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CLOSE RANGE ONE TO ONE AIR COMBAT MANEUVERING FOR AUTONOMOUS UAV

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ABSTRACT

Autonomous Control of UAV is a complex problem that has many parameters requiring low level robust control. In air combat there are more than one aircraft and relative geometry of both sides are also included into this complex problem. Control objective is getting to an advantageous position rather than following a constant trajectory. Long term trajectory planning is not possible since relative geometry changes instantaneous. In this paper, a solution is proposed that chooses the right movement to take advantage on the other aircraft. The solution considers the energy conversion and turn radius heuristics. Depending on the relative geometry of both sides, air combat controller decides on the movement and synthesizes the necessary control signal. An offensive and a defensive BFM scenario are designed to test the behavior of the system. The simulations demonstrated that the proposed scheme has considered the combat constraints.

INTRODUCTION

Robotic equipments are used for performing activities where it is difficult, expensive, dangerous or time consuming when done by human. When it comes to air combat, unmanned air vehicles (UAV) appear to be critical military weapons. UAVs are used by many countries for reconnaissance, observation, tracking in military areas and fire extinguishing, transportation in civil areas. Limited countries have developed UAVs for target determining and destruction and designed systems are kept secret for national sovereignty issues. These UAVs are remotely controlled from ground and attack on predetermined targets. Controlling the UAV from ground during air combat is not practical for UAVs since there are latencies between the human decision on ground, communication channels and digital mechanical processing on the platform and one human pilot is required per UAV. So it is an effective usage area to perform maneuvers to destruct opponent by teaching air combat rules and leaving the control completely to the autonomous UAV. UAVs also have more maneuvering capabilities since constraints of human biology are not applied on them.

“Basic Fighter Maneuvers” (BFM) has been popular after World War II. There are one-to-one, one-to-many and many-to-many maneuvers performed by war fighter pilots during close air engagement for evacuation from rockets, defensive or offensive purposes which are also known as dog-fight.

The domain information about air combat is documented by [Shaw, 1985] and is the text book of flight schools in many air forces. Using manned aircraft for air combat is dangerous for human and it is hard and expensive to train and maintain fighter pilots. [Burgin and Sidor, 1988] has developed rule-based systems to support human pilots. Implementing air combat as a pursuer-evader game by [Isaacs,

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1951] calculates a limited range of combat besides fighter can be an evader while it is pursuing. Influence Diagrams are utilized by [Virtanen, 2006] but planning horizon is limited due to complicated state vector. A human cognitive model is designed by [Andriambololona and Lefeuvre, 2003]. [McManus, 1990 and McManus and Goodrich, 1989 and Rodin and Amin, 1992] proposes and compares using AI techniques for air combat maneuvering. [McGrew and How and Bush and Williams and Roy, 2010] proposes Approximate Dynamic Programming method for pursuing an evader in air combat. [Ure and Inalhan, 2012] proposes a sliding mode controller design to define primitive aerial movements and compose maneuvers from them.

Our work advances the subject area in terms of controlling the BFM logic. Assuming that there are 2 equivalent aircrafts in an air combat, the relative geometry and advantage of both sides are calculated, an appropriate BFM is decided and control signals are generated to execute the BFM movements. This should be considered the contribution of the current work.

This paper is organized as follows: In the next section we introduce the definitive terms of the problem. The “System Dynamics” section defines the proposed system and dynamics. “Air Combat” section defines how the relative geometry is calculated and BFM logic is executed. “Simulation Results” section discusses the output of the system and analysis the results. The last part constitutes the concluding remarks.

PROBLEM DEFINITION

The objective of an air combat scenario is to move your aircraft into a position where you most probably shoot the other aircraft or minimize the ability of being shot by the other aircraft starting at any position. This depends on the positional advantage of both aircrafts which depends on the “relative geometry” to each other.

Aircraft is controlled by selecting “control actions” using the pilot stick and gas pedal. The outputs of these inputs are transferred into mechanical assemblies like propulsion system, ailerons, elevators and rudder. After applying aerodynamic equations with atmospheric coefficients, forces on 3 dimensions are calculated. In this paper this chain is neglected and focused on the forces since the real focus is not on controlling these mechanics.

When moving in 3 dimensions, some other transformations like energy conversion have to be considered. In air combat energy is an important resource to preserve. Slowing down the aircraft or instant acceleration has too much cost. For example the system should choose to increase the altitude to lower the speed and calculate the required turn radius for a particular relative geometry.

In a real air combat, both sides are maneuvering instantly to take advantage. Both sides can be in offensive position while was defensive in the previous action of the engagement. So classical pursuer-evader tactics is not applicable since pursuer only considers pursuing and evader only considers evading. Since relative geometry changes instantly, there is no need to over plan for a long horizon.

SYSTEM DYNAMICS

To keep the airframe simple, point mass equations are used. Using point mass, angle of attack, roll angle, side slip angle and angular velocity of bank angle are neglected. The system is composed of the aircraft system and air combat controller. Aircraft system has a state with initial values. Control variables are forces acting on the system. The dynamics of the system between forces and states are same as point mass as expressed below. The system imports the desired reference position to move, calculates range and angular errors and determines required forces.

Air combat controller (ACC) imports the states of both aircrafts and outputs the reference position. ACC has 2 main blocks. First block computes the relative geometry. Relative geometry does not care about the magnitude of the velocity but the angles. It also calculates the additional potential velocity which can be converted to actual velocity if one aircraft has more altitude. Second block decides the maneuver to make and calculates the reference position to move. The reference position is the output of the ACC.

Aircraft System

Point mass; is a constant mass in the space which has position [x y z], moving with velocity v in angles of χ in X axis and γ in Z axis. With the forces applied on the body axis of the point, the system changes the velocity and angles using below dynamics and modifies the position in space.

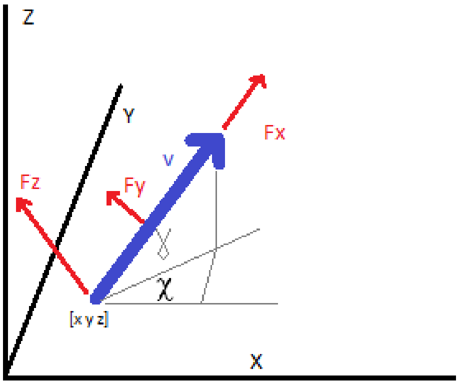


Figure 1 Point mass

<u>States</u> of the system: $[x\ y\ z\ v\ \gamma\ \chi]$

<u>Inputs</u> to the system: $[F_x\ F_y\ F_z]$

F_x is applied on the direction of v vector.

F_y is applied perpendicular to v vector pointing right.

F_z is applied perpendicular to v vector pointing up.

<u>Dynamics</u> of the system:

Magnitude of the velocity and acceleration is modified by F_x with below equations.

$$\dot{v} = \frac{F_x}{m} \tag{1}$$

$$v_t = v_0 + \int_0^t \dot{v}(\tau)dt \tag{2}$$

Flight path angle γ is modified by F_z with below equations.

$$\dot{\gamma} = \frac{F_z}{mv} \tag{3}$$

$$\gamma_t = \gamma_0 + \int_0^t \dot{\gamma}(\tau)dt \tag{4}$$

Heading angle χ is modified by F_y with below equations.

$$\dot{\chi} = \frac{F_y}{mv\cos(\gamma)} \tag{5}$$

$$\chi_t = \chi_0 + \int_0^t \dot{\chi}(\tau)\, dt \tag{6}$$

Position $[x\ y\ z]$ at time t is calculated with below equations;

$$x_t = x_0 + \cos(\gamma)\cos(\chi)\int_0^t v(\tau)dt \tag{7}$$

$$y_t = y_0 + \cos(\gamma)\sin(\chi)\int_0^t v(\tau)dt \tag{8}$$

$$z_t = z_0 + \sin(\gamma)\int_0^t v(\tau)dt \tag{9}$$

Control Loop

The control loop imports the reference and current states, calculates error and provides required input to the aircraft system.

Reference

Reference is the desired position $[X_d\ Y_d\ Z_d]$.

State

State is the current position of the system and angles of the velocity. Using reference and state the range (r) to the reference point and desired angles are calculated. This is a 3 element vector $[r\ \gamma_d\ \chi_d]$

$$r = \sqrt{(X_d - X)^2 + (Y_d - Y)^2 + (Z_d - Z)^2} \tag{10}$$

To keep angle errors between [-π ... π] atan2 is applied. i.e. $\alpha = \mathrm{atan2}(\sin(\alpha), \cos(\alpha))$

$$\chi_d = \mathrm{atan2}\left(\frac{Y_d - Y}{\sqrt{(X_d - X)^2 + (Y_d - Y)^2}}, \frac{X_d - X}{\sqrt{(X_d - X)^2 + (Y_d - Y)^2}}\right) \tag{11}$$

$$\gamma_d = \mathrm{atan2}\left(\frac{Z_d - Z}{r}, \frac{\sqrt{(X_d - X)^2 + (Y_d - Y)^2}}{r}\right) \tag{12}$$

Error

Error is the range and angular difference from current state to reference point. The error has 3 components. These are range, flight path angle and heading angle errors. $[E_r\ \mathrm{E}_\gamma\ \mathrm{E}_\chi]$

Range error is the distance to reference position in body X axis

$$E_r = r\cos(E_\gamma)\cos(E_\chi) \tag{13}$$

Flight path angle error is angular difference of velocity vector to reference position on Z axis

$$\mathrm{E}_\gamma = \mathrm{atan2}(\sin(\gamma_d - \gamma), \cos(\gamma_d - \gamma)) \tag{14}$$

Heading angle error is angular difference of velocity vector to reference position X axis

$$\mathrm{E}_\chi = \mathrm{atan2}(\sin(\chi_d - \chi), \cos(\chi_d - \chi)) \tag{15}$$

Force Controller

The necessary force signals required to modify the system state to recover the error is calculated with PID controller using the formulas below.

$$\ddot{y} = \ddot{r} + K_d\dot{e} + K_p e \tag{16}$$

$$\ddot{r} - \ddot{y} + K_d\dot{e} + K_p e = 0 \tag{17}$$

$$\ddot{e} + K_d\dot{e} + K_p e = 0 \tag{18}$$

$$(s^2 + K_d s + K_p)E(s) = 0 \tag{19}$$

$$(s + \sqrt{K_p})^2 E(s) = 0 \tag{20}$$

$$(s^2 + 2\sqrt{K_p}s + K_p)E(s) = 0 \tag{21}$$

$$K_d = 2\sqrt{K_p} \tag{22}$$

$$F_x = \ddot{E}r + K_{d1}\dot{E}r + K_{p1}Er \tag{23}$$

$$F_y = \ddot{E}\chi + K_{d2}\dot{E}\chi + K_{p2}E\chi \tag{24}$$

$$F_z = \ddot{E}\gamma + K_{d3}\dot{E}\gamma + K_{p3}E\gamma \tag{25}$$

$$K_p = [1\ 64\ 64] \tag{26}$$

$$K_d = [2\ 16\ 16] \tag{27}$$

AIR COMBAT

Air combat maneuvering can simply be expressed as “moving the aircraft to a position that one can probably shoot the enemy or survive from enemy's weapon”. Relative geometry between each aircraft determines if one is in offensive or defensive position by calculating an advantage function. Air combat controller proposes the desired position to move.

Relative Geometry

Relative geometry is the range (line of site vector) between the position of two aircrafts and angles of the velocity vectors between the range [r, ATA1, ATA2]. These angles are named "Antenna Train Angle" (ATA).

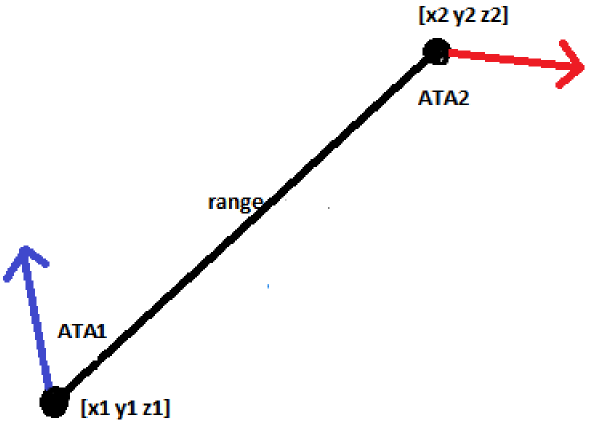


Figure 2 Relative Geometry

The range between 2 points is the norm value of the two. The change in the range is the closure velocity V_c of both points.

$$r = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + (z_1 - z_2)^2} \tag{28}$$

$$V_c = \frac{dr}{dt} \tag{29}$$

Advantage function is how probably one can shoot the other aircraft. There are 2 advantages. These are angular and energy advantage.

Angular advantage is how close ones velocity vector is to the range vector. Lower ATA has more advantage. Since cos(0) = 1 and cos(π)=-1, the cosine of ATA can be accepted as the angular advantage of the aircraft. Calculation of cosine of the angle between range and velocity vector is;

$$d_x = x_1 - x_2, d_y = y_1 - y_2, d_z = z_1 - z_2 \tag{30}$$

$$\cos(ATA_1) = -\frac{(d_x\cos(\gamma_1)\cos(\chi_1)) + (d_y\cos(\gamma_1)\sin(\chi_1)) + (d_z\sin(\gamma_1))}{r} \tag{31}$$

$$\cos(ATA_2) = \frac{(d_x\cos(\gamma_2)\cos(\chi_2)) + (d_y\cos(\gamma_2)\sin(\chi_2)) + (d_z\sin(\gamma_2))}{r} \tag{32}$$

Energy advantage is how much additional velocity can be gained from the altitude difference if one aircraft has larger altitude. Assuming that the aircraft falls down to the same altitude of the other with preserving the initial velocity, the final velocity can be calculated as;

$$d_z = \frac{(v_f + v_0)t}{2} \tag{33}$$

$$t = \frac{v_f - v_0}{g} \tag{34}$$

$$v_f^{\,2} - v_o^{\,2} = 2gd_z \tag{35}$$

$$v_f = \sqrt{v_0^{\,2} + (2d_z g)} \tag{36}$$

Turn radius

Turn radius is the radius of the circle that aircraft route draws. The minimum value of the turn radius (R_{min}) is constrained by the maximum pressure (P_{max}) that the body of the airframe can resist. This dictates a maximum angular acceleration. Minimum turn radius at velocity v is;

$$R_{min} = \frac{m \times v}{P_{max}} \tag{37}$$

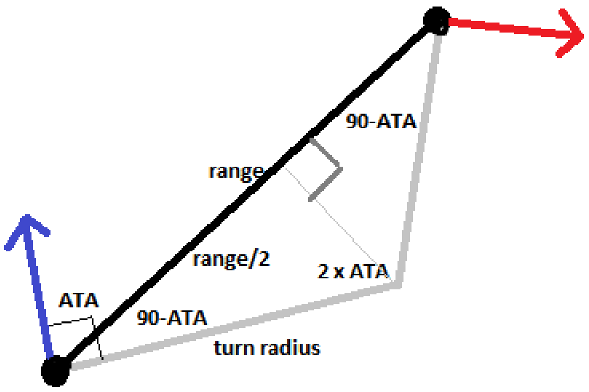


Figure 3 Turn radius

If one aircraft tries to get angular advantage, then it should turn towards the other as quickly as possible. The range between two aircrafts dictates the below maximum turn radius where $ATA > 0$.

$$R_{max} = \frac{r}{2\sin(ATA)} \tag{38}$$

Minimum turn radius is important at close ranges. If minimum turn radius is less than maximum turn radius, then speed should be decreased. An acceptable maneuver to decrease speed with preserving energy is to climb up without applying additional force ($\gamma = \frac{\pi}{2}$, $F_x = -mg$) and complete the turn when velocity is low enough.

$$v < \frac{rP_{max}}{2m\sin(ATA)} \tag{39}$$

Defensive Break

The simplest defensive maneuver is to turn right or left sharply when other aircraft has angular advantage. Turning direction (o) is the sign of $\chi_1 - \chi_2$. Turning with angle of π/2 is to switch v_x and v_y .

$$o = sign(atan2(\sin(\chi_1 - \chi_2), \cos(\chi_1 - \chi_2))) \tag{40}$$

$$v_x = v\cos(\gamma)\cos(\chi) \tag{41}$$

$$v_y = v\cos(\gamma)\sin(\chi) \tag{42}$$

$$R_x = X - ov_y \tag{43}$$

$$R_y = Y + ov_x \tag{44}$$

$$R_z = Z \tag{45}$$

COMPLETE BLOCK DIAGRAM

The block diagram consists of two aircrafts and two air combat controllers.

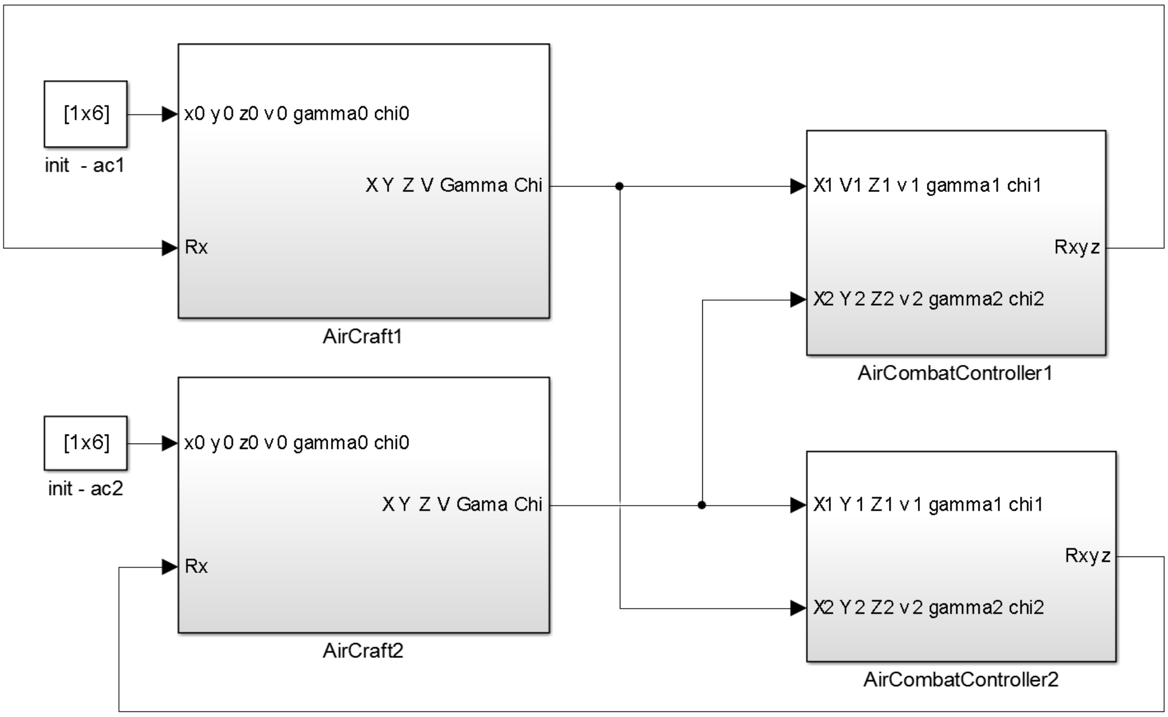


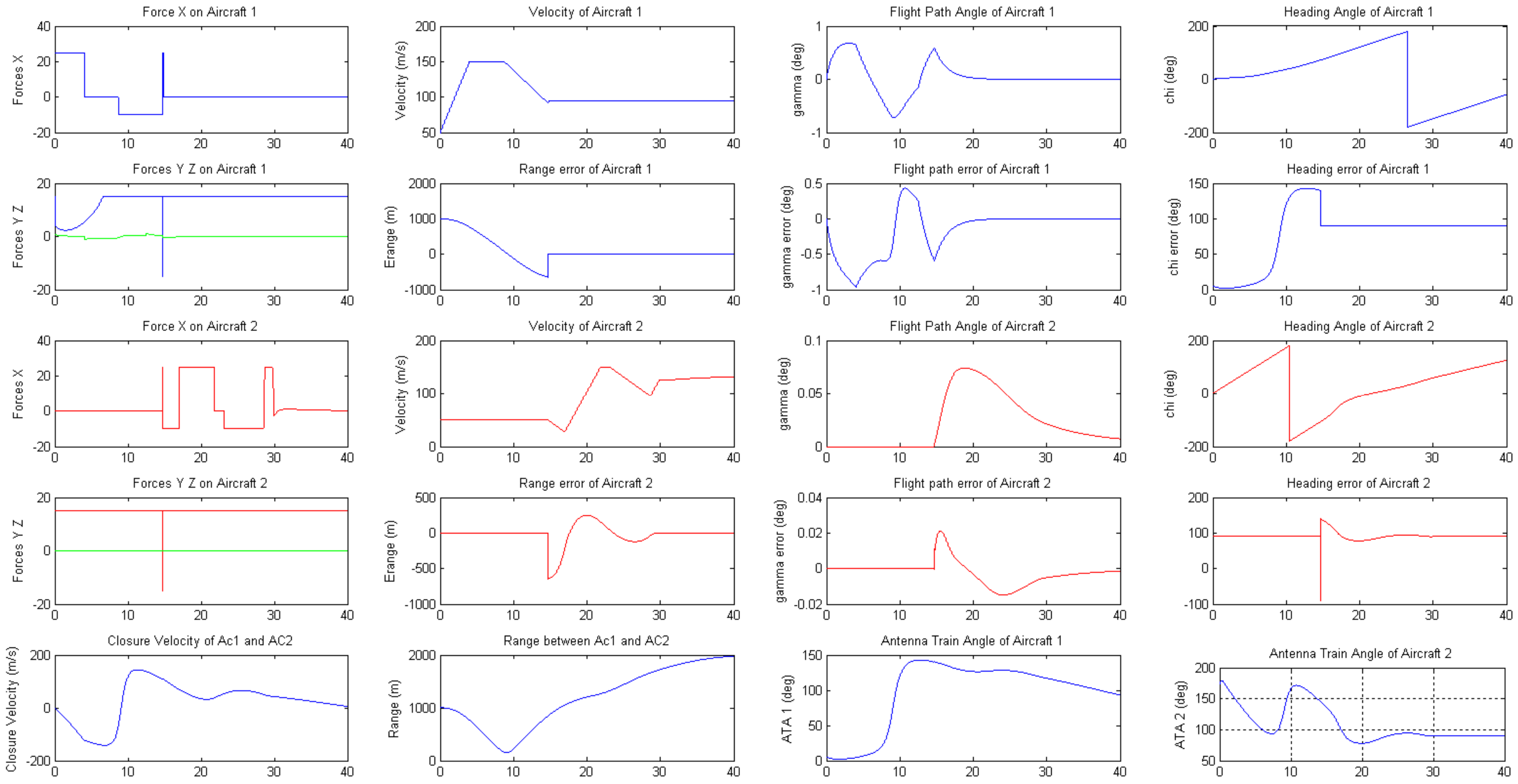
Figure 4 Complete Block Diagram

Aircraft state is input as the 1st state to its own air combat controller and other aircrafts state is as the 2nd and the same for the second controller as well. 1st ACC generates reference position for 1st AC and 2nd ACC for the 2nd AC.

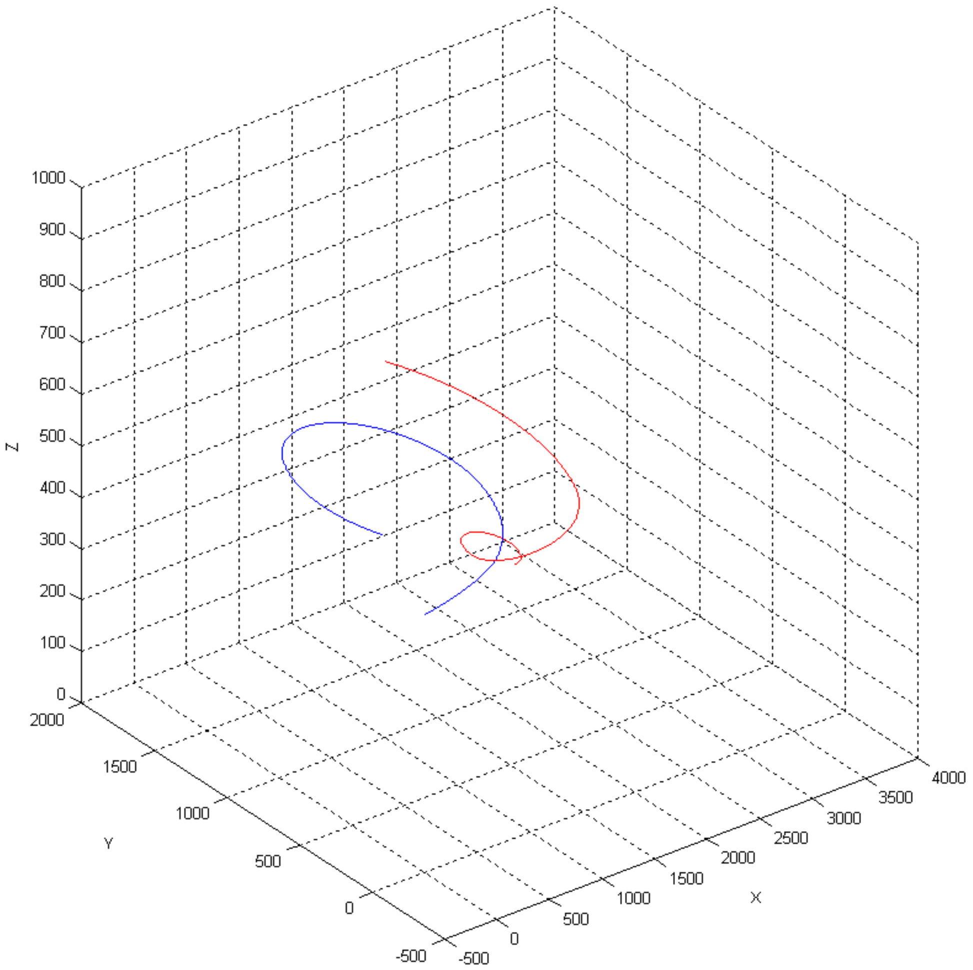
SIMULATION RESULTS

Simulation is run starting in a relative geometry scenario that blue aircraft has positional advantage. The results are plotted in 3-D flight route in [X Y Z] axis and time series of 2-D plots. 2-D plots are grouped into 3 sets. First is the force, acceleration, velocity, flight path angle, heading angle of first aircraft. Second set is the same as first set for the second aircraft. Third set is the relative geometry which includes range, closure velocity, turn radius of AC1 and antenna train angles of AC1 and AC2.

States


Force X on Aircraft 1
Forces X
40
20
0
-20
Velocity of Aircraft 1
Velocity (m/s)
200
150
100
50
Flight Path Angle of Aircraft 1
gamma (deg)
1
0
-1
Heading Angle of Aircraft 1
chi (deg)
200
0
-200
Forces Y Z on Aircraft 1
Forces Y Z
20
0
-20
Range error of Aircraft 1
Erange (m)
2000
1000
0
-1000
Flight path error of Aircraft 1
gamma error (deg)
0.5
0
-0.5
-1
Heading error of Aircraft 1
chi error (deg)
150
100
50
0
Force X on Aircraft 2
Forces X
40
20
0
-20
Velocity of Aircraft 2
Velocity (m/s)
200
100
0
Flight Path Angle of Aircraft 2
gamma (deg)
0.1
0.05
0
Heading Angle of Aircraft 2
chi (deg)
200
0
-200
Forces Y Z on Aircraft 2
Forces Y Z
20
0
-20
Range error of Aircraft 2
Erange (m)
500
0
-500
-1000
Flight path error of Aircraft 2
gamma error (deg)
0.04
0.02
0
-0.02
Heading error of Aircraft 2
200
100
0
-100
Closure Velocity of Ac1 and AC2
Closure Velocity (m/s)
200
0
-200
Range between Ac1 and AC2
Range (m)
2000
1000
0
Antenna Train Angle of Aircraft 1
ATA 1 (deg)
150
100
50
0
Antenna Train Angle of Aircraft 2
ATA 2 (deg)
200
150
100
50
0
10
20
30
40

3-D Flight route



Evaluation

The simulation results show that the aircraft with less advantage tries to make defensive break maneuver and draws a circle around itself. The offensive AC tries to converge to the defensive AC fast where ATA is close to 0. When ATA is too high for acceptable turn radius and range is close, the offensive AC tries to increase altitude and decrease speed until it can turn towards the other AC as defined by [Shaw, 1985].

CONCLUSION

The objective of this paper was to demonstrate that an air combat controller can provide reference points to execute a BFM maneuver and generate signals to move the aircraft to the reference point without human interaction. The wisdom included in the BFM controller was to take care of energy conversion and turn radius which are critical decisions of a combat fighter. Real combat fighter pilots study every BFM maneuver in [Shaw, 1985] separately. Every BFM maneuver has its own heuristics and wisdom which has to be solely investigated.

This paper has shown that an autonomous combat UAV can make decisions depending on the relative geometry using the given BFM logic and can execute this decision in 3-D environment without human interaction in one-to-one air combat.

We restricted our study to control the error between current and reference points using simple point mass equations. We also covered only one BFM maneuver. Future work should focus on extending this approach using more complex non-linear plants and investigate every BFM scenario in its own context.

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