Defence Science Journal, Vol 47, No 3, July 1997, pp. 295-316

Unmanned Air Vehicles & Simulation

P.S. Krishnan, P.K. Panda and J. Jayaraman

Aeronautical Development Establishment, Bangalore-560 093.

ABSTRACT

A general account of unmanned air vehicles (UAVs) is given and their various roles, both lethal and non-lethal ones, are discussed. Elements of an UAV system used for reconnaissance, surveillance and target designation have been described to highlight the role of simulation in acquisition, design, development, testing, evaluation, and operation of such a system. Various applications of simulation studies for UAVs are mentioned. An attempt has been made to highlight how simulation helps in identifying design deficiencies and thus improve the design through the following three typical problems encountered during design and development of UAVs at the Aeronautical Development Establishment:(i) launch dynamics of *Lakshya*, (ii) tow system dynamics, *Lakshya* tow body, and (iii) hardware in-line simulation - way point navigation—*Nishant*.

1. INTRODUCTION

With increasing cost and complexity of manned aircraft,[1] the concept of unmanned air vehicles (UAVs) is seen as a possible solution for a wide range of applications in the high risk military environment. This is mainly due to the 'fearlessness' of UAVs, as there is no chance of losing highly trained and skilled personnel, as in the case of manned aircraft.

UAV systems are inherently a combination of several highly interactive elements and design decisions, and though apparently having little influence on one particular element, they may have profound repercussions on other elements and thereby affect the overall systems' performance. Simulation permits the whole system design to be examined in an integrated manner.

Simulation of UAV systems becomes complex due to the presence of a remote pilot-in-the-loop. Commands are generated for remote piloting. The delays, however short, in the uplink chain and downlink display to the pilot and its fidelity have an impact on the final performance of the system. Specially in the case of payload operation and net recovery, these delays, being a part of the active control loop, control the performance and reliability of operation.

2. UNMANNED AIR VEHICLES

UAV is an air vehicle having a remote operator providing continuous or intermittent commands during several phases of its flight, or it is automatically piloted without human interaction, as in a drone. Basically, UAVs are classified as lethal and non-lethal. Lethal UAVs cause irreversible damage to destroy the enemy's assets. Cruise missiles and attack drones fall under this category. Non-lethal UAVs do not cause permanent damage or destruction. They include those with electronic combat payloads. The classification tree is depicted in Fig. 1. Both fixed and rotary wing UAVs are in use. The presently identified missions that can be accomplished with UAVs are :

Received 03 January 1997

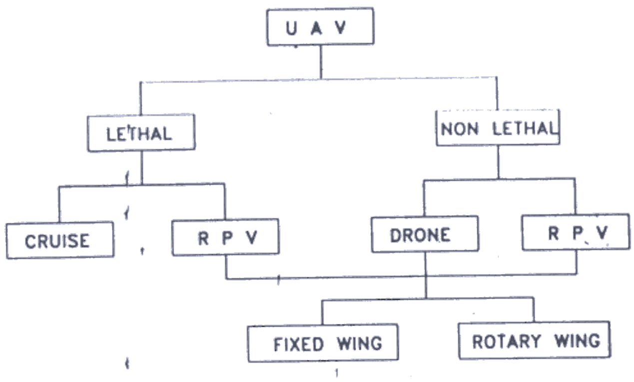

Figure 1. Classification of UAVs

- Aerial targets
- Situation reconnaissance (Recee) (photographic, infrared linescan, forward looking infrared)
- Target designation (detection, identification, measuring, illumination, damage assessment)
- Electronic intelligence (ELINT)
- Communications intelligence (COMINT)
- Active (jammer, decoy) and passive (chaff, flares) electronic counter measures (ECM)
- Electronic counter-counter measures (ECCM)
- Saturation of enemy air defence by using decoys
- Communication [relay function, command, control & Communication (C^3), over the horizon]
- Air strike against fixed radiating targets (defence suppression, as well as suppression of enemy C^3 capability)
- Air strike against vehicles (especially the enemy's second echelon), and
- Integrated strike force with manned aircraft

2.1 Components of a Recee & Surveillance UAV

The main components of a recee and surveillance UAV are: Air vehicle, payloads, launch, recovery stations, datalink and ground stations. The components of such a UAV are presented in Fig. 2, wherein the relevant factors which drive commonality and differences among user requirements too are identified.

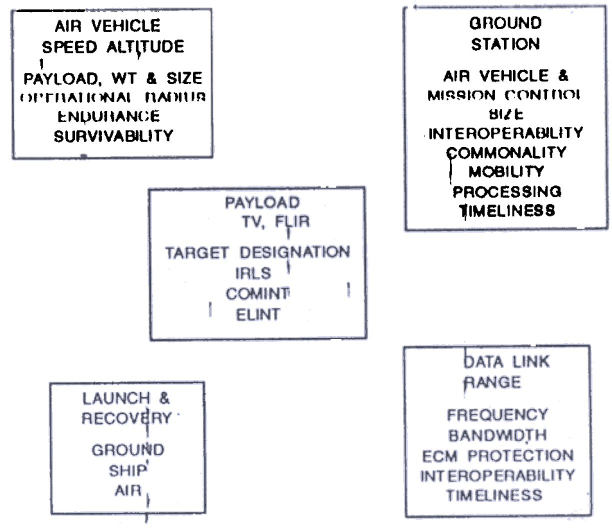

Figure 2. Components of a surveillance UAV

3. SIMULATION AS APPLIED TO UAVs

Simulation as a tool has been extensively used for UAVs. Cromwell[1] has reviewed the information on weather and battle-induced containments (WBIC) modelling techniques and supporting test results for their suitability for assessing payload performance of the remotely piloted vehicle (RPV) during each critical mission/task in smoke alone or smoke and dust from various rounds conditions.

Mauger[2] has discussed the two methods used at RARDE in advising the Army Operational Requirements Branch regarding operational effectiveness, viz., simulation and wargame. Effectiveness *vs* battle time of an RPV and drone-based mix of systems for medium range surveillance has been discussed. Jackson & Rose[3] have addressed the improvement in mission effectiveness achieved by using electronic support measures on UAVs to enhance their prime imagery reconnaissance mission.

Cleveland, *et al.*[4] have discussed the theoretical derivation of refinements in self-organising control techniques and implementation of self-organising controller logic in the form of breadboard digital hardware and programs for real time simulation of RPV flight with six degrees of freedom (6-DOF) without limitation on small aerodynamic angles.

Alpin[5] has dealt with digital simulation and control of Machan UAV using full force aerodynamics, large perturbation geometry, digital real-time simulation using both stand-alone and iron bird simulation modes to evaluate various control law designs aimed at non-skilled piloting and to optimise the gains in these control laws. Aslin, *et al.*[6] have reported the development of a simulation facility to assess the performance of flight control laws of Machan UAV when faced with a realistic non-linear system. The facility uses low power computing and offloads the computational overhead of flight control and display generation to dedicated microcomputers; the real-time aspects of simulation have been optimised. Thomasson[7] has described the simulation developed for gust insensitive UAV XRAE1 and XRAE2 which are considerably slower than real-time ones. But with the advent of powerful PCs and graphics capability, a relatively low cost simulation facility could be developed which could provide man-in-the-loop simulation for any part of the flight, such as landing that may require a pilot input. Robertson[8] simulated UAV runs in real-time on a VME-based computer at 100 Hz, and verified proper operation of the flight computer.

Jenkins[9] has discussed some aspects of application of knowledge-based system techniques for route planning as a component of a broader mission planning application. Pierce[10] has described the hybrid combination of artificial intelligence (AI) and conventional processing technologies to provide expert assistance and an enhanced man-machine interface to a non-technical operator for preflight and inflight mission requirements. During preflight, the system provides an intelligent mission planning work-station for flight and specific payload operation planning based on mission requirements, intelligence and digital terrain data. During inflight operations, the system provides an intelligent interface for the control and presentation of vehicle operations, payload operations and sensor data acquisition. This reduces the operator workload and skill requirements. McKay[11] has described the McDonnel Douglas mission planning program tactical aircraft mission planning system established and used by the US Navy for fixed wing aircraft, helicopters, UAVs and missiles. Software modularity ensures developmental integrity for each supported program. Cooper[12] has discussed the need for synergestic coordination and mission planning to realise the force multiplication benefits of joint UAV/piloted aircraft operations. According to him, the mission support system II, an off-the-shelf asset is available to provide this coordination. Donnenberg, *et al.*[13] have discussed how intelligence driven mission planning station and battle area tactical simulation may be combined in an RPV mission planner today. Planning pertains to the collection and assimilation of relevant intelligence data which include friend and enemy threat tactical, communication and situation data. Simulation includes guidance algorithms that select optimum routings for air-to-ground penetration missions. It includes graphics to plan an effective RPV mission quickly, viz., plan view, God's eye view, perspective view and analytical statistical graphs.

It is seen that simulation is used as a decision-making tool during the acquisition process for assessing

- Cost-effectiveness,
- Survivability/vulnerability, wherein questions, such as utility of expendable and reusable systems could be answered, and
- Mission effectiveness.

Systems simulation permits the designer to examine aspects of design uncertainties by analysing the system performance after modelling the configuration chosen and environment as close as possible to that which will be encountered in operation. In the design and development phase of UAVs, simulation is used to assess

- Mission effectiveness,
- Total system simulation,
- Air vehicle performance, stability and control analysis, and
- Air vehicle navigation, including hardware in-line simulation to assess the performance of way point navigation system, flight control system, etc.

In the testing and evaluation phase of UAVs, simulation is applied to

- Hardware in-line simulation,
- Ground testing of integrated UAV system, which also includes the ground control station, etc.,
- Postflight analysis, and
- Mission reconstruction and evaluation

In the operational phase of UAVs, simulation is extensively used for

- Controller/pilot training,
- Mission planning,
- Mission reconstruction, and
- Payload operator training.

The controller/pilot training simulator is intended to initially train the controller and also keep him proficient in the usage of the UAV system during long non-flying periods. Mission planning makes use of topographic, threat databases, UAV performance model, line of sight and field of view analysis for datalink, sensor and air vehicle relay positioning to plan the mission profile, route and mission accomplishment. Mission reconstruction is an effective method for identifying errors committed in training and in actual flight. Recorded data can be replayed several times to identify and correct the crew and system. Payload operator training uses the simulator part of the payload station to train the payload operator in recognising, identifying and tracking the target.

Table 1. Comparison of Indian UAV

ULKA	*LAKSHYA*	*KAPOTHAKA*	*NISHANT*
Air launch	Ground/ship launch	Ground launch	Ground launch
Expendable	Reusable	Reusable	Reusable
Rocket	Gas turbine	Piston	Wankel
Supersonic at high altitude	High subsonic	Low speed	Low speed
Low endurance	medium endurance	medium endurance	high endurance
Aerial target	Aerial target	Aerial target cum recee	Recee surveillance
			Target acquition

4. SPECIFIC SIMULATION PROBLEMS

The Aeronautical Development Establishment has been in the field of UAVs for over two decades, with products, such as *Ulka*, an air launched supersonic expendable target system, *Lakshya*, a high performance subsonic reusable aerial target system, mini RPV *Kapothaka*, a technology demonstrator recee system, and Mini RPV *Nishant*, a multirole reusable UAV. The features of these systems are compared in Table 1. Simulation has been extensively used in all phases of design, development, testing and evaluation for a variety of problems. However, three specific problems are described here to highlight how simulation has helped in identifying design deficiencies and improving the design.

4.1 Launch Dynamics of *Lakshya*

The pilotless target aircraft (PTA) with the booster during booster thrust line alignment is shown in Fig. 3. The PTA has a gas turbine sustainer engine mounted under the low wing. Thus, the engine thrust axis is offset from the centre of gravity (CG) of the PTA, which imposes a pitch up moment on it. In flight, the flight control system (trim elevator) neutralises this moment. But at launch, this pitch up moment is reduced

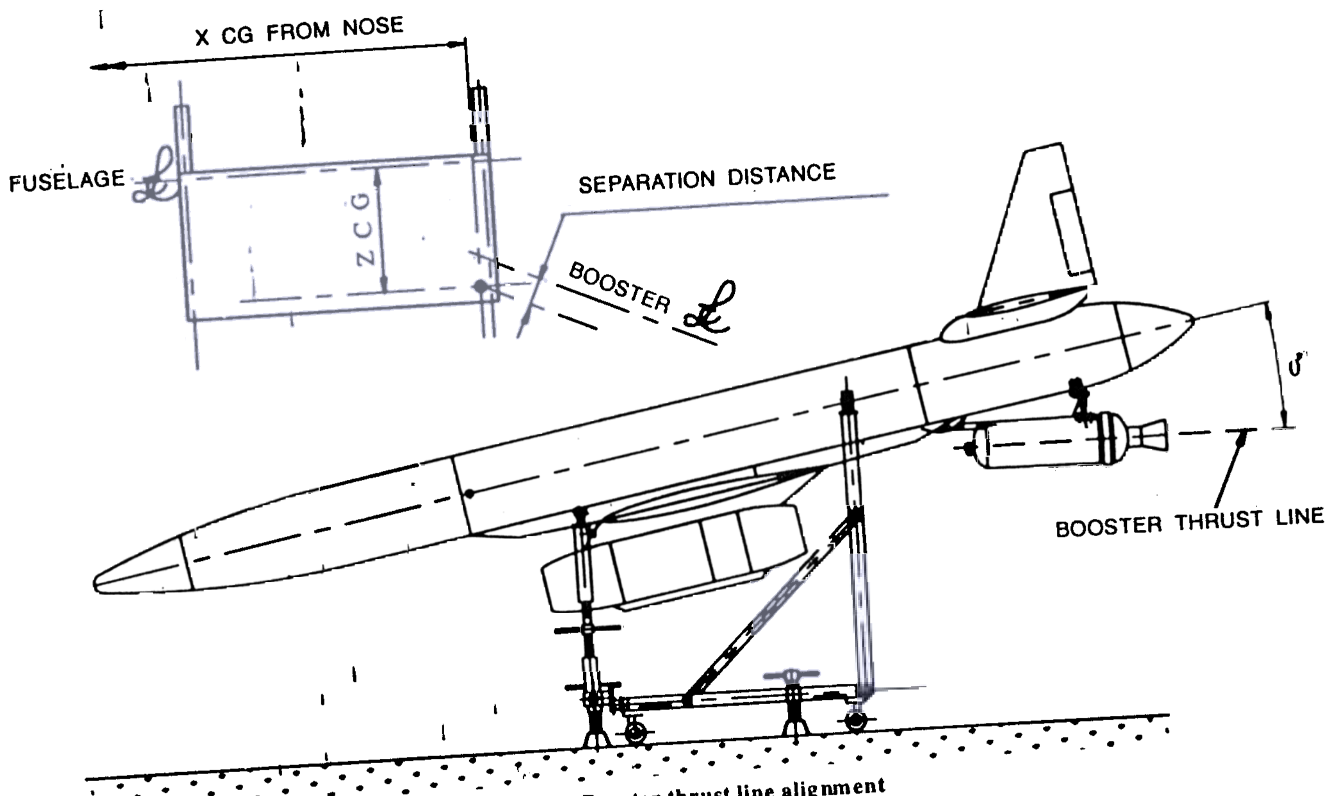

Figure 3. Booster thrust line alignment

considerably by making the booster thrust line to pass above the CG by a known separation distance. A small pitch up is always preferred, as it gives the necessary altitude for autorecovery of the target safely in the event of launch failure. Although, boost launch from a zero length launcher should be a well-understood area, several known and unknown variables degrade the launch performance reliability.

For this purpose, a term equivalent booster thrust misalignment (EBM) in longitudinal plane is defined as the combination of equivalent effect of all identified sources of error. The identified sources of error are:

(a) Booster thrust with tolerance

(b) Errors in engine rpm setting

(c) booster misalignment tolerance

(d) Estimation and location of CG

(e) Variation of engine thrust from its model

(f) Ambient temperature and pressure changes from the assumed conditions for booster and engine thrust for booster thrust line setting

(g) Moment of inertia

(h) Pitch rate arising as initial condition due to dynamics on launcher

(i) Flexibility of fuselage aft of CG due to launch loads

(j) Variation in peak thrust from average thrust of booster

(k) Initial rigging inaccuracies of lifting surfaces, and

(l) Free play in the control system.

Several other factors which affect launch dynamics are:

(a) Launch angle and its tolerance

(b) Weight of the vehicle, error in measurement

(c) Prevailing wind conditions at the time of launch, and

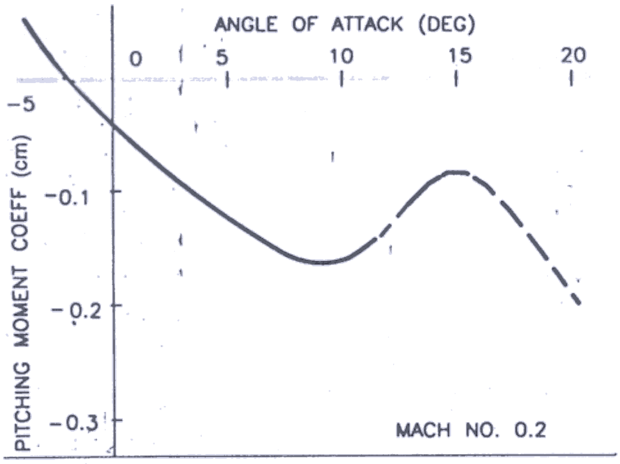

Figure 4. ***Lakshya*** **longitudinal stability**

(d) Change in weight due to prelaunch engine run being different.

Some of the above factors are known and can be quantified. Others can be estimated as EBM statistically after postflight simulation and matching the trajectory.

Tolerances in these parameters give rise to unbalanced pitch up or pitch down moment, resulting in the development of a high angle of attack. On booster burn out, sudden removal of booster thrust causes a further unbalanced pitching moment. In addition, there is a sharp change in static margin during the launch phase due to (i) Propellant and fuel consumption with time, and (ii) Jettisoning of booster automatically at two seconds after launch.

Due to all these rapid changes in flight configuration and conditions associated with an accelerating flight and non-linear characteristics of longitudinal stability shown in Fig. 4, simulation studies, including active controls, were required to freeze the control law.

These studies indicated the following:

Need for a small static margin at launch (unstable configuration not acceptable) (Fig. 5),

- CG management through fuel sequencing,
- Roll and pitch control gains for launch phase different from that of cruise phase,
- Rudder deflected in response to yaw rate to contain veering and sideslip,
- 10° angle of attack as the design limit during launch phase compared to 7° during cruise, and
- The need for pitch rate feedback in the longitudinal control loop after eight launches to improve the launch reliability.

Considerable efforts were made in the form of simulation studies to arrive at a separation distance and also freeze the control laws.

The control laws for longitudinal and lateral loops were primarily designed for cruise phase mainly from stability considerations. The approach was to use similar control laws with minimum changes (only control gains changes) for the launch phase. The main criterion for the launch phase was to minimise the excursions in angle of attack and roll angle. To achieve this, the roll gain was increased six times and the pitch gain was reduced to 0.375 times as compared to the cruise values. Also, the time after launch until these changes are to be effected was arrived at as 2.3 s for roll and 4.5 s for pitch. The results of roll gain change are presented in Fig. 6.

An EBM giving rise to a pitch up moment corresponding to angle of attack development of 10° was considered to be the maximum value permissible. The results of simulation to decide the EBM limits for a configuration with tow body and pitch rate feedback are presented in Fig. 7. The longitudinal control scheme is depicted in Fig. 8. Without the pitch rate feedback during the launch phase, an EBM of ± 0.4° corresponding to ± 8 mm of separation distance was the limit. Only pitch position feedback was found to be adequate for the launch phase for the assumed tolerances before the first flight. Postflight simulation was carried out after each flight to match the trajectories to obtain the actual tolerances. After eight launches, due to

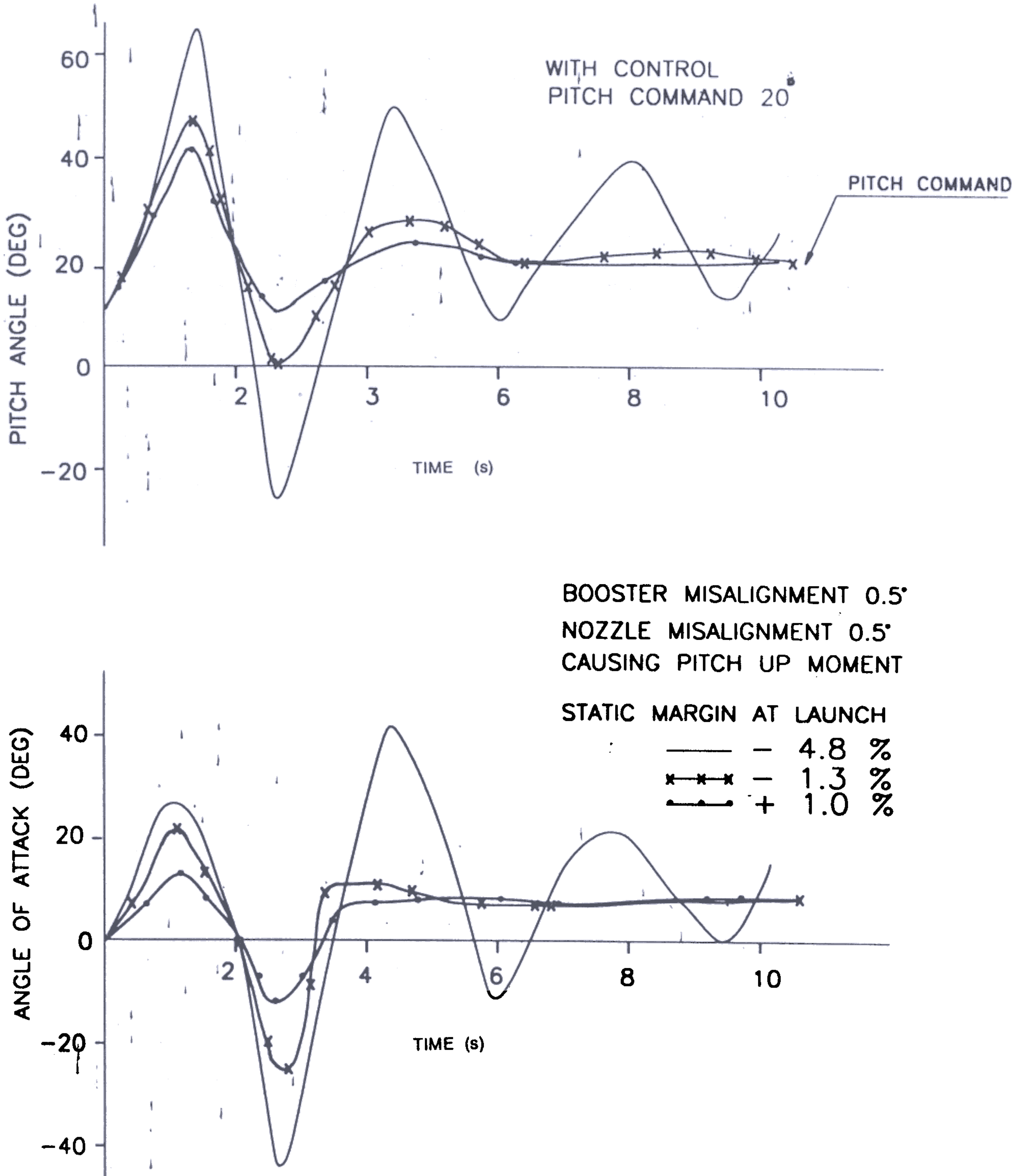

Figure 5. Effect of longitudinal stability on launch phase

failures observed at launch (resulting in pitch angle exceeding 45° in two cases leading to recovery), a review was carried out and it was found necessary to modify the design to cater for higher tolerances. Pitch rate feedback was introduced at this stage. With pitch rate feedback, the EBM tolerance was enhanced to ± 0.8° corresponding to ± 16 mm of separation distance for the clean configuration and

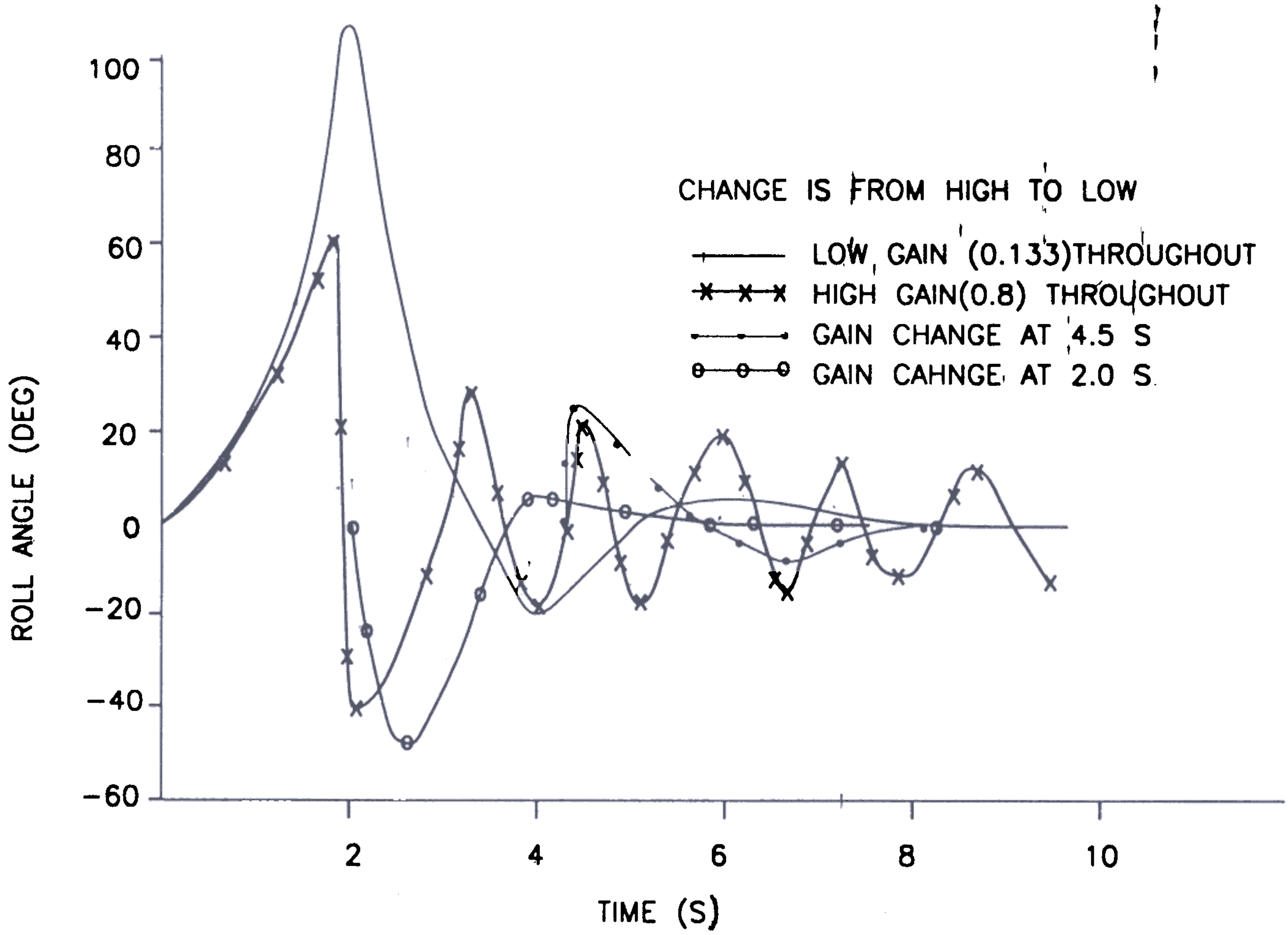

Figure 6. ***Lakshya*** **launch phase—roll gain changeover time**

± 1.2° in tow body configuration (high weight and mass moment of inertia). After this modification, the launch phase success has been improved in actual launches of *Lakshya* exceeding the reliability level of 95 per cent.

Dynamics of *Lakshya* on the zero length launcher is another aspect which has been studied through simulation. The air vehicle is supported on the launcher at the rear on two launcher pins restrained from forward movement by two shear pins (hold back device) and one support in front. Rotary movement about the pin is permitted. The vehicle can take off only if the following two conditions are satisfied:

(a) Component of force across the shear pin exceeds the strength of the shear pins, and

(b) The vertical component of thrust exceeds the weight of the vehicle.

Before these two conditions are satisfied, the vehicle may rotate around the rear support or the front support, depending on the moment developed due to weight, thrust and reactions at the support. The contribution of the dynamics on the launcher to the pitch angle developed at 2 s after launch determined the acceptable shear pin strength and the maximum rise time of booster thrust at ignition. Successful launch is achieved if the pitch angle remains within +45° to -6° and roll angle within ± 45°.

The results of simulation studies conducted to arrive at the limiting wind conditions at launch are presented in Fig. 9. The vehicle was launched with

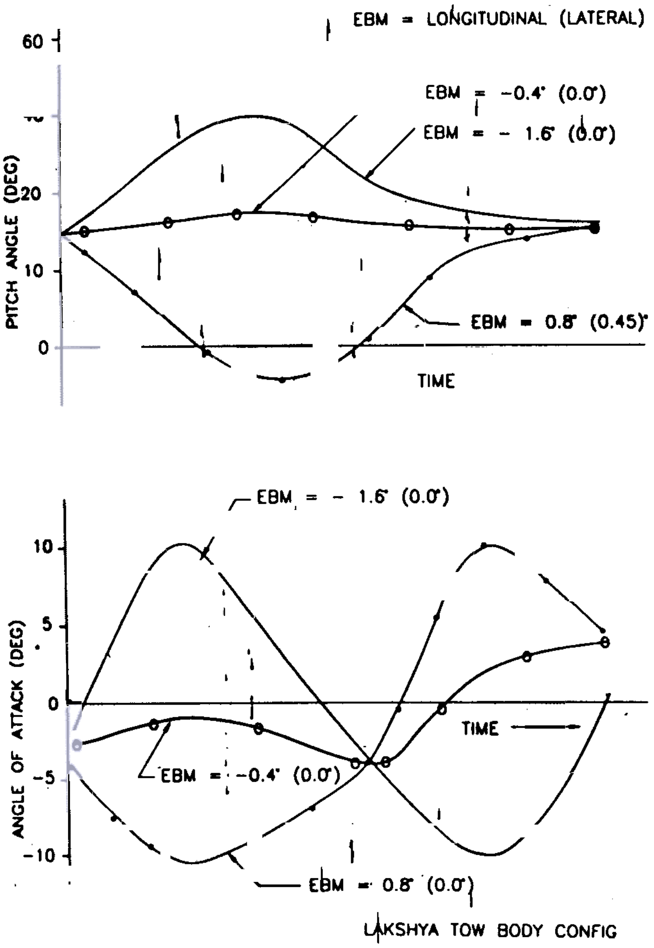

Figure 7. EBM limits—rate feedback in longitudinal control loop.

surface wind conditions in different directions and an EBM in both longitudinal and lateral planes was established. Allowing an EBM of ± 0.15° (separation distance of ± 3 mm) for wind conditions, the allowed wind envelope has been established. Successful launch has been accomplished at 14 knots cross-wind in a case of ship launch.

4.1.1 Ship Launch - Lakshya

Ship launch adds several other parameters to be included in simulation studies. Ship dynamics imposes a non-zero initial condition of attitude and their rates on *Lakshya* leading to build up of angle of attack, roll and sideslip angles. A sensitivity analysis made through simulation studies is used to prescribe a go-no-go criterion for acceptable ship motion at launch. The results of these studies are presented in Fig. 10.

4.2 *Lakshya* Tow System Dynamics

Lakshya carries subtargets under its wing pylons. On command, a subtarget (tow body) is deployed. Weapon training is carried out by weapon engaging of these subtargets. The cable drum carrying 1.1 km tow cable unwinds at a controlled rate, due to the braking system built into it, on deployment of the subtarget, to enable target towing. Simulation studies are made to estimate the following:

(a) Safe separation of tow body from aircraft wing pylon on deployment

(b) Cable unwinding dynamics—rate of cable payout

(c) Residual velocity at the instant of tow snatch, snatch load arising thereby

(d) Cable tension during normal tow, relative position of tow body w.r.t. towing aircraft

(e) Stability of tow cable and tow body, and

(f) ;—relative

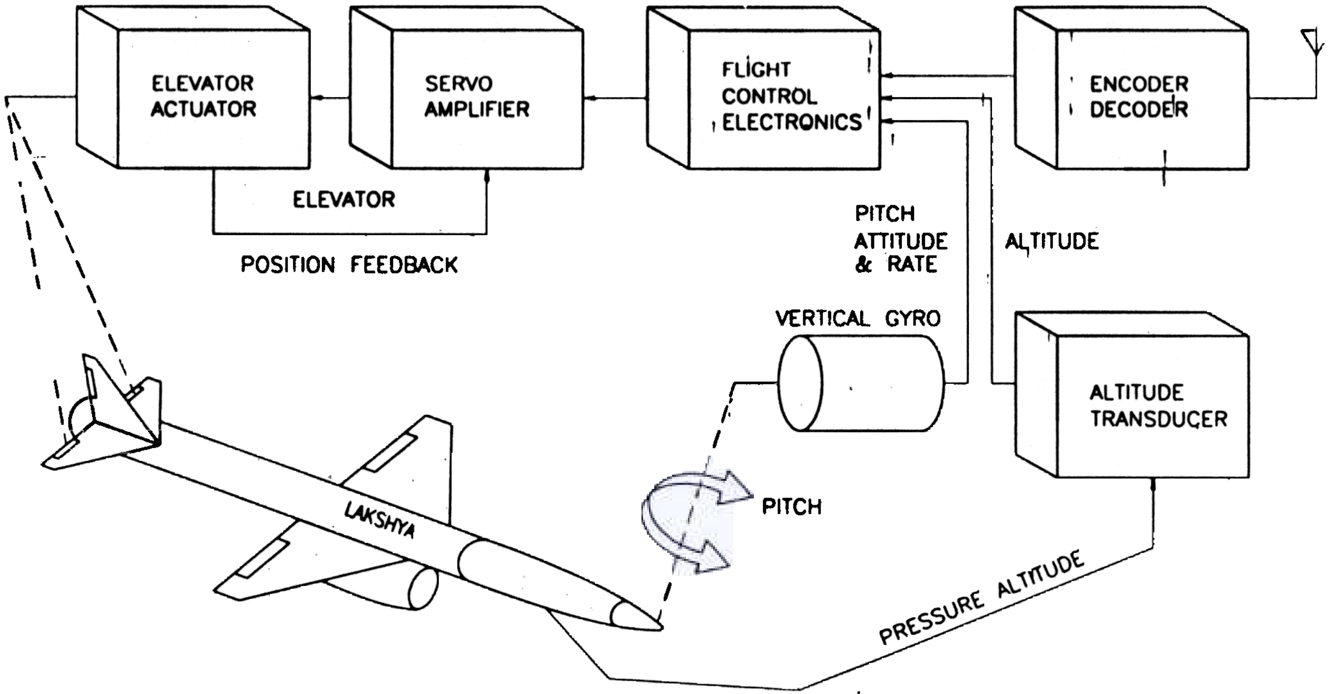

Figure 8. Longitudinal control scheme

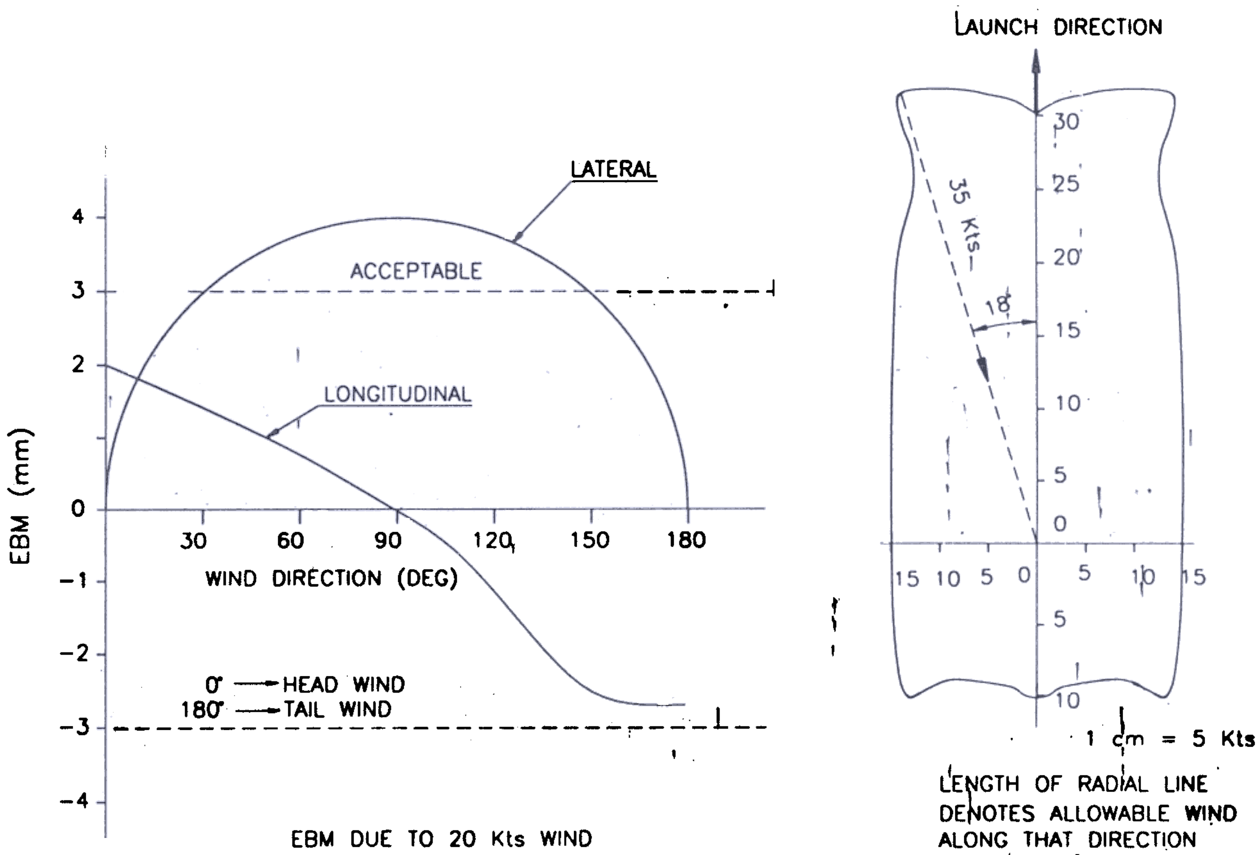

Figure 9. Allowable surface wind envelope launch phase—*Lakshya*

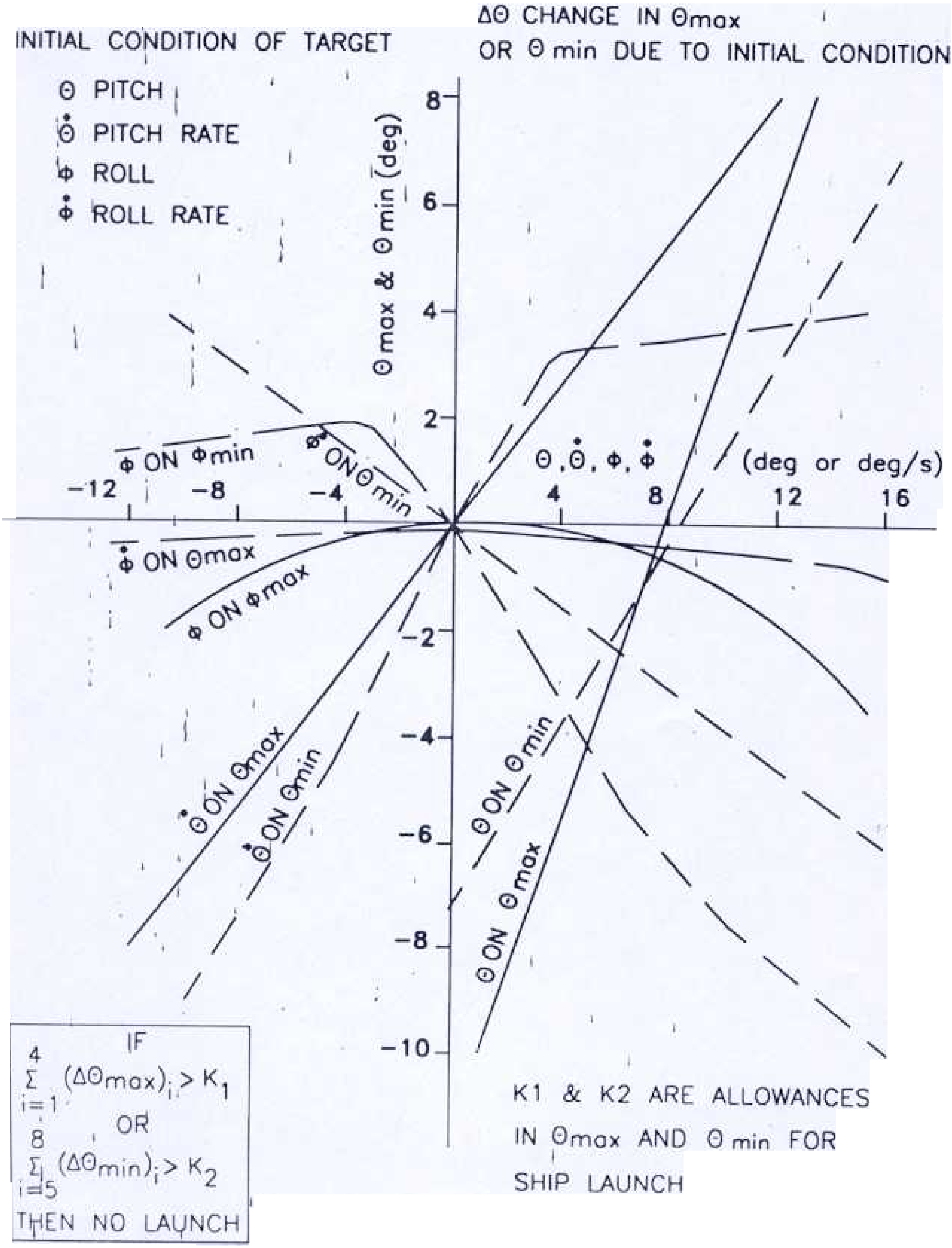

Figure 10. Effect of initial conditions on launch boundary

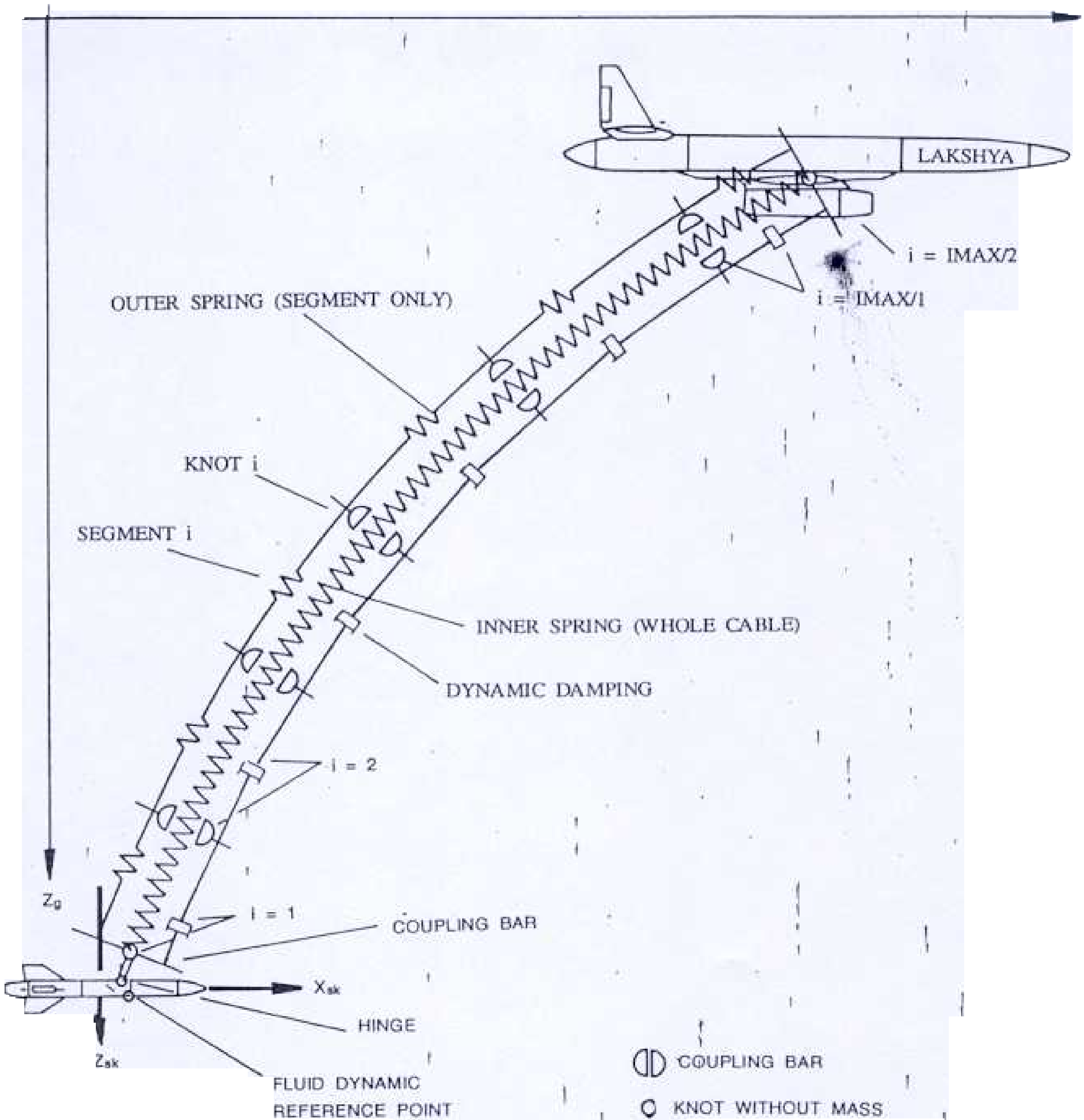

Figure 11. Model of towed system

model of a towed system is shown in Fig. 11. SEIS[21] and S1L3[22] computer programs for the two-dimensional stationary and three- dimensional dynamic motions of towed systems have been adapted for this analysis. In the model, the physical cable is replaced by a mathematical model consisting of concentrated mass points linked together by springs (called outer springs) and dampers, both without mass. Additionally, one continuous spring (called inner spring) is added to avoid numerical difficulties due to discretisation of mass distribution. Neither the inner nor the outer springs are able to transfer bending moments. The stiffness of the cable is distributed to the outer and

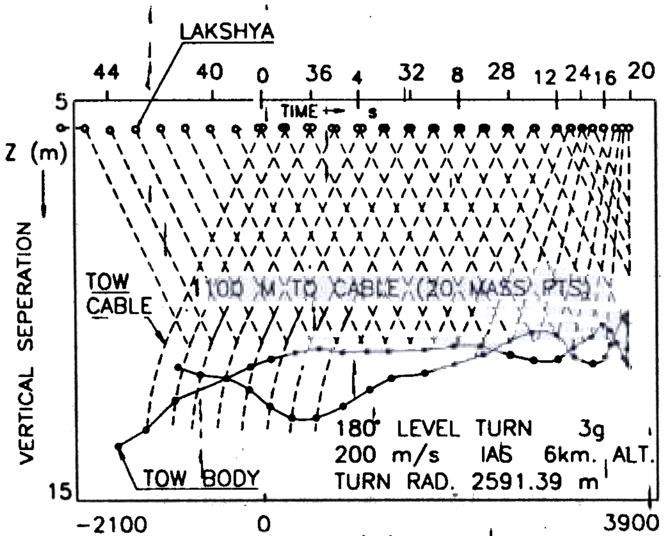

Figure 12. *Lakshya* **tow system trajectory (x,z)**

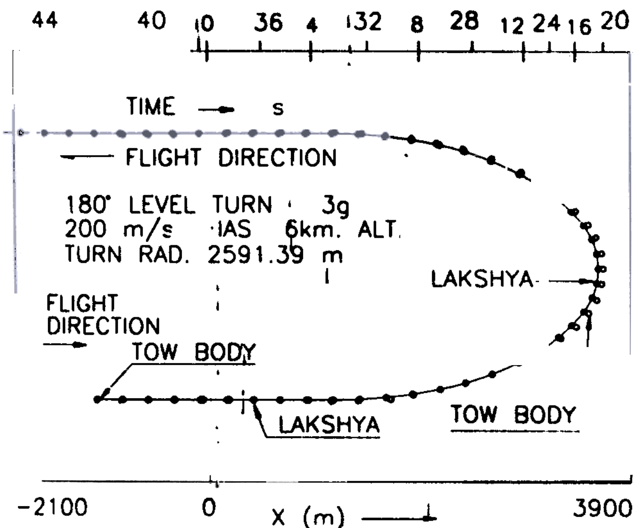

Figure 13. *Lakshya* **tow system trajectory (x,y)**

inner springs. To locate the mass points, the unstretched cable is divided into segments. The whole cable mass is distributed equally to all mass points.

One end of the cable is linked to the tow body by a coupling link at the end of a coupling bar. The other end is linked to *Lakshya*. The two coupling links and the mass points are called knots.

The fluid dynamic forces are determined for each half-segment by combining the normal forces and the tangential forces. Thereby, it is assumed

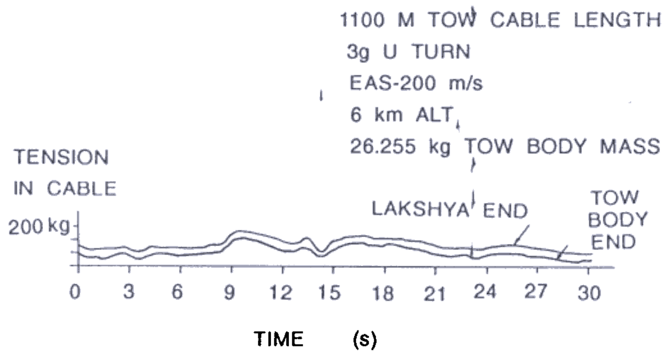

Figure 14. Tow body—cable system dynamics-cable tension

that these half-segments are rigid and have the same velocity as the neighbouring knots. The inner cable forces (tension and damping) and the fluid dynamic forces acting on the half-segments neighbouring the mass point determine its acceleration. Together with the dynamic behaviour of the tow body and the prescribed motion of *Lakshya*, the velocities and acceleration of the cable knots form a system of differential equations that can be integrated by the Runge-Kutta method, if the starting conditions are known with sufficient accuracy. The starting conditions for a three-dimensional case are determined from a solution of the two-dimensional case. The tow body fluid dynamic behaviour is known. The results of the simulation when *Lakshya* takes a 3 g turn are presented in Figs 12 and 13. It is seen that the tow body enters the turn at the point where *Lakshya* enters the turn. Tow body executes a larger radius of turn as compared to *Lakshya*. The tension in the tow cable during the 3 g turn is shown in Fig. 14. The tow cable tension and relative position of tow target w.r.t. the towing aircraft are plotted against time. Simulation studies have helped in laying down stability boundaries in terms of the towing speed of *Lakshya*. The effect of speed of *Lakshya* on tow body dynamics is shown in Fig. 15 and that of tow body drag on tow body dynamics in Fig. 16. During flight testing and evaluation, tow body instability was observed resulting in oscillations in the pitch plane of *Lakshya*. Solution was found through simulation. Additional drag plates on the tow body were installed, which helped in overcoming the problem. In tow system, tow cable

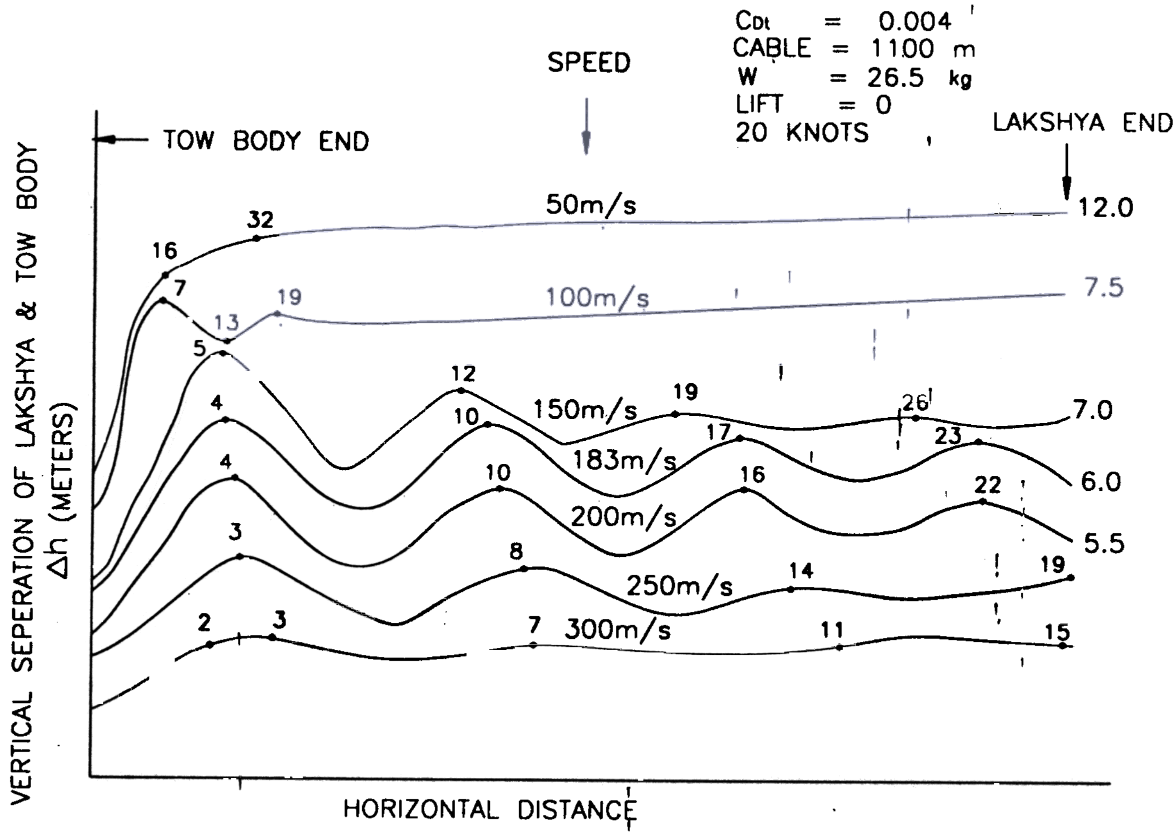

Figure 15. Effect of speed on tow body dynamics

has to be chosen with a very low factor of safety. Higher factors of safety are not achievable. Hence, the correct estimate of cable tension at the towing end is necessary. This is possible only through simulation studies.

4.3 Hardware In-line Simulation—*Nishant* Flight Control & Way Point Navigation

The dynamics of many of the systems of UAV is beyond the linear region and its simulation enables one to study the interaction of the dynamics of all the subsystems to provide the desired responses. Simulation is carried out during various phases of development of the system, viz., conceptual design, preliminary design, detailed design, system requirements verification, system validation, flight planning, postflight analysis and user training.

The block schematic of the most important flight system, viz., flight control mission & navigation system (FCMNS) of *Nishant* is shown

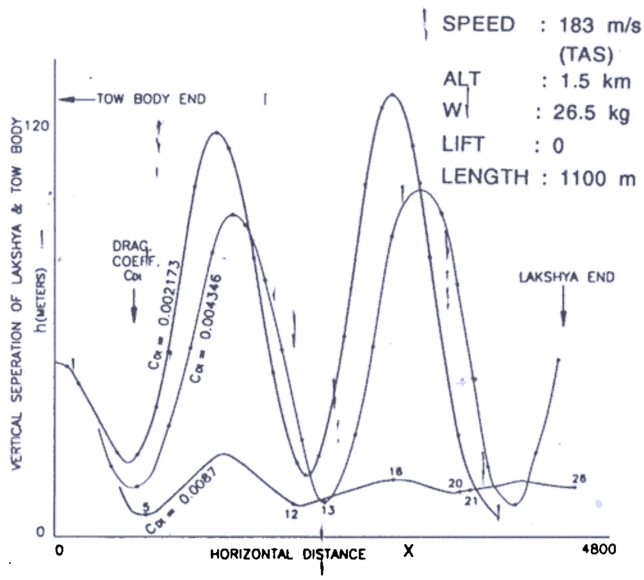

Figure 16. Effect of drag. coeff. C_{Dt} on tow body dynamics

in Fig. 17. The capability of the UAV to perform missions is enhanced by FCMNS, which gives it the reconfigurable mission capability. For non-skilled ground operators, the UAV is given

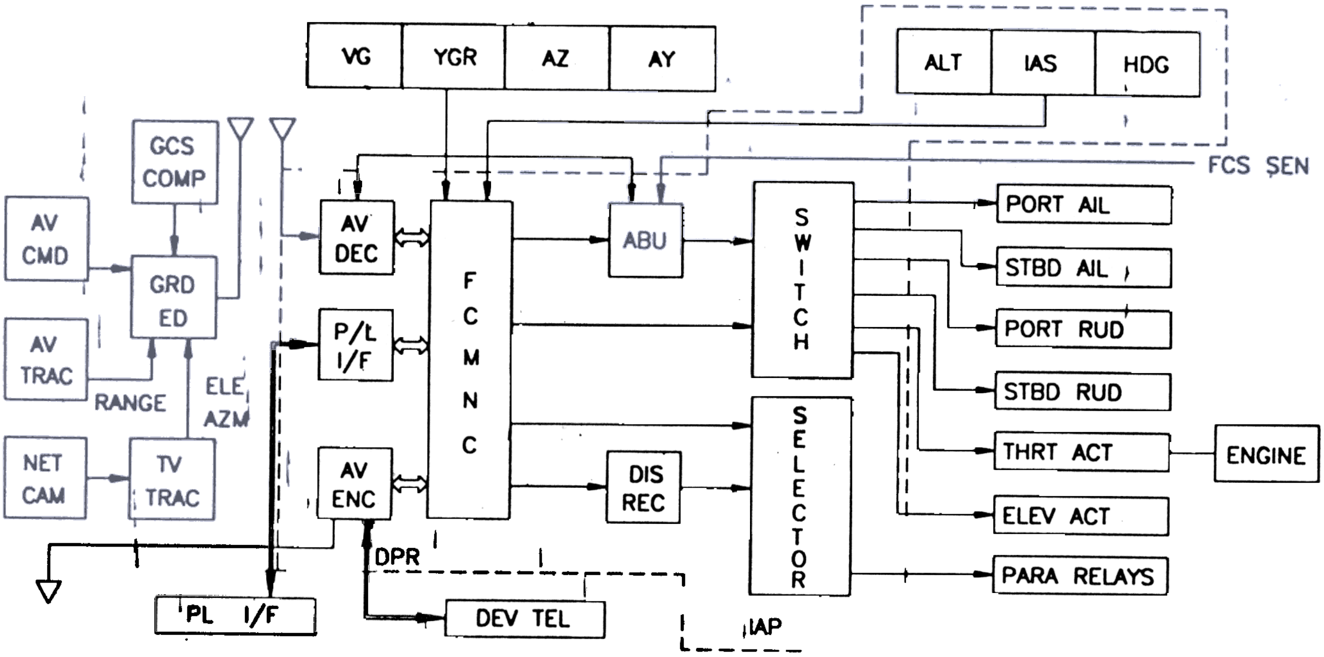

Figure 17. Flight control missio & navigation system—*Nishant*

sufficient onboard intelligence to present itself as a user-friendly system. FCMNS encompasses flight control, navigation sensors, a multiprocessor avionics computer called integrated avionics package (IAP) for datalink, mission, flight control and navigation functions, and flight control actuators. It provides the vehicle with capabilities such as automated launch, intelligent cruise and recovery, inflight reprogram- mable way point navigation, automated loiter programs over target, get-U-home, TV guided net recovery, etc.

Control and mission strategies for such a computer system are designed using a judicious combination of linear, non-linear design analysis, and off-line and real-time simulations. The hardware-in-the-loop simulation (HILS) is an important milestone in the design of this complex FCMNS for *Nishant*. A typical block schematic for the HILS used at various stages of the flight vehicle development is shown in Fig. 18. It shows the IAP running at 100 Hz commanding the control actuators. The surface deflections are fed back to a real-time computer, AD 100. The launch instant (t = 0) is synchronised in both IAP and AD 100. 'Full force' model of the aircraft, engine, atmospherics, sensor models, etc. resident in the computer AD-100 (running at 1 kHz) generates the responses (as in flight), e.g. roll, pitch, pressure altitude, IAS, heading, etc. These outputs are looped back into the IAP in an appropriate format, viz., analog heading is converted to RS232 and X, Y is converted into latitude and longitude of global positioning system (GPS) format and is sent through RS422. The IAP output signals, written on the dual port random access memory (DPRAM) of development telemetry, are monitored by a PC 486 using a digital I/O card. This PC offers a graphical display of the outputs and engineering values of these parameters. The vehicle flight modes and commands are generated by an uplink simulator which outputs the uplink data in a pulse code modulation (PCM) stream, which is decoded by the IAP and is written on to an internal DPRAM from where the flight control processor reads it. A strip chart recorder, plotter/printers complete the HILS setup. Using this setup or its lower versions, HILS is carried out for

- Control law and digital implementation studies, including software development,
- HILS with the integrated air vehicle system, prior to first flight of *Nishant*, and

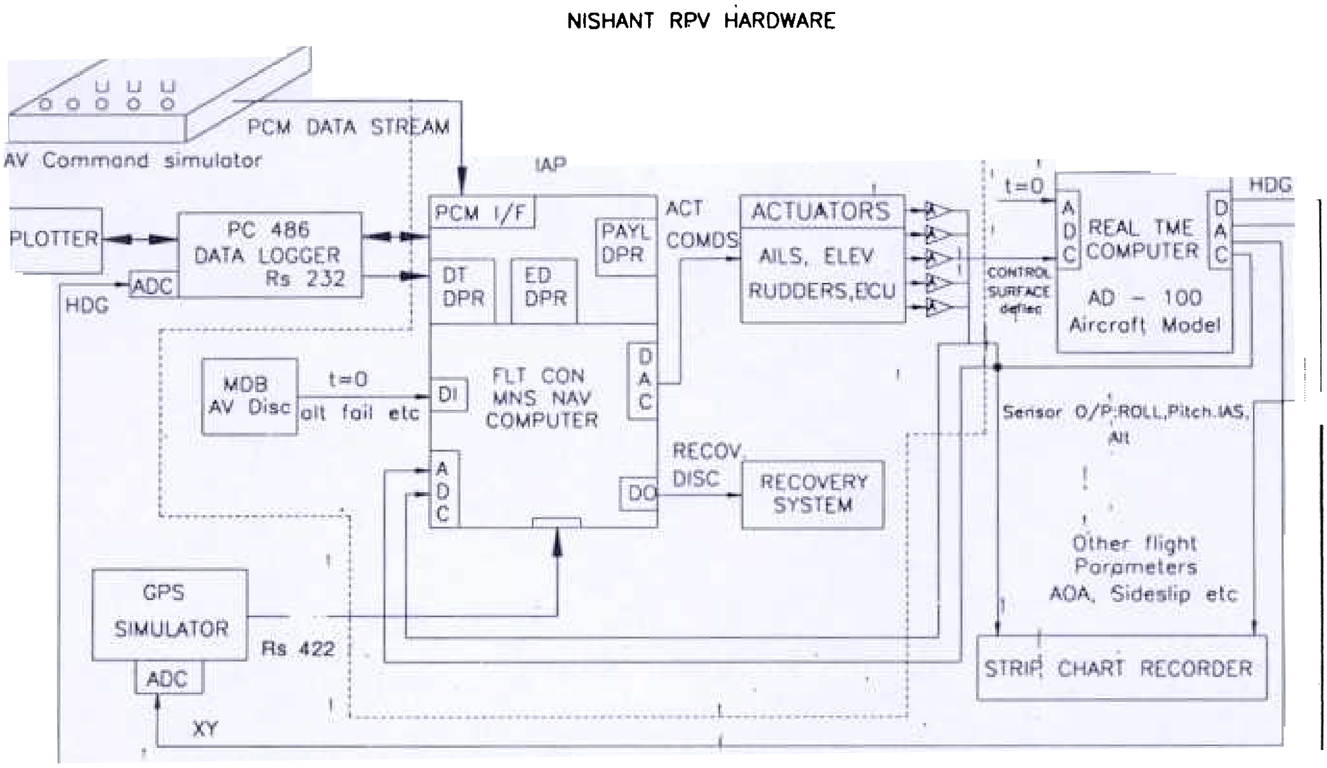

Figure 18. Block schematic of *Nishant* hardware-in-the-loop

HILS with integrated avionics package alone to validate the integrity of modified software, packages, as the development flights progress.

In the initial stages of *Nishant* development, the following problems were addressed through HILS :

Stability of the control system due to digital implementation,

Adequacy of actuator specification, performance,

Software validation in HILS module-by module, and

- Feedback to flight control processor hardware design regarding adequacy of memory size, clock speed, finite word length, overall loop noise, etc.

Nishant benefitted from HILS studies in this initial phase. The actuator rates were seen to be adequate; the actuator servo loop was tuned. The breadboard design of the flight control computer required hardware tuning, including building margins in its clock rate; gains in certain control loops had to be cut down to minimise overall system noise and also to avoid stability problems arising out of large amplitude responses of actuators. It gave immense confidence to the software designers and accelerated their work by providing online corrections to the modules designed by them by a timely midway feedback during the development process. It also helped in clarifying the system level understanding of software engineers and enabled them to be well prepared for the next stage of HILS carried out just before the first flight.

In the next stage, the integrated air vehicle was interfaced with the real-time computer AD-100. The actual datalink hardware was used to simulate the IAP and the actuators responded to drive the actual control surfaces. The simulation results were acquired in the same manner through the telemetry datalink as in a real flight. The aircraft model

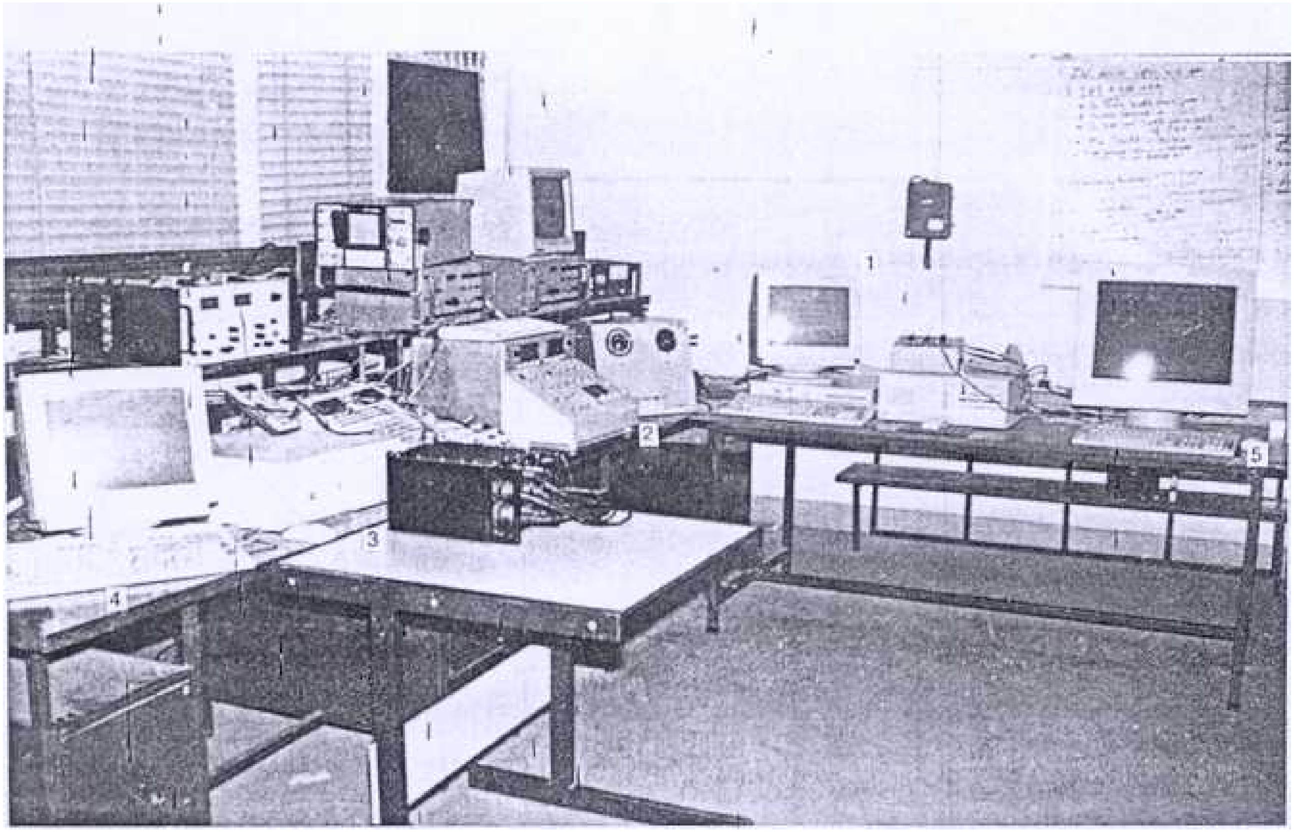

Figure 19. HILS test setup

resident in AD-100 responded to the piloting inputs from the ground-based pilot and IAP, as in flight.

Pilot-in-the-loop simulation enhanced the confidence of the pilot and the flight clearance team. It also allowed the air vehicle integration team to get an overall first hand knowledge of not only 'what' of the IAP hardware and software but also 'why' of it and how it influences the flight. This enabled smooth takeover by the integration team.

After the first flight of *Nishant*, software updates were made to include those originally planned and additional features dictated by flight tests as necessary to improve the performance of the system. This resulted in IAP configuration changes. Also, changes in datalink strategies resulted in changes in IAP configuration. To cater to the need for real-time simulation, the real-time software (of the aircraft model and other connected models running at 1 kHz) was also developed in a Pentium PC having necessary I/O capability. This simulation platform was very handy to carry out HILS in the work spot of IAP activity. Various other features like development of graphics for synthetic meters (using Lab Windows software), interface to simulate outputs of GPS (through RS422/RS232C) were added. HILS setup using Pentium, which is an effective method of developing a low cost system, is shown in Fig. 19. It shows a typical way point navigation track plot where the vehicle has been commanded to fly a way point track formed by four way points. The IAP software computes the leg to be flown, taking the current X and Y computed, the cross-track error and the distance to reach the way point. On reaching the way point, the next leg is automatically chosen and the vehicle is made to fly the next track. The capability of the IAP software to perform different exigency plans (due to GPS fail, uplink loss, etc.) while being in way point navigation is tested out in HILS.

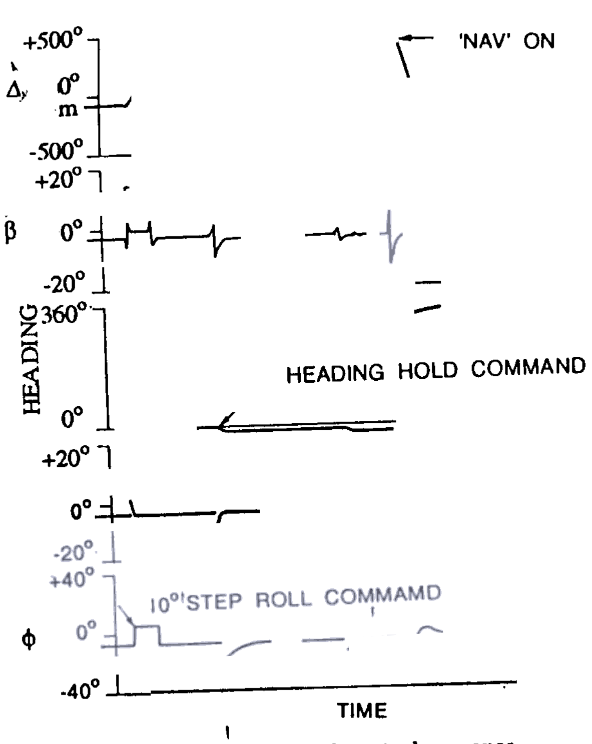

Figure 20. Lateral control response

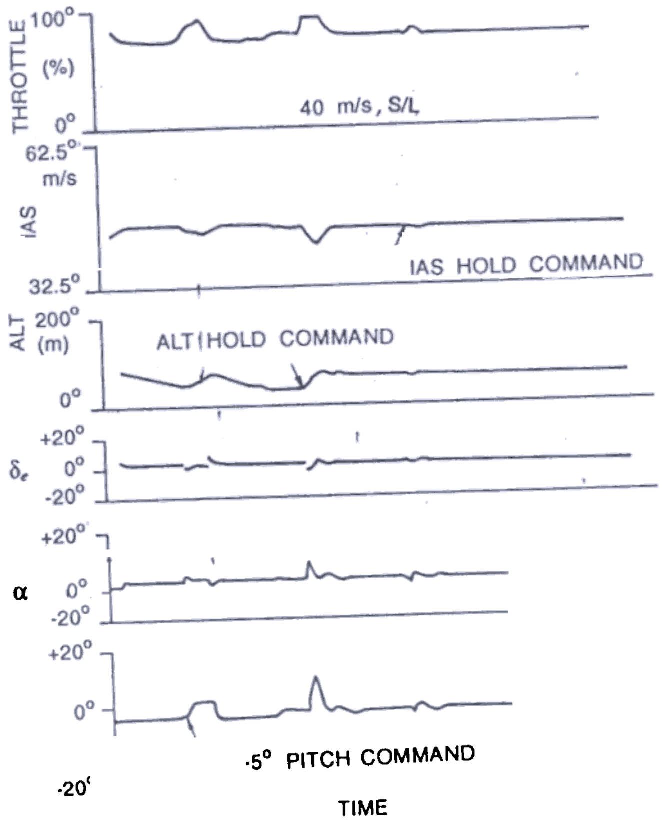

Figure 21. Longitudinal control response

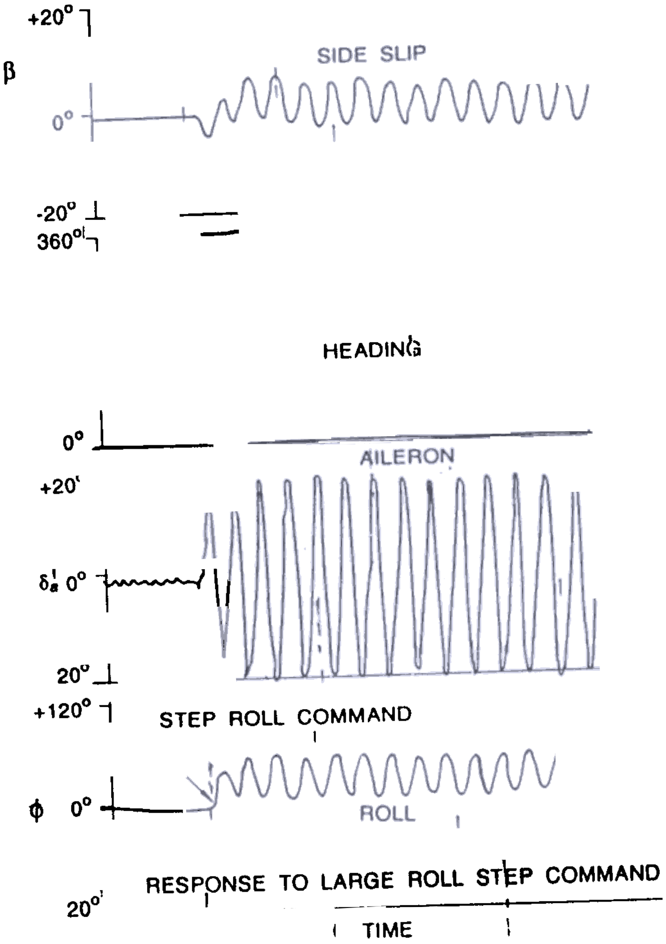

Figure 22. Roll control response

Using only the IAP, the software modules were validated in HILS to show the adequacy of stability of all the control loops. Results of longitudinal and lateral parameter responses are presented in Figs 20 and 21. The roll, pitch control loops, the altitude, indicated air speed (IAS) and heading hold loops, the cross-track error control loop (used in way point navigation) are seen to be stable. There are no singularities in the IAP software considering the typical combination of inputs noticed during HILS. The need for roll gain reduction to reduce the aileron actuator lag for large amplitude movement is evident from Figs 22 and 23. Figure 22 shows the effect of actuator lag resulting in roll oscillations and Fig. 23 shows the effect of roll gain reduction. Figure 24 shows the results with *Nishant*

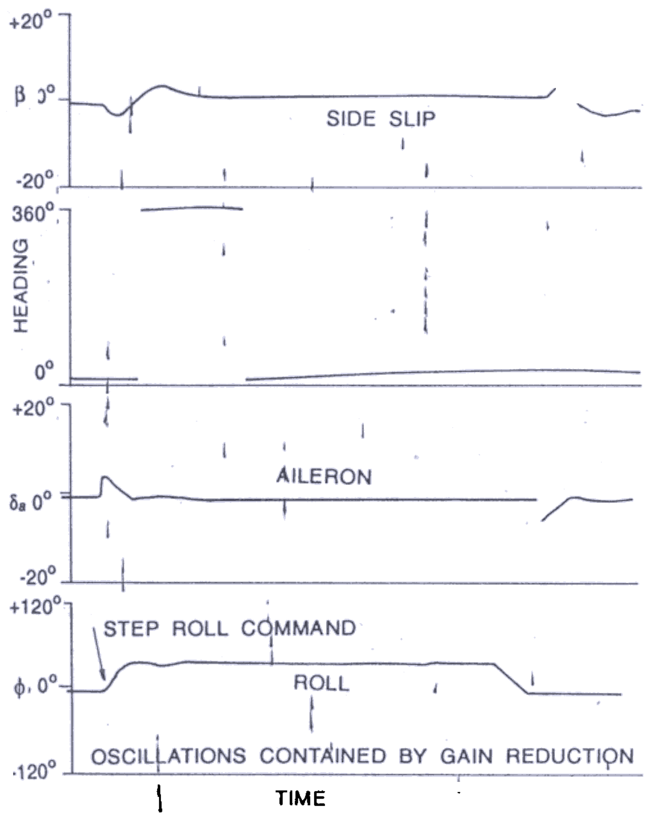

Figure 23. Effect of roll error gain reduction

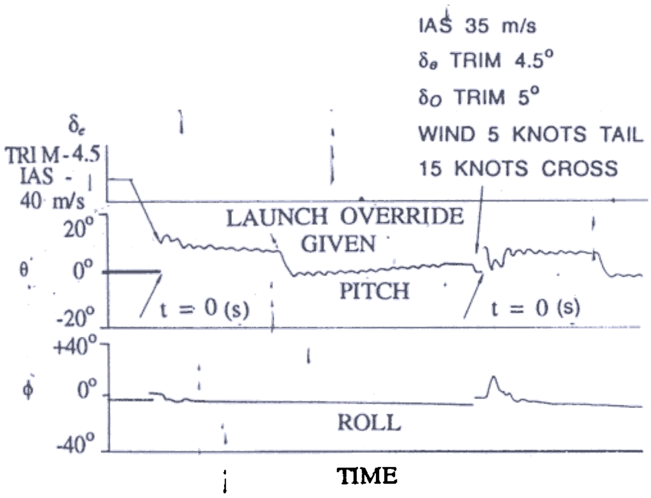

Figure 24. ***Nishant*** **HILS launch phase**

air vehicle system in the loop. It shows the response of pitch and roll in the launch phase up to forced end of launch by a launch override command from the control console. The pitch oscillations are due to the dead zone in the elevator actuation system. The effect of IAS error due to its feedback in the launch phase can be seen to reduce the pitch command in launch. Figure 25 shows roll and pitch responses in the uplink command loss mode, where the vehicle is put in a 15° orbit and climb at 5° pitch. The command loss was removed and a normal parachute recovery was commanded which has put the vehicle in open-loop by setting the control surfaces neutral. This leads to phugoid oscillation of the vehicle in the simulation which does not have the parachute dynamics in it.

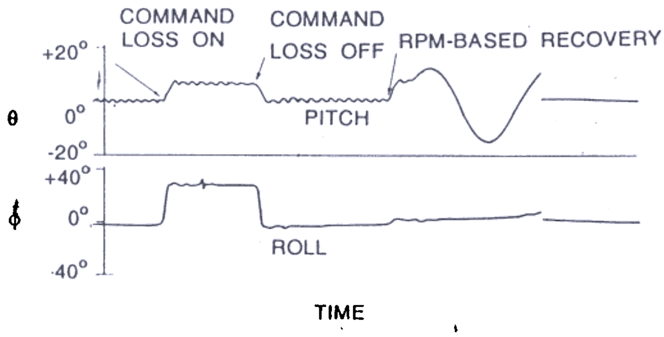

Figure 25. ***Nishant*** **HILS command loss situation**

The HILS has been extensively used in the development of *Nishant*. It has provided numerous feedbacks to correct the hardware and software design of IAP, the control laws, the mission requirements and even the other flight control hardware, such as actuators. Success of flight control system (FCS) performance in *Nishant* flights extended over several hours is largely attributed to the extensive HILS carried out.

5. ASSESSMENT OF INDIAN SCENARIO : UAV SIMULATION

Considerable strength in the following areas has been built up over the years:

(a) Air vehicle performance, stability and control analysis,

(b) Air vehicle control and navigation including HILS,

(c) Ground testing—computer-aided testing,

(d) Postflight analysis,

(e) Mission/route planning,

(f) Mission reconstruction, and

(g) Controller/pilot training.

The following areas are still in the embryonic stage.

(a) Cost and mission effectiveness

(b) Payload operator training simulator

(c) Total system simulation, including payload sensor modelling

(d) Mission planning—joint UAV manned aircraft operations and intelligence sifting system, and

(e) Intelligent mission planning using digital terrain data, line of sight of payload sensor, optimum route for survivability mission accomplishment, etc.

6. CONCLUSION

Simulation as a tool is essential for UAV design, development, testing and evaluation, and operation. Since man-in-the-loop is remotely placed, he cannot cater to all emergencies; therefore, more realistic simulation is necessary to reap the full benefits of the system. Modern weapon systems are making the battlefield into an extremely lethal environment in which real-time decisions and control are essential for survival. The importance of UAVs as a force multiplier has been recognised. It is found to be a cost-effective way to accomplish several missions with reduced risk to human life. Recent advances in speech technology and computer processing, advanced navigation, mission planning, sensor modelling and spatial databases, and artificial intelligence enables the operator to concentrate on mission goals and operations than mechanics. This has been made possible by the application of simulation techniques.

REFERENCES

1. Cromwell, M.H. A survey of simulation and test results for assessing RPV performance in a WBIC environment. NTIS, USA, July 1980, AD-A091603; SPC- 615.
2. Mauger, F.E. RPV operational effectiveness assessment methods. RPV Third International Conference, Royal Aeronautical Society and University of Bristol. 13-15 Sept 82, Bristol, U.K.
3. Jackson, A.W. & Rose, E.A. Electronic support measures for unmanned air vehicles. Shepherd Conferences, Second European Conference. 16-17 June 1994, Paris, France.
4. Cleveland, D. *et al*. RPV/self organising control demonstration system, Vol. II. Hardware description, system operation and maintenance and RPV simulation, NTIS, USA, Feb 1974. AD-781080.
5. Alpin, J. Digital simulation and control of the Machan UMA. Third International Conference on Remotely Piloted Vehicles, Royal Aeronautical Society and University of Bristol, 13-15 Sept 1982 Bristol, U.K.
6. Aslin, P.P.; Hatfield, J.V.; Oxtoby, A.J.A. & Patton, R.J. A real time simulation of a non-linear RPV incorporating head up type colour graphics. Fifth International Conference on RPVs, Royal Aeronautical Society and University of Bristol, 9-11 Sept 1985, Bristol, U.K.
7. Thomasson, P.G. The development of a PC based real-time simulator for UMAS. Tenth International Conference on RPVs, Royal Aeronautical Society and University of Bristol, 29-31 March 1993, Bristol, U.K.
8. Robertson, S.D. A real-time hardware-in-the-loop simulation of an unmanned aerial vehicle. NTIS, USA, Aug 1992; AD-A262477; WL-TR-93-3005.
9. Jenkins, P. Automated route planning using knowledge based systems. Sixth International Conference on RPVs, Royal Aeronautical Society and University of Bristol, 6-8 April 1987, Bristol, U.K.
10. Pierce, R. An intelligent mission planning and operations work station for our unmanned air vehicle. Fifteenth Annual Tech Symposium & Exhibition of the Association of Unmanned Vehicle systems, 6-8 June 1988, California, USA.

11. Mckay, L.M. Tactical aircraft mission planning system. Sixth Annual Tech. Symposium & Exhibition UAVs, 17-19 July 1989.

12. Cooper, B.G. The role of automated mission planning in synergestic management of UAV and piloted aircraft operations. Sixth Annual Tech. Symposium & Exhibition UAVs, 17-19 July 1989.

13. Donnenberg, K.; Batney, M. & Kuklen, C. An intelligence driven RPV mission planner. NTIS, USA, Aug 1989. N90-15924/5; AGARD-CP-436.

14. Phillips, W.H. Theoretical analysis of oscillations of a towed cable. USA, Jan 1949, NACA TN 1796.

15. Stevens, G.W.H. Factors affecting the design of a system for towing a body on a long length of wire. RAE-TN-Mech Engg 335, March 1961.

16. Hopkin, H.R. An approximate treatment of the stability of a towed unbanked object in a condition of zero lift. HMSO, UK, 1971. ARC R&M 3675.

17. Pierce, D. & Beecham, L.J. Some aerodynamic considerations of the flight characteristics of towing systems using long tow lines at high speeds. HMSO, UK, 1972. ARC-CP-1235.

18. Narkis, Y. Approximate solution for the shape of flexible towing cables. *J. Aircraft*, Sept 1977, 14(9), 923-25.

19. Narkis, Y. Deployment forces in towing systems. *J. Aircraft*, Feb 1978, 15(2), 123-24.

20. Karlsen, L.K. Large scale dynamics of long flexible cables towed through air, KTH Aero TN 61. Royal Institute of Technology, Sweden, 1981.

21 Bock, K.W. & Kapp, R. 'SEIS', computer program for the two-dimensional, stationary movement of towed systems. Dornier, Dec 1983.

22. Bock, K.W. & Kapp, R. 'S1L3', computer program for the three-dimensional, dynamic movement of towed systems, Dornier, Dec 1983.

Contributors

Shri PS Krishnan obtained his BTech and MS in Mechanical Engineering both from Indian Institute of Technology, Madras, in 1972 and 1981, respectively. He joined DRDO at the Defence Research & Development Laboratory (DRDL), Hyderabad in 1972. Since 1976, he has been working at ADE, Bangalore, as Scientist F. The areas of his work include design and development of inertial navigation systems for manned aircraft, development and testing of multiplexed FBW actuators for LCA, flight control systems for unmanned air vehicles, navigation, stabilised platforms, etc.

Shri PK Panda obtained his BE (Mechanical Engineering) and Post-Graduate Diploma in Space Engineering and Rocketry from Birla Institute of Technology, Ranchi, in 1966. He also did his ME (Aeronautical Engineering) from Indian Institute of Science, Bangalore, in 1970. He joined DRDO at ADE, Bangalore, in 1970. The areas of his work include aerodynamics, flight mechanics and controls for unmanned air vehicles.

Shri J Jayaraman obtained AMIE from Indian Institute of Science, Bangalore. He joined DRDO at the Aeronautical Development Establishment (ADE), Bangalore, in 1961. At present, he is the Group Director, Unmanned Air Vehicles Programme. The areas of his work include composite materials, mechanical system design, airframe design, and unmanned air vehicle systems. He received *Dr VM Ghatge Award* (1991) of the Aeronautical Society of India for his outstanding contributions in the field of Aeronautics. He is also the recipient of two *DRDO Cash Awards* for fluffy and reusable rocket pod development. He also got *DRDO Scientist of the Year Award* (1994) in Flight Sciences. He is the fellow of Institution of Engineers, India and member of Aeronautical Society of India.