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Simulation of Fighter Aircraft Weapon Systems for Design & Performance Evaluation

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ABSTRACT

Simulation forms an essential tool in the system design and performance evaluation of fighter aircraft weapon systems. The various guidance strategies used for weapons like guns, missiles, bombs in the air-to-air or air-to-ground missions, for aiding the pilot for an effective delivery have been studied through extensive off-line and pilot-in-loop simulation. The pilot workload analysis carried out in the high fidelity cockpit simulator at the Aeronautical Development Agency, Bangalore, provides the system designer an effective means to tune the various subsystems for better performance. The paper focuses on all these aspects to bring out the importance of simulation in the overall fighter aircraft weapon system design.

NOMENCLATURE

- λ Lead angle vector
- V_a LCA true airspeed
- V_m Bullet muzzle velocity
- V_t Target velocity vector
- R Present range to target
- R_f Bullet distance travelled
- ω Line of sight angular rate
- T_o Initial time
- T_f Time of fight of bullet
- dV/dt Target acceleration vector

1.

mission, the pilot plays a pivotal role. This means design of a complex system consisting of man, machine and man-machine interface. Hence, modelling and simulation are essential to carry out the design of such weapon systems and subsequently their performance evaluation through pilot-in-loop studies.

This paper describes the typical weapon system of a fighter aircraft. Off-line and real-time (pilot-in-loop) simulation studies which are used in the design and performance evaluation of fighter aircraft weapon systems are brought out. Mathematical models, block diagrams and numerical techniques used in simulation are touched upon briefly. Computation of the errors of a weapon system in terms of its subsystem errors is discussed for a particular case. Pilot-in-loop simulation at the Aeronautical Development Agency (ADA) used in the design and evaluation of weapon systems is described.

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2. MATHEMATICAL MODELS, NUMERICAL TECHNIQUES & NATURE OF SIMULATION

2.1 Mathematical Models

Mathematical models form the base of simulation. The complexity and structure of mathematical models are to be decided upon based on the purpose of simulation. The models are influenced by requirements like off-line simulation, pilot-in-loop real-time simulation, sensitivity analysis, etc. Simulation of weapon systems involves the model of sensors, control and guidance computation systems, data latencies, display symbol dynamics, etc. In addition, modelling the pilot for off-line analysis is also important.

2.2 Numerical Techniques

Selection of appropriate numerical techniques is also very important. Weapon systems being dynamic in nature demand solution of non-linear differential equations which have to be solved simultaneously. The time constants of various elements of the system may be widely varying. In such situations, the accuracy of solution and the available computational time influence the method of solution, selection of different integration step sizes, etc.

2.3 System Design

System design and performance evaluation of fighter weapon system are carried out through two modes of simulation.

2.3.1 Off-Line Simulation

Off-line simulation is normally used during the critical design phase wherein accuracy of the results and sensitivity analysis assume prime importance. Mathematical models which form the backbone of simulation, accommodate most of the parameters which influence the system. This analysis is augmented by including the pilot model and evaluating the performance of the design. The off-line simulation model along with the pilot model is a benchmark for the real-time pilot-in-loop simulation.

2.3.2 Pilot-in-Loop Real-Time Simulation

Pilot-in-loop real-time simulation is used for evaluating the pilot-vehicle interface. Emphasis here is on pilot workload analysis during the mission, related to weapon delivery. The severity of pilot workload adversely influences the performance of the weapon system. The pilot workload is influenced by the operations of the pilot in the cockpit and dynamics of the weapon system. The reaction of the pilot to a threat scenario and the time taken for action to meet the threat are ensured through pilot-in-loop simulation. With the multiple roles the fighter aircraft have to perform, feedback of pilot workload analysis to the overall system design is mandatory for efficient delivery of the weapon system. Hence, the simulation demands a high fidelity cockpit environment and weapon system dynamics.

3. FIGHTER AIRCRAFT WEAPON SYSTEM SIMULATION

3.1 Description

To support the pilot in making an effective delivery of the weapons, the aircraft is equipped with various sensors like radars, inertial navigation systems, air data sensors, radio altimeters, laser rangers, infrared search and track system, etc. The measurements and the processed outputs from these units are acquired by the mission computer and processed to generate the cockpit display symbols for steering the aircraft and commands to the weapon system for preparation and delivery. The pilot steers the aircraft on the basis of these symbols, makes decisions to deliver the weapon on the basis of the information provided to him on various cockpit displays and finally commands the release of weapon at the correct instant. The weapon system is a pilot-in-loop feedback control system which has to be designed for accuracy and dynamic responses acceptable to the pilot. A typical block diagram of fighter weapon system is shown in Fig. 1.

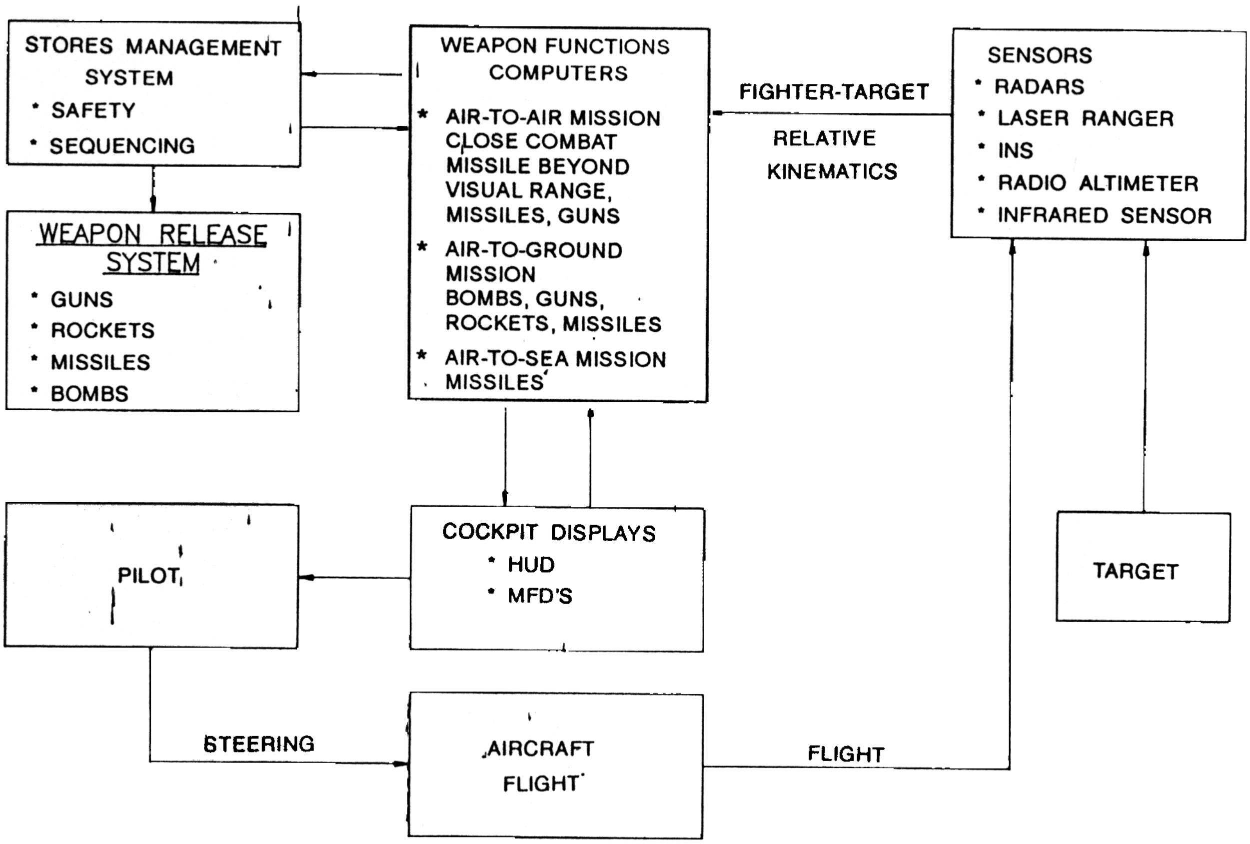

Figure 1. Block diagram of fighter aircraft weapon system

3.2 Air-to-Air Mission

3.2.1 Gunnery

The general air-to-air gunnery fire control problem is to fire projectiles at a moving target from a moving platform (like the LCA) so as to score hits on the target. The gun fire control system provides the pilot with head-up display (HVD) to steer the aircraft and fire the gun at the correct time. Two popular methods of gun fire control systems are described here.

3.2.1.1 Continuous Computation of Tracer Line Concept

A snapshoot gunsight mode is incorporated, so that the gun can be used for highly dynamic situations in which there are relatively short transient target tracking opportunities. The Continuous Computation of Tracer Line (CCTL) concept (Fig. 2) computes positions of bullets which are released from the aircraft at a specified time interval between them. The CCTL is a line connecting a fixed number of bullet positions corresponding to a set of predetermined bullet flight times (Fig. 2(a)). The trace of bullet points is mechanised in HUD. These positions are displayed as a synthetic trajectory that enables the pilot to observe the relationship between the path of the bullet and the target as if he had been firing continuously. The bullet positions are computed by using bullet ballistics taking into consideration the aircraft velocities, body rates, normal acceleration, etc.

Real-time computation of bullet positions by solving non-linear differential equations for displaying the tracer line on HUD with smooth animation is not feasible because of high periodicity at which these tasks have to be carried out. Therefore, the focus is on developing empirical

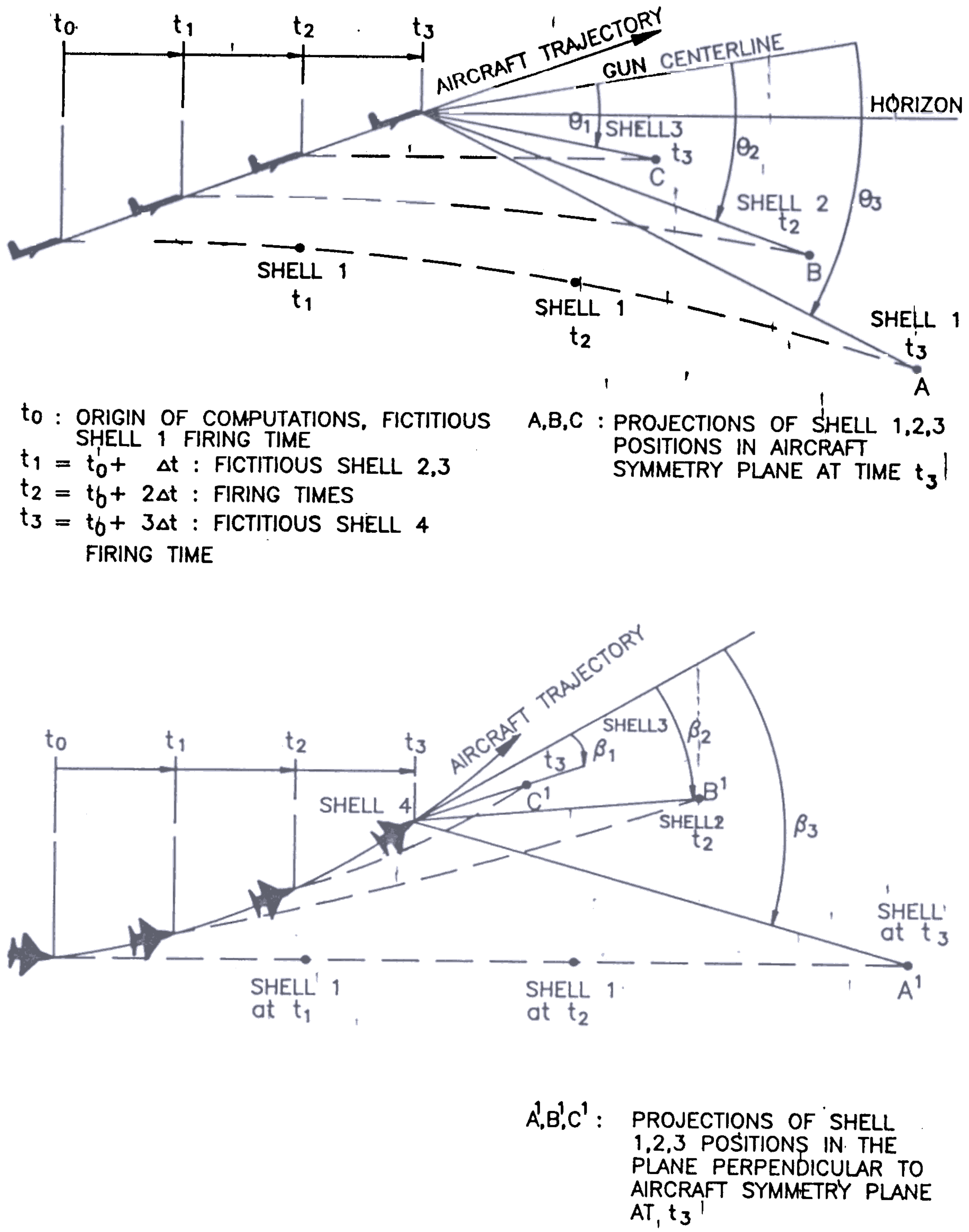

Figure 2. Tracer line generation principle

relations which enable faster computations of bullet positions to generate the guidance cues on HUD and assist in issuing the firing commands at the correct time. The empirical relationships are evolved on the basis of the results obtained from extensive off-line simulation studies. The

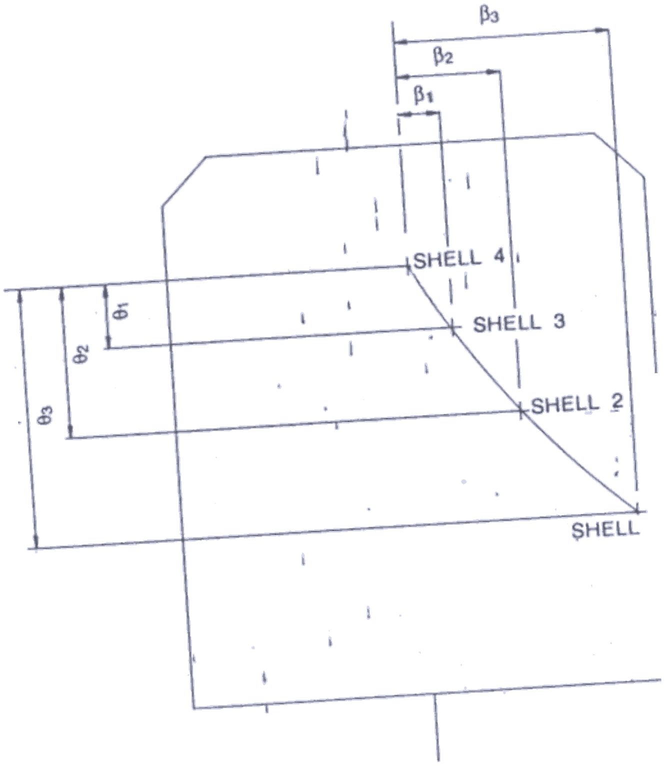

Figure 2(a). Representation of tracer line on head-up display at time, t_3 (for 4 fictitious shell).

complexity of generating these empirical relations increases when all the higher order effects are considered. Factor like gun offsets from the aircraft body axis, orientation of gun axis, angular rate influences on the bullet, manoeuvres of the target, to name a few, influence the outcome.

Using empirical equations to compute the position of the bullets as a function of time after release, fighters speed, altitude and orientation, the CCTL guidance cues are implemented in a pilot-in-loop simulator to carry out pilot workload analysis.

A simplistic point model has been developed taking into account the effects of gravity forces and drag forces. Mechanisation in HUD is done by generating empirical relationships to compute the range as a function of the release altitude, aircraft release velocity and release angle.

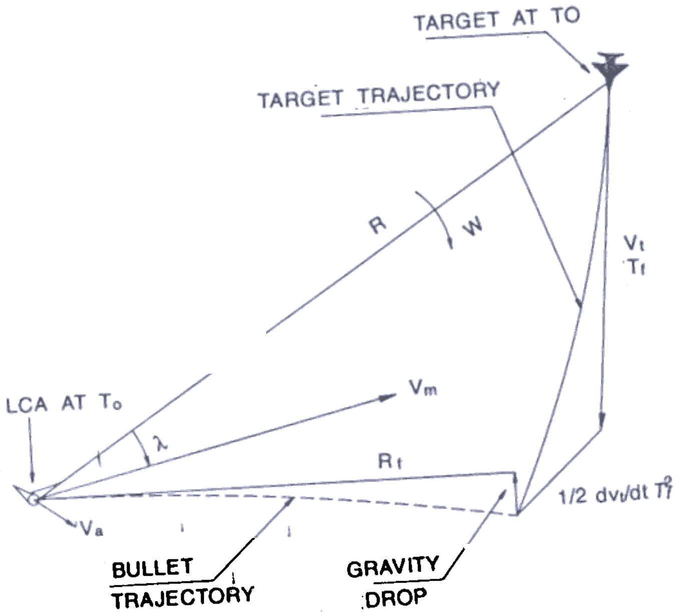

Figure 3. LCOS solution polygon

3.2.1.2 *Lead Computing Optical Sight*

This type of guidance is provided to pilots for use in less dynamic encounter situations in which the pilot has the opportunity to smoothly track the target. The solution of such a problem requires calculation of lead angle defined as the angle between the line of sight and the line joining the gun platform to the collision point. This lead angle is a function of target motion, aircraft motion, gravity effects, aerodynamic drag, etc. Once the lead angle is computed, the solution is transformed to the display for placement of symbology on HUD.

An off-line simulation software with the models of the fighter, target, bullets and pilot as a controller has been developed. The model of the LCOS problem represented as a polygon in vector space is illustrated in Fig. 3. Initially, for a simplified case of planar head-on/tail chase encounters, lead angle computation algorithms are evolved. These algorithms will be subsequently evaluated in pilot-in-loop simulation having high fidelity cockpit and LCA flying qualities. Various target manoeuvres will be tried out.

3.2.1.3 Sensitivity analysis

Performance of the weapon systems under various parameter perturbations is a very important input to the system designer during the design process. Sensitivity of system performance to the inaccuracies in parameters like velocity of the target/aircraft, height, fighter-target range, etc. is being studied.

3.2.2 Air-to-Air Missiles

The LCA carries two types of air-to-air missiles for combat purposes.

3.2.2.1 Close Combat Missile

In an air-to-air close combat role, with missile as the weapon, the pilot needs real-time decision support (i.e. symbology in HUD) for launching the missile, which would ensure the best kill probability with the given aircraft system, weapon capability and the operational situation encountered.

Simulation helps to evolve guidance systems that assist the pilot in steering the aircraft to arrive at the best launch success range for a missile in a given encounter. The simulation package considers the target parameters (i.e. closing speed, direction, manoeuvrability), weapon characteristics (aerodynamic, propulsion, guidance, control and structural limits), the launch parameters (launch velocity and direction of launch), relative geometry between the interceptor and the target aircraft, and a host of other parameters.

As mentioned earlier, with multiple tasks the onboard computer performs, solving the equations of motion for generating the firing envelopes in real-time is not feasible and the need for an empirical relationship again becomes critical. The best launch success range is depicted to the pilot in the HUD as firing envelopes derived from empirical relationships. These empirical relationships are evolved based on the large databases of missile-target interception trajectory simulations.

A simulation package for missile target interception based on point mass equations of motion, including the models of propulsion, aerodynamics, guidance and IR seeker has been developed. This has been used extensively in generating firing envelopes for various encounter geometries. Sensitivity of launch success ranges and kill probability to the encounter parameter like relative position and velocities is determined. Empirical equations are being generated for computing the launch success ranges with respect to dominant encounter parameters.

3.2.2.2 Beyond Visual Range Missile

For medium range target interception, the fighter aircraft carries a beyond visual range (BVR) air-to-air missile with all-weather capabilities. A dual mode guidance consisting of a mid-course phase and a terminal phase is adopted for the missile. The inertial navigation system provides guidance in the mid-course phase with two or three updates from the fighter aircraft. Once the active radar seeker takes over in the terminal phase, the missile homes on to the designated target. Updates to the missile from the fighter aircraft in the mid-course phase are essential because of the incapability of the missile to get the information about the target motion in this phase. Extensive modelling and simulation work is being carried out to study the effectiveness of BVR missile combats and to evolve guidance schemes for pre-guidance and autonomous guidance phases.

3.3 Air-to-Ground Weapon System

The air-to-ground weapons are required to deliver weapons using visual and blind attack techniques against predesignated, in-flight designated or undesignated targets. The algorithms employed in air-to-ground mission include computation of weapon trajectories, positioning of

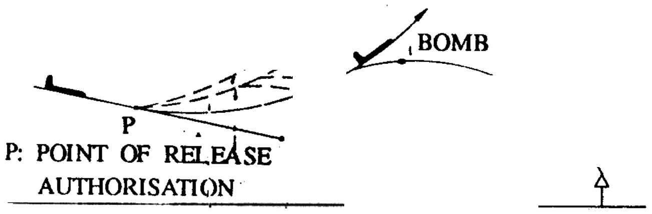

Figure 4. Dive toss mode

display symbols on HUD, generation of release authorisation cues corresponding to the weapon time to go, release at the correct instant, etc.

The fighter aircraft has a wide spectrum of air-to-ground attack weapons, including rockets, low-drag bombs, retarded bombs, runaway denial bombs, laser-guided bombs, air-to-ground missiles, etc. Two modes of delivery of air-to-ground weapons are discussed here.

3.3.1 *Continuously Computed Impact Point*

In the continuously computed impact point (CCIP) mode, continuous prediction of the weapon impact point is accomplished primarily through trajectory integration. The weapon trajectory and the corresponding impact point computation include the effects of non-standard atmosphere, weapon characteristics, gravitational variations, coriolis acceleration, winds and wind shear effects with variable time steps. These computations are used to position the reticle on HUD to enable the pilot to steer the fighter to the correct heading and issue the release command at the correct instant of time.The algorithms will be simulated and evaluated on the cockpit environment simulator.

3.3.2

on HUD is such that the bomb range computed is found equal to or greater than the target range. This is the CCRP mode release authorisation.

A computational scheme for determining the instant of issue of authorisation in the CCRP mode has been developed. The scheme has two parts, one for determining the aircraft position relative to the target location based on the sensor information. The other part determines whether the weapon can reach the designated target if the dive-toss manoeuvre is initiated from the current position.

Modelling and simulation is carried out for a dive-toss attack mode, wherein the aircraft dives from a certain level and pulls up before releasing the weapon. There is a finite time delay between the time at which the pilot is given release authorisation and the time at which he actually commences his pull-up. During this time delay, the aircraft would have traversed a certain distance which is taken into account. The release height for the weapon is calculated and from this height the bomb trajectory is computed along the bomb fall axis. The current information in terms of latitude and longitude of the fighter aircraft is transformed into the bomb fall axis through a set of coordinate transformations and all computations are done in this frame. The impact point is again transformed into the local frame by a reverse set of transformations.

3.4 Error Analysis

The weapon delivery system of the fighter aircraft normally consists of sensors, display systems, weapon ejection system and computational systems. All these equipment have certain inaccuracies which contribute towards the total system error or the impact point errors. Simulation is an essential tool to arrive at the total system error and helps the designer to fine-tune his design by laying down tolerances.

Monte Carlo simulation is carried out on the simulation software by specifying the statistical parameters of system inaccuracies to obtain

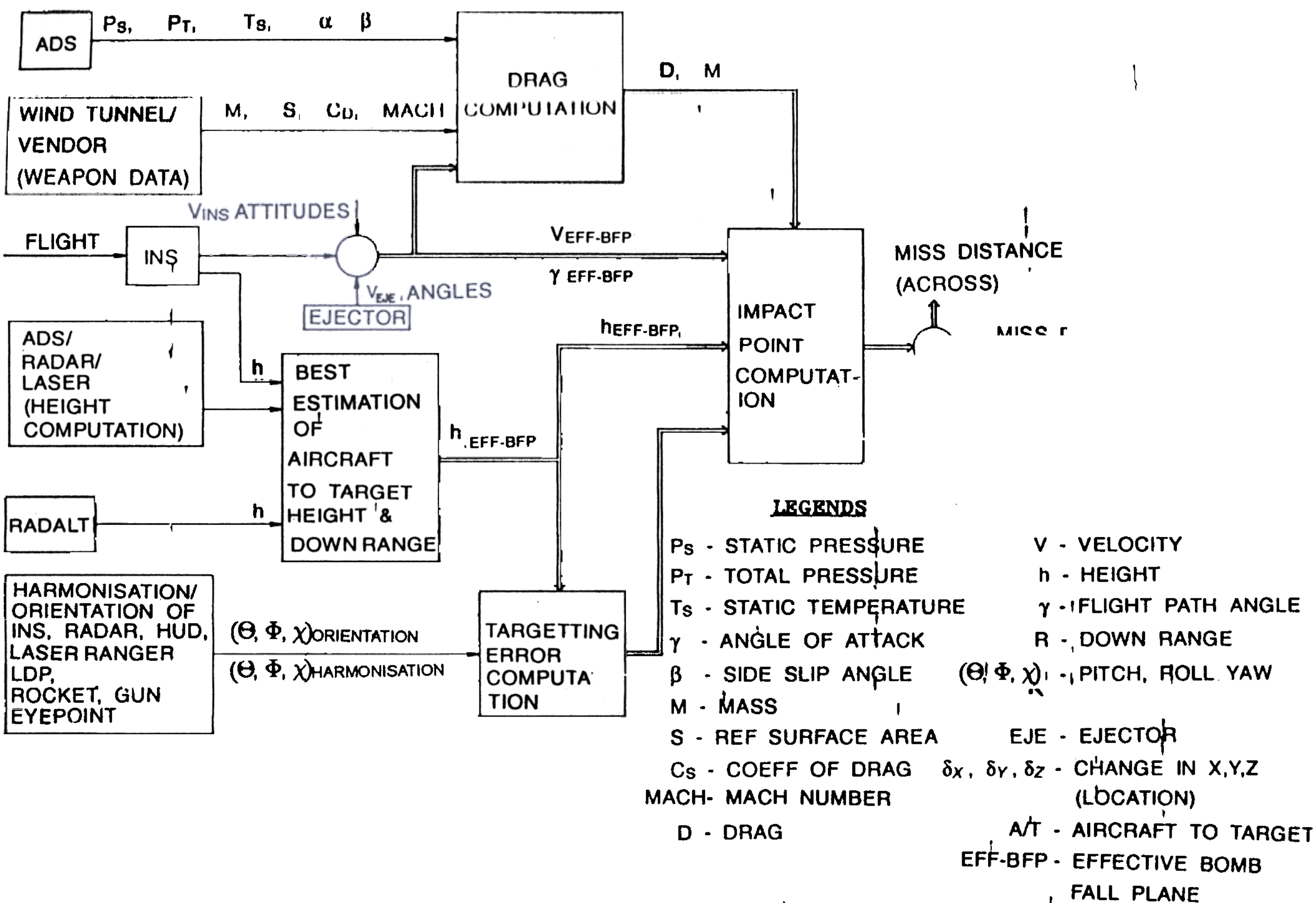

Figure 5. Computational flow AGWAAS

statistical parameters regarding the impact point errors.

A software has been developed for analysing the impact point errors of the fighter aircraft air-to-ground weapon delivery system. The data-base of this software accepts the inaccuracies of a particular system in terms of its 3σ variations and computes the final system error. This air-to-ground weapon aiming performance analysis software (AGWAAS) package is being used extensively and suitable modifications are being carried out to use this for any weapon delivery system. Conceptual block diagram for carrying out the air-to-ground error analysis, is depicted in Fig. 5.

4 COCKPIT ENVIRONMENT FACILITY

The cockpit environment facility (CEF) at ADA is a high fidelity cockpit with LCA flying qualities. This facility performs three major functions in the process of design and performance evaluation of the fighter aircraft weapon system. Firstly, the pilot-in-loop simulation is carried out wherein the algorithms of all the weapon systems are validated by integrating them with the avionics and associated system functionality.

The algorithms described in the earlier sections for different missions are presently in the process of integration with the CEF. This exercise provides various inputs to the designer by carefully studying the pilot workload. Based on the response of the pilot in the selected combat mode, further tuning or redesign is carried out. Secondly, the different symbologies displayed on HUD get evaluated by the pilot. Each of the different modes of delivery—CCTL, LCOS, CCIP, CCRP, etc.—needs to have different symbologies to be

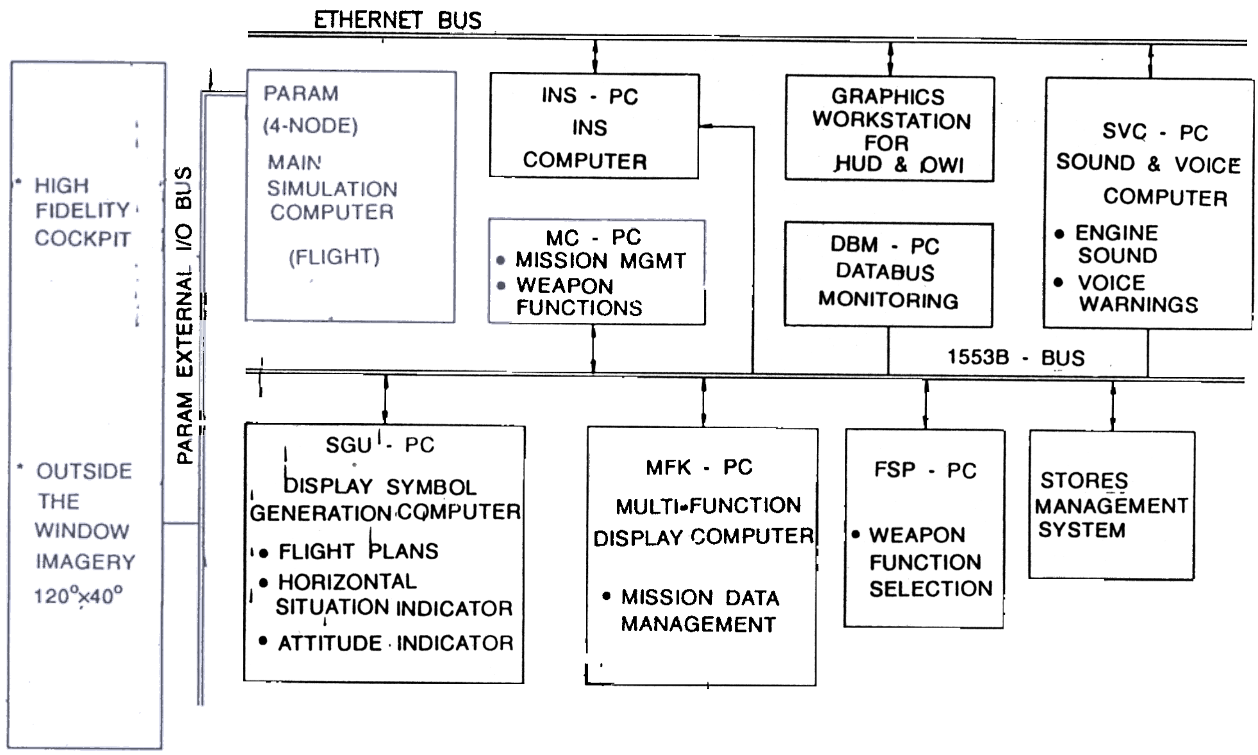

Figure 6. High fidelity cockpit environment facility for weapon system evaluation

placed on HUD. These symbologies are derived by considering the mode of delivery and its functionality as a closed loop system. The ergonomics of the cockpit forms the third major function of the CEF. Functionality block diagram of the high fidelity cockpit environment facility at ADA for weapon system evaluation is shown in Fig. 6.

5. CONCLUSION

The paper highlights the various important aspects of modelling and simulation activities related to the design, development and validation of weapon systems of a fighter aircraft. The importance of modelling and simulation in the development of a complex system consisting of man, machine and man-machine interface as a closed-loop system is specially emphasised. The impact of various error sources on the total system error for a typical air-to-ground mission is dealt with. The importance of the high fidelity cockpit to carry out pilot workload analysis to validate and improve the weapon system performance is brought out elaborately.

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