Adaptive Simulated Pilot

Phillip D. Stroud*
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

Introduction

THE decision-making behavior of commanders, analysts, and weapon operators dominates what happens in combat. Battlefield simulation (an essential analysis and training tool) needs models that can emulate the behavior of these decision makers. This Note describes the development and implementation of a model of the pilot in an airborne laser theater missile defense (ABL-TMD) system.[1,2] The pilot's cognitive task is to steer the aircraft on a path that maximizes protection against missiles, while remaining within an assigned rectangular region of airspace. It is demonstrated that a pilot model based on a Darwinian cognitive architecture can generate more realistic, humanlike behavior than scripted flight paths or preprogrammed rule-based models.

The ABL-TMD concept is shown in Fig. 1. Missiles are launched from within a scenario dependent threat region. The ABL shoots the missiles with a high-power laser during their boost phase. The minimum constant-altitude turning radius for the aircraft is about 24 km, so the pilot must plan turns sensibly to avoid crossing the boundaries. The field of fire of an ABL is blocked aft, and so the pilot must decide when to turn the plane to engage missiles that are launched behind the field of fire.

The measure of performance (the missile intercept probability) depends on such factors as the laser power, beam transmitter diameter, laser wavelength, beam jitter, and turret slew rate. Another set of factors characterizes the scenario and may change drastically during the course of a regional conflict: the size and location of the launch zone(s), the missile types, the number of launches, and the timeline of launches. The software package ELASTIC has been developed to simulate the operation of the ABL system in the TMD environment. ELASTIC consists of a collection of C++ classes to construct actors that model the ABL aircraft, missiles, a missile tracker, a fire controller, a pilot, and the laser beam. It employs a laser propagation model[3] and a boost phase missile fly-out model of sufficiently high fidelity to ensure reliable evaluation of the missile intercepts. The laser system parameters have been arbitrarily selected to provide roughly a 50% intercept probability for a nominal threat geometry (one launch zone, 200 km deep, 400 km wide, and 200 km distant from the front edge of the assigned ABL region). On the order of 10,000 engagements must be simulated to obtain an estimate of the intercept probability that is valid to within 0.5%.

The adaptive pilot model is constructed with a three-part Darwinian cognitive architecture. The first part is a parameterized rule-based behavior, which provides a mapping from a set of inputs (two plane location coordinates, the plane heading, and a flag indicating the presence of a missile behind the field of fire) onto a turn (left or right). The second part is an internal evolutionary apparatus, which generates and maintains a population of alternative control parameters for the rule set. It implements a genetic algorithm to evolve this population, using a chromosome representation of the control parameters, with genetic crossover, mutation, and fitness-based selection. The third part is an internal simulation by which the pilot represents the external world and evaluates alternative behaviors. The internal simulation in the pilot model is also constructed from the ELASTIC package, giving a simulation within a simulation.

Rule-Based Pilot Behavior

The behavior of human pilots has been captured into a collection of 15 IF/THEN rules. The conditions in these rules contain trigonometric and algebraic relations among the heading, the plane coordinates, and seven adjustable parameters (the left- and rightmost coordinate that the pilot will fly, offsets behind the front of the ABL box of right- and left-heading set lines, two Boolean flags specifying whether the plane must turn forward at the right and left extremes of its orbit, and a maximum desired heading for approaching the corner turning circles). Rule prioritization resolves conflicts when several rules can be invoked.

The five highest-priority rules keep the plane from crossing the front or sides of the box when heading forward. The next two rules prevent the plane from crossing a side of the box when the plane is heading rearward. If possible, the plane will execute a forward turn, but if necessary it will execute a rearward turn. The next three rules make the plane follow a rearward diagonal line tangential to the front corner turning circles so that a forward turn can be executed. The next rule checks to see whether the fire controller has requested that the plane turn toward a target to bring it into the field of fire.[4] The next two rules make the plane fly along lines parallel to the front of the box by turning rearward if ahead of these lines. The next rule ensures transition from left-side to right-side behavior, and the lowest-priority rule turns the plane toward the threat.

Adaptation of Pilot Behavior

A 7-bit gene is used to represent each of the five real-valued parameters, allowing 128 possible values for each. The two Boolean flags can be represented with 1 bit each. The control parameters can, thus, be represented as a chromosome consisting of a string of 37 bits. Each of the $2^{37} = 1.37(10)^{11}$ different 37-bit strings represents a different set of control parameters and a different pilot behavior.

A simple form of genetic algorithm is used to search for better adapted control parameters as follows.[5] First, the internal simulation scenario is initialized to the currently perceived external conditions. An initial population of 36 trial chromosomes is constructed by mutating the original (current best) chromosome (with a 15% bit flip probability). The fitness of the pilot behavior corresponding to each of these trial chromosomes is then evaluated by internal simulation of 10,000 missile engagements. Then, the population is evolved by stepping through generations, looping over the four processes of 1) fitness-based selection of parents; 2) generation of new trial chromosomes, using genetic crossover and mutation operations; 3) fitness evaluation of the new chromosomes; and 4) incorporation of new chromosomes into the population, replacing less-fit chromosomes. The mutation rate is started at a large value and is decreased after each generation using a power law annealing schedule. Whenever a chromosome is found that has better estimated fitness than the current reactive behavior, the control parameters are replaced with the better values.

Results

Nominal Performance of Simple Behavior

In a nominal scenario, the missiles are launched from a rectangular launch zone that extends from 200 to 400 km in front of the

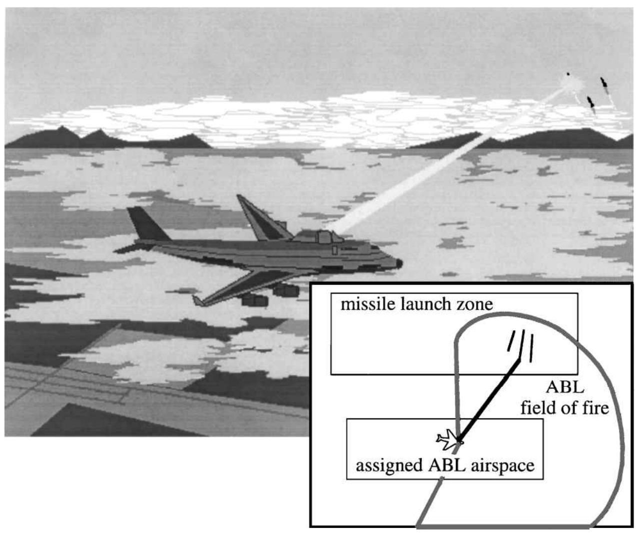

Fig. 1 Airborne laser destroys theater missiles during their boost phase. The pilot's cognitive task is to maximize coverage of the missile launch zone while staying in assigned airspace.

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*Technical Staff, Technology and Safety Assessment Division.

assigned ABL air space and has a width of 400 km. Each sortie in this scenario has 110 missiles launched over a 2.5-h period. Each launch occurs at a random location within the launch zone and at a random time. It is rare for there to be more than one engagable missile at a time. The assigned ABL air space has a width of 500 km and is centered left to right on the threat. The trajectories carry the missiles to a range that is uniformly distributed on the interval from 400 to 600 km. The general direction of the missile flight is over the ABL zone, with a $\pm$25-deg spread in missile launch direction.

A scripted figure-eight orbit, in which the plane never turns away from the threat, has been used in several missile defense simulations. The effectiveness of this flight behavior is assessed by simulating 91 sorties, consistent with the nominal scenario. The figure eight is contained in a 240 $\times$ 48 km rectangle at the front center of the ABL box, centered left to right on the threat launch zone. This expert flight controller allows the ABL to intercept 5426 of 10,010 simulated missiles, giving an intercept probability of 54.2% $\pm$ 0.5% and a leakage fraction of 45.8%.

Automatic Discovery of Improved Behavior

The pilot model can search for behaviors that are better adapted to the nominal scenario than the figure-eight script. After evaluating 544 trial control parameter sets against the nominal scenario, a new pilot behavior, designated flyConA, was discovered that intercepts 6235 of 10,010 missiles. The leakage fraction is reduced from 45.8% to 37.7%. A sample flight path generated by flyConA is shown in Fig. 2a. The pilot model has discovered that a racetrack configuration outperforms the figure-eight controller. It also has found that the clockwise racetrack should be offset to the left, so that the turn away from the threat occurs closer to the center of the threat than the turn into the threat. It has also adjusted the offset of the leftward- and rightward-heading legs to balance the needs to be closer to the threat, to have room to turn to the target, and to avoid having to turn backward to make the turns at the ends of the racetrack.

Automatic Behavioral Adaptation to Unanticipated Conditions

The adaptive pilot model has been demonstrated in a simulated regional conflict, during which the missile threat changes. At the start of the conflict, the threat differs from the nominal threat in that the launch zone is only 100 km deep because of the opposing force's desire to reach deeper targets. When the pilot model evaluates its initial behavior, flyConA, with its internal simulation of the initial threat, it finds that 7978 of 10,010 missiles would be intercepted, for a leakage fraction of 20.3%. The pilot model then evolves the control parameters against the initial threat scenario. After evaluating 644 trial control parameter sets, a new pilot behavior is obtained that would intercept 8646 of 10,010 missiles, reducing the leakage fraction to only 13.6%. This new pilot behavior, designated flyConB and shown in Fig. 2b, is characterized by the tendency to be about 13 km farther back in the assigned ABL airspace. This behavior was neither produced by the human pilots nor considered in developing flight-path scripts. However, the behavior appears reasonable for this threat and within the bounds of what a human might do.

As the regional conflict progresses, the opposing forces switch to another launch configuration, with two 40 $\times$ 40 km launch zones, 300 km apart. The first is located 300 km in front of the ABL's assigned air space, whereas the second is located 200 km in front. Now 60% of the missiles are launched from the second zone. When the current behavior, flyConB, is evaluated against this threat, 6568 of 10,010 missiles would be intercepted, for a leakage fraction of 34.4%. The pilot model again employs its evolutionary apparatus and finds (after internal evaluation of 566 trial behaviors) a new behavior that intercepts 7290 of 10,010 missiles, reducing the leakage fraction to 27.2%. As shown in Fig. 2c, this behavior, designated flyConC, produces a complicated, asymmetric figure-eight configuration. It is easy to imagine unlimited variations on this threat scenario, with various proportions of the missiles launched from each box and various launch box locations and sizes. Each variant threat would lead to a best-adapted flight controller. This approach of adapting to any given scenario is more practical than the approach of preprogramming pilot behaviors for every conceivable scenario.

Near the end of the simulated regional conflict, the opposing force prepares to attack a secondary target located to the left of the original target. One 50 $\times$ 50 km launch zone is located 100 km to the left of and 250 km in front of the assigned ABL air space. When the current behavior, flyConC, is evaluated against this new threat, 4042 of 10,010 missiles would be intercepted, giving a leakage fraction of 59.6%. The pilot model again evolves its behavior, finding a new behavior (after evaluating 604 trial control parameter sets) that intercepts 8201 of 10,010 missiles, dramatically reducing the leakage fraction to 18.1%. This new flight behavior, designated flyConD and shown in Fig. 2d, flies a small angled racetrack in the front left

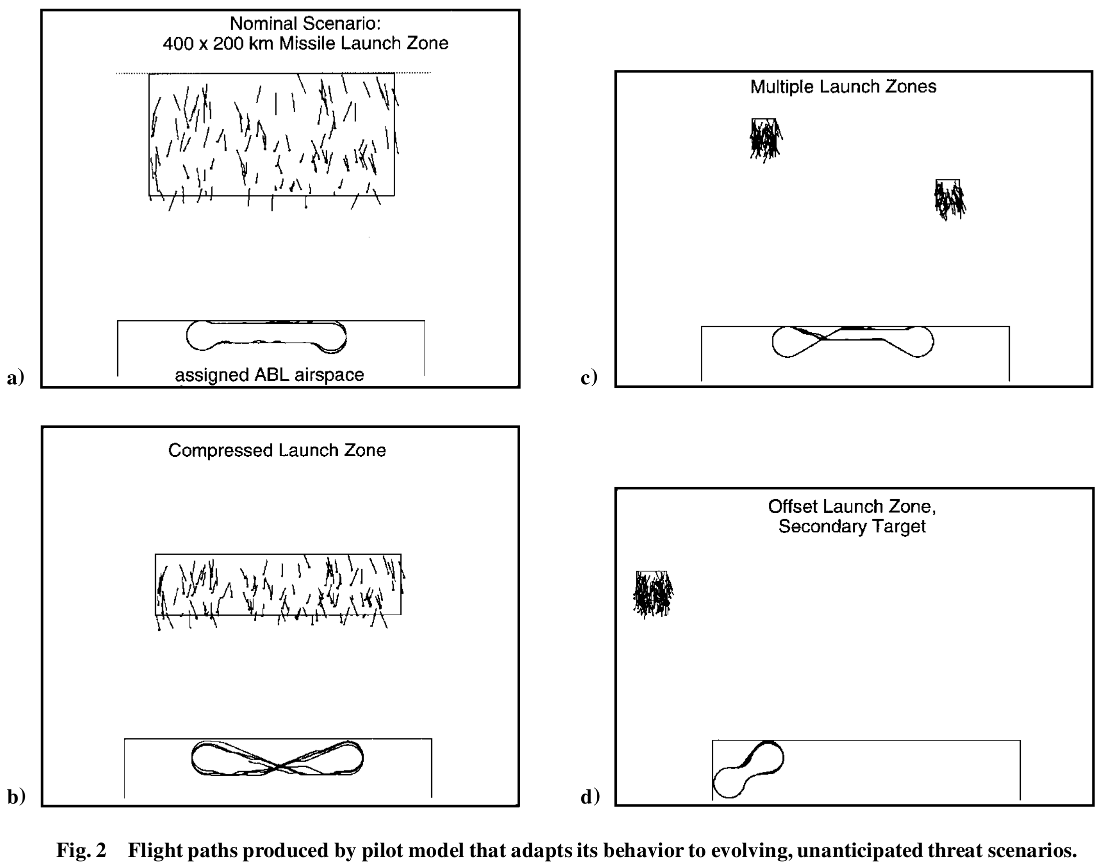

Fig. 2 Flight paths produced by pilot model that adapts its behavior to evolving, unanticipated threat scenarios.

corner of its assigned air space. It is likely that a human pilot would develop a similar behavior.

Conclusion

The implementation of pilot behavior with a parameterized set of rules is seen to be an effective way to represent a vast array of alternative behaviors. It can easily be set to mimic the behavior of human operators over a limited domain. In addition, any knowledge obtained during the evolutionary adaptation can be readily extracted from the new control parameter values. The genetic algorithm is seen to be an effective method for evolving a population of trial control parameters in a continuous search for better-adapted behaviors in a complex, dynamic environment. The use of an internal simulation is seen to be a practical way to represent knowledge about the external world.

The adaptive pilot model was able to generate behaviors that were significantly better than those of preprogrammed models. Like the human pilot it emulates, the pilot model can adapt its behavior when faced with novel threats and, thus, significantly reduce the fraction of missiles that leak through.

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Chaos in Wraparound Fin Projectile Motion

W. Asrar,* M. F. Baig,† and S. A. Khan*
Aligarh Muslim University, Aligarh 202002, India

Nomenclature

C_d	= coefficient of drag
C_l	= rolling moment coefficient
C_N	= normal force coefficient
C_n	= yawing moment coefficient
C_y	= lateral force coefficient
d	= body diameter, reference length
I_{xx}, I_{yy}, I_{zz}	= moments of inertia
I_{xy}, I_{xz}, I_{yz}	= products of inertia
l, m, n	= x, y, z components of aerodynamic moments
M	= Mach number
p, q, r	= roll, pitch, and yaw rates
Q	= dynamic pressure
S	= reference area, $\pi d^2/4$
T_x, T_y, T_z	= thrusts in x, y, and z directions
T^2	= torus with two frequencies
T^3	= torus with three frequencies
t	= time
V	= translational velocity
W_0	= total mass
α, β, Ψ	= angles of attack, side slip, and yaw
δ	= fin cant angle
δ_1, δ_2	= thrust misalignment angles
θ, ϕ, φ	= rotation angles
ω_p	= pitch frequency

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*Reader, Department of Mechanical Engineering.

†Lecturer, Department of Mechanical Engineering. E-mail: met44mfb@amu.nic.in. Member AIAA.

Introduction

PROJECTILES with wraparound fins (WAF) have acute inherent dynamic instability. They show unfavorable damping characteristics, which lead to unpredictable flight behavior in pitch and yaw rates as well as in angle of attack and sideslip angle. Through the concept of a slightly asymmetric missile, Nicolaides[1] showed the possibility of roll resonance. Nicolaides[2] further put forward the idea of roll lock-in and catastrophic yaw. A more general analysis of the motion of rolling asymmetric bodies was presented by Murphy.[3] Nayfeh and Saric[4] analyzed the roll resonance of a re-entry vehicle and obtained necessary conditions for roll lock-in to occur. A more detailed work on roll lock-in of finned projectiles was done by Murphy.[5] Ananthkrishnan and Raisinghani[6] explored the stability of lock-in solutions and roll resonance.

A numerical study of nonlinear dynamics of WAF projectiles from the viewpoint of chaos is presented here. The aims of the study are to find the boundaries of periodic, quasiperiodic, and chaotic motions; to ascertain whether roll–pitch resonance lock-in occurs through phase portrait analysis; and to activate roll breakout by controlling the rotation number.

The scope of the work can be seen from two viewpoints: either elimination of chaos during the design phase of WAF projectiles or inclusion of controlled chaos to make the space–time trajectory unpredictable.

Mathematical Model

The equations of motion are derived with respect to a fixed-plane coordinate system. The x-axis points downrange, the y-axis points to the left looking downrange, and the z-axis points up:

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \big[QSdC_l + qr(I_{yy} - I_{zz}) + (q^2 - r^2)I_{yz} + pqI_{zx} - prI_{xy} + qI_{xy} + rI_{zx}\big]\big/I_{xx} + (-pI_{xx} + qI_{xy} + rI_{xz})/I_{xx} \tag{1}$$

$$\frac{\mathrm{d}q}{\mathrm{d}t} = \big[QSdC_m + rp(I_{zz} - I_{xx}) + (r^2 - p^2)I_{zx} + qrI_{xy} - pqI_{yz} - pI_{xy} + rI_{yz}\big]\big/I_{yy} \tag{2}$$

$$\frac{\mathrm{d}r}{\mathrm{d}t} = \big[QSdC_n + pq(I_{xx} - I_{yy}) + (p^2 - q^2)I_{zx} + qrI_{xy} - qrI_{zx} + pI_{zx} + qI_{yz}\big]\big/I_{zz} \tag{3}$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -\frac{QSC_{d\,\mathrm{wind}}}{W_0} + g\cos\phi(\cos\theta\sin\alpha\cos\beta + \sin\phi\cos\theta\sin\beta - \sin\theta\cos\phi\cos\beta) + \frac{T_x}{W_0}\cos\alpha\cos\beta + \frac{T_y\sin\beta + T_z\sin\alpha\cos\beta}{W_0} \tag{4}$$

$$\frac{\mathrm{d}\alpha}{\mathrm{d}t} = -\frac{QSC_l}{W_0V\cos\beta} + q - \tan\beta(p\cos\alpha + r\sin\alpha) + \frac{g}{V\cos\beta} + (\cos\phi\cos\theta\cos\alpha + \sin\theta\sin\alpha) - \frac{T_x\sin\alpha - T_z\cos\alpha}{W_0V\cos\beta} \tag{5}$$