varphi}} \approx U_{\dot{\varphi}}$ and the estimation $\hat{\dot{r}}$, which depends on shooting conditions, according to:

$$U = K_f\hat{\dot{\varphi}}\ , \ K_f = \frac{N\,|\,\hat{\dot{r}}\,|}{K_G K_e \cos\xi_o} \qquad (4.2)$$

where K_G - sensor gain, K_e - gain of the system "autopilot-missile", ξ_o - lead angle (Deskovski 1990, 2003).

In the simulation model we can use an improved proportional navigation, and optimal laws based on modern control theory (Slamic 1998, Shneydor 1998). In this paper we investigated homing-guidance process with classic proportional navigation (4.1), (4.2). As we can see (Fig. 3.2) – the closing velocity and the lead angle depend on the shooting regime (incoming/ outgoing target), as well as from the parameters of the target motion (target's position and velocity). So, with fuzzy logic application we provide setting of all necessary values of the parameter (4.2) in all shooting regimes. Fuzzy logic concept is described in the next section.

Choosing a good guidance law enables quality guidance process (small dynamic error, good transient response behavior, etc.) as well as enlargement of the launching zones and target hitting. The latter are very important for each missile system application.

5. FUZZY LOGIC CONTROL IN HOMING GUIDANCE SYSTEMS

In the decision process for the shooting regime, we have applied knowledge base, implemented in Matlab Fuzzy Logic Toolbox, where we performed the reasoning process and obtained the output variables. The obtained ratio missile-target is defuzzyfied and transfer to the system as an executive command. There are 2 options for the system operation – first, informative way, which will indicate (audio-visually) to the operator for the launching moment, and second, automatically performed launching when all conditions for successful shot are satisfied. In the paper we give the complete rule base of the type:

IF $\boldsymbol{V_e} = \boldsymbol{LN}$ AND $\boldsymbol{\varphi_0} = \boldsymbol{SP}$ THEN $\boldsymbol{\dot{r}} = \boldsymbol{LP}$ AND $\boldsymbol{\xi_0} = \boldsymbol{ZO}$

(Input variables are the velocity V_e and the angle φ_0 and output variables $\dot{r}$ and ξ_0). For each variable's values we defined 5 fuzzy regions: LN, SN, ZO, SP, LP.

The crisp sets of values for each variable are:

V_e (m/s) = [-250,250], φ_0(rad) = [0, 1.07],

$\dot{r}$ (m/s) = [250, 750], ξ_0(rad) = [-0.45, 0.45].

Based on calculated $\dot{r}$ and ξ_0 we calculate the constant $f(\hat{\dot{r}},\hat{\dot{\varphi}},\hat{\xi}_o) = K_f = N\,|\,\hat{\dot{r}}\,|/(K_G K_e \cos\xi_o)$, and so we update the whole missile guidance process. The application of fuzzy logic for the calculation of $\boldsymbol{K_f}$ brings an adaptation of the fire control system. This is to say, it is calculated automatically for any shooting regime (incoming/outgoing target), which is more flexible than many weapons with fixed constant.

The FIS editor, presented below, shows the higher-level information of the inference mechanism for the fuzzy knowledge base.

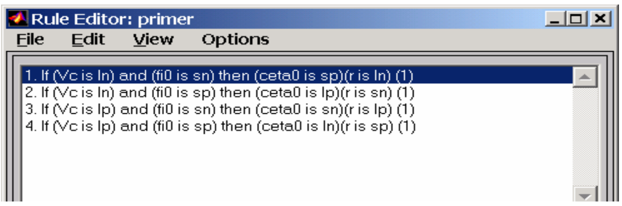


Fig. 5.1. Computational rule knowledge base

6. SIMULATION EXPERIMENTS AND RESULTS

For testing of the simulation model – we used hypothetic anti-aircraft missile with known geometric, mechanic and aerodynamic characteristics (Deskovski 1990, 2003). The missile has length l=2m, diameter d=0.125m, surface $S=d^2\pi/4=0{,}01227m^2$; the mass, the motor pressure, the inertial moments, the position of the mass center and the derivatives of the aerodynamic coefficients are variable and are given in a table, depend on time t, i.e. mach number Ma. The values of the mass and the inertial moments at the start are: m=40 kg, I_x=0,08 kgm^2, $I=I_y=I_z=12$ kgm^2

On Fig. 6.1 and 6.2 – we show the trajectories of homing-guidance in the vertical plane for a) incoming, b) outgoing target. The target is maneuvering with acceleration a_{cz}= 4g. These simulation results are obtained from the general simulation model of the homing guidance system, implemented in FORTRAN. The launching for the incoming and outgoing regimes is performed when the initial value of the LOS angle is $\varphi_o = 45^o$, and the target height is 2000 m, and velocity is 250 m/s.

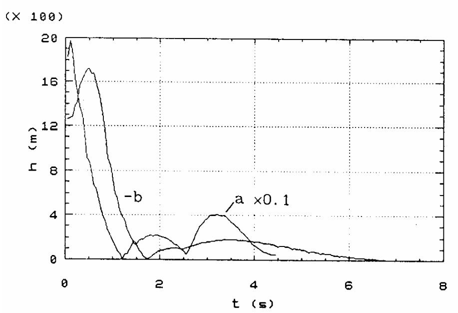


Fig.6.1. Total homing-guidance missing

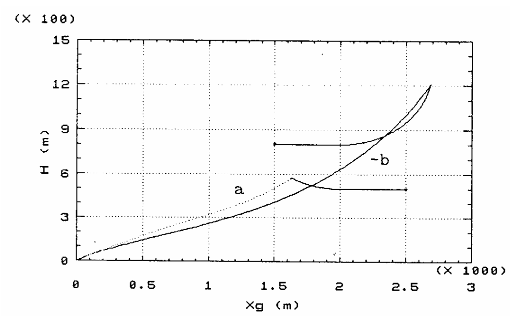


Fig. 6.2. Homing-guidance trajectories

The simulation results, obtained via using MATLAB-SIMULINK support, for the guidance in the vertical plane are given on Fig. 6.3 and Fig. 6.4. We show the flight trajectories for incoming/outgoing target, which flies with speed 250m/s on height 2000 m, but it doesn't maneuver $a_{cz}=4g$. The trajectory intersection is the meeting point.

On Fig. 6.4 we show the homing-guidance error only in the outgoing regime when fuzzy logic is not applied a) and when it is applied b). We can see that in the second case when the fuzzy block is applied, it gives suitable parameters for the shooting regime, and the error (which has the same initial value in both cases), converges to zero faster. In the system without a fuzzy block, there is no possibility for parameter changing in the guidance law.

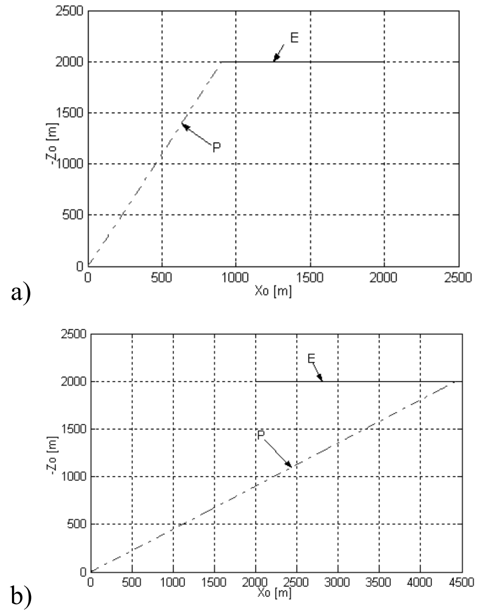


Fig. 6.3. Trajectories of the missile and the target – a) incoming and b) outgoing regime.

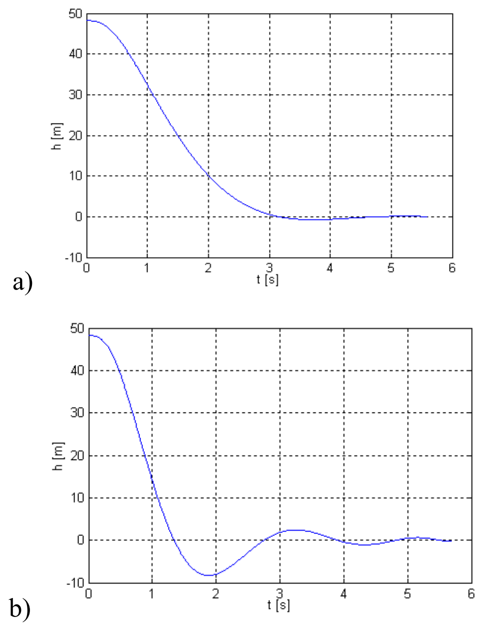


Fig. 6.4. The error in the outgoing regime: a) without, b) with application of fuzzy logic in the system

The diverging of the homing guidance process in the meeting point region is natural and well known in the theory of the homing-guidance systems (Deskovski

1990, 2003). In the real missile homing guidance systems there is a blinding effect of the coordinator in the target region, so the guidance loop is interrupted and the flight is no more guided, i.e. we avoid the error increasing close to the target.

7. CONCLUSION

In this paper we described a complete simulation model of guidance and control system for short-range missiles, developed for teaching purposes in Macedonian Military Academy. The topics in External ballistics give cadets knowledge in guided missiles movement, which are considered as dynamic systems and controlled objects. We presented simulation model for homing-guidance system in the vertical plane, and its realization has been performed using MATLAB/SIMULINK platform. The simulation model is suitable for investigating the dynamics of the system and its sub-systems dynamics as well as for exploring and testing of guidance and control laws. In this work, we investigated the classical guidance law – proportional navigation – with and without use of fuzzy logic rule knowledge base.

The models based on fuzzy logic can be applied in many different types of information processing, such as static and adaptive control systems, process modeling, signal estimation, planning and decision etc. The reason for this is the simple development of these systems and their compatibility with the typical habits of a human expert, aspects that are important when the controlled process is not well defined.

In this paper we have applied a fuzzy-rule based system that is based on the input parameters, the current position of the target, the surroundings and the system itself, obtained from the system sensors. It enables estimation of the launching zone, providing information when the most suitable moment for launching occurs. With the use of fuzzy logic we can also provide necessary parameters for the guidance law, which depend on shooting conditions. The use of fuzzy logic for calculation of the guidance law parameters brings an adaptation of the missile system – depends on shooting regime (incoming / outgoing target) and target motion parameters. In this paper we presented a possible general solution for fire control systems in the anti-aircraft defense when the system is equipped with enough sensors that will capture the target motion.

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