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Hardware-in-Loop Simulation for Missile Guidance & Control Systems

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ABSTRACT

The purpose of the guidance law is to determine appropriate missile flight path dynamics to achieve mission objective in an efficient manner based on navigation information. Today, guided missiles which are aerodynamically unstable or non-linear in all or part of the flight envelopes need control systems for stability as well as for steering. Many classical guidance and control laws have been used for tactical missiles with varying degrees of performance, complexity and seeker/sensor requirements. Increased accuracy requirements and more dynamic tactics of modern warfare demand improvement of performance which is a trade-off between sophisticated hardware and more sophisticated software. To avoid increase in cost by hardware sophistication, today's trend is to exploit new theoretical methods and low cost high speed microprocessor techniques.

Missile test flights are very expensive. The missile system with its sophisticated software and hardware is not reusable after a test launch. Hardware-in-loop Simulation (HILS) facilities and methodology form a well integrated system aimed at transforming a preliminary guidance and control system design to flight software and hardware with trajectory right from lift-off till its impact. Various guidance and control law studies pertaining to gathering basket and stability margins, pre-flight, post-flight analyses and validation of support systems have been carried out using this methodology. Nearly full spectrum of dynamically accurate six-degrees-of-freedom (6-DOF) model of missile systems has been realised in the HILS scenario. The HILS facility allows interconnection of missile hardware in flight configuration. Pre-flight HILS results have matched fairly well with actual flight trial results. It was possible to detect many hidden defects in the onboard guidance and control software as well as in hardware during HILS.

Deficiencies in model, like tail-wag-dog (TWD), flexibility, seeker dynamics and defects in the guidance and control system were demonstrated in HILS. Appropriate design modifications were introduced and tested in record time to reduce the number of expensive flight trials.

INTRODUCTION

Missile guidance and control system design has undergone phenomenal change due to the modern warfare tactics employed with the advent of computers and microprocessor technology. This sophistication of warfare tactics demands more brain power in the embedded software carried by the missile with the application of superior model and intelligent tools. Use of optimal estimators to replace the conventional lowpass filters is the current trend. This is because more information about missile dynamics and noise covariance is available to the designer due to the increased computational power of present-day processing technology in terms of speed and precision. Design of more advanced guidance laws has become

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possible due to the availability of more accurate and complete information about missile states rather than only line of sight rate and other navigation information. The increased brain power resident in embedded processors has necessitated the use of even more superior and efficient validation methodologies with practical demonstration of missile-target engagement scenario. This is made available in today's simulation computers by high speed hardware logics with inherent parallelism and superfast communication speeds. Missile and target motion simulation along with hardware actuators and associated electronics are also necessary elements of the test bed for validating the guidance and control system with actual hardware and flight software. This sophisticated setup helps to update and freeze the complex non-linear guidance and control systems which is otherwise dependent mostly on linear design methodology.

Hardware-in-loop simulation (HILS), as applied to missile technology, was at its infancy in the mid-eighties in India. Today, a number of guided missiles with inertial/radar guidance, aerodynamic control/thrust vector control (ADC/TVC), and onboard computer (OBC)/analog control are successfully launched with acceptable performance. The increased brain power of the embedded software needs rigorous validation with demonstrated reliability. HILS is used for system design verification, quick flight software generation, verification and validation, system integration, pre-flight and post-flight analyses and demonstration of system performance.

HILS for the guided missile programme started with non-real-time (NRT) environment, evolving into a real-time (RT) missile model with the availability of powerful simulation computers. Uncertainty in the missile model is one of the major hindrances for finalising the software design. Flight systems hardware, like sensors, actuators, onboard computer, real engine with the thrust frame, other fin assemblies and various seeker systems are introduced directly in HILS to minimise the uncertainty. Introduction of these hardware along with sophisticated instrumentation has helped in evaluation of performance of the missile system in a more realistic scenario. Off-nominal cases are also simulated in HILS for demonstrating the robustness of the guidance and control software/hardware system design by stressing it to various disturbances. Essentially, the objectives as met by HILS are:

- Flight software design and validation,
- Flight computer hardware validation, and
- Integrated guidance and control system software and hardware validation.

This paper chronologically highlights guidance and control design issues, modelling and simulation techniques and validation methodologies for guided missile application in defence. Relevant conclusions and suggestions are summarised.

2. GUIDANCE & CONTROL DESIGN

Knowledge (navigation), decision (guidance) and action (flight control system for steering and stability) are three distinct systems required for a missile guidance and control system (Fig. 1). The onboard inertial system (gimbaled/strap-down) supplies information on position, velocity and attitude of a missile with respect to a reference coordinate frame. Target sight line rate from inertially stabilised strapped-down seekers (RF/IR) and other area scene generation from imaging sensors are fundamentally navigation processes. Ground radar/laser systems also generate navigation information for guidance, which is essentially a kinematic feedback control system for ensuring missile-target intercept. The explicit or implicit guidance schemes for mid-course and various proportional navigation-oriented laws for the seeker during the terminal guidance are used. Command guidance to the line of sight is also used for radar-guided missiles. The action process consisting of a flight control system with sensors (for rates, acceleration) and control actuators (electric/pneumatic/hydraulic) steers (aerodynamic and/or thrust controls) the missile based on a guidance law after ensuring adequate stability.

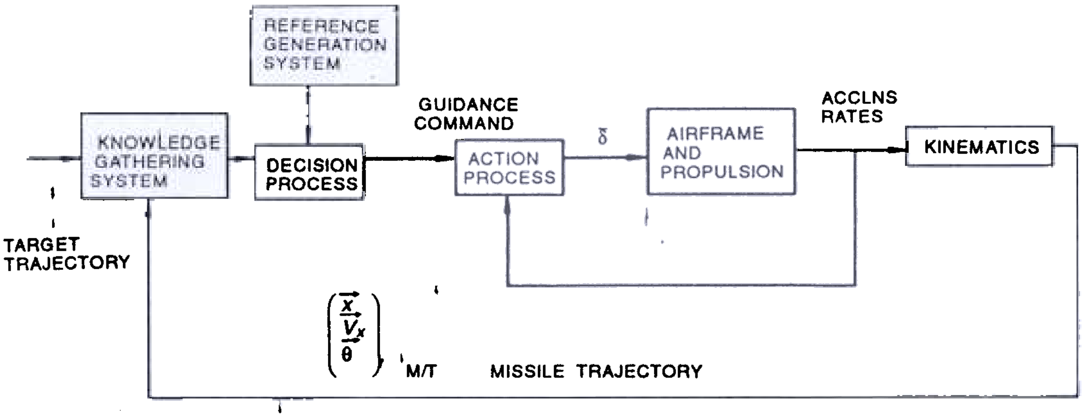


Figure 1. Missile guidance and control block diagram

The airframe in coordination with the propulsion system is used to produce forces and moments for meeting the guidance and control requirements. The guidance and control law used in current missiles still relies heavily on classical control design techniques which are based on standard linear control theory. The specific guidance and control law varies from one missile to another (depending on size, weight, thrust, cost, etc.) but the following characteristics are common:

- The outer guidance loop controls the translational degrees-of-freedom, while the inner autopilot loop controls the missile lateral acceleration (latax) or attitude,
- Proportional feedback is generally used to correct the missile course in the guidance loop,
- In the inner autopilot loop, the roll, pitch and yaw channels are uncoupled and are usually controlled independent of each other,
- Sensors typically measure pitch, yaw rates and roll angle,
- All commands are amplitude or force constrained to ensure stability of the missile, and
- No explicit state estimators are used and signals are filtered to reject high frequency noise.

Classical controllers have simplicity in design and implementation, but they do not use the total information available which, in turn, degrades guidance law performance. Classical design techniques have also progressed by taking advantage of the latest software improvements and modern state space methods.

In earlier missiles, a pursuit form of guidance was used in which steering commands were generated to drive the angle between line of sight and missile velocity vector to zero. The missile steers to head straight for the stationary or slowly moving target. This law degrades against manoeuvering targets and ends in tail chases, though it has the advantage of being relatively insensitive to system noise. The development of proportional navigation was a major breakthrough in homing missile guidance, where steering commands are given to drive the sight line rate to zero. This law was proved to be optimum for constant velocity of target and missile. It assumes inertia-less missile, where the only optimal criterion is to minimise terminal miss distance. When real thrust and drag are present, proportional navigation is not optimum even against constant velocity targets. There have been several attempts to combine the good features of proportional and pursuit guidance into an overall composite guidance law by providing a time varying weighting factor for each[1]. Command to line of sight and dynamic lead are the other guidance laws that are used for missile applications. These guidance laws resident in embedded processors form a vital link for the missile system, which needs rigorous validation in HILS.

The autopilot performs the function of translating the guidance command to engine and fin commands. The missile response to these commands depends upon aerodynamic and kinematic properties of the airframe and the physical properties of the surrounding air mass. The function of the missile autopilot is three-fold:

- To maintain stability of the airframe (which is inherently unstable for current missiles) over the performance envelope,
- To provide adequate airframe for the guidance system, and
- To reduce the sensitivity of guidance performance to vehicle parameter variations and disturbances.

The reliance of classical control techniques in autopilot design results in an autopilot with three independent channels for pitch, yaw and roll. These motions are assumed uncoupled, because classical control techniques are generally limited to a single input-single output linear system. In flight, inherent coupling occurs between the steering and the roll motion, leading to stability problem with increased angle of attack. To overcome this problem, autopilot designers limit the steering response speed for which the roll bandwidth is kept much higher. The angle of attack is also limited to overcome this problem. The autopilot gain in each channel is variable to give optimum performance for different Mach numbers and, dynamic pressures. Gain schedule based on Mach number and air density (possibly other states also) is used for various classes of missiles. The autopilot topology normally used is two/three loop with acceleration and rate feedback. It is better to include autopilot characteristics in guidance law derivation. Various aerodynamic controls like tail, canard or wing are used by the control system, depending on the mission requirements and the subsystems used. Thrust vector, secondary thrust vector and bang-bang control are also used. Electric, hydraulic and pneumatic actuator systems are used, depending on the mission requirement and available size of the subsystem. Digital autopilots using *state-of-the-art* microprocessors/microcontrollers add flexibility to the control system design.

The methodology and techniques used for guidance and control system design for missile systems have been shaped by the particular requirements of these programmes and availability of the computing and special purpose simulation facilities. The approach used is based on standard control system design and development techniques, but emphasises simulation both as development and performance validation tool. Figure 2 shows a current version of an idealised methodology for design in flow chart form. Several computer-aided control system packages which run on distributed networks are available to the designer. Simplified models for use in this design are developed analytically. The built-in feature of the software package which generates a linearised model is also used employing numerical perturbation techniques. The short period rigid body simplified model is initially excited by the trajectory parameters at various points of time and control margins are computed using standard frequency domain techniques for the preliminary design. Point mass trajectory is used for kinematic study of guidance capture and miss distance. The short period study may be extended for flexibility models in design validation with appropriate controller for phase/gain stabilisation. The guidance performance is evaluated in 3-DOF with stability studies at this stage and is further extended with full 6-DOF model. This iterative loop is preferable to be continued with available inputs from aerodynamic/structural/propulsion data and the available OBC architecture, sensor and actuation subsystems. The guidance and control algorithm, as tested in the previous phase, is then used for the generation of flight software. The aim here is to build a hierarchical, highly decoupled, modular, cohesive software with maximum use of higher level languages and custom-built executives. Finally, the

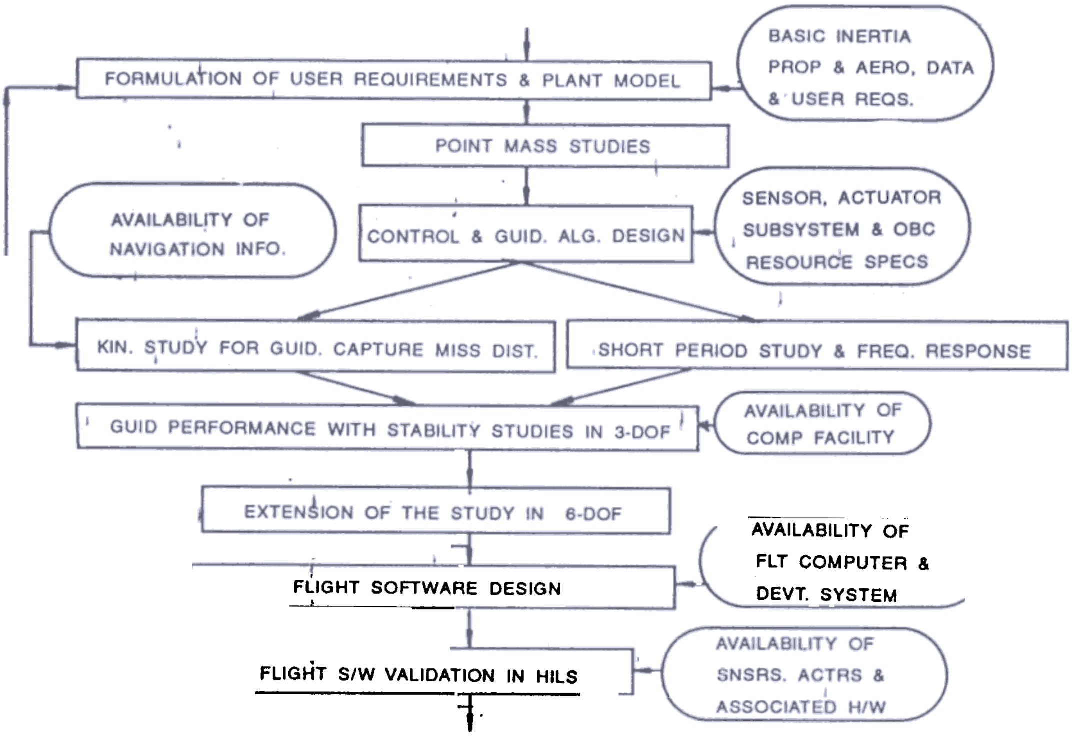


Figure 2. Methodology used for guidance and control design, and validation

flight software is validated in HILS, which includes sensor and actuator hardware with different configurations. This iterative loop goes back right to the requirement stage to satisfy guidance and control design. The classical techniques of using low-pass filtering for attenuating the noise inherent in the guidance signal and using proportional navigation to steer the missile towards the target were developed before the advent of modern control and estimation theory. The current approach for finding more precise navigation information is to separate the wanted signal from the noise by using information about the vehicle dynamics rather than filtering based only on frequency content[1]. This approach to filtering for guidance and control system can take care of random errors (drift, scale factor stability, etc.)[2].

In a typical guidance system, because of lack of statistical information (hardware manufacturers mostly specify the tolerances approximately), linearisation approximations, modelling errors and the fact that implementable filters are of reduced order state type, the covariance matrix of the onboard filter bears little relation to true statistical covariance matrix of errors in estimated state. Selection of appropriate error states, system outputs, working with modest word size and making the computational module working in RT with the available microprocessors is the guidance and control design problem. Linearisation about the current best estimate of state and extension of the algorithm to tackle certain non-gaussian features in an engineering way[3] are the trends in filtering techniques used for guidance systems. Decomposition of filter algorithm into time update and measurement update allows measurement at arbitrary intervals in addition to open ideas for aided inertial navigation (e.g. global positioning system, doppler velocity, terrain contour matching and scene matching systems).

The aim of future work is to achieve better guidance/navigation accuracies with the use of appropriate terminal guidance philosophy to correct, in a short time, the trajectory errors accumulated during the mid-course guidance phase. These sophisticated trends of guidance and

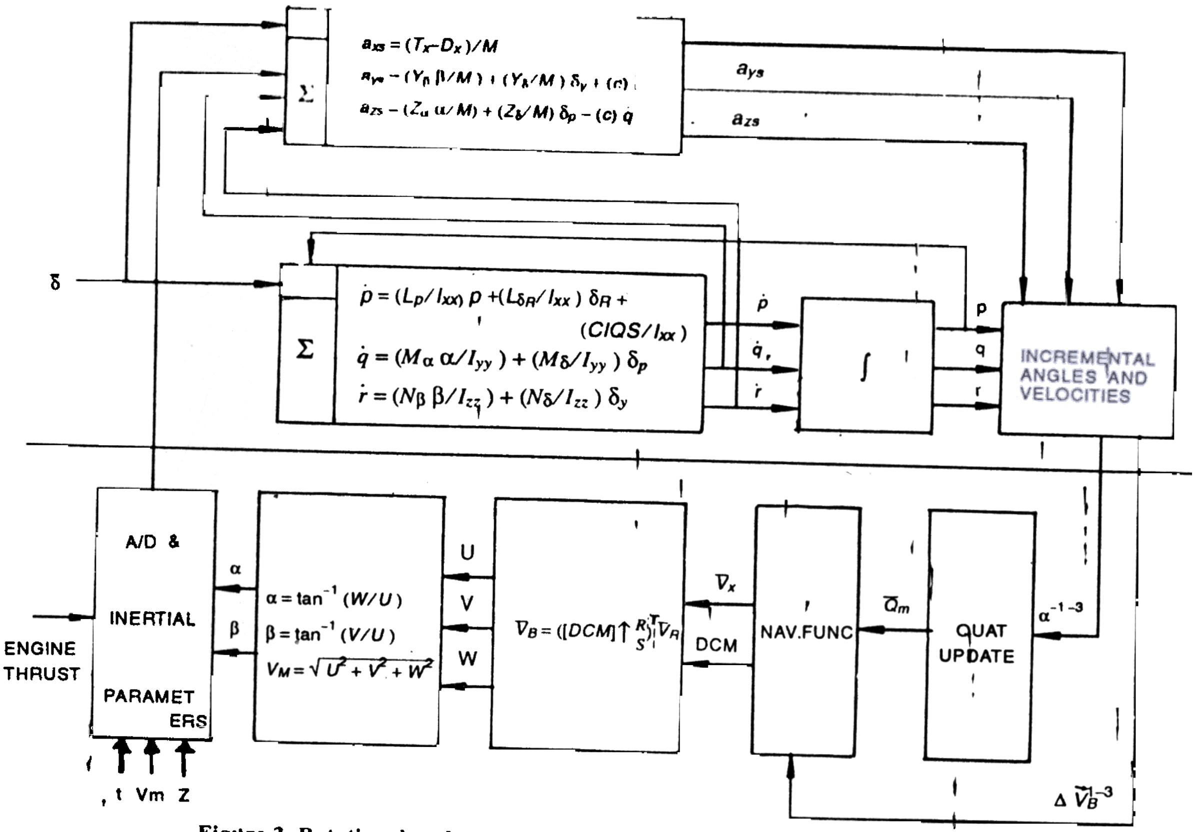


Figure 3. Rotational and translational loop job allocation in real-time missile

control design have a direct bearing on the validation complexity.

3. MODELLING & SIMULATION

The validity of the guidance and control design depends on the refineness and proximity of the plant model to the real world. The actual terms and coefficients used in the 6-DOF model depend very much on the availability of aerodynamic, propulsion and inertial data as well as engineering judgement. To have a feel of the missile dynamic behaviour with the control algorithm, the plant may be simplified initially to a 2-DOF (planar) rigid body model with plant parameters at various instants of trajectory. Simultaneously, trajectory equations of motion with forward acceleration (3-DOF) for a variable point mass are developed for kinematic studies. The 2-DOF model equations are combined with the trajectory variable functions (thrust, drag, etc.) for the development of 3-DOF planar model. This 3-DOF model with ideal actuators and sensors allows preliminary studies on navigation, guidance and control. This can be extended to 5-DOF model without roll, before using the full-fledged 6-DOF model. The actuator and sensor models are progressively introduced. A typical rigid body model consisting of 6-DOF equations used for a missile is given in Fig. 3. Pitch, yaw, roll deflection commands (δ_p, δ_y, δ_r) generated by OBC excite the 6-DOF plant for steering and stability using TVC, ADC, etc.

A 3-axis coordinate frame is defined to have its origin at centre of gravity (CG) of a missile which moves as a function of mass. External forces and moments acting on the body due to thrust and aerodynamic forces are generated in the body frame. Another reference frame of importance is the one fixed on the earth surface. The body's attitude relative to the earth-fixed frame is required for transforming the body translational accelerations to the earth frame. Angular accelerations are integrated to generate body angular rates which further generate the body quaternions to resolve

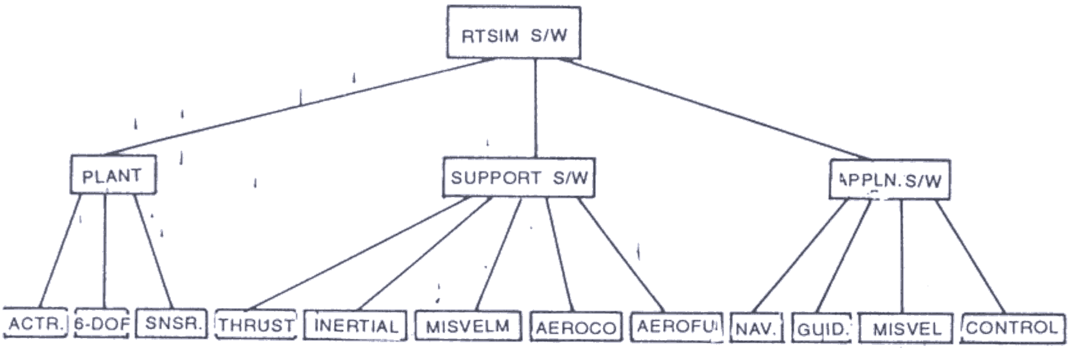


Figure 4. HILS software structure

incremental body velocities to reference velocities. The resulting reference velocities on integration will give the positions. The typical 6-DOF rigid body equations as given in Fig. 3 are derived from Newton's second law of motion[4]. The Euler axes are fixed to the body. The moment equations about Eulerian axes are written and implemented as[5] rotational accelerations after neglecting dynamic derivatives (which has little influence) and the effect due to coupling[5]. The effect of engines (for TVC) and fins (for ADC) is accounted in Z_δ, Y_δ, M_δ, N_δ, and L_δ factors.

A top-down hierarchical methodology has been followed for the entire simulation, as shown in Fig. 4. The 6-DOF equations are divided into translational and rotational loops for ease of implementation. The entire software is broken into support software, plant model and onboard mission software. The lower hierarchical modules of the support software supplement inertial, aerodynamic (AEROCO, AEROFU) and thrust functions. MISVELM module computes Mach number and dynamic pressure. The thrust, engine deflections (δ_{eo}) and fin deflections (δ_{fo}) are the forcing functions for the plant. Mission events and aerodynamic functions are also used as inputs to the plant. The plant consists of actuator and sensor models along with 6-DOF equations. α, β are also generated within the plant and are used by the support software. The onboard mission software is delinked from the missile model for the ease of introduction of the OBC in HILS.

The primary function of the onboard RT task is to extract the knowledge (navigation information) from the inertial system, process the position, velocity and attitude-related navigation information for decision to generate guidance command based on the available reference generation system. The onboard digital processor (autopilot) steers and stabilises the missile system based on the guidance commands and feedback from sensors (rates, accelerations). The deflection commands generated by the OBC are output to the actuation subsystem which, in turn, excites the airframe and propulsion system. The airframe, in coordination with the propulsion system, is used to produce forces for accomplishing mission objectives. The outer guidance loop (Fig.1) controls the kinematics, while the autopilot loop controls the missile lateral acceleration or attitude. The inner autopilot loop roll, pitch and yaw are not coupled. The control modules are supported by MISVEL module (onboard dynamic pressure and Mach number generation) for adaptive gain scheduling. The engine, fin commands (δ_{ec}), (δ_{fc}), height (Z), and velocity (V_m) are passed on to plant and support software respectively (Fig. 4).

The model software (plant and support software) and onboard software are required to be synchronised in RT. The software structure has to be converted to a timing diagram for generating model as well as onboard RT executive. The scheduling is achieved through three time cycles—major, submajor and minor cycles for the model. In the application software also, timing is

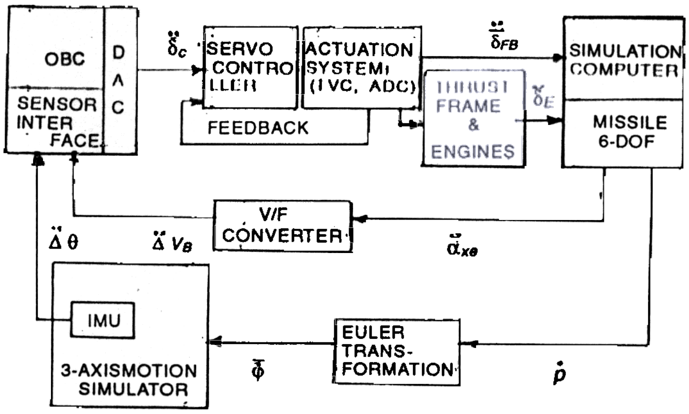


Figure 5. Integrated HILS

achieved through three time cycles, where the incremental angles and incremental velocities are sampled at every minor cycle. The actuators used are modelled within the plant with appropriate damping and bandwidth[6]. Actuator rate limits are also taken into account in the model. Subsequently, model actuators are replaced by hardware actuators along with engine thrust frame and fins.

Appropriate models are also used for simulating strapped-down sensors which are eventually replaced by flight sensors in the integrated HILS, as shown in Fig. 5, for a typical surface-to-surface missile (SSM). The flight inertial measuring unit (IMU) comprising strapped-down sensors is mounted on a 3-axis motion simulator, which should have a higher bandwidth with a lower drift rate. Appropriate Euler angle rates are generated to drive the motion simulator. The hardware actuators along with hydraulic pump, accumulator, filter and servo controller electronics as used in flight are also introduced. The thrust frame, cold engines with gimbals are also used with the hardware actuators in the hope of revealing hidden defects in hardware or software. The engine acceleration in two perpendicular axes are sensed by piezo-electric accelerometers for exciting TWD effect[7]. It was conclusively proved in HILS for a typical SSM that TWD associated with low damping introduced by gimbaled engines, thrust frame and hardware

$$a_{xs} = \left(\frac{T_x - D_x}{M}\right)$$

$$a_{ys} = \left[\left(\frac{Y_\beta \beta}{M}\right) + \left(\frac{Y_\delta}{M}\right)\delta_{EY} + C\dot{r}\right] + \left[2\left(\frac{M_R l_R}{M}\right)\ddot{\delta}_{EY}\right]$$

$$a_{zs} = \left[\left(\frac{Z_\alpha \alpha}{M}\right) + \left(\frac{Z_\delta}{M}\right)\delta_{EP} - C\dot{q}\right] - \left[2\left(\frac{M_R l_R}{M}\right)\ddot{\delta}_{EP}\right]$$

$$\dot{p} = \left[\left(\frac{L_p}{I_{xx}}\right)p + \left(\frac{L_\delta}{I_{xx}}\right)\delta_{ER} + \left(\frac{C_l Q_{sd}}{I_{xx}}\right)\right] + \left[2\left(\frac{M_R l_R l_g}{I_{xx}}\right)\ddot{\delta}_{ER}\right]$$

$$\dot{q} = \left[\left(\frac{M_\alpha \alpha}{I_{yy}}\right) + \left(\frac{M_\delta}{I_{yy}}\right)\delta_{EP}\right] - \left[2\left(\frac{I_R + M_R l_R l_g}{I_{yy}}\right)\ddot{\delta}_{EP}\right]$$

$$\dot{r} = \left[\left(\frac{N_\beta \beta}{I_{zz}}\right) + \left(\frac{N_\delta}{I_{zz}}\right)\delta_{EY}\right] - \left[2\left(\frac{I_R + M_R l_R l_g}{I_{zz}}\right)\ddot{\delta}_{EY}\right]$$

where

$$\delta_{EP} = \frac{\delta_{YE1} + \delta_{YE2}}{2} \; ; \; \delta_{EY} = \frac{\delta_{ZE1} + \delta_{ZE2}}{2}$$

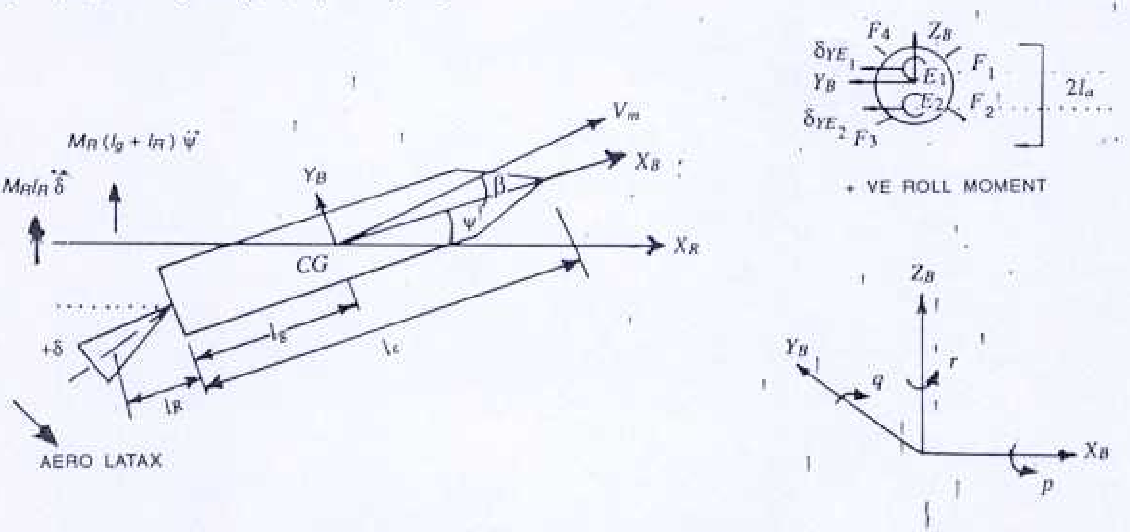


Figure 6. TWD effects in 6-DOF model

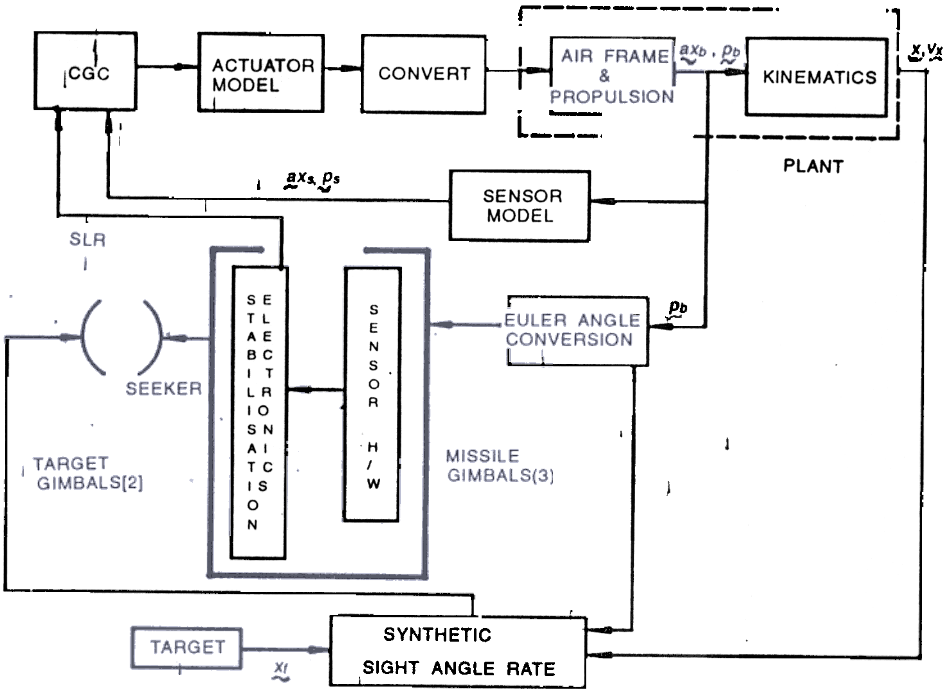


Figure 7. Setup for seeker in HILS

actuator compliance is the primary source for roll oscillations. The model information which is missing in Fig. 3 for TWD in roll is shown explicitly[8] in Fig. 6. The engine acceleration in pitch, yaw and roll (δ_p, δ_y, δ_r) are fed to the enhanced model via piezo-electric accelerometers.

Missiles with higher slenderness ratio have to undergo HILS, which may reveal bending mode oscillations. Missile parameters, including flexibility-related parameters, are to be considered at various points on the trajectory with a much higher order model[9]. The short period mode RT HILS can be performed for some cases and may be extended for integrated 6-DOF HILS. The loss of autopilot stability due to unanticipated rates sensed by control sensor needs to be examined. Deflection and its rate limits are to be implemented for non-linear modelling in simulation.

For surface-to-air missiles (SAM), ground-based radar noise is modelled through signal generators (specified mean and standard distribution). Seeker- based systems need detailed seeker modelling before mounting on the 3-axis motion simulator for final HILS. A target motion system with bandwidth much higher than that of guidance and seeker trackloop bandwidth is a necessity for seeker HILS. A typical HILS set up for seeker[10], as realised, is given Fig. 7. Electronic and IR-target arrays may be introduced for ease of simulation. The seeker system as well as the entire guidance and control system need to be introduced in HILS independently.

Development of missile model in RT is one of the major challenges in HILS. Mainframe digital computers, hybrid computers, multiple mini-computers and specialised digital computers are used at various stages of missile system design and validation. Simulating a complex missile system in RT is a more elegant way than mathematically obtaining the closed form solution of the coupled differential equations. An engineer's desire to observe realistic effect (in time domain) for non-linearities and discontinuities on a linearly tuned guidance and control system can be met with an appropriate simulation facility.

The RT missile model demands a large computing power for time domain HILS. Further, introduction of actual flight subsystems in the

HILS avoids the uncertainties arising due to simplifications in mathematical model. Facility is geared up to connect entire missile hardware, actual/simulated ground computers with sophisticated and flexible I/O interfaces to bring more connectivity in a RT simulation environment. To sum up, the following steps are executed to realise HILS:

- Formulation of 6-DOF model,
- Separation of translational and rotational equations,
- Top-down hierarchical structure for the integrated software,
- Development of engineer's block diagrams or data flow diagrams,
- Task scheduling, distribution (timing diagram) and software development,
- Establishing simulation with model and application software on an RT platform,
- Establishing HILS with sensor and actuator models along with the OBC, and
- HILS with integrated flight hardware

Sometimes, it may be necessary to excite the entire HILS with integrated hardware in one plane before executing the final HILS.

4 DESIGN UPDATE & VALIDATION

Missile launches are very expensive and one-shot operations. The missile has to fly with navigation, guidance and control software in RT. *A priori* validation of the onboard software with the missile model in RT is a necessity before the actual launch. In addition, model and design updates are necessary due to changes arising in the course of algorithmic *vis-a-vis* software development, flight trial experience and original requirement specifications. The validation process should not be mixed up with the verification process. Validation is the process to determine that simulation behaves like the actual missile system, whereas verification is intended to ascertain that equations are implemented correctly (Fig. 8).

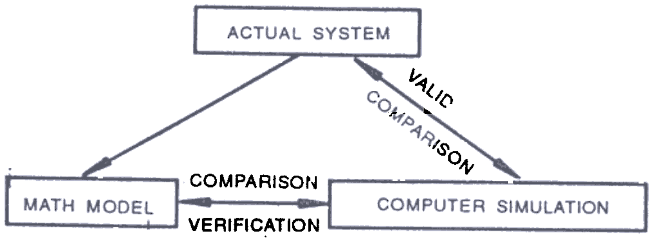
The methods normally used for validation include the following:

- Stability studies with time and frequency response using conventional linear control system design techniques at various points of the trajectory,
- Extension of the short period time response study to RT,
- 3-DOF/5-DOF and 6-DOF study with guidance and control on various test beds, including RT setup,
- Independent testing of the navigation software along with the hardware for both static and dynamic conditions, and
- Near flight input profile (FLIP) was also designed at the developement stage of the software for initial validation.

Sometimes, the phase lag and other implementation (inappropriate time cycles, mis-synchronisation aspects with RT software worsen the situation and usage of RT simulation tools helps in highlighting design problems at an early stage. Certain zones in the trajectory, especially low dynamic pressure region, control system-switchover and terminal phase high manoeuvering stress the sensor and actuator specification requirements. High rates (more than the design) experienced by sensors and high flow rates demanded by actuators may force a relook into the software/hardware. Saturation, bias and other non-linearity effects of the hardware (actuators, sensors, seeker, etc.) were experienced during HILS, which helped in validating the design under extreme conditions. Finally, validation of the software and hardware is carried out in the following steps:

- All digital 6-DOF simulation on two independent platforms (preferably version closer to OBC implementation)
- Integrated application software testing on available RT computer along with the RT simulation computer,

Problem: General Mathematical Modelling and Simulation Methodology



SYSTEM, MODEL, SIMULATION CORRELATION

BASIC TECH. COMPONENTS:

Requirements which final simulation must satisfy.

2. Equation for representing actual system.
3. Program equations for simulation.
4. Compare simulation program to the model and modify the mistakes.
5. Compare simulation results with actual results.

VERIFICATION

Process to determine that a program causes computer to operate as intended by the software designer (i.e. equations are programmed correctly).

VALIDATION

Process to determine that computer simulation behaves like actual system in all pertinent respect.

Figure 8. Verification and validation

- OBC software and hardware validation with simulation computer in OBC-IN-LOOP environment, and
- Integrated software and flight hardware validation with simulation computer and flight motion simulator.

Important states and parameters, including structural loads and dynamic pressure are monitored throughout the flight profile for evaluating the performance of the missile system. In addition, guidance, control and navigation are independently validated[10]. A typical plot showing important missile states and parameters in a simulation run is given in Fig. 9. Disturbance cases are also simulated in various test beds. Higher thrust with lower drag and lesser mass for simulating high velocity case and their complementary conditions along with static margin variations are simulated for stretching the software to its limits as well as validating the guidance and control design in its entirety. Gathering basket

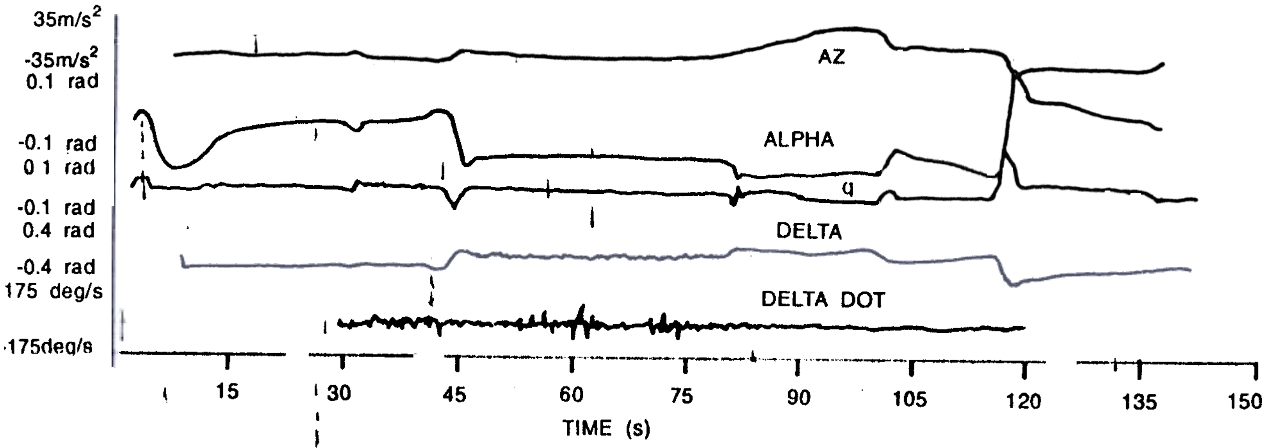


Figure 9. A typical plot in a simulation run

during start of closed-loop guidance and the guidance stiffness, cutoff velocity, low dynamic pressure guidance behaviour in relation to actuator rates (which stresses the hydraulic flow rates), and terminal phase guidance behaviour are some of the critical performance issues which have to be looked into during HILS. Prelaunch and in-flight mission sequencing functions alongwith navigation and alignment are also reviewed.

The embedded flexibility filter in-flight software was validated with the higher order flexible missile model [9] in HILS, where the same is not possible in all digital NRT simulation or RT rigid body 6-DOF HILS. The seeker-system tested independently for stabilisation and trackloop under trajectory dynamic conditions without the guidance loop gave sufficient insight for upgrading seeker design. This helped to validate the embedded guidance software independently, since 6-DOF model with autopilot and other hardware subsystems has been validated a *priori* [10].

Many hidden software and hardware deficiencies of design and implementation have surfaced during HILS only. It has helped in generating the missing information for guidance and control designer as well as knowledge base for a missile model. Very high actuator rates, quantisation problems during rate extraction, computational delay and roll oscillations due to TWD are some of the problems which have been detected, corrected and tested in HILS, leading to successful flights. The primary source of undue roll oscillations due to low damping introduced by gimbaled engines, thrust frame and hardware actuator compliance TWD was demonstrated in HILS and suitable design changes after introducing digital filter were also validated (Fig. 10). Incorrect control gains due to erroneous height information from navigation resulting in roll oscillations was also demonstrated. For worst case disturbances, control gain margins, in tune with 6 db and phase margin as low as 20° have been verified in HILS even in a conditionally stable situation. Typical cases with lower margins, yet with acceptable performance, were also validated. For a missile with a higher slenderness ratio (l/d about 20), the loss of autopilot stability due to unanticipated rates sensed by control sensors has been proved and corrective measures were taken which was further validated in the same test bed. The effect of injected body rate to seeker line of sight rate (decoupling ratio) in proportional navigation guidance was demonstrated in HILS and adequate decoupling was provided by the seeker designer.

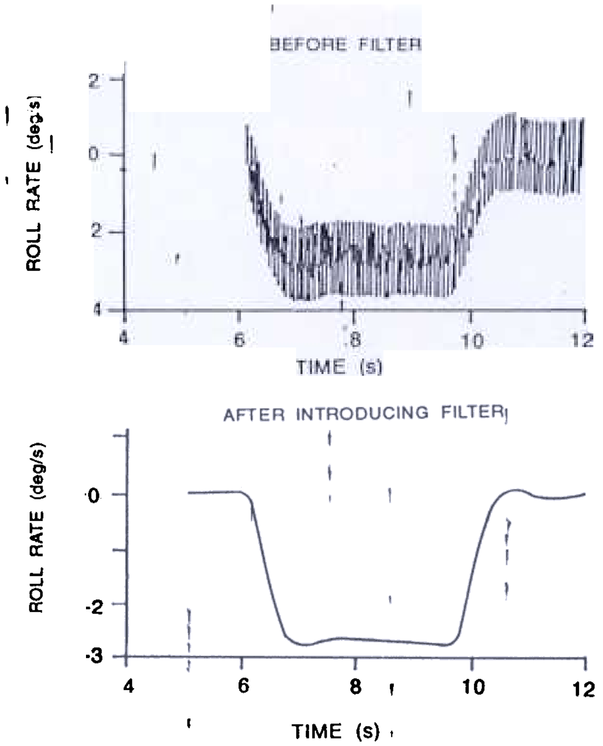


Figure 10. Roll rate before and after introducing filter

For completeness, the launch computer along with its hardware and software was also included in integrated HILS. The opto-isolators and the actual communication links were employed to create a near launch scenario in HILS environment. This helped to excite the launch computer system during the auto-launch phase with all mission-related functions (like pressure build up, thrust build up, etc.). Interfacing the telemetry system consisting of onboard PCM unit and ground receiver unit helped in clearing the onboard telemetry software also. Critical in-flight parameters are made available for post-flight analysis (PFA) to study the performance of the mission. Comparative studies are carried out between the in-flight performance and the HILS results. The HILS test bed is energised with the same input data as available from the telemetry, whereby detailed PFA of the mission is conducted. Missing links in model as well as design were traced back through HILS—proving its efficacy as a powerful tool for PFA also.

5. CONCLUSIONS & SUGGESTIONS

The methodology and techniques described in this paper have been proved to be effective in the development of reliable flight hardware and software for missile systems. The procedure described is used in missile flight test programmes where there is no room for errors and low margins in guidance and control software and hardware.

Models ranging from point mass to rigorous 6-DOF are necessary for validating the design. Judicious inclusion of flexibility and slosh in short period 6-DOF is necessary, depending on the missile configuration. Inclusion of certain hardware should be attempted at any cost to increase the reliability of flight software and hardware design. Guidance and control system using OBC, seeker and its RT software cannot be evolved with NRT all digital 6-DOF simulation. Further, the flight software design along with OBC, guidance and control RT hardware can be validated only in an integrated form in HILS. Many hidden software and hardware deficiencies of design have surfaced during HILS only.

HILS for guided missile system has been established in India. Today, the RT onboard computer software with closed-loop strapped-down inertial guidance for missile system has undergone successful user trials after rigorous validation in HILS. Pre-flight HILS results have matched fairly well with those of actual flight trials, resulting in reduction in the number of flight trials. Radar and seeker guided missiles are also evaluated for performance validation in HILS.

Actual failures (due to TWD, lower thrust, poorer class of sensors, flexibility, etc.) have been demonstrated in HILS and appropriate design modifications were introduced in record time. Radar noise and flight seeker are introduced directly for various failure mode simulation studies. HILS facility has helped in generating algorithm for TWD in roll, detection of inappropriate control gain scheduling due to height errors, validating flexibility filters, evaluating the radar-based guidance system and detecting imperfections in the seeker systems. The common sensors for control and navigation were subjected to trajectory dynamics in HILS and actual capabilities of the complete hydraulic system were established. The seeker with its stabilisation and trackloop was tested independently as well as with the missile guidance in various configurations. The bias and the spread of the radar-guided system errors were also introduced with the actual ground-based guidance system. The scope has been extended to include flexibility effects of missile in RT HILS. HILS results were correlated with guidance and control stability margins and limitations of the linear study resulting out of saturation, discontinuities and other non-linearities were brought out. It was used as an on-line design tool for guidance and control system. The methodology adopted has helped in transforming a preliminary paper design to an actual weapon system.

Though the embedded software may be proved in HILS with the specified plant, the necessity of flight trial remains, to find out hidden links in the model itself. Expert systems having access to integrated knowledge bases and supported by learning features with the help of neural networks and automation, including virtual reality, in HILS will help in faster delivery of more reliable guidance and control systems.

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