A MONTE CARLO COMPUTATION OF THE FIRING ENVELOPE OF A VISUALLY GUIDED MISSILE: INTEGRATED GUIDANCE, CONTROL AND IMAGE PROCESSING ALGORITHMS

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Abstract. *Missile design is often separated into distinct subsystems such as seeker stabilization, target detection and tracking, guidance, and autopilot. The miss distance strongly depends on proper integration of those critical subsystems and the prototyping of visually guided missiles. A low-cost integrated solution based on a PC running Matlab is an attractive option to test new ideas on guidance, control and image processing algorithms. A bottom-up image synthesis of a missile homing in on a target embedded in a planar background was used in an integrated project that evaluates the different missile subsystems. This paper obtains the firing envelope of a visually homing missile encompassing dynamics and constraints of the missile seeker, canards, non linear motion equations, sensor errors, image processing for target detection and tracking, and proportional navigation guidance. For a given realistic simulation scenario, the main result concerns the influence of a correlation-based detection algorithm on the firing envelope obtained when the target centroid is always detected and without uncertainty. Results showed that the detection algorithm distorts the original firing envelope due to its enormous dependency on the choice of the signature mask size. Moreover, for the chosen launching geometry, missile angular motion was much less significant to miss distance degradation than inadequate mask sizing.*

Keywords: *firing envelope, image generation, computer vision, missile integrated design.*

1. Introduction

In general, missile design is separated into distinct subsystems such as seeker stabilization, target detection and tracking, guidance, and autopilot. The miss distance strongly depends on proper integration of those critical subsystems and problems arise when systems are too complex to be modelled fully. According to Hallberg *et al.* (1999), prototyping of visually guided missiles for field testing is an expensive mean to ascertain whether subsystem integration in its initial stages is adequate for the intended objectives. In this phase, unpredicted dynamical coupling among subsystems can affect the performance of computer vision algorithms, thus presenting an unfavorable risk-to-benefit ratio to prototyping and field testing that may cause vehicle loss.

The use of a computational tool for the integrated design and simulation of guidance, control, and computer vision subsystems of a visually guided missile is technically and economically quite attractive (Menon and Ohlmeyer, 2001). A realistic simulation comprising the simultaneous operation of the subsystems presented in Fig. 1 calls for a computational tool that synthesizes images of the target and its environment acquired by the camera as the vehicle moves, what demands for an expensive software and a high-performance hardware to deal with the huge computational workload (Doehler and Bollmeyer, 1997), (Mehler, 2000), (Yilmaz *et al.*, 2004).

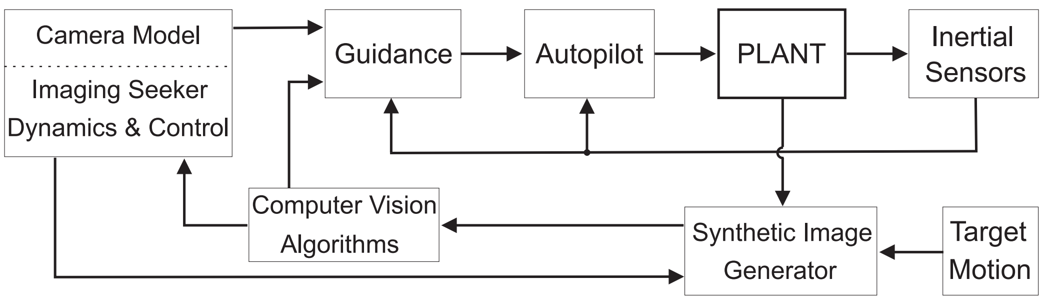

Figure 1. Main subsystems of a visually guided missile.

Missile performance and the limitations of the image-based closed loop can be investigated by simulating separately the following subsystems: *computer vision algorithms* - by using characteristics of the missile, target and background image data; and *seeker stabilization, guidance and autopilot* - assuming that the target has been detected with a bounded uncertainty. However, a general performance index for the overall system is difficult to evaluate before prototyping and conducting test flights, what results in excessive design iterations and may not always exploit synergistic relationships existing between interacting subsystems (Menon and Ohlmeyer, 2001).

In this way, a less realistic, low-cost solution based on a PC running Matlab becomes an acceptable, attractive option to test the integrated operation among the guidance, control, image processing subsystems. Jacob and Waldmann (2004) developed the basic sequence of transformations of a two-dimensional homogeneous coordinates-based synthetic image generation tool where the synthetic images are generated from a *seed-image* containing the target and its background, whereas the camera positioning and attitude in relation to the world frame are described according to cartesian coordinates and Euler angles in aeronautical notation, respectively. Given information about the the camera and the synthetic world, this new tool computes the pixel values as the missile homes in on a target embedded in a planar background.

An important method to investigate the hit-or-miss missile performance in a realistic simulated battle scenario is the firing envelope. As stated by Shinar and Tabak (1994), the *no-escape* firing envelope of a guided missile is defined as the closure of the set of initial conditions, for which the maximum miss distance achieved by the optimal missile avoidance strategy is smaller than the *lethal range* of the missile warhead. Due to the difficulty to obtain analytical solutions to these interception trajectories, this problem is usually simplified in order to obtain approximated results, what necessarily does not provide a realistic test for the missile homologation. A good suggestion to overcome these difficulties is to combine analysis and detailed simulation to derive data for missile avoidance and attack over the complete operational envelope of the missile (Neuman, 1990).

This paper aims at investigating the hit-or-miss performance of a realistically modelled visually guided missile (Waldmann, 2002)-(Jacob and Waldmann, 2004) by obtaining its firing envelope. The focus and contribution lie on the obtention of a new firing envelope that, besides encompassing dynamics and constraints of the missile seeker, canards, non linear motion equations, sensor errors, and proportional navigation guidance, now also uses information from the online image processing via a correlation-based algorithm for the target detection. For a given simulation scenario, the main result concerns the influence of a correlation-based detection algorithm on the firing envelope obtained when the target centroid is always detected and without uncertainty. The performance tests run over a synthetic gray-level image containing the signature of a T-72 tank embedded in four Markov random fields with the same statistics modelling the target background, given the position and attitude of the missile camera with respect to the target. For a fixed signature mask size, best results were obtained when it tightly encloses the entire target. Results also showed that, for the chosen missile launching geometry, the vehicle yaw, pitch, and roll motion did not contribute effectively to the decreasing of the missile performance as the sizing mask did.

Information about the integrated simulator of a visually guided missile and details about the computer vision algorithm are presented in Section 2. The firing envelope obtained by the traditional procedure and that obtained by the correlation-based algorithm in a realistic simulation scenario are shown in Section 3. Conclusions are in Section 4.

2. Integrated Simulation of a Visually Guided Missile

The missile integrated system project, in accordance to the subsystems presented in Fig. 1, is feasible via Simulink, a Matlab's single accessible tool with low cost and high benefits.

2.1 Matlab-Based Image Generator

The success of the overall missile performance evaluation depends essentially on the ability of the image generator to render realistic scenes corresponding to camera position and attitude relative to the inertial frame S_I. Due to the limitations of the tool (Jacob and Waldmann, 2004), the synthetic world seen by the camera is flat, which is a good approximation in fast interception problems.

Matlab's Image Processing Toolbox version 3.1-R12.1 contains a *Spatial Transformations* easy-to-use tool able to perform operations with two-dimensional homogeneous coordinates. The configuration parameters of the image generator are presented next.

Virtual World Image is a time varying two dimensional array $[V]$ structured to represent the image background and realistic targets. Based on target dynamics, the target model moves independently over the background. The parameter vector $\mathbf{W}= [0\, u]m$ contains the squared world dimensions over a plane, and the central position of the target model is given by $\mathbf{T}= [x_T\, y_T]m$.

Camera Parameters are classified as *fixed* and *variable*. The former is described by vector $\mathbf{C_{sf}} = [d_{CCD}\, R_h\, R_w]$, where d_{CCD} is the diagonal length in metersof the CCD (*Channel Coupled Device*), and R_h and R_w are the CCD resolutions in height and width, respectively. The focal distance f is given by $\mathbf{C_{sv}} = [f]m$.

Camera Positioning and Attitude are given by three-dimensional cartesian coordinates and *aeronautical sequence* of Euler angles in relation to inertial frame, respectively. The camera is on board the aerial platform, and its position and attitude can be represented likewise, that is, by the position vector $\mathbf{C_p} = [x_I\, y_I\, z_I]m$ and the attitude vector

Ca $= [\psi\,\theta\,\phi]^o$, where ψ is *yaw*, θ is *pitch*, ϕ is *roll*, and the aeronautical sequence is defined as $\psi \to \theta \to \phi$.

Generated World Image is a R_hxR_w time-varying two-dimensional array $[G]$. Interpolation methods and gray level adjustment can be used to improve the image quality.

2.2 Simulated Scenario

Simulations were based on a cruciform skit-to-turn missile guided in three-dimensional engagements against one non-maneuvering target by pure proportional navigation, in accordance to Waldmann (2002). With the purpose of rendering a realistic image, a real X band SAR image of a Russian T-72 tank was obtained from the MSTAR SAR Database of the Center of Imaging Science at Johns Hopkins University. The 16 gray level-based and 0.30m resolution 128x128 image was superimposed over a background generated in a 0.45m resolution 4000x4000 array according to a 128 gray level-based causal Markovian field with known statistics. The simulated optical image is obtained according to **Csf** $= [1/3in\,512pix\,512pix]$ and **Csv** $= [0.05]m$.

The left picture in Fig. 2 presents the simulation scenario considered by the Matlab-based image generator. The visually guided missile is launched from **Cp** $= [0\,0\,-z_I]m$, $z_I > 0$, with attitude vector **Ca** computed for the target centered in the generated camera image. As the missile homes into the target, the interception error vector **E**$=$ $[Xe\,Ye\,Ze]m$ is computed in accordance to the difference between the target and missile positions at each time instant t for each coordinate axis. A realistic generated image at $t = 0.025s$ is shown by the right picture in Fig. 2 for **Cp** $=$ $[0\,0\,-875]m$ and **T**$=[825\,1450]m$.

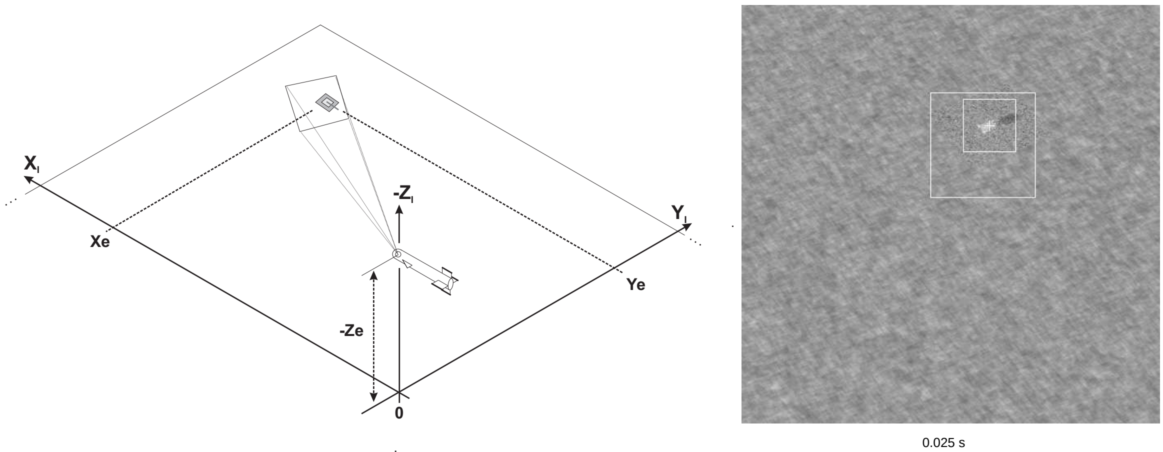

Figure 2. Simulation scenario and the generated image of a T-72 tank.

2.3 Computer Vision Algorithm

The target image correlation algorithm consists in first determining a signature mask containing the entire target and then compute its correlation value in a given search region. Inside the search region, the estimated position of the target centroid is given by the center of the signature mask position where the correlation value is the highest. The signature mask is replaced for that with the highest correlation value at each instant of time. The number of correlation evaluations inside the search region is determined by the quantity of signature shifts along the horizontal and vertical directions.

The right picture in Fig. 2 shows a synthetic image of the T-72 tank and a pair of squares. The outer one represents the search region, whereas the other is the signature mask. The cross is at the center of the signature mask to be saved for using in the following image. Given the missile dynamics and the background containing a target image, it is necessary to determine the signature mask sizes, the search region and the respective signature mask shifts that yield a successful correlation-based interception. The correlation algorithm used a search region with size defined as twice that of the signature mask and centered on the most recent estimate of target position in the image plane. The signature mask size in pixels should be multiple of two.

3. Missile Interception Envelope

First, the missile behavior for the usual procedure of assuming the target centroid always detected is studied. Then, with this interception envelope, the idea is to compare the results with those obtained by using the computer vision algorithm with different image backgrounds, that is, the robustness of the target detection algorithm will be tested for several camouflages.

The initial procedure is to select the initial condition space over which the problem should be solved, and then discretize the space into a grid of adequate resolution. Grid resolution should not incur into an excessive computational load when determining those regions where the control law given by Waldmann (2002) is effective. It is assumed that the target always detected without uncertainty.

As a general simulation scenario to obtain a firing envelope that results in the destruction of the target, the missile was launched from a host vehicle at initial positions $\mathbf{C_p} = [0\,0\, -z_I]m$ with $z_I = \{1000, 1025, 1050, ..., 1225\}$, whereas the initial velocity vector was given by $[510\,10\,4]m/s$ and the roll rate by $220^o/s$. The target position was given for $\mathbf{T}$=$[x_T\, y_T]m$, where $x_T = \{1450, 1500, 1550, 1600\}$ and $y_T = \{950, 975, 1000, ..., 1300\}$. The camera frame rate is given by $120 frames/s$. Missile dynamics and other sensor characteristics can be found in (Waldmann, 2002).

By assuming that the target centroid is always detected, one missile was launched for each different initial vector $\mathbf{C_p}$ and, in general, the results showed that the target was always intercepted, that is, *miss distance* smaller than $5m$. Therefore, for this case, a 3-D firing envelope was obtained. Figure 3 shows some of the relative trajectories, in terms of the error between target and missile positions, for $z_I = Z_e = 1000m$.

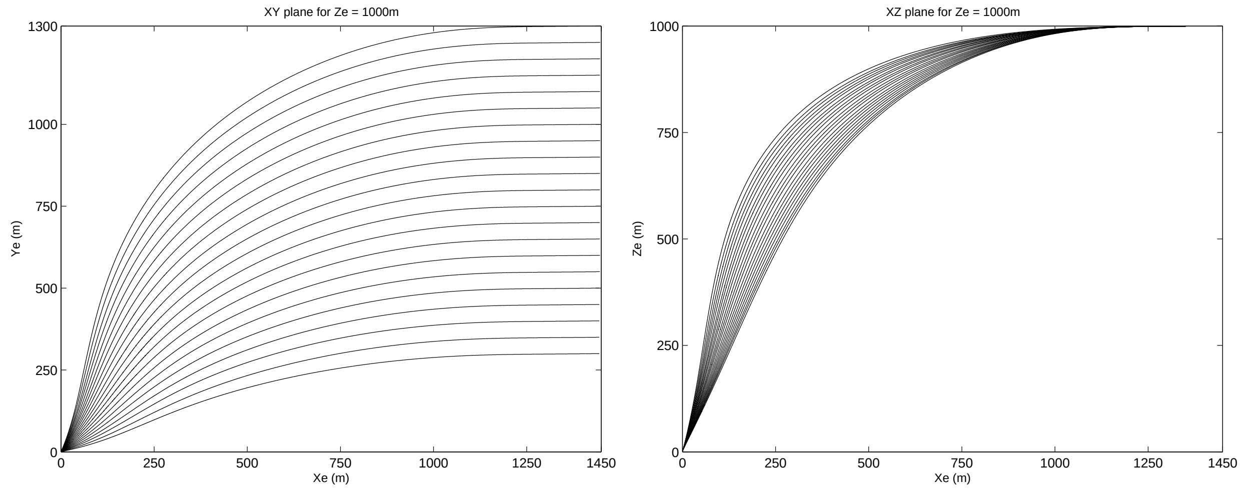

Figure 3. Errors of missile trajectories for Ze = 1000m, miss distance $\leq$ 5m and target always detected.

To investigate the robustness of the correlation-based target detection algorithm, four different image backgrounds were used for all initial conditions in the grid. As presented by Jacob and Waldmann (2004), when the signature mask size is 64x64 pixels with a shift of 8 pixels, the correlation-based detection algorithm performs very similar trajectories to those obtained by assuming that the target centroid is detected, except near the end of the interception. The signature mask size was chosen to completely enclose for as long as possible during the engagement.

Figures 4 and 5 present the gray level score for the firing envelope obtained for a miss distance smaller than $5m$. In general, as the initial missile launching position becomes distant from the target, the number of hits decrease significantly. Other interesting point is that as Ye increases, that is, as the lateral distance of the target becomes bigger, the number of hits also decreases. Initially, it could be argued that the missile attitude contributes for this bad scenario. However, as presented in Fig. 6, for $Xe = 1450m$, $Ye = \{600, 1200\}m$ and $Ze = 1000m$, the ψ and ϕ angle dynamics are smooth and very similar, what demonstrates, in accordance to the correlation picture, that the signature mask size is the crucial point in this case. Therefore, for a fixed size signature mask, best results were obtained when it tightly encloses the entire target. However, a trade-off exists between the accuracy in target centroid position estimate and workload requirements for real-time applications.

According to Jacob and Waldmann (2004), correlation peaks increased significantly to approximately one with signature mask size encompassing solely the target and very small shifts within the search region. However, this mask sizing incurs in a severe trade-off in terms of the computational workload in a low-cost PC. These results showed that the use of an adaptive size masking is essential to keep the correlation-based detection during the engagement.

Efforts now concentrate on generation of more realistic images of the target at close range with PC-compatible computational workload, and integrated testing of computer vision algorithms for target tracking, missile navigation, guidance, and homing. Approaches to keep a satisfactory correlation-based detection performance during the engagement are also being studied.

4. Conclusion

For a given realistic simulation scenario, the firing envelope of a visually homing missile was obtained encompassing dynamics and constraints of the missile seeker, canards, non linear motion equations, sensor errors, image processing for

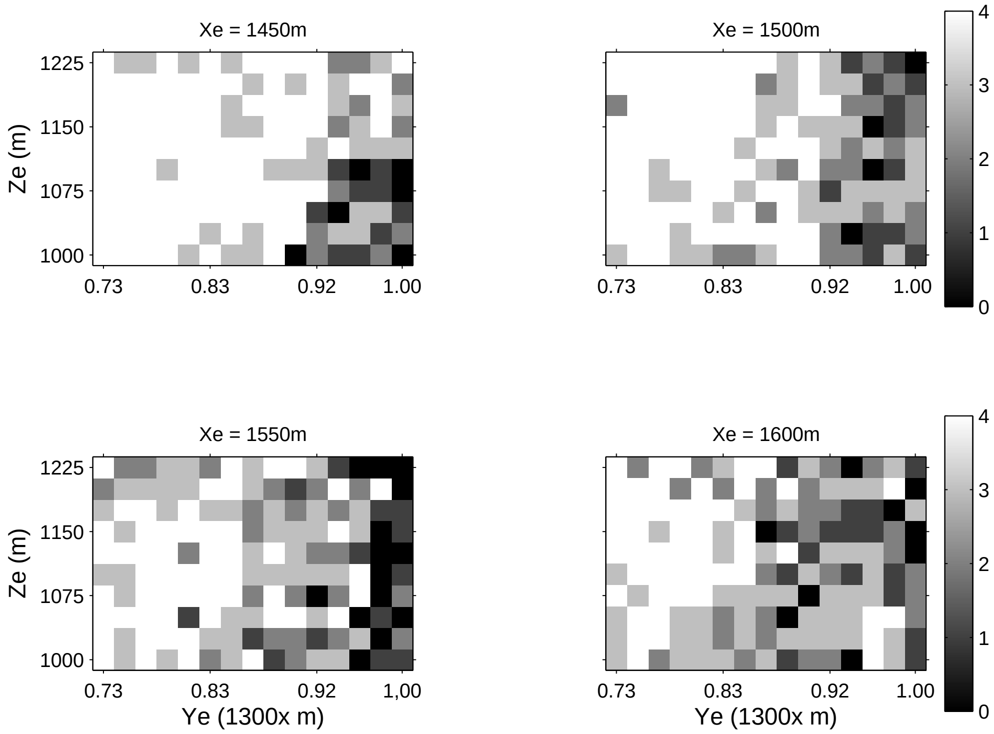

Figure 4. Gray level score for the firing envelope in the YZ plane for miss distance $\leq$ 5.0m.

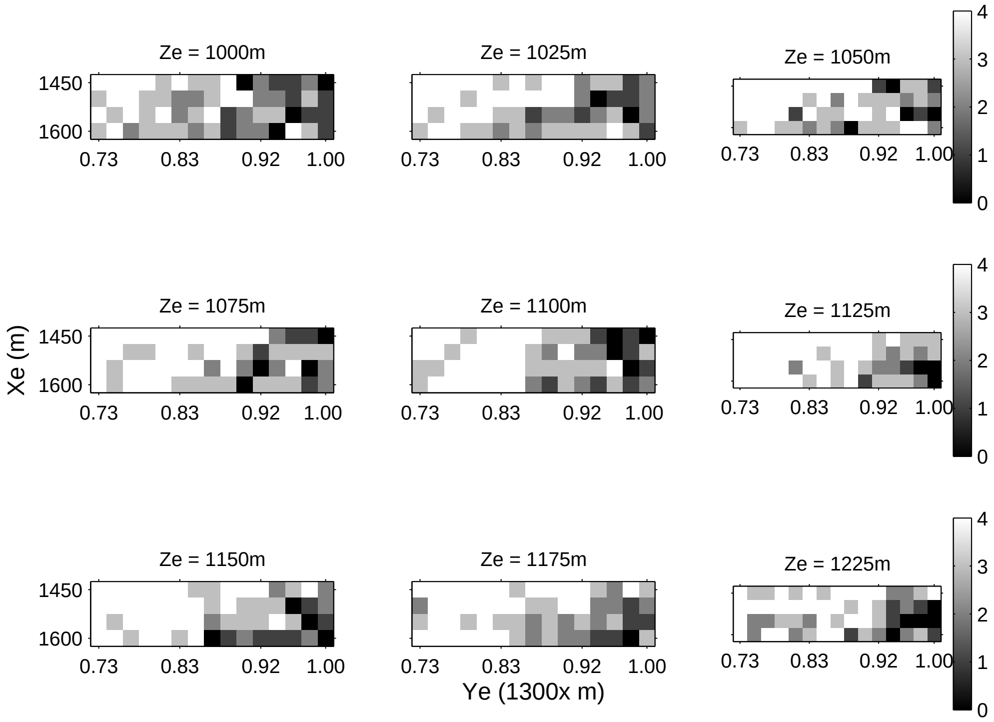

Figure 5. Gray level score for the firing envelope in the YX plane for miss distance $\leq$ 5.0m.

target detection and tracking, and proportional navigation guidance. Results concerning the influence of a correlation-based detection algorithm on the firing envelope show that the missile performance depends strongly on the choice of the signature mask size. Moreover, for the chosen missile launching geometry, the missile attitude did not contribute effectively to the performance degradation as the sizing mask did. This computational methodology gives insight and approximate answers to difficult missile engagement problems, presents storage requirements for table lookup, and mainly evaluates the effects of a computer vision algorithm in a generic, but realistic, interception scenario.

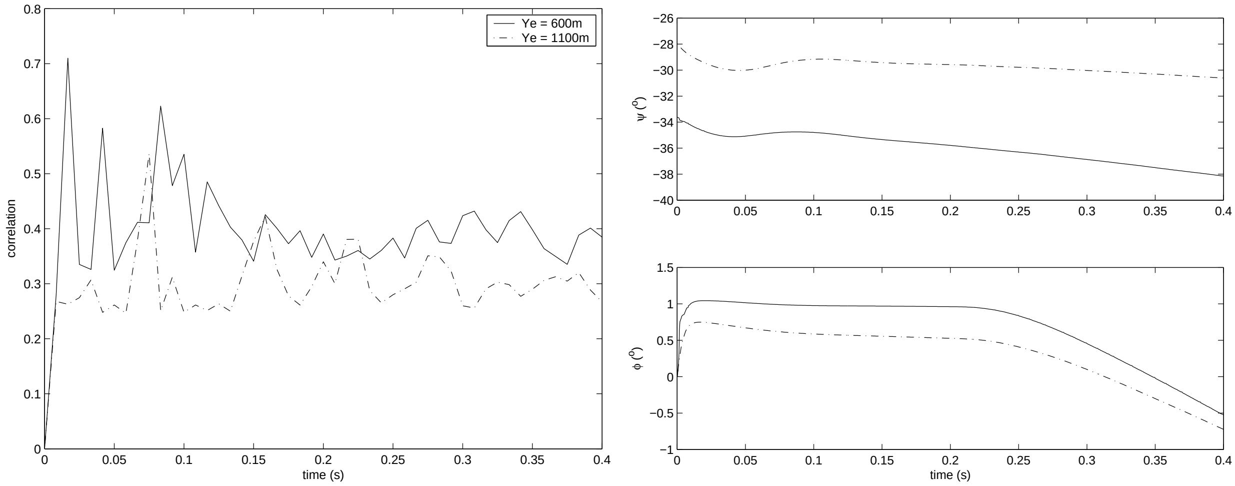

Figure 6. Correlation values and ψ and ϕ critical missile attitude obtained for different missile launching positions.

5. Acknowledgements

The first author would like to thank The State of São Paulo Research Foundation (FAPESP) under Grant 02/10632-0. The second one was supported by Casimiro Montenegro Filho Foundation (FCMF) under Grant 94/2002-ITA ‘Control Systems for Aerospace Applications’. Both thank Professor Cairo L. Nascimento Jr., Mr. Marcelo M. Garcia, and FAPESP under Grant 03/09433-5 for the computational workload support.

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