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Anti-Tank Guided Missile Performance Enhancement Part-2: Robust Controller Design

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Abstract

The performance of antitank guided missile systems is measured through the minimum miss-distance and its capability to overcome target maneuver and different sources of errors including disturbances and noises. Toward these performance constraints, the guidance and control is considered, which is one of the most interesting and challenging problem areas for antitank missile. Therefore, this paper considers an antitank guided missile system belonging to the first generation for the design and analysis. The design and analysis necessitates somehow accurate model (objective of Part-1 of the paper) for the system and a robust control design philosophy (objective of Part-2 of the paper).

Transfer functions representing the missile-control system dynamics in pitch and yaw planes are identified via hardware in the loop (HWIL) simulation and considered for investigation and validation against previous work and reference flight data. These transfer functions are obtained and justified in Part-1 of the paper and consequently this part is devoted to design a robust controller and implements it within the 6DOF simulation. The jetvator control loop for both pitch and yaw channels of the intended guided missile system with compensation network are designed using H_∞ and investigated such that the system is stabilized and the performance requirements are satisfied with disturbance rejection and measurement noise attenuation. To stay on the robustness of these controllers and their ability to withstand against disturbances, the measurements are corrupted with noise and the system performance is investigated. The obtained results showed superior features of H_∞ in stabilizing the system with only one controller allover the flight envelope and withstand some of the uncertainty sources.

Keyword: Guidance and Control, Hardware-in-Loop Simulation, System Identification, Robust Control.

1- Introduction

The ever-increasing development of tanks capabilities necessitates the design of accurate control and guidance system for an antitank missile in presence of disturbance, measurement noise, and un-modelled dynamics. To achieve this objective, an adequate nonlinear mathematical model representing the dynamical behaviour of the underlying missile was obtained for different flight phases. However, mathematical model cannot precisely represent a real physical system and there is always uncertainty. This uncertainty is due to unknown or unpredictable inputs (disturbance, noise, etc.) and unpredictable dynamics [11]. To overcome

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the different sources of uncertainty, robust control is used to design the autopilot such that the system is stable with the ability to reject the disturbances and minimize the effects of the measurement noises. The performance specifications include the overshoot, speed of response, steady state error and system stability which are the main objectives to the designer. The main problem for designing classical controllers involves the judicious choice of pole (s) and zero (s) to alter the root locus or frequency response of the uncompensated system so that the required performance specifications are satisfied. Meeting these objectives with guided missiles through classical controllers is usually difficult especially these applications are time varying stochastic.

Missile flight control systems must guarantee stability and performance in the face of large modelling uncertainties and noise. This requires the feedback controller to maintain system stability and loop performance for the overall flight envelope. Therefore, it is necessary to design a control system that performs adequately over a range of plant parameters. This control system is said to be robust when it maintains a satisfactory level of stability and performance over a range of plant parameters and disturbances [3, 4]. Thus, the objective is to investigate the robustness of the designed autopilot against uncertainties due to modelling and noise. Therefore, the controller, to be designed and implemented within the missile control system, should be insensitive to model uncertainties and be able to suppress disturbances and noise over the whole envelope of operation, i.e. should be robust. This paper is devoted to design the jetevator control using the H_∞ in state space form and its applications on guidance and control performance analysis.

A feedback-control system must satisfy certain performance specifications, and it must tolerate model uncertainties. The most elementary feedback control system has three components: the plant, sensors to measure the outputs of the plant, and a controller to generate the plant's input [4, 10], Fig. 1.

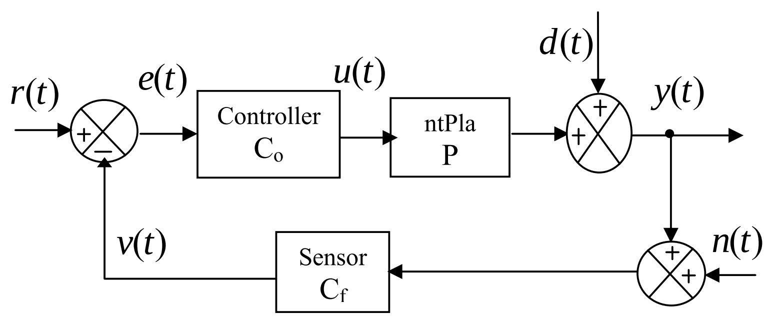

Fig. 1: Feedback control system

r(t) is the command (or reference) input that the system must follow or track.
d(t) the disturbance input that must be rejected by the system. Disturbances represent actual physical disturbances acting on the system such as wind gusts, disturbances owing to actuators, or uncertainties resulting from modelling errors in plant or actuator.
n(t) is the measurement noise introduced into the system via sensors, and it is usually considered to be random high-frequency signals.
y(t) the plant output signal that should track the input command in presence of the disturbance *d,* sensor noise *n* and un-modelled dynamics.
u(t) actuating signal that should be varying smoothly toward zero effort.
e(t) is the tracking error that should be zero, spatially at steady state.

The contribution of system inputs to the actual output *y(t),* the tracking error $e(t)$, and the controller/actuator output signal, *u(t),* is described by the sensitivity function (S), the complementary sensitivity function (T) and the control sensitivity function *(M)* [1, 2, 3, 13]. From these relationships it can be clarified that:

- **Disturbance rejection:** The loop gain (**$|PC_oC_f|$**) should be large to yield small S and minimizing the effects of disturbance.
- **Tracking:** The loop gain (**$|PC_oC_f|$**) should be large to yield small S and keep tracking errors small.
- **Noise suppression:** the loop gain should be small to yield small T and consequently minimize the effects of noise on the system output and tracking errors.
- **Actuator limits:** M must be bounded to ensure that the actuating signal driving the plant does not exceed plant tolerances. In addition the control energy should be minimum so that smaller actuators can be used.

Tracking and disturbance rejection requires small sensitivity but noise suppression requires small complementary sensitivity, Fig. 2. However, reducing both transfer functions to zero simultaneously is not possible because these two transfer functions add up to unity. This conflict can be avoided by noticing that, in practice, command inputs and disturbances are low-frequency signals whereas the measurement noise is high-frequency signal. Therefore, both objectives can be met by keeping *S* small in the low-frequency range and *T* small in high frequencies. In addition, the control-energy constraint requires keeping *M* small, which can be achieved by keeping *T* small as $M = C_oS = T/P$. Desirable shapes for sensitivity and complementary sensitivity transfer functions are such that S must be small at low frequencies and roll off to 1 (0 dB) at high frequencies, whereas T must be at 1 (0 dB) at low frequencies and get smaller at high frequencies.

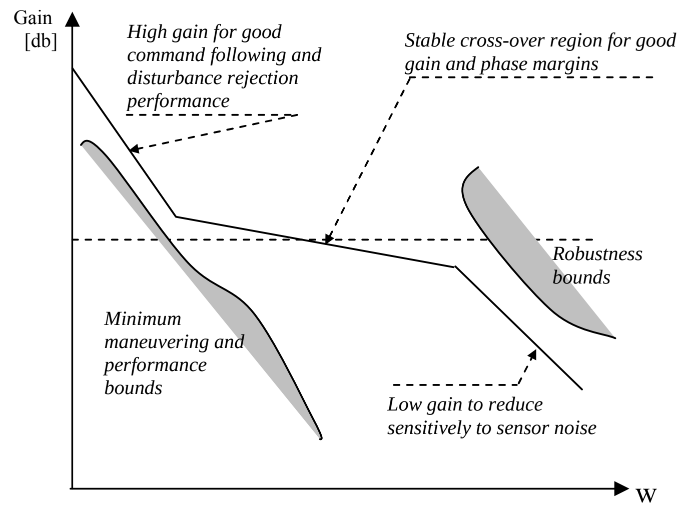

Fig. 2: Desirable shape for the open-loop frequency response of a feedback system

Putting together these effects, a general desired shape for the open-loop transfer function (or loop gain) of a properly designed feedback system can be arrived as shown in Fig. 2. The general feature of this loop gain is that it has high gain at low frequencies (for good tracking and disturbance rejection) and low gain at high frequencies (for noise suppression). The gain at the intermediate frequencies typically influences the gain and phase margins. Bode has shown that for a stable system, the slope of the magnitude plot should not exceed -40 [dB/dec], that is the transition from low- to high-frequency range must be smooth (e.g. -20 [dB/dec])[1, 2, 3].

2- Robust Control

One way to describe the performance of a control system is in terms of the size of certain signals of interest. For example, the performance of a tracking system could be measured by the size of the error signal. There are several ways of defining a signal's size (i.e. several norms for signals), among these norms is the ∞-Norm. The ∞-Norm of a signal u(t) is the least upper bound of its absolute value $\|u\|_\infty := \sup_t |u(t)|$. There are several robust techniques, among them is the H_∞ where a quantitative measure for the size of the system uncertainty is considered. The infinity norm of the transfer function relating the input to the output is the worst-case gain between the two, where both the input and output are measured either by their energy or peak value [4]. Other measures of gain can also characterize worst-case amplifications, but in ways which seem to be less useful in practice.

The set of all stable transfer functions whose infinity norms are finite forms a *Hardy space* [2, 3, 4]) and denoted by $\|H\|_\infty$. Moreover, it is the approach which gives much of recent robust control theory its name. The theory is of great interest because it gives solutions to realistic robust control problems known as $\|H\|_\infty$ optimization problems. One would expect it to be harder than LQG theory, because *min-max* optimization problems are usually harder than quadratic ones, but in fact recent developments have shown the theory to have remarkable similarities with the LQG theory, and LQG problems can even seen as special cases of $\|H\|_\infty$ problems. In addition to the theoretical advances, one should add that a major reason why this theory is of practical interest is the availability of low-cost interactive software, like MATLAB, which makes it possible to perform all the necessary computations quickly and easily.

2.1 Types of uncertainties

No mathematical system can precisely model a real physical system; there is always uncertainty. Uncertainty means that we cannot predict exactly what the output of a real physical system will be even if we know the input, so we are uncertain about the system. The real problem in robust control system design is to synthesize a control law which maintains system response and error signals to within pre-specified tolerances despite the effects of uncertainty on the system. Uncertainty may take many forms but among the most significant are noise/disturbance signals and transfer function modeling errors in addition to un-modeled nonlinear distortion. Consequently, it had adopted a standard quantitative measure for the size of the uncertainty using H_∞ norm [1, 2, 3]. The model error Δ can be represented by an unknown transfer function that indicates the difference between the actual process and its model. This general setup allows a control system designer to capture all these uncertainties, both structured and unstructured, and formulate them into the design.

2.2 H_∞ Control theory

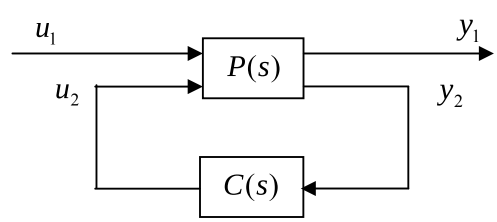

Fig. 3: Small Gain Problem

The methods of H_∞ synthesis are especially powerful tools for designing robust multivariable feedback control systems to achieve singular value loop shaping specifications. The *standard H_∞ control problem* is sometimes also called the *H_∞ small gain problem*. The small-gain theorem states that if *a feedback loop consists of stable systems, and the product of all their gains is smaller than one, then the feedback loop is stable*. That is, assuming that the blocks P and C in Fig. 3 are stable, then the closed loop system remains stable if $\|T_{y_1u_1}\| < 1$, where $\|T_{y_1u_1}\|$ is the feedback closed loop transfer dynamic. The small gain problem shows a general set-up, and the problem of making $\|T_{y_1u_1}\|_\infty \le 1$ is also called the *small-gain problem*. The H_∞ design problem can be formulated as follows: Given a state-space realization of an augmented plant *P(s)*:

$$P(s)=\left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{array}\right] \qquad (1)$$

Find stabilizing feedback control law:

$$u_2(s)=C(s)y_2(s) \qquad (2)$$

such that the norm of the closed-loop transfer function matrix:

$$T_{y_1u_1}=P_{11}(s)+P_{12}(s)[I-C(s)P_{22}(s)]^{-1}C(s)P_{21}(s) \qquad (3)$$

is small.

The state-space model of an augmented plant $P(s)$ with weighting functions $W_1(s)$, $W_2(s)$, and $W_3(s)$ which penalizing the error signal, control signal and output signal respectively Fig. 4 so that the closed-loop transfer function matrix is the weighted mixed sensitivity:

$$T_{y1u1}\overset{\Delta}{=}\begin{bmatrix} W_1S \\ W_2M \\ W_3T \end{bmatrix}$$

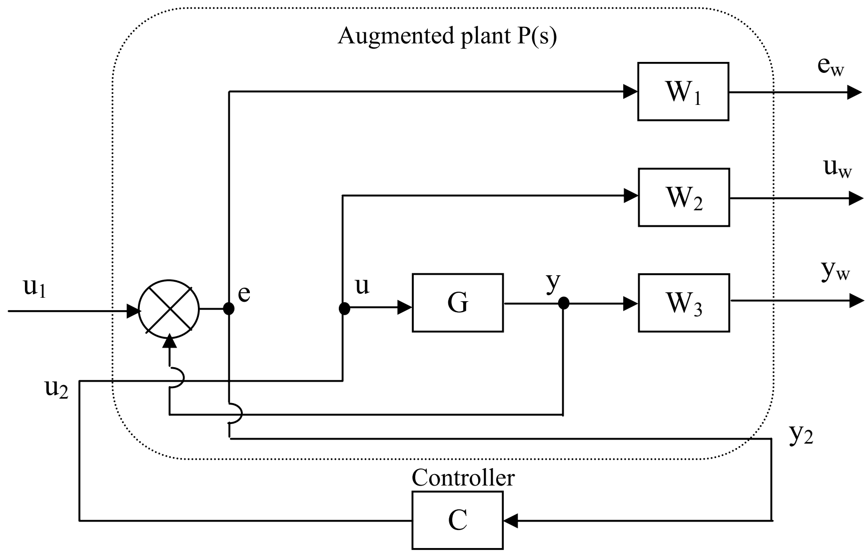

Fig. 4: Augmented plant $P(s)$

The augmented plant P(s) with state space realization:

$$P(s)=\begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix}=\left[\begin{array}{cccc|c|c} A_G & 0 & 0 & 0 & 0 & B_G \\ -B_{W_1}C_G & A_{W_1} & 0 & 0 & B_{W_1} & -B_{W_1}D_G \\ 0 & 0 & A_{W_2} & 0 & 0 & B_{W_2} \\ B_{W_3}C_G & 0 & 0 & A_{W_3} & 0 & B_{W_2}D_G \\ \hline -D_{W_1}D_G & C_{W_1} & 0 & 0 & D_{W_1} & -D_{W_1}D_G \\ 0 & 0 & C_{W_2} & 0 & 0 & D_{W_2} \\ \widetilde{C}_G+D_{W_3}C_G & 0 & 0 & C_{W_3} & 0 & \widetilde{D}_G+D_{W_3}D_G \\ \hline -C_G & 0 & 0 & 0 & I & -D_G \end{array}\right] \qquad (4)$$

$\widetilde{C}_G=P_0\,D_G+P_1\,C_G\,A_G+.....+P_n\,C_G\,A_G^n\,B_G, \widetilde{D}_G=P_0\,D_G+P_1\,C_G\,B_G+.....+P_n\,C_G\,A_G^{n-1}\,B_G$

Where A_G, B_G, C_G, D_G is the state space matrices of the planet G, $A_{W_1}, B_{W_1}, C_{W_1}, D_{W_1}$ is the state space matrices of the weight function W_1, $A_{W_3}, B_{W_3}, C_{W_3}, D_{W_3}$ is the state space matrices of the weight function W_3, and $P_0, P_1,..., P_n$ is the polynomial coefficient of W_3. The two Riccati equations involved in the H_∞ control solution are as follows [1, 2, 3]:

$$A^* X_\infty + X_\infty A + X_\infty (\gamma^{-2} B_1 B_1^* - B_2 B_2^*) X_\infty + C_1^* C_1 = 0 \tag{5}$$
$$A Y_\infty + Y_\infty A^* + Y_\infty (\gamma^{-2} C_1^* C_1 - C_2^* C_2) Y_\infty + B_1 B_1^* = 0 \tag{6}$$

Solving the two Riccati equations for X_∞ and Y_∞ for certain γ, the controller $C(s)$ can be constructed:

$$C(s) = \begin{bmatrix} A_K & -ZL \\ F & 0 \end{bmatrix} \tag{7}$$

Where,

$$A_K = A + \gamma^{-2} B_1 B_1^* X_\infty + B_2 F + ZLC_2$$
$$Z = (I - \gamma^{-2} Y_\infty X_\infty)^{-1}$$
$$L = -Y_\infty C_2^*$$
$$F = -B_2^* X_\infty$$

The design of H_∞ controller to be used in controlling a general process can be carried out through the following steps [3]:

Step1: Determine the type of uncertainty present and its structure (multiplicative, additive, etc.).

Step2: Parameterise the weighting functions in the cost function leaving unknown coefficients to be selected or tuned until the objective reached (e.g. an integrator is typically employed in the error or the sensitivity term and a lead term is employed for the control weighting or control sensitivity function).

Step3: Considering only the sensitivity or error weighting term select a suitable weighting function to give adequate performance robustness, disturbance rejection robustness and tracking performance

Step4: Introduce the control or control sensitivity weighting term increasing its gain until adequate measures of stability robustness and measurement noise rejection have been achieved. This normally involves tailoring the high frequency characteristics of the controllers whilst Step-3 concentrates on the low frequency behaviour.

Step5: Once the frequency domain trade-offs between sensitivity and control sensitivity costing have been made, a simulation of the transient response characteristics should be inspected to ensure the adequacy of performance.

Step6: If the steady state error is too large, the gain can be increased by penalizing the sensitivity function or error term at low frequency using its weighting function.

Step7: If the bandwidth of the controller is too wide, greater roll-off can be introduced at an earlier point by using a lead term on the control sensitivity function or by introducing a measurement noise model which has high gain in this frequency range.

Step8: Performance and robustness properties can be assessed using the structured singular value (μ) tools.

Before attempting a controller design, control and error weighting functions, which reflect the frequency and time domain requirements, must be selected. A good feedback design for a particular system is obtained by selection of the frequency dependent weighting functions W_1 and W_3. At low frequency the system is required to be insensitive to disturbances while at high frequency it is required to filter out unwanted signals especially the measurement noises. The selection of error and output weighting functions does not involve precise rules but general guideline gained from experience practice can be outlined [3, 4].

3- Controller Design using H_∞ Control

Performance of antitank guided missile systems is measured through the minimum miss distance and the capability of the missile to overcome target manoeuvre and different sources of errors and disturbance noises. The objective of guidance process is to correct the missile trajectory through its flight and to overcome the external and internal source errors. Toward this objective a robust autopilot is designed and compared with the conventional or classical one (PID). The design is applied for the missile three flight phase's models and each controller is tested with the other models to select the best controller. The design and analysis use trials to select the values of error and output weighting functions. A simple method to selecting weight functions for the H_∞ control technique can be given as the plant P(s) is the actuator and the missile airframe augmented with the two weighting functions w_1 and w_3 where, w_1 penalizing error signal "e" and w_3 penalizing plant output "y". In the present work/design the value of the w_2 weighting function, which penalizes the control signal, is taken equals to unity.

3.1 Robust controller for running up phase

Selecting the weight function that specifies the H_∞ technique can be given by the following relations:

$$w_1 = \gamma * \frac{1+S/a}{b(1+S/c)}, \qquad w_3 = \frac{1+S/d}{e(f+S/g)} \tag{8}$$

where a, b, c, d, e, f, g, γ are the tuning parameters for adjusting the system performance. The effect of these parameters varying upon the guidance system performance (rise time, overshoot, steady state error and settling time) is analysed such that it should verify the system stability and performance requirements small overshoot, small settling time. After different trials for choosing these weighting functions they are found to have the forms:

$w_1 = 45 * \frac{1+S/30}{0.05\,(1+S/0.01)}$ and $w_3 = \frac{1+S/1.25}{2.75\,(7.5+S/350)}$.

The transfer function of the obtained controller for the running up phase given as follows:

$$K = \frac{c_1 s^6 + c_2 s^5 + c_3 s^4 + c_4 s^3 + c_5 s^2 + c_6 s^1 + c_7}{d_1 s^7 + d_2 s^6 + d_3 s^5 + d_4 s^4 + d_5 s^3 + d_6 s^2 + d_7 s^1 + d_8} \tag{9}$$

where the controller coefficients are

C_1	C_2	C_3	C_4	C_5	C_6	C_7	
-600.9	-2.32e6	-2.21e9	-6.451e11	-2.367e13	-1.203e14	-2.65e13	
d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8
1	5141	9.396e6	8.147e9	2.725e12	2.641e14	4.167e15	4.165e13

The tracking performance (step response) of the inner loop at running up phase is shown in Fig. 5, where the designed robust controller uses the running up phase model.

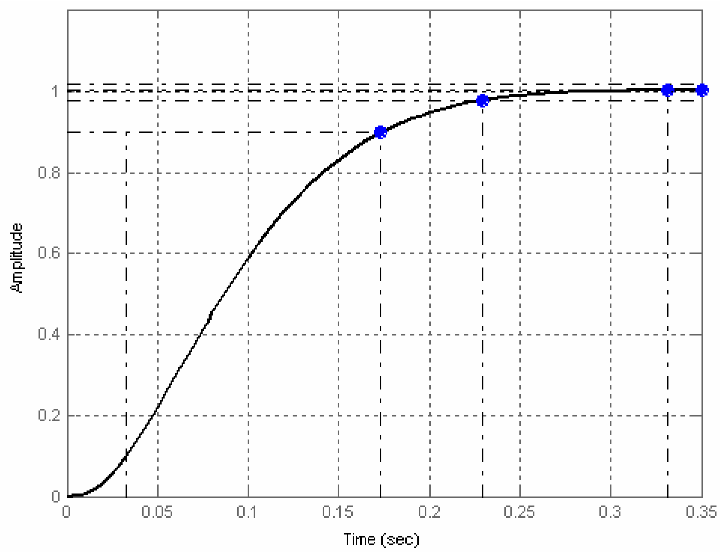

Fig. 5: Step response of the inner loop at running up phase using robust running up controller

Also the tracking performance (step response) of the inner loop at both gathering and guidance phases is shown in Fig. 6, where the designed running up robust controller is used. From these figures it is clear that the designed robust controller using the running up phase model as nominal planet confirm good tracking all-over the missile flight phases. However, the performance of the system minor loop is very slow (large rise and settling time) in case of gathering and guidance phases.

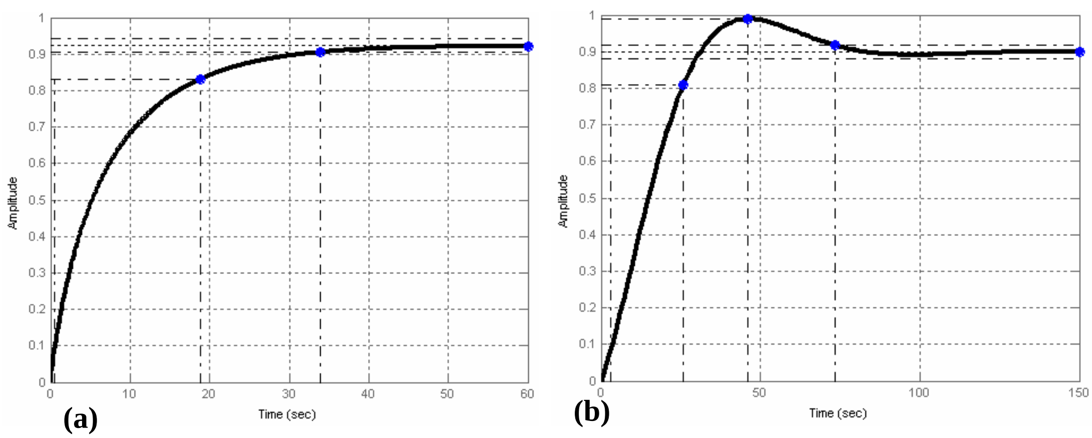

Fig. 6: Step response of the inner loop using robust running up controller for (a) gathering phase and (b) Guidance phase

3.2 Robust controller for gathering phase

Selecting the weight function that specifies the H_∞ technique can be given by the following relations:

$$w_1 = \gamma * \frac{1+S/a}{b(1+S/c)}, \qquad w_3 = \frac{1+S/d}{e(f+S/g)} \tag{10}$$

where a, b, c, d, e, f, g, γ are the tuning parameters for adjusting the system performance. The effect of these parameters varying upon the guidance system performance (rise time, overshoot, steady state error and settling time) is analysed. These parameters should be selected somehow to verify the system stability and performance requirements small overshoot, small settling time. After different trials for choosing these weighting functions they are found to have the forms: $w_1 = 45 * \frac{1+S/30}{0.05\,(1+S/0.01)}$ and $w_3 = \frac{1+S/1.25}{2.75\,(7.5+S/350)}$.

The transfer function of the obtained controller for the gathering phase given in the form as equation (9) where the controller coefficients are

C_1	C_2	C_3	C_4	C_5	C_6	C_7	
-9.259e4	-3.585e8	-3.405e11	-9.94e13	-3.648e15	-1.853e16	-4.083e15	
d_1	d_2	D_3	d_4	d_5	d_6	d_7	d_8
1	6368	1.512e7	1.741e10	1.032e13	2.69e15	2.06e17	2.06e15

The tracking performance (step response) of the inner loop at gathering phase is shown in Fig. 7, where the robust controller designed using the gathering phase model. In addition, the designed controller tested with the other two missile flight phases, the inner loop become unstable with the running up phase while the guidance phase performance is shown in Fig 8.

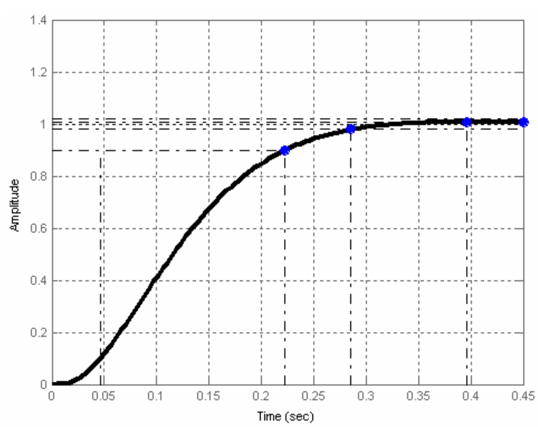

Fig. 7: Step response of the inner loop at gathering phase using robust gathering controller

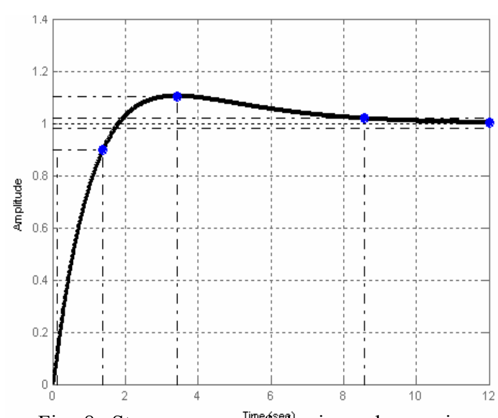

Fig. 8: Step response of the inner loop using robust gathering controller for Guidance phase

3.3 Robust controller for guidance phase

Selecting the weight function that specifies the H_∞ technique can be given by the following relations:

$$w_1 = \gamma * \frac{1}{a(1+bS+S^2)}, \qquad w_3 = \frac{c+d\,S}{e} \tag{11}$$

where a, b, c, d, e, γ are the tuning parameters for adjusting the system performance. The effect of these parameters varying upon the guidance system performance (rise time, overshoot, steady state error and settling time) is analysed. These parameters should be selected somehow to verify the system stability and performance requirements small overshoot, small settling time. After different trials for choosing these weighting functions they are found to have the forms: $w_1 = 0.37 * \frac{1}{0.0225(S^2+8S+1)}$ and $w_3 = \frac{0.45\,S + 1.25}{1.5}$.

The transfer function of the obtained controller for the guidance phase given in the form as equation (9) where the controller coefficients are

C_1	C_2	C_3	C_4	C_5	C_6	C_7	
-3.05e5	-5.465e8	-3.304e11	-7.196e13	-2.647e15	-1.695e16	-9.804e14	
d_1	d_2	d_3	d_4	d_5	d_6	d_7	d_8
1	5843	1.116e7	8.928e9	2.731e12	2.301e14	1.674e15	2.089e14

The order of the controller transfer function reduced to the forth order using the Matlab control toolbox. The new controller has the following form

$$K = \frac{c_1 s^4 + c_2 s^3 + c_3 s^2 + c_4 s + c_5}{d_1 s^4 + d_2 s^3 + d_3 s^2 + d_4 s + d_5} \quad (12)$$

and its coefficients are

C_1	C_2	C_3	C_4	C_5
-0.8034	-2.938e5	-1.631e8	-5.682e9	-3.309e8
d_1	d_2	d_3	d_4	d_5
1	4338	5.128e6	5.566e8	7.05e7

The bode plots of both the designed controller and the reduced one are coincident up to 70 [kHz] i.e. the reduction of controller order has no effect during the working frequency band.

The tracking performance (step response) of the missile different flight phases for the inner loop is discussed, where the reduced order controller is used Fig. 9.

From the previous figures it is clear that this controller satisfy the performance requirements specification and robust requirements specification. In the following section the missile performance will be evaluate using the new robust controller. The obtained robust autopilot system as a minor loop in the guidance loop and

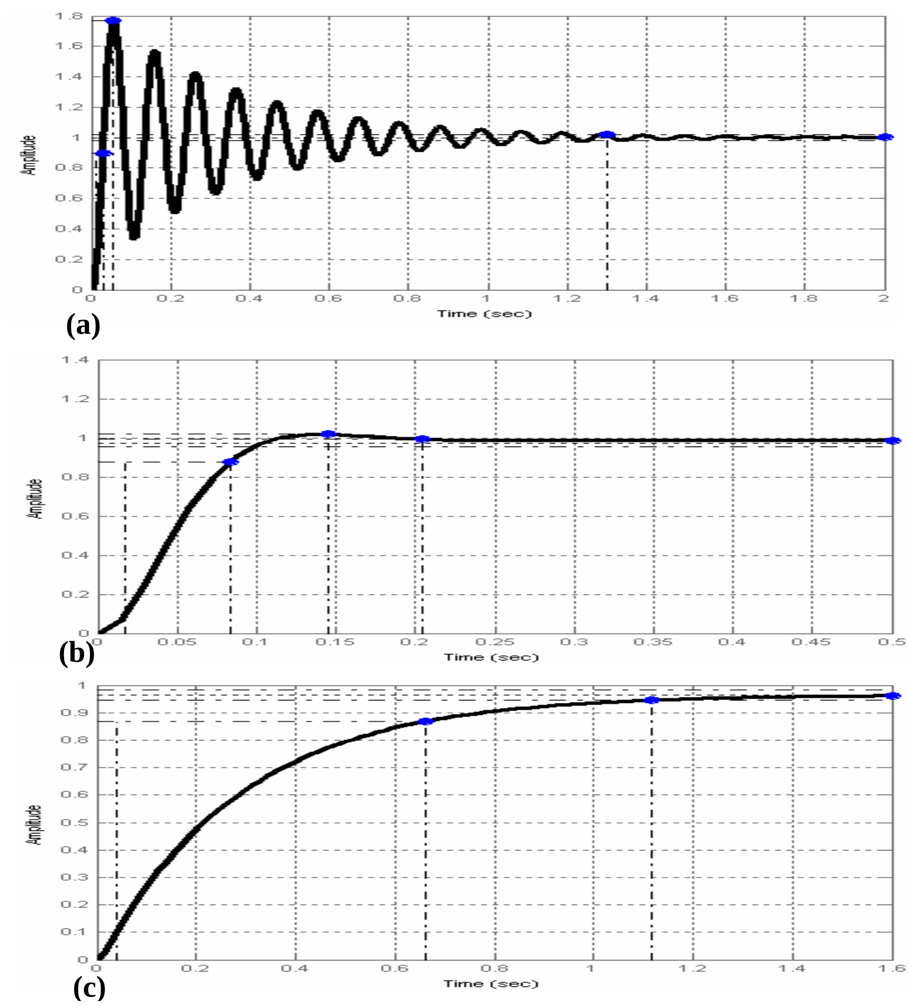

Fig. 9: Step response of the inner loop using robust guidance controller for (a) running up, (b) gathering, and (c) Guidance phase

using the same dynamics of the missile guidance system and other components in the guidance loop, leads to a robust guidance system

4- Evaluation of robust missile performance

To analyse the system performance and justify its robustness using each of the above various controllers, SIMULINK program is designed in conjunction with the 6DOF and used for this objective. The analysis considers the following performance parameters (figures are omitted for space):

- The control effort signal using the conventional (E-Pack) is oscillatory with less peak value than the robust controller. In other words, control effort signal in case of robust controller is faster with damped than conventional (E-Pack) controller.
- White measurement noise with zero-mean and unity variance is applied to the system at the feedback signal, with noise-to-signal ratio as 10 %. The results showed that the control effort is sensitive to noises in case of the conventional controller while the robust controller has the filtering nature during the missile flight phases.
- The robust controller rejects disturbances (oscillations of operator and wind injected at the system output) very fast than the conventional controller.

- **Flight Path Analysis**
  Using robust controller, the missile engagement scenario for target at range (R_{tx}) = 2800 [m], velocity (V_t) = 0 [m/sec], pitch LOS angel (Ψ_s) = 0 [mils], and yaw LOS angel (θ_s) = 0.25 [mils] is shown in Fig. 10.

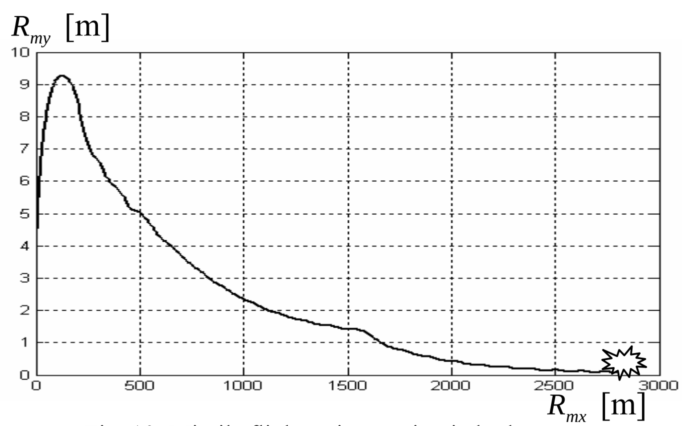

Fig. 10: Missile flight trajectory in pitch plane using robust auto-pilot

A comparison between the missile flight trajectories for same target parameters using identified E-Pack and robust autopilot with the reference trajectory are shown in Fig. 11.

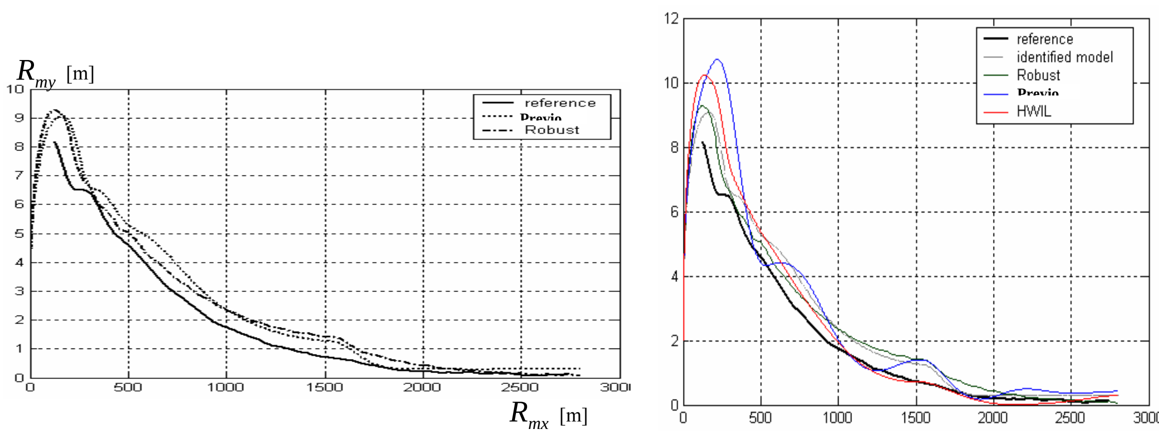

Fig. 11: Comparison between the missile flight trajectories in pitch plane using robust autopilot and E-Pack with reference trajectory

Moreover, increasing the missile thrust value about 15% from the nominal value causes the missile trajectory for E-Pack to have ground contact before the target while robust autopilot is capable to overcome this thrust uncertainty reach its target, Fig. 12.

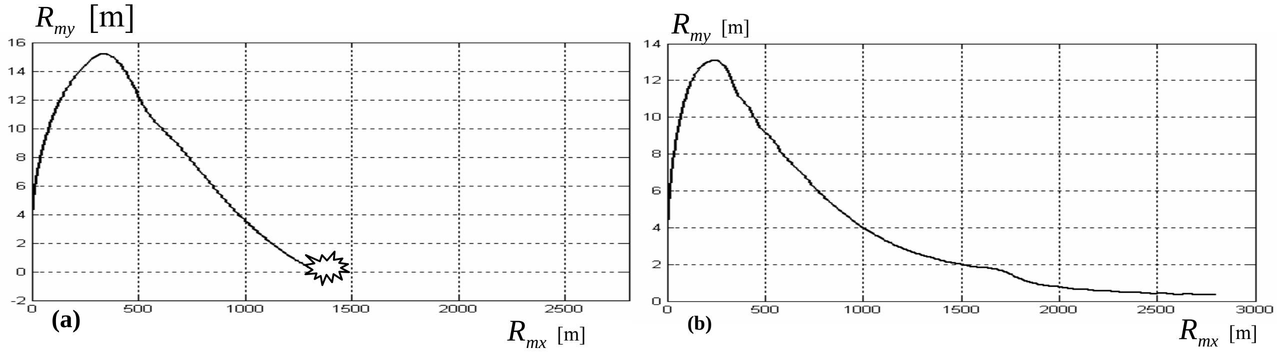

Fig. 12: Effect of thrust value change (a) E-Pack (b) Robust autopilot

5- Conclusions

This paper presented in brief the feedback control system and the nature of the underlying system. In addition, robust control techniques are highlighted especially the H_∞, with which the controller is designed. The results clarified that

- The control effort signal using the conventional (E-Pack) is oscillatory with less peak value than the robust controller. In other words, control effort signal in case of robust controller is faster with damped oscillations than conventional controller.
- The control effort is sensitive to noises in case of the conventional controller while the robust controller has the filtering nature during the missile flight phases.
- The robust controller rejects disturbances (oscillations of operator and wind injected at the system output) very fast than the conventional controller.
- The robust controller was robust enough to overcome system uncertainty due to 15% variation in missile thrust value from the nominal one and reach its target while the conventional has ground contact before the target.

Of course these advantages are paid in design complexity and higher order controller and consequently cost.

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