

## 6DOF Missile Trajectory Simulation Using Reusable Frame and Models

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**Abstract.** A reusable frame and appropriate models are designed for six degree of freedom (6DOF) missile trajectory simulation. The importance of establishing trajectory simulation model in missile design and experiment is described at first. Guidance Navigation and Control (GNC) loop as the core component in missile is discussed with emphasis on performance limitations. Design Patterns (DP) in software engineering are utilized to accomplish module partition. Reusable design is conducted in a two-step process: frame design and models design. This method can improve design productivity and shorten design circle as its reusable frame and relevant models can applied to many kinds of missiles without major revisions. An air defense scenario is designed to validate the proposed model frame. The 6DOF trajectory simulation results are obtained. Results show that the method offers an effective and practical way to design parameters and evaluate performance of missile.

### Introduction

Missile as one kind of precision guided weapon is getting increasingly significant during modern warfare [1]. To solve the complexity of multidisciplinary design optimization (MDO), lots of factors coupled of missile system need to be investigated based on the sensitivity analysis [2]. A variety of methods can be used, as theoretical analysis model, analytical model, hardware-in-the-loop (HWIL) tests and field tests. Among these methods, modern synthetic simulation plays an important role in design parameters and evaluates performance of missile because of its lower cost and repeatability. Six degree of freedom (6DOF) refers to the displacement of a rigid body in three-dimensional space [3]. Specifically, the body is *free* to move forward/backward, up/down, left/right with rotation about three perpendicular axes, often termed pitch, yaw and roll. 6DOF trajectory simulation as an effective and practical way is getting extensive attention. Due to the complexity of MDO as well as diversity of missile types, 6DOF trajectory simulation usually could not easily conduct.

In this paper, a reusable frame and appropriate models are well designed to solve this problem. A two-step process is proposed with emphasis on reusable design. A typical scenario is also designed for further validation and demonstration.

### Trajectory Simulation

#### Missile GNC Loop

Guidance navigation and control (GNC) loop is the core of missile system. Take the surface-to-air missile (SAM) for example, the terminal phase of SAM engagement puts forward a high requirement on its GNC loop, depicted in Fig. 1, as one has to take several key factors into account including target high-speed, low-altitude, stealth (low RCS), unknown maneuver, onboard ECMs, fin-angle demand, autopilot tag, missile body aerodynamic characteristics [2].

Seeker outputs, i.e. missile-to-target (M2T) relative motion measurements, are converted into three axes acceleration demands by using a specified guidance law, such as the augmented proportional navigation (APN) law used in this paper. Considering real-time missile flying status, mainly its body

attitude, a control command unit generate control instruction transferred to the following execution device, i.e. a tail fin to stabilize body while guide the missile to the designated target according to the input acceleration demand. Tail fin responses the steering angle commands to achieve the actual fin angles. Once fin angles are changed, the interceptor SAM is aerodynamically controlled, and a 6DOF closed loop missile trajectory simulation is finally accomplished.

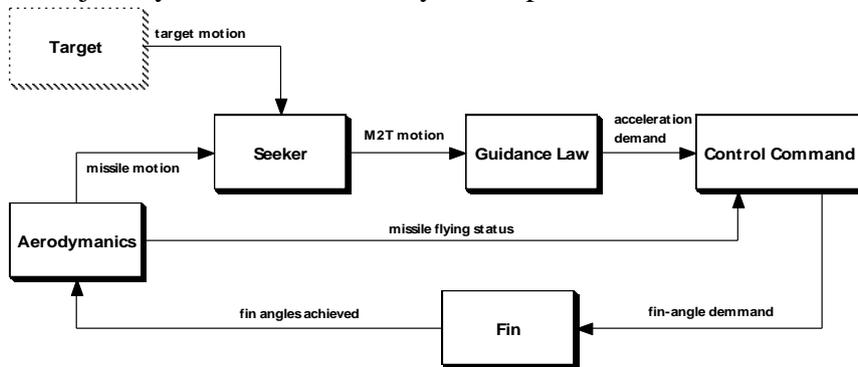


Figure 1. SAM's GNC loop.

## Design Pattern

To conduct 6DOF trajectory simulation, modern simulation techniques could be utilized to help improve design productivity and shorten design circle. Design pattern (DP) in software architecture is a formal way of documenting a solution to a design problem in a particular field of expertise [4]. Take the *Strategy Pattern* (also known as the policy pattern) for example; it is a design pattern that enables an algorithm's behavior to be selected at runtime, and it lets the algorithm vary independently from client that uses it. As an example, strategy pattern can be used in missile guidance law design, as a variety of law could be selected by clients, as proportional navigation (PN), augmented proportional navigation (APN) shown in Fig. 2. Each pattern describes a problem that occurs over and over again in practice, and then depicts the core of solution to that problem. We can use this solution without ever doing it the same way twice. Accordingly, design productivity would improve drastically.

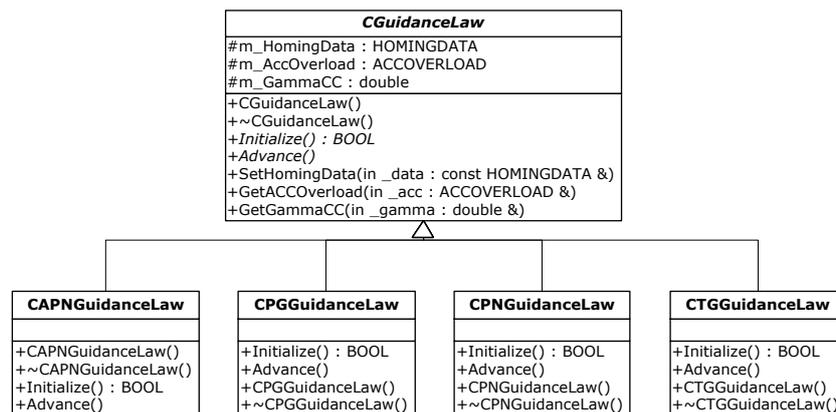


Figure 2. Strategy pattern used in guidance law design.

## Reusable Frame Design

### Functional Requirement and Interfaces

In the first place, we have to carefully research the functional requirement. In the form of dynamic link library (DLL), 6DOF trajectory simulation model can be chosen to fit the needs of versatility and expansibility. As depicted in Fig. 1, the complexity of MDO in missile systems could easily confuse capacity requirements with auxiliary needs. One has to set up an abstract logic structure diagram of missile system as well as trajectory simulation. The trajectory simulation is considered from the black

box perspective only; the only interactions shown are those between this model and the system actors. Accordingly, we list the functional requirements and relevant interfaces as below.

**Initialization.** The initialization process should be conducted as soon as a missile object created. Those initialization parameters include missile mass, size, initial flight status, aerodynamic feature, thrust data, rotation inertia, mass decreasing rate, flight range, etc.

**Presetting.** Missile as one kind of precision guided weapon needs launch data presetting, such as initial body position, velocity, heading, attitude and selected target information (for detection use).

**Command Input.** During the phase of terminal guidance (as homing guidance), seeker outputs are converted into three axes acceleration demands to guide the missile to the designated target. While in the phase of midcourse flight (as remote command guidance), command from ground control station is sent to missile for the flight attitude control. After responding to the input instructions, the missile is aerodynamically controlled, and closed loop missile trajectory simulation can finally accomplish.

**Flight Solution.** Flight solution is the main task of simulation model. Those rotation angles and linear displacements of missile body are solved corresponding to the input instructions.

**Status Inquiry.** By inquiring trajectory simulation model, one can obtain the real-time flight status as well as missile internal status, including acceleration demands, control instruction, steering angle commands, actual fin angles and onboard navigation outputs.

**Termination.** A fuse module in missile model can be used to sense M2T motion in near-field and thus complete the final detonation decision; missile trajectory simulation would then terminate.

### Configuration Items

By modularizing model design, one can separate content from structural presentation. Some other basic design principles as simplicity, tolerance and decentralization are also followed. As depicted in Fig. 3, missile model is divided into *seven* main parts (sub-systems), including I/O interface, thrust, navigation, guidance & control, aerodynamic, kinematics and master control.

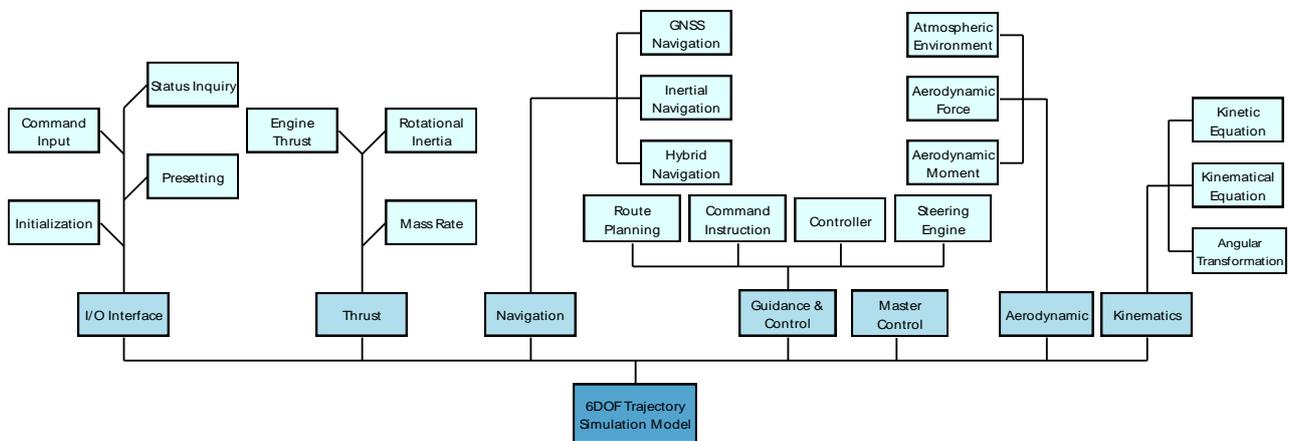


Figure 3. Configuration items.

**I/O Interface.** It is designed to execute input/output data exchange, including model initialization, command input, missile status inquiry, etc.

**Thrust.** It is divided into three parts: engine thrust, rotation inertia and mass decreasing rate.

**Navigation.** This item is designed to obtain missile real-time flight navigation solution by using onboard navigation apparatus, as GNSS, inertial navigation system (INS) and their integration.

**Guidance & Control.** It is the core of missile model. Command inputs are converted to demands of acceleration, then transferred to control instruction fed to the following execution device. Tail fin responses the steering angle commands to achieve the actual fin angles.

**Aerodynamic.** It describes missile aerodynamics characteristic. Once fin angles are changed, the missile body is aerodynamically controlled.



## Simulation Test

A typical air defense scenario is designed. Note that we *only* focus on the terminal guidance phase of engagement; the midcourse guidance is *not* considered. Some key experiment parameters are listed in Table 1, and their values and units are also described.

Table 1. Table headings.

	Parameters	Values	Units	Notes
1	initial target position	(7000, 1000, 0)	m, m, m	X, Y, Z-axis component in the reference frame, i.e, local level frame (LLF)
2	initial target velocity	(200, 0, 0)	m/s, m/s, m/s	
3	initial missile position	(0, 200, 400)	m, m, m	
4	initial missile velocity	(600, 0, 0)	m/s, m/s, m/s	
5	initial missile attitude	(0, 0, 0)	$^{\circ}$ , $^{\circ}$ , $^{\circ}$	yaw, pitch, roll, respectively
6	effective navigation ratio	4.5	--	used in APN guidance law
7	trajectory update period	10	ms	same as seeker update period

The 6DOF trajectory simulation is finished as below. Real-time missile and target motion data is sent to a functional seeker model to extract M2T relative motion measurements, i.e. range, range rate, line-of-sight (LOS) angles and their rates. After inertial angular rates of LOS are estimated in seeker model, homing guidance is then accomplished by the APN law. The fin-angle instruction is generated in BTT control unit to guide SAM interceptor to target while stabilize missile body. Tail fins response the angle command; actual fin angles in three axes is achieved. SAM is aerodynamically controlled, and a 6-DOF closed loop trajectory simulation is finally finished.

Firstly, missile-to-target relative motion in the reference frame (i.e. LLF) is shown in Fig. 6, where missile attitudes (yaw, pitch, roll, angle of attack and angle of slide) are also described in Fig. 7.

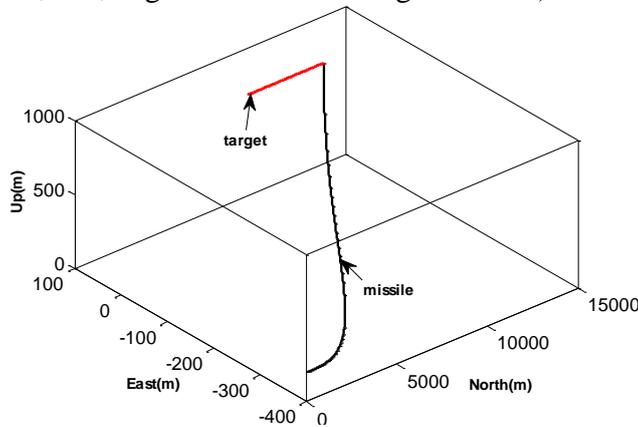


Figure 6. Missile-to-target relative motion in LLF.

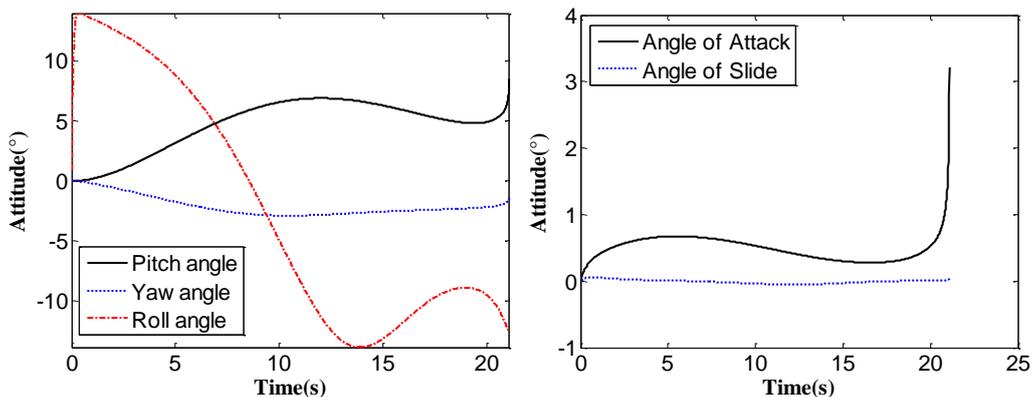


Figure 7. Missile attitudes in LLF.

The command and actually achieved missile overloads in azimuth channel are compared in Fig. 8. The impact made by autopilot lag and missile aerodynamic characteristics on actual overload can be reflected. Body rates in three axes are also shown in Fig.8. These measured LOS angles are compared with true values in Fig. 9, where good angle estimation performance of seeker model is shown.

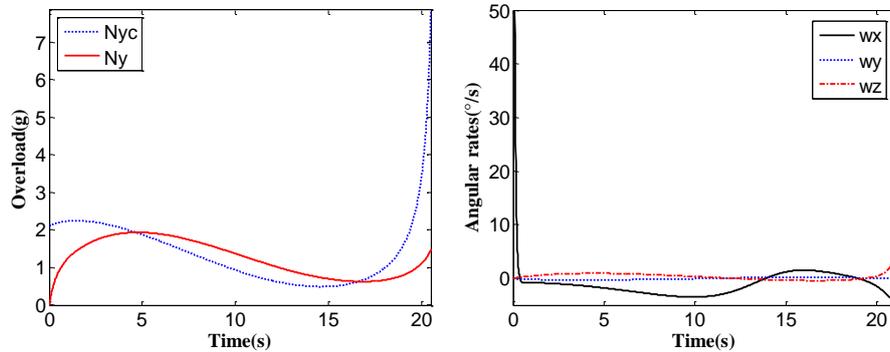


Figure 8. Missile accelerations (left) and body rates (right)

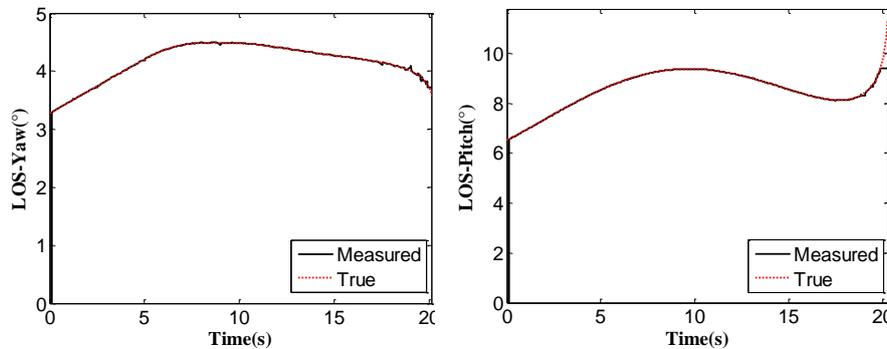


Figure 9. Line-of-sight angle measurements (left: yaw, right: pitch).

## Summary

A reusable frame and appropriate models are designed for 6DOF missile trajectory simulation thus to offer an effective and practical way to design parameters and evaluate performance of missile system. A study will follow up in reusable model verification and its application.

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